6 Mitigation Measures and Solutions

Other sections of this document have introduced what we know about 6PPD and 6PPD-q, including toxicity, fate, transport, and environmental sampling methods. This section provides possible mitigation strategies and potential solutions. These include the following:

- Assessing chemical alternatives to 6PPD in tires
- Mitigating the impacts of 6PPD-q in the environment through pollution prevention, air particulate mitigation, and stormwater source control measures
- Evaluating what is known and unknown about remediating 6PPD-q if it persists in the environment

6.1 Introduction

Near-term and long-term solutions are being evaluated to reduce and prevent harm to aquatic organisms and ecosystems from 6PPD and 6PPD-q. Additionally, many of the proposed solutions could address human health impacts, if 6PPD-q is found to negatively affect human populations. This section describes the status of identifying potential alternatives to 6PPD in tires, evaluating and implementing mitigation strategies such as SCMs and air particulate mitigation, and determining the need for remediation of media that have been impacted by 6PPD-q. This section also provides a description of policies, regulations, and laws that could be considered by decision-makers when assessing potential 6PPD planning activities.

Some of the research described throughout this section addresses TWPs or TRWPs instead of 6PPD-q explicitly. Because 6PPD-q was discovered very recently, TWP and TRWP research can be a helpful resource for assessing potential mitigation effectiveness. Additionally, the TWP and TRWP research studies included in this document were limited to studies where preventing or mitigating TRWP pollution is also likely to address 6PPD and 6PPD-q.

6.2 Tire Alternatives and Innovation

6PPD is a widely used anti-degradant found within all automotive tires and serves a critical role in tire safety and performance. 6PPD protects the components of the tire from degrading via ozone, oxygen, thermal degradation, and mechanical fatigue. Eliminating 6PPD in tires without an available alternative that offers comparable performance would compromise tire safety.

A process to identify potential alternatives to 6PPD in tires that do not have equivalent or worse hazard traits or other regrettable tradeoffs is known as an alternatives assessment. The National Research Council defines an alternatives assessment (AA) as the “process for identifying and comparing potential chemical and nonchemical alternatives that could replace chemicals of concern on the basis of their hazards, comparative exposure, performance, and economic viability” ([National Research Council 2014, p.13]). The careful consideration of replacement chemicals and other types of alternatives can help avoid regrettable substitutes.

Any potential less-toxic alternative for use in tires would need to be tested for multiple characteristics before being deployed. A chemical alternative to 6PPD would have to be compatible with other tire materials, including rubber, the manufacturing process, and the vulcanization process and provide protection from ozone and oxygen for the life of the tire.

Potential alternatives to 6PPD in tires would need to meet relevant regulatory requirements to ultimately be brought to market. Chemicals that will be entered into commerce in the United States are regulated by USEPA under the TSCA. Under TSCA, USEPA “…evaluates potential risks from new and existing chemicals and acts to address any unreasonable risks chemicals may have on human health and the environment” (USEPA 2023c). New tires are also regulated for safety and performance by the Department of Transportation National Highway Traffic Safety Administration under the Federal Motor Vehicle Safety Standards.

6.2.1 Potential 6PPD Alternatives

Multiple recent and ongoing efforts address the identification of potential alternatives to 6PPD in tires. The examples below are not an exhaustive list:

California’s Safer Consumer Products Program**:** California’s DTSC began regulating 6PPD in motor vehicles tires through the Safer Consumer Products Program on October 1, 2023. DTSC included a section on potential alternatives to 6PPD as part of its Priority Product Report and on its website, which also discusses reducing the formation of TRWP and the release of 6PPD-q via other methods. These include coatings to prevent ozone from reaching tires, airless/nonpneumatic tires, and spring tires. The DTSC regulations require each tire manufacturer to conduct an alternatives analysis in order to continue selling tires in California. In their alternatives analyses, tire manufacturers are required to analyze and compare the hazards and adverse environmental impacts of potential alternatives to 6PPD. The reports are required to evaluate the benefits and tradeoffs of replacing 6PPD. This process leverages the technical expertise of the tire manufacturers and enables them to meet vehicle safety and consumer product safety requirements while providing a rigorous, transparent, and scientific framework for evaluating and comparing potential alternatives to 6PPD. The tire manufacturers' preliminary AAs were submitted on March 29, 2024; these reports can be viewed here. This submittal will be followed by a more in-depth analysis of several promising alternatives. Final alternatives analysis reports are due in mid-2025, but DTSC may grant requests for extensions of the submittal deadline to a later date. Many of the proposed alternatives are other PPD chemicals; although, some companies propose other types of chemicals, such as specialized graphene and lignin.

Washington's 6PPD Action Plan and Safer Products for Washington program: Washington State is developing a statewide action plan, funding research to fill in data gaps, conducting an AA to assess other potential tire anti-degradants, and developing specific data requirements and standards to assess the hazards of the alternatives. "Technical Memo: Assessment of Potential Hazards of 6PPD and Alternatives" (Washington State Department of Ecology 2021[2UEJGNJ2] Washington State Department of Ecology. 2021. "Technical Memo: Assessment of Potential Hazards of 6PPD and Alternatives." https://www.ezview.wa.gov/Portals/_1962/Documents/6ppd/6PPD%20Alternatives%20Technical%20Memo.pdf.) provides an overview of known toxicological hazards of chemicals that are or have been used as anti-degradants in tires. The Safer Products for Washington program, which aims to reduce toxic chemicals in consumer products, identified 6PPD as a priority chemical.

Collaborative Innovation Forum: Washington and California have both supported the "Collaborative Innovation Forum: Functional Substitutes to 6PPD in Tires" (Sustainable Chemistry Catalyst 2023[8F7X8M2J] Sustainable Chemistry Catalyst. 2023. "Collaborative Innovation Forum: Functional Substitutes to 6PPD in Tires. Meeting Report." https://static1.squarespace.com/static/633b3dd6649ed62926ed7271/t/63ee6cd15eb30a0fd4f0630d/1676569810601/6PPD-in-Tires-Innovation-Forum-Meeting-Report.pdf.), which is developing a road map for identifying safer alternatives to 6PPD.

University of California, Berkeley Study: A 2021 University of California, Berkeley study investigated alternative PPDs and several other options, including modification of 6PPD to prevent quinone formation, food preservatives, lignin-derived chemicals, and alternative rubber formulation, which would require less protection against ozone. The project did not evaluate the alternatives for their potential toxicity and viability for use in tires.

Flexsys and USDA: In April 2023, Flexsys, a major 6PPD manufacturer, and the U.S. Department of Agriculture (USDA) announced a Cooperative Research and Development Agreement to design and evaluate novel alternatives to 6PPD.

USEPA Small Business Innovation Research: USEPA is providing funding to support development and commercialization of rubber anti-degradant technologies for tires and other rubber products that are of lower concern for human health and the environment through the 2024 Small Business Innovation Research program.

USTMA and USGS: The USTMA announced in 2023 that it is partnering with the USGS on a research project to assess and refine methods of evaluating potential alternatives to 6PPD for use in tires. They are working to establish a new method for in vitro toxicity testing of alternatives to 6PPD through a Collaborative Research and Development Agreement.

The following case study describes another source control effort. It focuses on reducing copper in brake pads. This case study describes the partnerships formed for this effort and some of the challenges faced when addressing contamination through source control.

CASE STUDY: Source Control for Roadway Stormwater Pollutants

Stormwater pollutants from vehicles can be addressed through source control initiatives. Source control means reducing or removing the pollutant from its source, rather than treating or removing it once it is released. The following case study on copper brake pads demonstrates how states and industry can work with the USEPA to reduce stormwater pollutants.

Copper at elevated concentrations in stormwater runoff is highly toxic to fish and other aquatic organisms. Copper can interfere with a fish's sense of smell, thereby harming the ability of migratory species—especially salmon—to navigate to their spawning grounds and making them more vulnerable to predation. Other studies show that young salmon are especially vulnerable to the toxic effects of copper. Since the 1990s, states and municipalities have recognized that vehicle brake pads are a significant source of copper contamination in urban stormwater runoff. As they wear, brake pads release fine dust containing copper and other metals; this dust is deposited on roadways where stormwater can suspend and transport it to streams and other waterways.

To address the copper stormwater contamination problem, the states of California and Washington enacted legislation in 2010 to phase out the use of copper in vehicle brake pads and shoes by 2025. Washington adopted the “Better Brakes Law” (Chapter 70A.340 RCW) that phases out the sale of brake material containing copper exceeding 5% (by weight) by 2021 and requires a further reduction to no more than 0.5% (by weight) if low-copper alternatives are available. Similarly, in 2010 California adopted its Brake Pad Law (SB346) with the same deadline for reducing copper concentrations to no more than 5% (by weight) by 2021; California also set a 2025 deadline for limiting copper concentrations to no more than 0.5% (by weight).

Both statutes addressed the concern over finding suitable alternatives to copper brake pads by directing the state regulatory agencies to study alternatives and determine whether low-copper pads were available and whether extensions of the deadlines were needed. The statutes also addressed the problem of stranding inventories of copper brake pads exceeding limits by allowing manufacturers to sell their existing inventories of noncompliant materials after the deadlines.

Spurred by the laws in California and Washington, in January 2015 the Brake Manufacturers Council (BMC), Motor & Equipment Manufacturers Association (MEMA), USEPA, and the Environmental Council of the States signed a memorandum of agreement to reduce the use of copper and other materials in motor vehicle brake pads(“Memorandum of Understanding on Copper Mitigation in Watersheds and Waterways between U.S. Environmental Protection Agency and Motor & Equipment Manufacturers Association, Automotive Aftermarket Suppliers Association, Brake Manufacturers Council and Heavy Duty Manufacturers Association and Auto Care Association and Alliance of Automobile Manufacturers and Association of Global Automakers, Inc. and Truck and Engine Manufacturers Association and Environmental Council of the States” 2015[27XI297B] “Memorandum of Understanding on Copper Mitigation in Watersheds and Waterways between U.S. Environmental Protection Agency and Motor & Equipment Manufacturers Association, Automotive Aftermarket Suppliers Association, Brake Manufacturers Council and Heavy Duty Manufacturers Association and Auto Care Association and Alliance of Automobile Manufacturers and Association of Global Automakers, Inc. and Truck and Engine Manufacturers Association and Environmental Council of the States.” 2015. https://www.epa.gov/npdes/memorandum-understanding-copper-mitigation-watershed-and-waterways.). Specifically, the agreement calls for reducing copper in brake pads to less than 5% by weight in 2021 and no more than 0.5% by 2025. In addition to copper, this initiative reduces mercury, lead, cadmium, asbestiform fibers, and chromium-six salts in motor vehicle brake pads. The agreement also included guidance related to making and labeling friction-material packaging and products (Figure 6-1). The LeafMark™ certification marks shown in the figure are a visual representation of the allowable concentration of copper, selected other metals, and asbestiform fibers in brake pads for each environmental compliance level (A, B, or N). The LeafMark™ certification mark is owned by MEMA and BMC and is not in any way affiliated with USEPA.

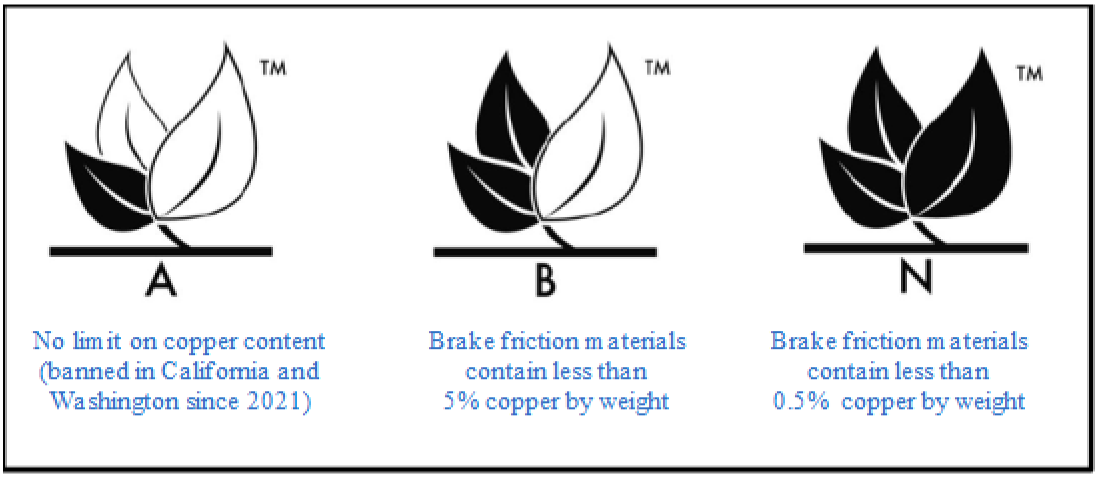

Figure 6-1. LeafMark™ label symbols for friction-material packaging.

Source: LeafMark™ used with permission from MEMA.

In a 2022 report to the legislature, the California regulatory agencies reported that more than 60% of brake pads on the market contained less than 0.5% copper (by weight). The report estimated this led to a 28% decrease in copper entering urban stormwater runoff.

6.2.2 Hazard Assessment

A technical memorandum released in November 2021 from WA Ecology under the direction of the Washington State Legislature evaluated the known hazards of several potential alternatives, including several other PPDs. Although some potential alternatives were identified with lower hazard than 6PPD, at the time of the report none of the alternatives had been tested for toxicity to coho salmon. In addition, the suitability of the alternatives from a performance perspective compared to 6PPD was questioned in comments by industry members.

6.2.3 Hazard Criteria

No state or federal regulations currently specify toxicity criteria for potential alternatives to 6PPD, and this lack of regulatory certainty may hinder the development of alternatives to 6PPD. In an effort to address this problem, WA Ecology has released the hazard criteria that they will be using to define “safer” for their AA. The hazard criteria guidance uses the Safer Products for Washington criteria, which includes several human health and environmental health criteria like carcinogenicity, reproductive or developmental toxicity, skin or respiratory sensitization, acute or chronic aquatic toxicity, and bioaccumulation. In addition to these criteria, WA Ecology’s guidance includes additional aquatic toxicity criteria. First, to be considered a safer alternative to 6PPD, toxicity testing must be performed on coho salmon, rainbow trout, and two other trophic levels of test organisms such as a forage fish or macroinvertebrates. This testing must be done for alternative chemicals and their degradants after exposure to ozone. Since it is known that these chemicals will find their way into salmon-bearing streams, WA Ecology has also set an upper limit on the toxicity of these potential alternatives; the LC_{50}, must be greater than 0.1 mg/L (WA Ecology, n.d.[IHA5X6FP] WA Ecology. n.d. “6PPD - Washington State Department of Ecology.” Accessed July 25, 2024. https://ecology.wa.gov/waste-toxics/reducing-toxic-chemicals/addressing-priority-toxic-chemicals/6ppd.).

6.3 Mitigation Practices

This section describes many efforts to understand how to mitigate the effects of 6PPD-q on the environment by preventing, treating, or managing 6PPD-q before it causes negative environmental impacts. Mitigation actions include pollution prevention efforts and control measures for stormwater and air quality mitigation.

6.3.1 Pollution Prevention

USEPA (1999) provides a universal reference on pollution prevention, including a description of a multi-component program that can be implemented to prevent pollutants from entering the environment or reaching sensitive receptors. Implemented actions could involve physically separating pollution sources from receiving waters and/or managing activities that are pollution sources. Some entities, such as WA Ecology, refer to this type of mitigation as source control. The Washington State Stormwater Management Manuals define source control measures as: “A structure or operation intended to prevent pollutants from coming into contact with stormwater through physical separation of areas or careful management of activities that are sources of pollutants.”

The following information describes the current state of knowledge on the predicted potential pollution prevention measures that could be used to mitigate 6PPD-q in stormwater. This information is provided for general information and is not intended to replace site-specific evaluation of the appropriateness and feasibility of these or any other potential pollution prevention measures.

6.3.1.1 Driver Behavior

Driver behavior has a direct impact on the generation rate of TRWP. Frequent or abrupt acceleration and braking, as well as sharp high-speed turns can all increase tire wear rate (Zhang et al. 2024[V4RZKMVQ] Zhang, Qijun, Tiange Fang, Zhengyu Men, Ning Wei, Jianfei Peng, Tianqiang Du, Xinfeng Zhang, Yao Ma, Lin Wu, and Hongjun Mao. 2024. “Direct Measurement of Brake and Tire Wear Particles Based on Real-World Driving Conditions.” Science of the Total Environment 906:167764. https://doi.org/10.1016/j.scitotenv.2023.167764.). Proper tire inflation also plays a role in the wear rate of passenger vehicle and heavy truck and bus tires. Research by Verschoor and de Valk (Verschoor and De Valk 2018[Z9893S5Z] Verschoor, A.J., and E. De Valk. 2018. “Potential Measures against Microplastic Emissions to Water.” Rijksinstituut voor Volksgezondheid en Milieu. https://rivm.openrepository.com/rivm/handle/10029/622058, DOI:10.21945/RIVM-2017-0193.) indicate that TRWP emissions could potentially be reduced by 14% through the use of tire pressure monitors. Improper vehicle suspension alignment can also increase tire wear rates. Education regarding driver practices and vehicle maintenance can reduce the generation rate of TRWPs (AcuTread 2017[TTV33B74] AcuTread. 2017. “Tire Wear | AcuTread Tire Service | Retreading Manufacturers.” AcuTread (blog). February 28, 2017. https://acutread.com/resources/post/factors-influence-tire-wear/.), which may reduce 6PPD-q in the environment.

The “Puget Sound Starts Here” campaign (September–October 2023) was an effort in WA State to cultivate more awareness over how proper tire care can reduce 6PPD-q in stormwater. The campaign used the Terry the Tire mascot as an attention grabber, with message recall, videos, and social media posts all used to show how easy it is to check and inflate your tires. Figure 6-2 presents an example of how Terry the Tire was used in this campaign.

Figure 6-2. Example of how Terry the Tire is used in the “Puget Sound Starts Here” campaign.

6.3.1.2 *Driving Alternatives*

According to U.S. Department of Energy statistics from 2020, 75% of people in the United States drive a personal vehicle to work, 9% carpool in a personal vehicle, 7% work from home, 5% take public transit, 3% walk, and 1% bike to work (Center for Sustainable Systems, University of Michigan 2023[ZD76DM9U] Center for Sustainable Systems, University of Michigan. 2023. “Personal Transportation Factsheet.” Center for Sustainable Systems. July 2023. https://css.umich.edu/publications/factsheets/mobility/personal-transportation-factsheet.). Increasing transportation options and reducing barriers to accessing those options reduces TRWP pollution in the environment through the reduced use of personal vehicles. Additional alternatives to driving personal vehicles include increased telework options and increasing the number of walkable and accessible communities.

6.3.1.3 *Vehicle Design*

Vehicle characteristics that have an impact on tire wear include mass, load and load distribution, type and condition of suspension, available torque, and drive wheel location (Robbins and Tran 2015[R78QJLSP] Robbins, Mary M., and Nam Tran. 2015. “Literature Review: The Impact of Pavement Roughness on Vehicle Operating Costs.” NCAT Report 15-02. Auburn University, Auburn, Alabama: National Center for Asphalt Technology.). (See also USTMA for additional information.)

The average electric vehicle is heavier due to the weight of the batteries and has higher torque than its gas-powered counterpart (Liu et al. 2021[XDW2JS3N] Liu, Ye, Haibo Chen, Jianbing Gao, Ying Li, Kaushali Dave, Junyan Chen, Matteo Federici, and Guido Perricone. 2021. “Comparative Analysis of Non-Exhaust Airborne Particles from Electric and Internal Combustion Engine Vehicles.” Journal of Hazardous Materials 420:126626. https://doi.org/10.1016/j.jhazmat.2021.126626.). Though electric vehicles are seen as a promising alternative for climate change and some air pollution mitigation, it is unclear whether electric vehicles will result in increased or decreased tire wear (OECD 2021[85YRE5NG] OECD. 2021. “Mitigation Technologies and Best Practices.” In Policies to Reduce Microplastics Pollution in Water. OECD. https://doi.org/10.1787/156bdfa5-en.; Liu et al. 2021[XDW2JS3N] Liu, Ye, Haibo Chen, Jianbing Gao, Ying Li, Kaushali Dave, Junyan Chen, Matteo Federici, and Guido Perricone. 2021. “Comparative Analysis of Non-Exhaust Airborne Particles from Electric and Internal Combustion Engine Vehicles.” Journal of Hazardous Materials 420:126626. https://doi.org/10.1016/j.jhazmat.2021.126626.). How electric vehicle technologies affect tire wear is a complex and often vehicle-specific issue. It is unknown whether there are current efforts underway to reduce tire wear through modification of vehicle load distribution, type and condition of suspension, or drive wheel location.

Several companies are developing devices to capture TRWP as they are generated. These include The Tyre Collective, GelbKo, and Nexen’s Pureback tire. Currently, none of these broader types of collection techniques are commercially available, and the extent to which they would reduce 6PPD and 6PPD-q release to the environment remains to be seen.

6.3.1.4 *Road Surfaces*

Road surface composition could affect tire wear, and the roughness and frictional characteristics of a paved surface might play an important role in tire wear. An improvement in roughness was found in asphalt rubber–asphaltic concrete friction courses over Portland cement concrete, resulting in reduced tire wear (Allen, Alexandrova, and Kaloush 2006[P4VNFFZD] Allen, Jonathan O., Olga Alexandrova, and Kamil E. Kaloush. 2006. “Tire Wear Emissions for Asphalt Rubber and Portland Cement Concrete Pavement Surfaces.” Arizona State University. https://azdot.gov/sites/default/files/2019/05/tire-wear-emissions-for-asphalt-rubber-portland-cement-concrete-April2006.pdf.). Nedrich (Nedrich 2022[7LRY36T6] Nedrich, Sara. 2022. Preliminary Investigation of the Occurrence of 6PPD-Quinone in Michigan’s Surface Water. https://doi.org/10.13140/RG.2.2.34478.59204.) compared 6PPD-q concentrations in surface water and puddle samples from rubber-modified asphalt (RMA) and traditional asphalt. The results from surface water samples taken from RMA road runoff locations were nondetect for 6PPD-q. The results from puddle samples on top of RMA and traditional asphalt contained similar concentrations. These results indicate that RMA might not be a direct source of 6PPD-q, although more research is needed to confirm. In another study, researchers found that RMA can serve as sorbents for 6PPD-q (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.).

Porous pavement has been found to improve water quality from arterial road runoff ([http://zotpress items=”{4911552:CF43N7NF}” style=”chicago-author-date”]; Holzer and Lindbo 2018[YE2TKX83] Holzer, Katie, and Torrey Lindbo. 2018. “Pervious Pavement Pollutant Study.” Presented at the Lower Willamette River Toxics Reduction Meeting, January 31. https://gaftp.epa.gov/region10/columbiariver/WWTRP/Meeting-2018-01-31/gresham-pervious-pavement-pollutant-study.pdf.), to remove the majority of TRWP mass, and to remove a significant portion of 6PPD-q from stormwater (Mitchell and Jayakaran 2024[TKDFS24E] Mitchell, Chelsea J., and Anand D. Jayakaran. 2024. “Mitigating Tire Wear Particles and Tire Additive Chemicals in Stormwater with Permeable Pavements.” Science of the Total Environment 908 (January):168236. https://doi.org/10.1016/j.scitotenv.2023.168236.).

6.3.1.5 Traffic Management

The design of the road itself impacts driving characteristics and tire wear. Reducing torque and friction, which are actions that contribute to tire wear, is the goal of traffic management as a mitigation effort. Actions to achieve this might include minimizing the need for high speeds, sharp turns, and reducing the frequency of acceleration and deceleration. Roundabouts and syncing up stop lights to increase traffic flow could also reduce TRWPs, so long as harsh braking and acceleration are avoided (Liu et al. 2021[XDW2JS3N] Liu, Ye, Haibo Chen, Jianbing Gao, Ying Li, Kaushali Dave, Junyan Chen, Matteo Federici, and Guido Perricone. 2021. “Comparative Analysis of Non-Exhaust Airborne Particles from Electric and Internal Combustion Engine Vehicles.” Journal of Hazardous Materials 420:126626. https://doi.org/10.1016/j.jhazmat.2021.126626.; Tonegawa and Sasaki 2021[9NME6IST] Tonegawa, Yoshio, and Sousuke Sasaki. 2021. “Development of Tire-Wear Particle Emission Measurements for Passenger Vehicles.” Emission Control Science and Technology 7 (1): 56–62.

https://doi.org/10.1007/s40825-020-00181-z.; Feißel et al. 2024[L8SQWPUC] Feißel, Toni, Miles Kunze, David Hesse, Valentin Ivanov, Klaus Augsburg, and Sebastian Gramstat. 2024. “On-Road Vehicle Measurement of Tire Wear Particle Emissions and Approach for Emission Prediction.” Tire Science and Technology 52 (1): 2–14. https://doi.org/10.2346/tire.22.21024.).

6.3.1.6 *Street Sweeping and Other Road Maintenance Activities*

The effectiveness of street sweeping for controlling TRWPs and potentially 6PPD-q is uncertain. Based on a literature review, a WA Ecology report suggested that street sweeping has a high potential effectiveness in capturing TRWP (Navickis-Brasch et al. 2022[MT6MFFH8] Navickis-Brasch, Aimee, Mark Maurer, Taylor Hoffman-Ballard, Susan Bator, and Jerry Diamond. 2022. “Stormwater Treatment of Tire Contaminants Best Management Practices Effectiveness.” https://fortress.wa.gov/ecy/ezshare/wq/Permits/Flare/2019SWMMWW/Content/Resources/DocsForDownload/2022_SWTreatmentOfTireContaminants-BMPEffectiveness.pdf.). The effectiveness of street sweeping depends on its efficiency in collecting various particle sizes, the frequency of street sweeping and timing relative to rain events, the type of street sweeping equipment used, and other impervious surfaces downwind of the road (Evergreen StormH20 2023). Studies to assess the effectiveness of street sweeping are underway, including a paired watershed study from the Stormwater Action Monitoring Program in Washington State.

Reducing road roughness (fewer bumps, potholes, etc.) through regular maintenance can result in reduced tire wear (Robbins and Tran 2015[R78QJLSP] Robbins, Mary M., and Nam Tran. 2015. “Literature Review: The Impact of Pavement Roughness on Vehicle Operating Costs.” NCAT Report 15-02. Auburn University, Auburn, Alabama: National Center for Asphalt Technology.). At the time this document was prepared, no studies that correlate a reduction in road roughness to less 6PPD-q in surface water were found, but a reduction in tire wear could result in less 6PPD-q reaching surface water.

6.3.2 Air Particulate Mitigation

TRWPs are suspended within the boundary layer of the tire (Kuraishi, Takizawa, and Tezduyar 2019[MJP3IDF9] Kuraishi, Takashi, Kenji Takizawa, and Tayfun E. Tezduyar. 2019. “Tire Aerodynamics with Actual Tire Geometry, Road Contact and Tire Deformation.” Computational Mechanics 63 (6): 1165–85. https://doi.org/10.1007/s00466-018-1642-1.). A portion of these TRWPs are deposited onto the road, and a portion becomes airborne. The extent of transport of these airborne particles at or away from the road depends on many factors including the size of particles emitted, the number and type of vehicles on the road, the activity of vehicles on the road, local meteorology, and local terrain conditions (Baldauf et al. 2009[CHVB6EB8] Baldauf, Richard W., N. Watkins, D. Heist, C. Bailey, P. Rowley, and R. Shores. 2009. “Near-Road Air Quality Monitoring: Factors Affecting Network Design and Interpretation of Data.” Air Quality, Atmosphere & Health 2 (1): 1–9. https://doi.org/10.1007/s11869-009-0028-0.; Wang et al. 2010[U9T8Q8YR] Wang, F., D.S. Chen, S.Y. Cheng, J.B. Li, M.J. Li, and Z.H. Ren. 2010. “Identification of Regional Atmospheric PM10 Transport Pathways Using HYSPLIT, MM5-CMAQ and Synoptic Pressure Pattern Analysis.” Environmental Modelling & Software 25 (8): 927–34. https://doi.org/10.1016/j.envsoft.2010.02.004.). A recent study in Boston, Massachusetts, estimated that 12% of $PM_{2.5}$ consisted of TRWP at sites from the roadside to 100 m away (Matthaios et al. 2022[IN77R968] Matthaios, Vasileios N., Joy Lawrence, Marco A.G. Martins, Stephen T. Ferguson, Jack M. Wolfson, Roy M. Harrison, and Petros Koutrakis. 2022. “Quantifying Factors Affecting Contributions of Roadway Exhaust and Non-Exhaust Emissions to Ambient PM10–2.5 and PM2.5–0.2 Particles.” Science of the Total Environment 835:155368. https://doi.org/10.1016/j.scitotenv.2022.155368.).

Studies have measured 6PPD-q in urban ambient air samples not located near roadways (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.; 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.; Zhang et al. 2022[G77DTKD6] Zhang, Yanhao, Caihong Xu, Wenfen Zhang, Zenghua Qi, Yuanyuan Song, Lin Zhu, Chuan Dong, Jianmin Chen, and Zongwei Cai. 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.; Wang et al. 2022[TMV9VLRS] Wang, Wei, Guodong Cao, Jing Zhang, Pengfei Wu, Yanyan Chen, Zhifeng Chen, Zenghua Qi, Ruijin Li, Chuan Dong, and Zongwei Cai. 2022. “Beyond Substituted p-Phenylenediamine Antioxidants: Prevalence of Their Quinone Derivatives in PM2.5.” Environmental Science & Technology, July, acs.est.2c02463. https://doi.org/10.1021/acs.est.2c02463.;

Wu, Venier, and Hites 2020[F7XN9GAC] Wu, Yan, Marta Venier, and Ronald A. Hites. 2020. “Broad Exposure of the North American Environment to Phenolic and Amino Antioxidants and to Ultraviolet Filters.” Environmental Science & Technology 54 (15): 9345–55. https://doi.org/10.1021/acs.est.0c04114.; Zhang et al. 2022[GHLGNCHV] Zhang, Ying-Jie, Ting-Ting Xu, Dong-Min Ye, Ze-Zhao Lin, Fei Wang, and Ying Guo. 2022. “Widespread N-(1,3-Dimethylbutyl)-N′-phenyl-p-phenylenediamine Quinone in Size-Fractioned Atmospheric Particles and Dust of Different Indoor Environments.” Environmental Science & Technology Letters 9 (5): 420–25. https://doi.org/https://doi.org/10.1021/acs.estlett.2c00193.; Wang et al. 2022[77EKBKUV] Wang, Wei, Guodong Cao, Jing Zhang, Zhifeng Chen, Chuan Dong, Jianmin Chen, and Zongwei Cai. 2022. “p-Phenylenediamine-Derived Quinones as New Contributors to the Oxidative Potential of Fine Particulate Matter.” Environmental Science & Technology Letters, August, acs.estlett.2c00484. https://doi.org/10.1021/acs.estlett.2c00484.) and along transects away from the road (Olubusoye et al. 2023[R8HSVPUG] Olubusoye, Boluwatife S., James V. Cizdziel, Matthew Bee, Matthew T. Moore, Marco Pineda, Viviane Yargeau, and Erin R. Bennett. 2023. “Toxic Tire Wear Compounds (6PPD-Q and 4-ADPA) Detected in Airborne Particulate Matter Along a Highway in Mississippi, USA.” Bulletin of Environmental Contamination and Toxicology 111 (6): 68. https://doi.org/10.1007/s00128-023-03820-7.). Because TRWPs containing 6PPD-q have been identified in airborne particulate matter samples collected away from the road, a holistic 6PPD-q mitigation strategy would need to target both air particulates and stormwater runoff.

Roadside vegetation and solid structures (for example, noise walls, fences) can be used to mitigate air pollution near the road. Some of this reduction is through dilution, and some is the result of the forms and characteristics of vegetation that can capture and remove airborne particles. Solid structures located adjacent to roadways, such as noise barriers or K-rail barriers, can inhibit air flow away from the roadway and increase the deposition of larger TRWPs, thus decreasing transport of TRWPs that may contain 6PPD-q (Baldauf et al. 2008[5F9IGYHU] Baldauf, R., E. Thoma, A. Khlystov, V. Isakov, G. Bowker, T. Long, and R. Snow. 2008. “Impacts of Noise Barriers on Near-Road Air Quality.” Atmospheric Environment 42 (32): 7502–7. https://doi.org/10.1016/j.atmosenv.2008.05.051.; Gallagher et al. 2015[I3SXYRM3] Gallagher, John, Richard Baldauf, Christina H. Fuller, Prashant Kumar, Laurence W. Gill, and Aonghus McNabola. 2015. “Passive Methods for Improving Air Quality in the Built Environment: A Review of Porous and Solid Barriers.” Atmospheric Environment 120:61–70. https://doi.org/10.1016/j.atmosenv.2015.08.075.; Baldauf et al. 2016[JF4ZB7DP] Baldauf, Richard W., Vlad Isakov, Parikshit Deshmukh, Akula Venkatram, Bo Yang, and K. Max Zhang. 2016. “Influence of Solid Noise Barriers on Near-Road and on-Road Air Quality.” Atmospheric Environment 129:265–76. https://doi.org/10.1016/j.atmosenv.2016.01.025.). Studies on K-rail barriers are limited, and to have this effect they must be next to the travel lane. Particles across a range of sizes, from larger coarse particulate matter to small nano-size particles, can also be removed by impaction and diffusion onto vegetation surfaces. These particles typically remain on the vegetation until removal by precipitation or as debris from falling leaves or needles. Certain vegetation characteristics can have positive effects, reducing the number of particles by 50% or more; however other vegetation characteristics (that is, highly porous, gaps between trees, high canopy trees) can lead to increased air pollution concentrations near the road (Baldauf 2017[JR7YD4FW] Baldauf, Richard W. 2017. “Roadside Vegetation Design Characteristics That Can Improve Local, near-Road Air Quality.” Transportation Research Part D: Transport and Environment 52:354–61. https://doi.org/10.1016/j.trd.2017.03.013.; Abhijith et al. 2017[CIIV2BTG] Abhijith, K.V., Prashant Kumar, John Gallagher, Aonghus McNabola, Richard Baldauf, Francesco Pilla, Brian Broderick, Silvana Di Sabatino, and Beatrice Pulvirenti. 2017. “Air Pollution Abatement Performances of Green Infrastructure in Open Road and Built-up Street Canyon Environments—A Review.” Atmospheric Environment 162:71–86. https://doi.org/10.1016/j.atmosenv.2017.05.014.; Tiwari et al. 2019[A2URNURS] Tiwari, Arvind, Prashant Kumar, Richard Baldauf, K. Max Zhang, Francesco Pilla, Silvana Di Sabatino, Erika Brattich, and Beatrice Pulvirenti. 2019. “Considerations for Evaluating Green Infrastructure Impacts in Microscale and Macroscale Air Pollution Dispersion Models.” Science of the Total Environment 672:410–26. https://doi.org/10.1016/j.scitotenv.2019.03.350.; Deshmukh et al. 2019[AZD7J8VP] Deshmukh, Parikshit, Vlad Isakov, Akula Venkatram, Bo Yang, K. Max Zhang, Russell Logan, and Richard Baldauf. 2019. “The Effects of Roadside Vegetation Characteristics on Local, near-Road Air Quality.” Air Quality, Atmosphere, & Health 12 (March):259–70. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7339705/.). “Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality” describes the characteristics of vegetation needed to achieve air pollution control and the characteristics to avoid (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.). Placing properly designed vegetation and solid structures along the roadside may help capture airborne 6PPD-q–containing tire particles at the roadside that can be treated using the stormwater runoff mitigation strategies described in the next section. This could prevent transport of 6PPD-q over large distances that will require treatment at the watershed level rather than focused on the roadside (Deshmukh et al. 2019[AZD7J8VP] Deshmukh, Parikshit, Vlad Isakov, Akula Venkatram, Bo Yang, K. Max Zhang, Russell Logan, and Richard Baldauf. 2019. "The Effects of Roadside Vegetation Characteristics on Local, near-Road Air Quality." Air Quality, Atmosphere, & Health 12 (March):259–70. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7339705/.).

Beyond mitigating for 6PPD-q, implementing air particulate mitigation strategies could lead to co-benefits or multiple environmental and social benefits. Communities near roadways are disproportionally lower-income, nonwhite, and often experience disproportionate environmental harms (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.; Antonczak et al. 2023[IETZJYHC] Antonczak, Brittany, Tammy M. Thompson, Mindi W. DePaola, and Gregory Rowangould. 2023. "2020 Near-Roadway Population Census, Traffic Exposure and Equity in the United States." Transportation Research Part D: Transport and Environment 125 (December):103965. https://doi.org/10.1016/j.trd.2023.103965.). Air particulate mitigation could reduce airborne 6PPD-q and address existing environmental justice concerns (Tian, Xue, and Barzyk 2013[JKKV3HH3] Tian, Nancy, Jianping Xue, and Timothy M Barzyk. 2013. "Evaluating Socioeconomic and Racial Differences in Traffic-Related Metrics in the United States Using a GIS Approach." Journal of Exposure Science & Environmental Epidemiology 23 (2): 215–22. https://doi.org/10.1038/jes.2012.83.) . These mitigation strategies could also reduce noise pollution and additional toxics in the environment (USEPA 2017[DPMSMEZ9] USEPA. 2017. "Living Close to Roadways: Health Concerns and Mitigation Strategies." Overviews and Factsheets. January 10, 2017. https://www.epa.gov/sciencematters/living-close-roadways-health-concerns-and-mitigation-strategies.). Installing roadside vegetation could also reduce the urban heat island effect, which is a climate change mitigation and adaptation measure (USEPA 2024[2P8GQ97U] USEPA. 2024. "Heat Islands and Equity." July 16, 2024. https://www.epa.gov/heatislands/heat-islands-and-equity.).

CASE STUDIES: Roadside Green Infrastructure Characteristics that Benefit Air Quality, USEPA

The following three field studies provided by USEPA demonstrate how roadside green infrastructure can improve air quality. The strategies used in these studies to mitigate particulate matter could also be beneficial for 6PPD-q mitigation when combined with stormwater treatment methods, though this remains untested. These studies are ongoing and unpublished.

The first study was conducted at Kemeny Park in Detroit, Michigan. Roadside vegetation was planted along the boundary between Kemeny Park and a major highway (I-75) in Detroit. Particulate matter and other air pollutant measurements were collected before the planting and measurements are currently being collected as the vegetation grows. Lessons learned are that planting new vegetation for air quality benefits can be difficult and planting mature vegetation provides greater air quality benefits although mature vegetation also has a lower survivability rate and requires some spacing to allow growth. Air quality benefits can be achieved after 3–5 years of growth. To achieve air quality benefits right away, hedges and bushes, or a solid structure like a fence, are needed to get initial air quality benefits while trees and larger vegetation grow.

The second case study took place at Brookfield Elementary School in Oakland, California. Roadside vegetation was planted along the boundary of a school playground behind a noise barrier along a major highway (I-880) in Oakland. Particulate matter and other air pollutant measurements were collected before planting and data collection continues as the vegetation grows. Lessons learned include the following: planting next to an existing noise barrier provides immediate air quality benefits from the solid wall, and these benefits increase as the vegetation grows. The case study highlights the need to adequately assess soil quality and provide stormwater management infrastructure simultaneously given the often harsh conditions present near large highways.

A third field study was conducted in the San Francisco Bay area. The study compared air quality downwind of a large highway and assessed how particulate matter and other air pollution varied behind different vegetation characteristics. Lessons learned include the following: vegetation must have low porosity, and vegetation must have coverage from the ground to the top of the canopy to achieve air quality benefits. Gaps in the vegetation, along with high-porosity bushes and trees, can actually lead to increased downwind air pollution levels (Deshmukh et al. 2019[AZD7J8VP] Deshmukh, Parikshit, Vlad Isakov, Akula Venkatram, Bo Yang, K. Max Zhang, Russell Logan, and Richard Baldauf. 2019. "The Effects of Roadside Vegetation Characteristics on Local, near-Road Air Quality." Air Quality, Atmosphere, & Health 12 (March):259–70.

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7339705/.).

The following case studies describe how vegetation, which is a green infrastructure feature, improves air quality. Field studies like these could be applied and tested to inform 6PPD-q mitigation.

6.3.3 Stormwater Runoff Mitigation: Stormwater Control Measures

Stormwater runoff can be defined as rain or snow melt that flows over the land surface rather than infiltrating into the subsurface. When flowing over impervious surfaces like paved streets, parking lots, and rooftops, runoff picks up numerous pollutants, including 6PPD-q. If left untreated, runoff can transport those pollutants into streams and other waterways, degrading water quality. Stormwater control measures, known as SCMs, are helpful tools to slow the flow of runoff and remove pollutants. SCMs function by capturing runoff and releasing it through natural processes (such as infiltration into the ground, evaporation, or evapotranspiration) and/or treating runoff as it flows through soils or vegetation prior to exiting stormwater facilities. Some entities refer to SCMs as BMPs. This document will use the term SCM for consistency, except when referring to a source document that uses the term BMP. Note that different entities use a variety of terminology for SCMs that filter and absorb stormwater, such as green infrastructure, green stormwater infrastructure, low-impact development, or nature-based solutions.

Multiple scientific publications point to bioretention, which refers to an SCM that infiltrates stormwater runoff into soil media, as an SCM that can reduce toxicity in stormwater, thus preventing acute mortality to coho salmon (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.; 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.; Rodgers et al. 2023[LZXSW5WM] Rodgers, Timothy F. M., Yanru Wang, Cassandra Humes, Matthew Jeronimo, Cassandra Johannessen, Sylvie Spraakman, Amanda Giang, and Rachel C. Scholes. 2023. “Bioretention Cells Provide a 10-Fold Reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling.” Environmental Science & Technology Letters, June. https://doi.org/10.1021/acs.estlett.3c00203.). Rodgers et al. (Rodgers et al. 2023[LZXSW5WM] Rodgers, Timothy F. M., Yanru Wang, Cassandra Humes, Matthew Jeronimo, Cassandra Johannessen, Sylvie Spraakman, Amanda Giang, and Rachel C. Scholes. 2023. “Bioretention Cells Provide a 10-Fold Reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling.” Environmental Science & Technology Letters, June. https://doi.org/10.1021/acs.estlett.3c00203.), concluded from a field experiment and modeling that bioretention cells provided a 10fold reduction in 6PPD-q mass loadings to receiving waters. Scientific and practical questions around bioretention remain, from design details to optimize performance to how to site bioretention SCMs. While bioretention may be a solution in some areas, other SCMs may be needed where bioretention is not feasible. This section documents ongoing projects to further investigate bioretention and projects investigating other SCMs for potential effectiveness in mitigating toxicity from 6PPD-q in stormwater.

6.3.3.1 Potential SCM Effectiveness: WA Ecology BMP Effectiveness Report

WA Ecology partnered with Osborn and Evergreen StormH2O to develop a literature review to assess different mitigation strategies and predict potential SCM effectiveness for 6PPD-q (Navickis-Brasch et al. 2022[MT6MFFH8] Navickis-Brasch, Aimee, Mark Maurer, Taylor Hoffman-Ballard, Susan Bator, and Jerry Diamond. 2022. “Stormwater Treatment of Tire Contaminants Best Management Practices Effectiveness.” https://fortress.wa.gov/ecy/ezshare/wq/Permits/Flare/2019SWMMWW/Content/Resources/DocsForDownload/2022_SWTreatmentOfTireContaminants-BMPEffectiveness.pdf.; Washington State Department of Ecology 2022[K2CG7KTE] Washington State Department of Ecology. 2022. “6PPD in Road Runoff Assessment and Mitigation Strategies.” 22-03–020. Olympia, Washington: Environmental Assessment and Water Quality Programs. https://apps.ecology.wa.gov/publications/documents/2203020.pdf.). The report evaluated currently published BMPs for presumed effectiveness at capturing and treating TRWPs, 6PPD, and 6PPD-q based on a literature review and the best judgment of subject matter experts (Table 6-1).

Table 6-1: Examples of BMPs and their predicted effectiveness, as hypothesized in the WA Ecology BMP Effectiveness Report

Ranking of Potential Effectiveness	**Example BMP**	**Category Definitions for Ranking Potential Effectiveness**
Flow and Treatment BMPs		
High	Bioretention, Infiltration Basins, Media Filter Drain, Dispersion	Dispersion, Infiltration, and some Biofiltration BMPs (that use bioretention soil media or compost) where the underlying soils meet soil suitability criteria, or BMPs that provide the treatment process sorption.
Medium	Sand Filter, Detention Ponds, Permeable Pavements	BMPs that provide sedimentation (removal dependent on size/detention time) or filtration (removal dependent on size of particles). May need a polishing layer/treatment train including sorption (for example, sand filter with zero valent iron layers).
Low	Perforated Stub-Out Connection, Vegetated Roofs, Tree Retention and Tree Planting	BMPs that do not provide infiltration, sorption, filtration, or sedimentation
Source Control BMPs		
High	BMPs for Streets and Highways, BMPs for Maintenance of Roadside Ditches	BMP separates a source (i.e., roadway, parking, etc.) from stormwater.
Medium	Education and Outreach Programs Related to 6PPD or 6PPD-q, Construction Wheel Wash	BMP partially separates 6PPD and 6PPD-q from stormwater (including education and outreach efforts); prevents 6PPD and 6PPD-q from entering stormwater from a minor source (i.e., traffic at a construction site).
Low	BMPs for Temporary Fruit Storage, BMPs for Railroad Yards	Unlikely to provide any measurable separation between 6PPD and stormwater.
Source: Stormwater Treatment of Tire Contaminants | Best Management Practices Effectiveness (Navickis-Brasch et al. 2022)		

Notes: BMPs=best management practices

6.3.3.2 Ongoing Research into SCMs for Mitigating Toxicity Related to 6PPD-q

Several research efforts are underway that test the effectiveness of SCMs at retaining and treating 6PPD-q. Some of these studies build off WA Ecology's effectiveness literature review (Navickis-Brasch et al. 2022[MT6MFFH8] Navickis-Brasch, Aimee, Mark Maurer, Taylor Hoffman-Ballard, Susan Bator, and Jerry Diamond. 2022. "Stormwater Treatment of Tire Contaminants Best Management Practices Effectiveness." https://fortress.wa.gov/ecy/ezshare/wq/Permits/Flare/2019SWMMWW/Content/Resources/DocsForDownload/2022_SWTreatmentOfTireContaminants-BMPEffectiveness.pdf.) and are seeking to verify and optimize the effectiveness of SCMs noted as having moderate to high potential effectiveness (Navickis-Brasch et al. 2022[MT6MFFH8] Navickis-Brasch, Aimee, Mark Maurer, Taylor Hoffman-Ballard, Susan Bator, and Jerry Diamond. 2022. "Stormwater Treatment of Tire Contaminants Best Management Practices Effectiveness." https://fortress.wa.gov/ecy/ezshare/wq/Permits/Flare/2019SWMMWW/Content/Resources/DocsForDownload/2022_SWTreatmentOfTireContaminants-BMPEffectiveness.pdf.). Other studies are investigating the effectiveness of new stormwater SCMs with different specifications or configurations. Ultimately, SCM effectiveness research helps describe several mitigation tools that could be applied depending on the location. Several examples of ongoing studies are described below, but this is not intended to be an exhaustive list.

6.3.3.2.1 6PPD SCM Effectiveness Research—WA Ecology

WA Ecology has contracted several BMP effectiveness studies supported by Washington State Legislative funds:

- The University of Washington–Tacoma has completed its study of various engineered and natural materials to gauge their effects on 6PPD-q in stormwater samples.

- King County is performing column tests with stormwater samples to help determine which mixtures of high-performance bioretention soil mixes (HPBSM), as defined in the WA Ecology Stormwater publications (Howie and Lubliner 2024[ZMESPTJ8] Howie, Douglas, and Brandi Lubliner. 2024. “Guidance on Using New High Performance Bioretention Soil Mixes.” Olympia, Washington: Washington State Department of Ecology, Water Quality Program. https://apps.ecology.wa.gov/publications/documents/2110023.pdf.) and Stormwater Manual (Washington State Department of Ecology 2018[8VMVK98Y] Washington State Department of Ecology. 2018. “Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies.” Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/documents/1810038.pdf.), might be most effective at reducing 6PPD-q.

- Herrera Environmental Consultants, in collaboration with King County Environmental Lab (KCEL), is testing TAPE, or Technology Assessment Protocol-Ecology, treatment technologies via influent and effluent of stormwater samples while also developing field sampling protocols and comparing 6PPD-q analysis results across two laboratories (see case study below for more information).

- KCEL is working on a project to characterize stormwater in a mixed highway and residential area. The wide range of contaminants measured in this study includes 6PPD-q.

- Washington State University, in partnership with Evergreen StormH2O, is working to create a street-sweeping manual that will help stormwater permittees across Washington State create new or improve existing street-sweeping programs.

- Pierce County Public Works is examining the effectiveness of decant facilities and granular activated carbon at addressing 6PPD-q.

CASE STUDY: 6PPD-q in Highway Runoff, BMP Effectiveness, and Field Protocol Development

Supported by WA Ecology, Herrera Environmental Consultants (Herrera) is conducting 6PPD-q sampling at the I-5 Ship Canal Testing Facility and the Oregon Department of Transportation Stormwater Technology Testing Center to improve understanding of 6PPD-q in stormwater. Herrera is partnering with KCEL, which is conducting the laboratory analyses of more than 400 6PPD-q samples. This sampling occurs throughout “storm events,” or when it rains for at least one hour following a somewhat dry period. Contaminants like 6PPD-q can accumulate on roads when there is little rain and can then be flushed into stormwater during storm events and discharged into salmon-bearing streams. The proposed sampling will do the following:

- Help assess whether existing field-sampling protocols for 6PPD-q need to be refined, for example, with respect to the use of carboys, bottle types, and pump tubing material. To ensure that protocols are reliable in different conditions, Herrera will test these field protocols over three storm events.
- Characterize 6PPD-q in untreated highway runoff in Seattle and Portland. Stormwater characterization helps stormwater managers understand the full chemical profile of contaminants in runoff throughout a storm event, including assessing whether there is variability in when 6PPD-q concentrations are highest during the storm. This information is essential for managing and regulating 6PPD-q.
- Evaluate the ability of emerging stormwater treatment technologies (TAPE) to reduce 6PPD-q concentrations. Depending on the device, TAPE devices have been proven to reduce the concentrations of phosphorus, oil,

suspended solids, heavy metals, and other contaminants in stormwater. This study will test some of these implemented devices for their effectiveness with 6PPD-q treatment.
- Assess whether there are differences between the reported values of 6PPD-q between two different laboratories: KCEL and Manchester Environmental Lab. Laboratory methods are still being developed, so it is crucial to understand what might contribute to differences in how laboratories analyze samples.

All in all, this project is expected to improve understanding of 6PPD-q levels in runoff, assess whether existing and already implemented stormwater technologies can filter this emergent contaminant, and help improve field sampling protocols to ensure that samples intended for 6PPD-q testing remain viable and reliable.

The Snoqualmie Indian Tribe is assessing the effectiveness of floating treatment wetlands, native vegetation, and grassy swales. They are also characterizing a high-use parking lot.

6.3.3.2.2 Stormwater Action Monitoring Program—WA Ecology

The Stormwater Action Monitoring Program, which is permittee-driven, permittee-funded, and facilitated by WA Ecology, has five 6PPD projects funded by the 2022–2023 and 2023–2025 provisos granted to WA Ecology’s Water Quality Program. These projects are in progress, and deliverables can be found on the Stormwater Action Monitoring—Effectiveness Studies webpage.

- Washington State University’s “Longevity of Bioretention Depths for Preventing Acute Toxicity from Urban Stormwater Runoff,” seeks to determine the efficacy of bioretention media over time.

- The City of Redmond seeks to study the benefits of street sweeping by evaluating receiving water conditions. This long-term project has, as of 2022, added parameters for 6PPD-q to its scope of study.

- Seattle Public Utilities, in collaboration with Herrera Environmental Consultants, is exploring the potential for reducing 6PPD-q by examining and characterizing street-sweeping loads from arterial roads in the City of Seattle, with study components including examining possible correlations between 6PPD-q and other stormwater contaminants as well as the characterization of particle size distribution, seasonality, and land-use differences.

- King County, in partnership with Whatcom County, is seeking to test HPBSM at a full-scale stormwater facility, building upon King County’s HPBSM column bench study (Howie and Lubliner 2024) to test and monitor how HPBSM performs in the field.

- The City of Tacoma, in partnership with the University of Washington– Tacoma, Herrera Environmental Consultants, and Aspect Consulting are monitoring stormwater outfalls for CEC, including 6PPD-q, at 15 sites in the Puget Sound region.

6.3.3.2.3 Floating Treatment Wetland / Biomedia Modules to Reduce Stormwater Contaminants with a Focus on 6PPD-q—University of Washington

Funded by King County, this research project has used floating treatment wetlands as a vehicle for placing a tested biomedia mix into the affected waterbody at the point of stormwater entry (Seebacher, Pierce, and Turner 2023[AZ6MCQ8J] Seebacher, Lizbeth Ann, Brianna Pierce, and Rob Turner. 2023. “Floating Treatment Wetland and Biomedia Module for Stormwater Treatment and 6ppd Quinone Removal.” https://doi.org/10.2139/ssrn.4471002.). Using a floating treatment wetlands / biomedia module planted with wetland species and a biomedia mix within and underneath, a mesocosm experiment resulted in 79% 6PPD-q reduction (255 ng/L to 53.5 ng/L) and 100% survival of juvenile coho after a 24hour exposure period with no symptoms of 6PPD-q toxicity. Foldvik et al. 2022[LQWXZHJA] Foldvik, Anders, Fedor Kryuchkov, Roar Sandodden, and Silvio Uhlig. 2022. “Acute Toxicity Testing of the Tire Rubber–Derived Chemical 6PPD-Quinone on Atlantic Salmon (Salmo Salar) and Brown Trout (Salmo Trutta).” Environmental Toxicology and Chemistry 41 (12): 3041–45.

https://doi.org/10.1002/etc.5487.This potential SCM would be considered a treatment facility and could be used at sites where other SCMs are not feasible or in addition to other SCMs to increase 6PPD-q removal. For more information, please see the floating wetland treatment webpage.

6.3.3.2.4 Other Relevant Stormwater Research

Addressing Stormwater Runoff with a Self-Contained Portable Treatment System (2023 Department of Transportation Small Business Innovation Research grants): Awardees will work to develop a mechanism to remove pollutants, including emerging contaminants such as 6PPD-q, from highway construction and urban stormwater runoff sources.

Development of On-Bridge Stormwater Treatment Practices (National Cooperative Highway Research Program): This project will develop on-bridge stormwater treatment applications for retrofitting bridges. 6PPD-q is among the analytes.

CASE STUDY: Mobile Biofiltration Unit—Nisqually Indian Tribe and Cedar Grove Compost

A pilot project by the Nisqually Tribe and partners has been testing a mobile biofiltration unit that is meant to filter harmful materials from stormwater at Ohop Creek in Washington. It collects stormwater from more than 13,000 square feet of roadway and filters it through layers of compost-based filtration media to remove toxic compounds. It also has an external polishing layer to remove phosphorous before the water is discharged to the wetlands near the creek. They first operated the unit in Summer 2022, and preliminary results from three rain events showed high effectiveness, reducing the 6PPD q levels low enough to not be acutely toxic to coho (greater than 90% reduction in 6PPD q concentrations). They are looking to conduct more sampling in the future with the goal of getting the system approved for use in projects across Washington.

Opportunities for Stormwater Retrofit (Washington Department of Transportation (WSDOT):

Projects include an emphasis on green infrastructure retrofits. One example is the Urban Stormwater Partnership—I-5 Ship-Canal Bridge Pilot in Seattle, which leverages partnerships to establish a multijurisdictional stormwater facility that treats high volumes of 6PPD-q and other pollutants, incorporates community-identified needs, and provides opportunities to research the effectiveness of 6PPD-q treatment.

Stormwater Management to Address Highway Runoff Toxicity Due to 6PPD-q from Tire Rubber ***(Transportation Pooled Fund Study):*** Project aims to equip departments of transportation with a targeted approach for effectively managing 6PPD-q in highway runoff and to provide regulatory agencies with a better understanding of department of transportation management options.

6.4 Remediation

Alternative chemicals and mitigation are the first line of preventive defenses against 6PPD-q in the environment. Remediation follows as a secondary tier of treatment strategies and as a long-term solution to treat 6PPD-q that is not captured by SCMs. The fate and transport of 6PPD-q in the environment is not well understood. Although 6PPD-q appears to have a short half-life in stormwater and in the aquatic environment (see Section 3: Properties of 6PPD and 6PPD-q), the propensity of 6PPD-q to sorb to organic matter in soil and sediments remains to be determined (see also Section 4.2: Soil and Section 4.3: Sediment).

The first step in determining if cleanup is necessary is identification of cleanup levels. These cleanup levels vary depending on the affected media, the constituent’s toxicity to human and other receptors, and the likely exposure pathway of the receptor. See Section 7 (Policies, Regulations, and Laws) for how these cleanup levels are determined by regulatory agencies. The purpose of this section is to provide an overview of what data and information are needed to identify future remedial strategies if and when it becomes apparent that cleanup is necessary.

6.4.1 Inputs Needed in the Remedy Selection Process

A widely used framework for identifying a preferred remedy is the USEPA Remedial Investigation/Feasibility Study (RI/FS) process (Figure 6-3); most states have similar processes, albeit often with different terminology for certain steps or documents. Although 6PPD and 6PPD-q in the environment are not within the scope of the CERCLA, also known as Superfund, the programs developed under the CERCLA regulatory framework can be instructive. Tables 6-2 through 6-6 describe the steps of the RI/FS process and the current status of applying the remedial process to 6PPD-q given the limited data currently available regarding fate and transport and toxicity for the compound.

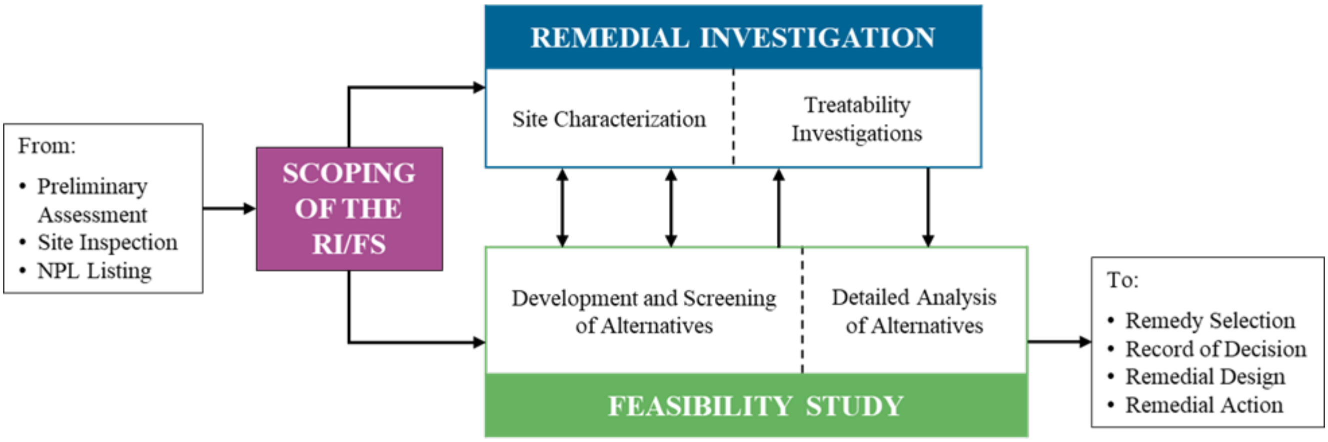

Figure 6-3. Simplified overview of the phased RI/FS process

Source: Adapted from USEPA (1988)

Table 6-2: Remedial Investigation Phase: Scoping

Step	Current Status and Notes
Collect and analyze existing data	Only limited data are currently available in many areas (see also: Section 4: Occurrence, Fate, Transport, and Exposure Pathways).
Identify initial project/operable unit, likely response scenarios, and remedial action objectives	Project area may be identified, based on limited data; likely response scenarios may be difficult to identify; and remedial action objectives may be difficult to identify, given the data gaps currently associated with human and ecological toxicity and persistence of 6PPD/6PPD-q in the environment.
State/federal ARAR identification	State or federal ARAR include media-specific and land use–related cleanup criteria (for example, MCLs, Eco-SSLs, or similar), which have yet to be developed for 6PPD/6PPD-q for human or ecological receptors.
Establish data quality objectives (DQOs)	DQOs may be difficult to establish, given the numerous data gaps (for example, toxicity, mobility, persistence, etc.)
Prepare project plans	See site characterization (Table 6-3) and treatability investigation (Table 6-4) below.

Notes: ARAR=applicable or relevant and appropriate requirements, Eco-SSLs=ecological soil screening levels, MCL=maximum contaminant levels

Table 6-3: Remedial Investigation Phase: Site Characterization

Step	Current Status and Notes
Conduct field investigation	Laboratory analysis of water, soil, sediment, and particulate samples is currently possible; however, sampling methods are not yet standardized for 6PPD-q.
Define nature and extent of contamination	Currently possible.
Identify federal and state chemical- and location-specific ARAR	State or federal ARAR include media-specific and land use–related cleanup criteria (for example, MCLs, Eco-SSLs, or similar criteria), which have yet to be developed for 6PPD/6PPD-q for human or ecological receptors.
Conduct baseline risk assessment	A baseline risk assessment may be difficult to perform due to the data gaps in toxicity, mobility, persistence, etc.

Notes: ARAR=applicable or relevant and appropriate requirements, Eco-SSLs=ecological soil screening levels, MCL=maximum contaminant levels

Table 6-4: Remedial Investigation Phase: Treatability Investigations

Step	Current Status and Notes
Perform bench or pilot treatability studies as necessary	Treatability studies will need to be conducted for all remediation technologies under consideration to evaluate their efficacy and cost-effectiveness relative to TRWPs, 6PPD, and/or 6PPD-q; current and future research related to SCMs may be informative (see also ITRC's Microplastics Guidance, Table 6-3(ITRC 2023); Remedy Selection for Contaminated Sediments (ITRC 2014[YN4LSVHV] ITRC. 2014. "Contaminated Sediments Remediation: Remedy Selection for Contaminated Sediments." August 2014. https://clu-in.org/download/contaminantfocus/sediments/Sediment-ITRC-CS-2.pdf.); Sediment Cap Chemical Isolation Guidance

Note: TRWPs=tire- and road-wear particles

Table 6-5: Feasibility Study Phase: Development and Screening of Alternatives

Step	Current Status and Notes
Identify potential treatment technologies containment/disposal requirements for residuals or untreated waste	Identify potential treatment and disposal technologies and complete an initial screen of technology types and process options to eliminate those that are clearly ineffective or unworkable at a site.
Screen technologies	Further evaluate process options based on effectiveness, implementability, and relative cost to select a representative process for each technology type.
Assemble technologies into cleanup alternatives	Multiple technologies may need to be assembled (for example, as a treatment train) to achieve applicable cleanup criteria.
Screen alternatives to reduce the number subject to detailed analysis	A typical range of alternatives evaluated at this step in the process is 5 to 10.
Identify action-specific ARARs	State or federal ARARs may include laws or regulations pertaining to the management of waste, land disposal restrictions, or other cleanup-related activities.

Notes: ARAR=applicable or relevant and appropriate requirements

Table 6-6: Feasibility Study Phase: Detailed Analysis of Alternatives

Step	Current Status and Notes

Analyze alternatives against the nine criteria used for Superfund projects or other, similar, sets of criteria applicable to non-Superfund remediation projects. The nine criteria below are part of the National Contingency Plan (40 CFR 300.430(e)(9)): Threshold Criteria 1. Overall protection of human health and the environment 2. Compliance with ARARs Primary Balancing Criteria 3. Long-term effectiveness and permanence 4. Reduction of toxicity, mobility, or volume 5. Short-term effectiveness 6. Implementability 7. Cost Modifying Criteria 8. State acceptance 9. Community acceptance	Evaluation of cleanup alternatives against the evaluation criteria (whether the nine criteria applicable to the CERCLA process or other federal or state criteria) depends on data and information that is generally not yet available but are areas of active or future research and development, as described above for the preceding steps. For example, the development of federal and state ARARs, specifically media- and location-specific cleanup levels, is necessarily dependent upon the outcomes of current and future research examining toxicity (in humans and other organisms) and fate and transport of TRWPs, 6PPD, and 6PPD-q in the environment. In addition, significant research, including bench-scale and pilot-scale studies, is needed to identify and develop treatment technologies or systems that are effective for these constituents. Evaluation of the community acceptance criterion may include community outreach efforts, including to communities with environmental justice concerns.
Analyze alternatives against other sets of criteria, for example, state sustainability criteria.	Evaluation of cleanup alternatives against state sustainability criteria is contingent in part on information specific to the technologies being evaluated (for example, quantity of greenhouse gases that will be emitted while implementing any given alternative).

Notes: ARAR=applicable or relevant and appropriate requirements, CERCLA=Comprehensive Environmental Response, Compensation, and Liability Act, CFR=Code of Federal Regulations, TWP=tire-wear particles

6.4.2 Cleanup Technologies: Recent Research

Current research efforts are generally focused on SCMs, but some of the technologies currently under development may eventually translate into remediation technologies. For example, a filtration medium deployed as part of a stormwater management and treatment program may be packed into a treatment vessel for groundwater remediation or can be used to treat wastewater generated during sediment dewatering. The SCM section describes current SCM technologies under research, including bioretention and infiltration basins.

6.4.3 Cleanup Technologies Development and Evaluation: Additional Resources

Existing ITRC guidance documents may provide additional information and remedy evaluation frameworks. Several are listed below:

- Microplastics (2023)—This report may provide a framework for evaluating approaches that may be effective for sample collection and analysis and capturing TRWP, given that TRWP are a type of microplastic (ITRC 2023).
- Stormwater Best Management Practices Performance Evaluation (2018)—This guidance provides details on post-construction stormwater SCM performance evaluation. The guidance is based on SCM life cycle processes from selection to long-term maintenance (ITRC 2018[MUH6ZPQV] ITRC. 2018. “Stormwater Best Management Practices Performance Evaluation.” 2018. https://stormwater-1.itrcweb.org/.).
- Remedy Selection for Contaminated Sediments (2014)—This guidance document is intended to assist decision-makers in identifying which contaminated sediment remedial technology is most favorable for a site based upon an evaluation of site-specific physical, sediment, contaminant, and land and waterway use characteristics. Any such evaluation must consider the demonstrated effectiveness of the technology relative to TRWP, 6PPD, and/or 6PPD-q (ITRC 2014[YN4LSVHV] ITRC. 2014. “Contaminated Sediments Remediation: Remedy Selection for Contaminated Sediments.” August 2014. https://clu-in.org/download/contaminantfocus/sediments/Sediment-ITRC-CS-2.pdf.).

- Other ITRC guidance documents may provide helpful tools such as frameworks for monitored natural attenuation that may be adapted to monitoring 6PPD-q in surface water, for the optimization of groundwater pump-and-treat systems or evaluation of in situ groundwater treatment technologies, and other steps in the evaluation of remediation processes. These documents are available on the ITRC website.