How can Municipal Governments in Metro Vancouver Reduce the Amount of 6PPD-Q Entering Fish-Bearing Watercourses?

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Abstract

This paper was originally written for Dr. Anna Hippmann's Environmental Science 201W course *Environmental Science in Practice*. The assignment asked students to pose an environmental science research question and answer it by reviewing the relevant literature. The paper uses APA citation style.

This paper reviews the body of literature concerning the tire antidegradation compound N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD) and its ozonated transformation product, N-1,3-Dimethylbutyl-N'-phenyl-p-quinone diamine (6PPD-Q) to assess the effectiveness and limitations of mitigation measures municipal governments in Metro Vancouver could adopt to protect aquatic ecosystems – and coho salmon (*Oncorhynchus kisutch*) in particular – from harms associated with these compounds. Based on the literature reviewed, a layered defense that avoids and contains tire wear particles, and filters urban runoff, is recommended as a 6PPD-Q mitigation strategy.

Introduction

Metro Vancouver is among the most densely populated regions in North America (Todd, 2024), with impervious surfaces covering 54% of the land area within the Urban Containment Boundary (Metro Vancouver, 2024). This high percentage of paved surfaces, combined with high annual precipitation, makes urban runoff a persistent challenge for aquatic ecosystems throughout the region.

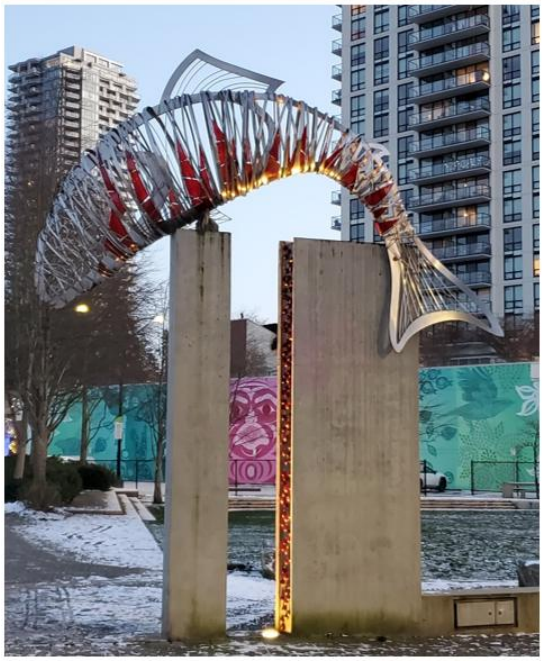
In a dramatic example of the problem, dozens of coho salmon (*Oncorhynchus kisutch*) returning to Brothers Creek in West Vancouver are

suspected to have been killed by urban runoff in October 2023 (Shen, 2023). Ecotoxicology researchers with Fisheries and Oceans Canada (DFO) suspect exposure to the oxidized form of a tire antidegradation compound, N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine – commonly abbreviated as 6PPD-quinone or 6PPD-Q – was the ultimate cause of death (Richter, 2023a). Since its identification in 2020 (Tian et al., 2021), 6PPD-Q has become the focus of research directed at mitigating the harms of urban runoff (Babaei et al., 2024; Dunagan, 2024). Coho salmon are acutely sensitive to 6PPD-Q exposure from urban runoff and are considered an indicator species for non-point source pollution and urban watercourse health (Chow, 2019; Morales, 2024).

Salmon are arguably the most ecologically and culturally important fish in British Columbia (Earth Economics, 2021). Returning salmon deliver significant subsidies of marine nutrients to terrestrial ecosystems (Helfield & Naiman, 2001; Hurteau et al., 2016; Quinn et al., 2018), and they are "irreplaceable and core to the identities and ways of life of Indigenous communities throughout the Pacific Northwest" (Earth Economics, 2021, p. 4). An Angus Reid survey found "[w]ild salmon are as culturally important to British Columbians as the French language is to the people of Quebec" (Hume, 2011), and communities throughout Metro Vancouver hold annual salmon celebrations and adorn public spaces with salmon themed art (Figures 1, 2).

Figure 1

Return of the Sockeye



Note. Ireland et al. (2010), *Return of the Sockeye* [sculpture], Spirit Square, Coquitlam B.C. Photo by Grayson Barke

Figure 2

Salmon themed pavement art

Note. Chong, (2012) St. George Rainway [pavement art]. Vancouver, B.C. Photo by J. Chong.

Municipal governments are vanguards of stream and salmon health in Metro Vancouver: they are responsible for protecting salmon habitat under both the Local Government Act and the Riparian Areas Protection Act (Fisheries and Oceans Canada [DFO], 2018). It is imperative municipal governments understand the threat 6PPD-Q poses to aquatic ecosystems – coho salmon in particular – and take mitigative action.

This review begins with background information on Tire Wear Particles (TWP) and the toxicity of 6PPD-Q, then moves to an analysis of practical measures municipal governments can take to mitigate the harms 6PPD-Q exposure can cause coho salmon. This review aims to help municipal governments in Metro Vancouver fulfil their responsibility to coho, residents, and the environment by organizing practical measures to reduce the amount of 6PPD-Q entering fish-bearing watercourses into a layered defense.

Tire Wear Particles & 6PPD-Q Toxicity

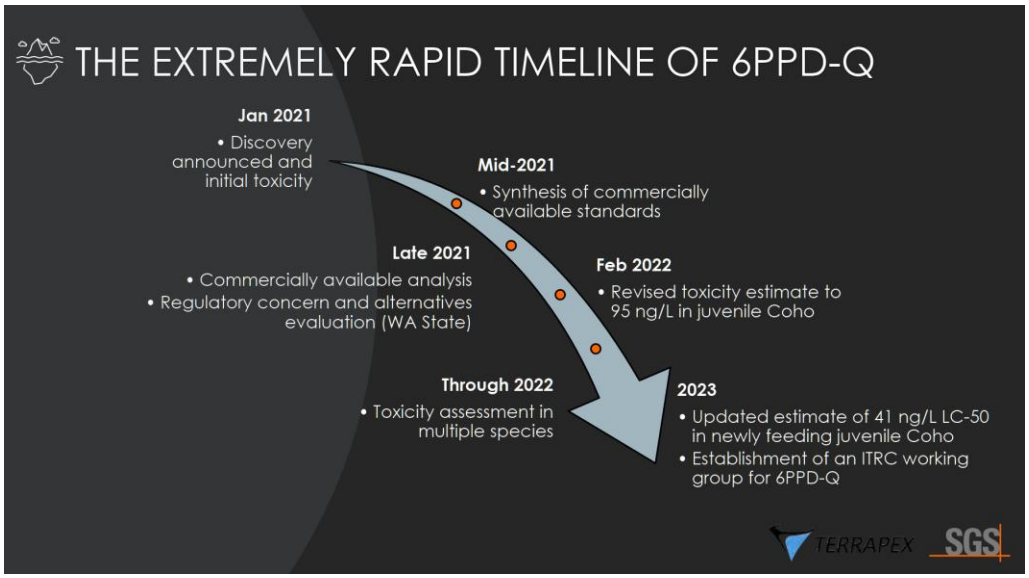
Bohara et al. (2024), provide a comprehensive review of the science produced on 6PPD-Q. They explain 6PPD is added to tires, belts, hoses, and other rubber products to make them more durable and resistant to degradation from heat and ozone exposure, which weaken the polymeric bonds in both natural and synthetic rubber (Cao et al., 2022; Cataldo, 2018, 2019; Dorofeev & Zemskii, 2017; Poldushova et al., 2016; Xu et al., 2022; Zheng et al., 2016). 6PPD is essential for ensuring the durability, longevity, and safety of modern road tires; without it, tires would be prone to failure within 1000 miles (Bohara et al., 2024). It is not an exaggeration to say the transportation and logistics underpinning the global economy could not exist without 6PPD. Even with 6PPD's stabilizing properties, however, fragments and particles containing 6PPD break off and enter the environment throughout the life and intended use of rubber products.

Tires are a significant and ubiquitous source of particles, dust, and residues containing 6PPD (Baensch-Baltruschat et al., 2020). Roughly 17 million tons of tires were produced globally in 2019, and that volume is projected to grow at 5-7% annually (Bijina et al., 2023). In the USA alone, over 1 million tons of tire wear particles (TWP) are released each year, while 1.32 million tons are released across the EU (Klöckner et al., 2021). The 6PPD molecules in TWPs are transformed by exposure to ozone into 6PPD-Q (the coho killing form) and almost two thousand tons of 6PPD-Q are produced from TWPs in the USA each year (Hu et al., 2022).

All said, every four-wheeled vehicle can contribute up to 500 grams of 6PPD-Q to the environment over its lifetime on the road (Johannessen et al., 2022). Admittedly, 500 grams may not sound like a lot, however, considering 6PPD-Q's currently accepted LC50 for juvenile coho salmon is only 41.0 ng/L (Lo et al., 2023), a single vehicle has the potential to produce over 12 billion coho-killing doses. Also, given that 6PPD-Q's LC50 for juvenile coho has been revised downwards several times since its initial toxicity assessment in 2021 (Tian et al., 2022; Lo et al., 2023), this number could be even higher (Figure 3).

Figure 3

Timeline of 6PPD-Q research after its identification in 2020



Note. This timeline was reproduced from a presentation given by Chandramouli et al., 2024, representing Terrapex Environment Ltd, at a SMART Remediation seminar held on January 25, 2024, in Brampton, Ontario.

When coho are exposed to these miniscule concentrations, 6PPD-Q rapidly increases the permeability of their blood vessels, affecting the blood brain barrier and causing effects akin to internal bleeding and cerebral hemorrhage (Greer et al., 2023). Outwardly, exposed coho appear disoriented, swimming erratically at the surface, gasping and spasming (Chow et al., 2019; Lo et al., 2023). After exposure, coho die within hours and do not recover even when returned to clean water (Chow et al., 2019; French et al., 2022; Lo et al., 2023).

Although work to assess the effects of 6PPD-Q on humans and species other than coho salmon is in its early stages, preliminary results suggest the potent toxicity of 6PPD-Q combined with expected global growth in vehicle and tire sales (and subsequent increase in TWPs) justifies rapid mitigative and regulatory responses from policy makers (King, 2024). As the stewards of many ecologically significant and culturally cherished fish-bearing watercourses, municipal governments in Metro Vancouver should adopt 6PPD-Q mitigation measures proactively, rather than waiting for senior levels of government.

Municipal Actions and Infrastructure Choices can Mitigate 6PPD-Q Harms

As long as 6PPD remains an ingredient in tires, municipalities should make efforts to minimize the volume of tire wear particles generated in their jurisdictions and take all practical and necessary steps to prevent tire wear particles and their leachate from entering the environment. Research shows the following actions effectively reduce the generation of TWPs and their dispersal into the environment, and when implemented together, provide a layered defense against 6PPD-Q's harms:

Avoid Using Recycled Tire Products in Public Amenities

While these actions seek to minimize the volume of TWPs and prevent their release into the environment, some municipalities intentionally spread TWPs, in the form of recycled tire crumbs (RTC), on sports fields. According to estimates made by Lassen et al. (2015), based on information from the Danish Hydraulic Institute (DHI, 2013), each football field can release up to two tons of RTCs every year, with many inevitably ending up in the environment (Luo et al., 2021). As there is no way of removing additives like 6PPD from tires when they are recycled, RTCs – and poured-in-place playground surfaces – can release 6PPD-Q and other contaminants of concern. Municipalities should opt for natural fields and playground surfaces whenever possible or ensure that rubber products used in public amenities do not contain 6PPD (King, 2024).

Trap Airborne Tire Wear Particles with Barriers and Vegetation

Ideally, TWPs and other forms of road pollution are contained within the roadway by barriers and removed by street sweeping at regular intervals (Interstate Technology & Regulatory Council [ITRC], 2024). In reality, it is not possible or desirable to isolate every road with barriers. TWPs can migrate up to 100 m from roadways (Matthaios et al., 2022), so it is important to use barriers to contain, and roadside vegetation to trap, TWPs wherever possible (Baldauf, 2017; ITRC, 2024). Inevitably, TWPs held by roadside vegetation will be remobilized by rainfall, making stormwater management the final (and arguably the most important) line of defense for keeping 6PPD-Q out of aquatic ecosystems.

Capture and Filter Urban Runoff

Long before 6PPD-Q was identified as the culprit in coho mortality events, researchers were devising methods to treat urban runoff and prevent its harmful constituents from entering sensitive environments. Across multiple peer-reviewed studies, bioretention filtration – where runoff passes through layers of soil, sediment, and organic material like woodchips – has proven effective at removing the most common contaminants found in urban runoff, including salt, metals, petrochemicals, nitrogen, phosphorus, bacteria, microplastics, and TWPs (Chaves et al., 2024; LeFevre et al., 2015; McIntyre et al., 2015; Smyth et al., 2021; Spromberg et al., 2016; Takaijudin et al., 2016).

Bioretention filtration testing on 6PPD-Q began immediately after its connection to coho mortality became clear, and results universally show it can keep 6PPD and 6PPD-Q out of waterways (McIntyre et al., 2023; Rodgers et al., 2023; Washington State Department of Ecology, 2022, 2024). As if to emphasize their importance, these promising bioretention results were published alongside concerning research showing 6PPD-Q harms coho embryos and juveniles even at sub-lethal concentrations (Greer et al., 2023). Another recently published study shows 6PPD and road salt have synergistically negative effects on zooplankton at the base of freshwater food-webs (Klauschies & Isanta-Navarro, 2022).

For Metro Vancouver municipalities, incorporating bioretention filtration into stormwater management means retaining as much greenspace, natural area, and permeable surface as possible, and adding features like raingardens, bioswales, and detention ponds in built up areas (Figure 4).

Figure 4

Natural and human-made forms of green infrastructure

Note. This image was reproduced from pg. 6 of Metro Vancouver's *Connecting the Dots: Regional Green Infrastructure Network Resource Guide* (2014). Report content provided by Diamond Head Consulting Ltd, Ecoplan International, & Calypso Design.

A research team from the University of British Columbia recently tested an existing rain garden's ability to remove 6PPD-Q from stormwater and found it to be 99% effective (Rogers et al., 2023). The City of Vancouver, the region's densest municipality, is aiming to "[c]apture and clean a minimum of 90% of Vancouver's average annual rainfall volume" using green infrastructure (City of Vancouver, 2019, p. 3). If all municipalities in the region matched and achieved Vancouver's goal, it would largely prevent urban runoff from polluting aquatic ecosystems. Metro Vancouver, the regional district organization, offers many guidance resources to help member municipalities integrate green infrastructure

into their urban design and stormwater management strategies (Metro Vancouver, 2015).

Limitations and Research Gaps

Although 6PPD has been added to tires for decades, the research community is just beginning to untangle its biological implications, while policy makers are challenged to act based on continually evolving information. Researchers have demonstrated how bioretention filtration can prevent 6PPD-Q from harming coho salmon in a remarkably short time; however, further research is needed to fully understand the threat 6PPD poses to human and ecological communities.

Improved understanding of how long 6PPD and 6PPD-Q persist in varying environmental conditions, and where in the environment these compounds are likely to accumulate, will help both researchers and policy makers target mitigation strategies (ITRC, 2024). As reported by Bohara et al. (2024), researchers themselves acknowledge their need for improved 6PPD-Q sampling and detection methods to improve the accuracy of their results, particularly the need to improve field sample preservation prior to analysis (Lo et al., 2023). A great deal of work remains to understand both the lethal and sub-lethal effects of 6PPD and 6PPD-Q on a range of organisms, including humans (ITRC, 2024). While almost every organism in urban areas is continually exposed to these compounds, and 82% of people tested in a recent study showed detectable amounts of 6PPD in their urine (Mao et al., 2024), there is currently no guidance on safe concentrations (ITRC, 2024; King, 2024).

Ozone exposure transforms 6PPD into 6PPD-Q, but there are other 6PPD transformation pathways and products that may threaten human and environ mental health (Bohara et al., 2024). 6PPD belongs to a class of structurally related chemicals called p-Phenylenediamines (PPDs), all with their own transformation products (e.g. IPPDQ, CPPDQ, and DPPDQ), (Zeng et al., 2023). Each of these will need to be investigated for biological interactions, both individually, and in combination with one another and other environmental pollutants. Research teams have already identified troubling interactions between PPDs that may increase their bioavailability (Jaeger et al., 2024). PPD interactions with other pollutants like road salt and polyaromatic hydrocarbons (PAHs) can also amplify their toxic effects (Klauschies & Isanta-Navarro, 2022; MacIntyre et al., 2023). The effects of repeated PPD exposure, and the potential for these compounds to bioaccumulate and biomagnify also need to be investigated (Greer et al., 2023).

While the world waits for 6PPD replacements or alternatives, the effectiveness of 6PPD and 6PPD-Q mitigation methods require continual assessment and improvement. So far, multiple assessments have shown that soil and other bioretention filtration media are effective at trapping and preventing the remobilization of 6PPD-Q and other runoff pollutants (MacIntyre et al., 2015, 2023; Mitchell & Jayakaran, 2024; Rogers et al., 2023). The persistence and half-life of trapped 6PPD-Q, however, has been identified by the ITRC as a key knowledge gap in Section 8 of their guidance document (2024). The effectiveness of measures to prevent tire wear particles from dispersing into human and terrestrial environments are also less well studied. Another continual challenge for municipal governments in Metro Vancouver will be adapting 6PPD-Q regulatory and policy actions from other jurisdictions to their local contexts.

Despite all these knowledge gaps and limitations, there is arguably sufficient information on 6PPD-Q's sources, fates, harms, and mitigation measures for municipal governments in Metro Vancouver to reduce the amount of 6PPD-Q entering fish-bearing watercourses.

Conclusion

This review identifies the ozone-transformed tire antidegradation compound 6PPD-Q as a clear threat to coho salmon – an ecologically and culturally important species for British Columbians – and provides municipal governments in Metro Vancouver with the information they need to reduce the amount of 6PPD-Q entering fish-bearing watercourses.

Analysis of peer-reviewed research suggests municipalities adopt a layered defense approach by:

1. Avoiding sports field and playground products with 6PPD;

2. Containing tire wear particles with roadside barriers and vegetation and removing them with street sweeping;

3. Filtering as much stormwater and urban runoff as possible through bioretention media before it is discharged into aquatic environments.

Municipal governments may already know where to prioritize these actions, if not, DFO research identifying local 6PPD-Q hotspots is forthcoming. Lastly, despite limitations and research gaps, this review concludes there is sufficient information for municipal governments in Metro Vancouver to reduce the amount of 6PPD-Q entering fish-bearing watercourses.

Growing and densifying cities present many environmental challenges for municipal governments to manage within their limited resources and capacities. In

this context, 6PPD-Q mitigation could easily be dismissed as an additional burden. Hopefully, municipal governments will recognize the co-benefits and opportunities 6PPD-Q mitigation offers. Cities that act on 6PPD-Q can proudly tell residents they are acting to protect salmon: a vital part of our ecosystems that British Columbians cherish.

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