EVALUATING TIRE ROAD WEAR PARTICLES IN THURSTON COUNTY, WASHINGTON: IMPLICATIONS TO STREAMS

By

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ABSTRACT

Evaluating Tire Road Wear Particles in Thurston County, Washington

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Tire road wear particles (TRWP) are made through the abrasion of tires on the road surface. Tire wear particles conglomerate and stick to other road particles and toxins once released into the roadway, where they may be weathered, aged, and biofouled from toxic chemicals and heavy metals (Lou, 2021). TRWPs are transporters of co-contaminants like 2-((4-Methylpentan-2-yl)amino)-5-(phenylamino)cyclohexa-2,5-diene-1,4-dione (6PPD-quinone), poly-aromatic hydrocarbons (PAHs), and heavy metals to urban streams (Baensch-Baltruschat, 2020). This study provides a spatial analysis of TRWP count and size based on four road types (primary, secondary, residential, and rural) in Thurston County, WA. Most TRWPs released to roadways are coarse, with sizes ranging from 1μm^2 to 175 μm^2. TRWP counts were assessed by road type, and primary roads contained between112 to 1225 particles, with a mean of 475 ± 441; Secondary roads had particle counts that ranged from 298 to 4200, with a mean of 1493 ± 1741; Residential roads ranged from 87 to 707, with a mean of 349 ± 264; Rural TRWP count ranged from 45 to 408, with a mean of 205 ± 173. The results showed that secondary roads had the most recorded TRWPs recovered from road dust samples but were not statistically different from the other road types. The highest TRWP counts recovered for road dust samples were found on two secondary roads: Eastside Street and College Street. These streets posed the most increased risks to urban streams for becoming biofouled with TRWP pollution, and targeted efforts to reduce particle loading from these roads into urban streams are recommended.

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Acknowledgments

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Introduction

Tire road wear particles (TRWP) are considered the second largest global contributor of microplastics to the environment (Verschoor et al., 2016; Lou et al., 2021). In the United States, it is estimated that over 1,120,000 tons of tire wear particles are released per year from roadways (Lou et al., 2021). Tire wear particles are emitted to the roadway through the abrasion of tires and road surfaces, where they are weathered, aged, and biofouled (Lou et al., 2021). TRWP forms primarily in conglomerates of tire and road materials in various sizes (Jekel et al., 2019). The size and density of TRWP relate to what it forms with on the road and can be a factor in TRWP toxicity and transportation (Jung et al., 202). The amount of TRWP emitted to the environment varies by region due to the many different land use practices and the number of roads. For example, research shows that driving habitats such as quick braking or accelerating and aggressive maneuvering, along with traffic network structures, heavily impact how much TRWPs are emitted to the roadway (Jekel et al., 2019). Densely populated urban areas with increased use of personal vehicles, transportation of goods, and higher concentrations of impervious surfaces would have increased rates of TRWP emissions (Charbouillot et al., 2023).

Tires are a globally significant pollution issue for both chemical and physical waste. Tires also represent only one facet of motor vehicle pollution, and, unfortunately, because of their immense importance to modern daily life, they are largely ignored as a major source of microplastic pollution. Furthermore, as we focus on utilizing low-carbon vehicles, we inadvertently increase the emission of tire road wear particles (TRWP) due to the increased weight of hybrid and electric vehicles (Charbouillot et al., 2023). Heavier vehicles equate to higher trends in tire and brake wear. The daily generation of microplastic-sized TRWP collects along the roadside, where it accumulates in road dust and is transported to streams via stormwater/roadway runoff (Charbouillot et al., 2023). It’s necessary to better quantify the amount of TRWPs found on roadways as they have important ecological impacts on urban streams.

Tire Road Wear Particles (TRWP) Significance

The fate and transport of TRWPs are significant issues of urban stream pollution because TRWPs potentially act as co-contaminant carriers of toxic chemicals and heavy metals that negatively affect aquatic environments and human health (Mennekes et al., 2022; Wagner et al., 2018). Researchers have confirmed TRWP chemical byproducts in various environmental samples such as air, soil, stormwater, surface waters, and road dust samples (Mennekes et al., 2022; Lou et al., 2021; Baensch-Baltruschat et al., 2020). However, few studies measure TRWP size and count from road dust. TRWP size and count represent two factors that increase their risks to streams. For example, the size of TRWP represents how readily the particles are transported and the ability to absorb/leach toxins they carry from the roadway to urban streams (Lou et al., 2021). Whereas the count of TRWP found on the roadway represents the number of TRWP pollutants transported to urban streams (Baensch Baltruschat et al., 2020). These factors determine the toxicity, transport, and fate of TRWP in the environment. In order to determine urban streams with increased risk, it is essential to identify how many TRWPs are sitting on the road waiting to be washed out to streams via roadway/stormwater runoff. By identifying regions of increased TRWP inputs, we can assess areas that need targeted green infrastructure for stormwater/roadway runoff mitigation.

Significant TRWP pollutants like 2-((4-Methylpentan-2-yl)amino)-5-(phenylamino)cyclohexa-2,5-diene-1,4-dione (6PPD-quinone) have been profiled as casual toxicants that induce Urban runoff mortality syndrome (URMS) and Coho mortality syndrome (CMS), which are fish die-off events observed in Puget Sound (Peters et al., 2022). As TRWP accumulates along the roadside, 6PPD, a tire additive used to maintain rubber stability, undergoes environmental transformations with ground-level ozone and creates the lethally toxic chemical 6PPD-quinone (Tian et al., 2020; Järlskog et al., 2022). Toxic stormwater flushes refer to heavy rain or snow melt, which transports large amounts of toxins from roadways into aquatic ecosystems (Peter et al., 2022). These stormwater flushes have been related to the observed URMS and CMS, which refer to the mortality events of aquatic species from exposure to toxic stormwater and roadway runoff (Peter et al., 2022; French et al., 2022). Before discovering 6PDD-quinone as the casual toxicant to induce CMS and URMS, studies showed that densely populated urban areas with high impervious land coverage were directly related to fish mortality events (Fiest et al., 2018). Expanding impervious surfaces increases the negative impacts of land use practices, human activities, and urban growth on stream ecosystems (Fiest et al., 2018). The increased impervious land coverage and dwindling freshwater resources put people and salmon at risk. A geospatial analysis of the distribution of TRWP among various road types can help identify areas that require targeted green infrastructure due to TRWP presence and abundance. Urban streams with susceptible species of URMS / CMS, along with increased TRWP inputs, downplay the success of significant ecological restoration goals, like the fish passage barrier projects in Washington State.

Since TRWPs transport roadway toxins like 6PPD-quinone to urban streams, which are the culprit of salmon mortality in Puget Sound, understanding the sum of tire microplastics (TRWP) found on the roadway is vital to determine whether certain roads or road types are hotspots for TRWP production. Few studies have quantified TRWP from environmental samples, most of which are located outside of the United States; however, virtually none exists in the Pacific Northwest at the time of writing this thesis. Since Puget Sound is an urban hotspot with crucial salmon runs under threat, doing this work in Washington State is essential. Furthermore, because the surface area of the particles can affect the sorption of pollutants onto particles, it is essential to quantify surface area simultaneously.

Research Questions

How does tire road wear particle (TRWP) size distribution vary among road types (primary, secondary, residential, and rural) in Thurston County, Washington? The second research question: Does the annual average daily traffic impact the average mean TRWP particle size and count? These research questions help provide insight into the spatial distribution of TRWP found on roadways, indicating regions that need to target stormwater and roadway runoff mitigations based on high emission rates.

Literature Review

Introduction

Tire road wears particle presence, and abundance are highly unknown, and only recently have research developments made progress in detailing the presence of TRWP emissions. The urbanization of streams poses one of the most significant threats to healthy freshwater ecosystems (Scholz et al., 2 011). Urbanization represents an area no longer in its natural state with increased impervious surfaces and various land uses that pollute the air, water, and soil (Scholz et al., 2011). Road development is one of the most significant factors that pollute the environment with petrol chemicals and heavy metals. Road networks act as the lifeblood of a communities economy and trade (TRCP, 2022). As the population grows, so does the variety of land use practices and road development that negatively impact stream water quality and biological function (Peter et al., 2022). One of the most harmful land use practices to urban streams is using paved roads and motor vehicles (Scholz et al., 2011). For example, tires emit toxins and physical debris into the roadway contributing to air, water, and soil pollution. Studying and monitoring densely populated areas with increased traffic for TRWP emissions is necessary to mitigate the loss of suitable stream habitats for economic and culturally iconic species like Pacific salmon (Lou et al., 2021). Washington's urbanization of streams led to the decimation of salmon populations in Puget Sound and resulted in the urgency to restore and conserve stream habitats (Sobocinski et al., 2021; Scholz et al., 2011). In order to aid the effort to conserve salmon species, more research on the presence and abundance of TRWP found on roads is necessary.

This literature review seeks to connect Tire Road Wear Particles (TRWP) as a significant source of non-point pollution in stormwater/roadway runoff which acts as physical and chemical waste to urban streams. Since TRWP are transporters of toxins from the road, they act as a non-point source of chemical pollution in urban streams which diminishes vital salmon habitats. TRWP's toxins from the roadway have been found to increase streams' toxicity, resulting in induced urban runoff mortality syndrome (French et al., 2022). In order to assess the extent of damage TRWPs have on streams, it is vital to get an accurate measurement of TRWP contents in road dust. For instance, determining the presence and abundance of TRWP on roadways can help determine which roads have increased risks for stormwater /roadway runoff pollution effects on urban streams.

Roadmap Connecting Tire Road wear particle (TRWP) Emissions and Urban Runoff Mortality Syndrome (URMS)

The literature review for this study covers various topics to provide a comprehensive viewpoint of tire road wear particle waste effects on the environment, specifically urban streams. Reviewing relevant legislation established to protect the environment from manufacturing and using toxic chemicals in consumer products gives the reader an understanding of how we can assert these policies to mitigate and monitor TRWP pollution. Following the legislative review, the literature review provides the global significance of TRWP pollution with production estimates. Then a review of tire compositions' physical and physicochemical characteristics helps to understand the fate and transport of TRWPs. The fate and transport of TRWP are related to the tire particle's size and density from environmental samples, providing the connection of TRWP pollution to urban stream degradation. The literature review then turns toward the effects of stream urbanization in relation to traffic and motor vehicle pollution, specifically tires. The review also covers the production, fate, and transport of 6PPD and its relation to Urban Runoff Mortality Syndrome in urban streams and Coho Mortality Syndrome. Once the relationship between the URMS and TRWP pollution is established, the literature review covers salmon habitat connectivity and the issues of TRWP pollution in reopened urban streams to sensitive species. Finally, the review covers some of Washington’s most notable tire pollution-related events, followed by the best green infrastructure mitigation options for lessening TRWP pollution in urban streams.

Environmental regulations to monitor chemicals exposures of point and non-point toxins

Environmental regulation and policy provide consumer and environmental protections from manufacturers who readily pollute the air and water during production. Environmental regulations are the number one way we fund the monitoring and mitigation of environmental pollution created by manufacturing and product uses. Therefore, it plays an essential role in addressing tire rubber pollution to the environment. In our modern chemical-laden world, many environmental toxins contribute to increased rates of communities diagnosed with neurological illnesses and metabolic disorders (MacKendricks, 2018).

The Toxic Chemical Act of 1974 and the Clean Water Act of 1972 implore federal, state, and counties to act on the protection of our communities from point and non-point toxic chemical pollution that adversely impacts human health and the environment (IDEM, 2022). The Clean Water Act introduced the National Pollution Discharge System (NPDES) program, which enables the government to reduce the allowed discharges of point source pollutants into water systems (IDEM, 2022). However, the success of the NPDES is limited in its effects on mitigating point source pollution, whereas non-point source pollutants are still a significant issue in aquatic management (IDEM, 2022). "Washington State's water quality standards for toxic substances code WAC 173-201A-040[5] is defined by human health-based water quality criteria which references 40 CFR 131.36, also known as the National Toxics Rule" (DOE, 2022). These codes of regulation and restriction only apply to a set list of toxins designated as dangerous to human health and have a defined action plan to address chemical contamination. Tire wear particles are co-contaminant carriers and creators of harmful, persistent organic chemicals such as PAHs, benzene-thiols, and heavy metals listed in the chemical action plan (DOE, 2022). The Pollution Prevention for Our

Future Act SSB 5135 was signed into law by Governor Jay Inslee on May 8, 2019 (Toxic-Free Future, 2019). This bill furthered Washington's progressive leadership in Environmental and Public Health preventative action against environmental injustice.

The investigation and prevention of toxic chemical exposure by the Washington State Department of Ecology (DOE) is through SSB 5135. DOE developed a Chemical Action Plan (CAP), which identifies, and phases out toxic chemicals used in consumer products (DOE, 2022). The law requires the agency to act on and seek out products containing any of the five classes of chemicals listed as a priority. According to SSB5135, a new group of chemicals will undergo this investigation every five years. Persistent toxic chemicals are compounds that do not readily break down, or they have even more poisonous metabolites which cause harm to the environment (Stohler, 2019). The policy contains five classes of toxic chemicals: PAHs, organohalogens, flame retardants, biphenyls, and PCBs (Stohler, 2019). Policy SSB5135 allows state agencies to ban chemicals and requires the disclosure of chemicals used in consumer product production. In the last fifty years, over 80,000 new synthetic chemicals have been invented and used in consumer and commercial products (Stohler, 2019). Tires are among this group of consumer products. Tire production has increased, and the need for chemical additives to meet consumer needs and safety regulations set by federal and state governments has also increased (UTMS, 2022). The list of chemicals for Washington’s chemical action plan may be expanded to include 6PPD. This tire rubber additive stabilizes rubber to increase its safety and performance. Tires additive 6PPD undergo an environmental transformation, creating a highly toxic byproduct, 6PDD-quinone, which presents eco-toxicity and human health risks.

History of Tire Production and Research

The 1950s began the global production of thermoplastics industrial manufacturing, and by 2013 approximately 322 million tons/year of thermoplastics had been produced (Kole et al., 2017). In 2016 the global market sold 12.3 million tons of natural rubber and 14.6 million tons of synthetic rubber (Kole et al., 2017). Tire rubber is considered one of two types of thermoplastics due to its elastomer content that enables the tire to withstand temperature and pressure fluctuations (Kole et al., 2017). Unfortunately, tire rubber is produced annually at rates the environment cannot support. Establishing the abundance and prevalence of environmental toxins like 6PPD-quinone, a chemical byproduct of 6PPD, a tire rubber additive, is essential in addressing the health of urban streams important for salmon life cycles. TRWP impacts urban streams and damages Washington's communities' health, economy, and culture. By constantly expanding our urban boundaries, we have poisoned the water, resulting in diminished vital habitat for culturally and economically important resources like Coho Salmon (O. Kisutch) (Scholz et al., 2011).

The Michelin Brothers created the first inflatable tire in 1895, and in the 1950s, the radial tire used today was produced (Halle et al., 2020). As innovations in tire production increase, so does the available research on tire rubber. In 1966 the first research paper on tire rubber particles and dust was published (Halle et al., 2020). In the 1970s, tire rubber research began to characterize tire rubber emissions on toxicity, size of particles, and abrasion patterns (Johannesen et al., 2021; Halle et al., 2020). In the 1990s, studies of TRWP turned toward the environmental impacts of tire pollution and began categorizing the chemical hazards from roadway runoff to water systems (Johannesen et al., 2021; Halle et al., 2020). Finally, in the early 2000s, environmental scientists began identifying and quantifying specific tire rubber wear chemical groups and heavy metals like polycyclic aromatic hydrocarbons, benzothiazoles, and Zinc (Zn) (Johannesen et al., 2021; Halle et al., 2020). Each decade in tire production has raised questions and concerns about the environmental pollution factors of tires' physical and chemical waste and how it may compromise human health.

In 2016 public concerns over the use of recycled tire crumb infill used for sports fields enacted a federal response from the Environmental Protection Agency (EPA), Centers for Disease Control (CDC), and the US Consumer Product Safety Commission (CPSC) (EPA, 2019). These agencies developed an action plan for the current research status and knowledge gaps of synthetic turfs' human health and environmental hazards. The technical report generated from the federal review noted that TRWP chemical leachates and heavy metals have multiple human exposure pathways, such as digestion, inhalation, and dermal contact, which may adversely impact developing bodies (EPA, 2019). As of 2020, we now recognize tire rubber as the second most prominent source of global microplastics that leach chemicals and heavy metals into the environment (Lou et al., 2021). In addition, tire tread wear in the early 2000s began to surface as a concern in heavy-traffic urban areas due to its presence in particulate matter (Kreider et al., 2010). Measuring urban air particulates has been linked to many developmental, reproductive, and increased cancer rates due to inhalation of poor air quality (Kreider et al., 2010).

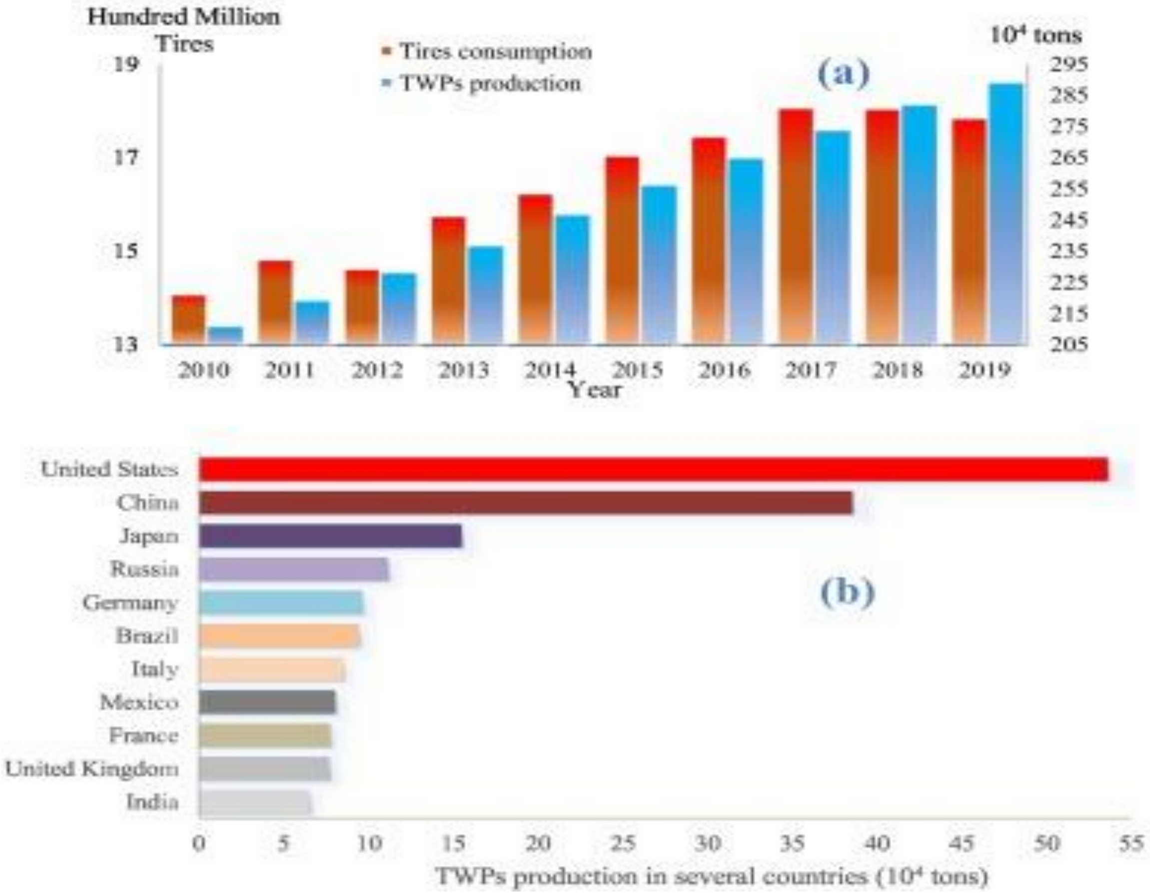
Tires represent a standard technology that has been innovated to provide consumers with better performance measures and safety for drivers. Post-WWII represents this modernization era where consumer goods became the new gold rush (MacKendricks, 2018). In such a competitive manufacturer and consumer world, tire manufacturers aim to provide their consumers with safe, high-performing products. For example, using 6PPD as an antioxidant helps lessen thermal degradation and protects tires in constant and dynamic conditions (USTMA, 2020). The National Highway Traffic Safety Administration regulates new tire manufacturing by the Motor Vehicle

Safety Act, 49 USC §§ 30103-30105 et seq. (NHTSA, 2008). Since discovering 6PPD-quinone's toxic effects on Coho salmon, tire manufacturers have responded to governmental inquiries regarding using and replacing 6PPD in tires. However, the US Tire Manufacturers Association affirmed that without 6PPD, tires would not meet the Motor Vehicle Safety Act standards (USTMA, 2020), preventing phasing 6PPD-quinone out of use in tire manufacturing.

Vehicle and tire production are essential indications of the total sum of tire rubber microplastics that enter the environment (Wagner et al., 2018; Lou et al., 2021). The global production of tires increased from 4.08 million in 2010 to 17.85 million in 2019 (Lou et al., 2021). As global vehicle production grows, so does the amount of tire wear particles, as shown in Figure 1, Box A (Lou, 2021). Figure 1, Box B indicates that the US has the highest production of tire wear microplastics emitted to the environment. One reason for this is related to the immensity of the United States transportation network, which contains many roads/lengths of roads, equating to high levels of tire wear products (Lou et al., 2021). Expanding our transportation network increases the production of TWP, which raises its toxicological effects in urban and rural streams via urban expansion.

Figure 1.

Global tire production with the global tire wear production.



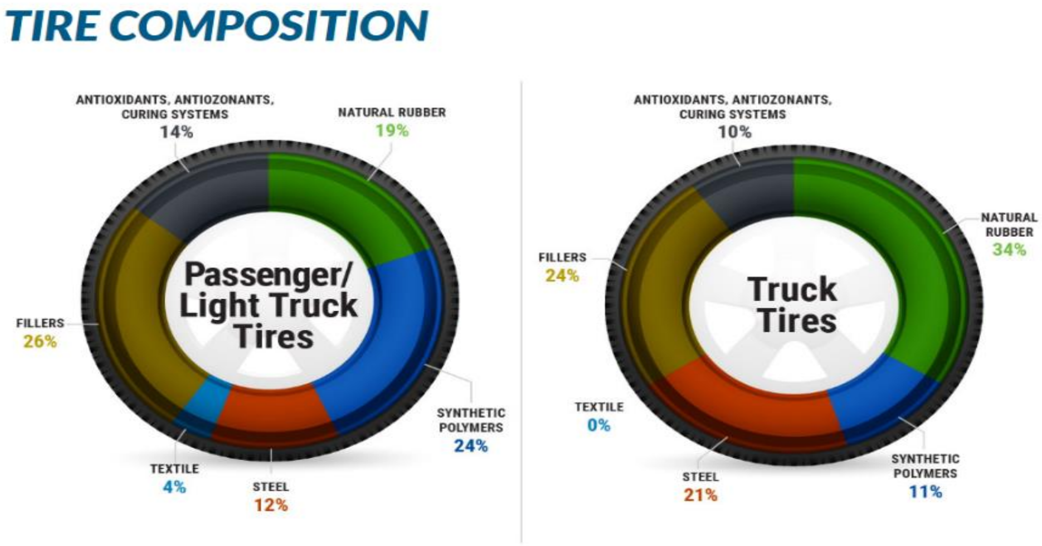
Note: a) Global production and consumption of TWPs from 2010-2019. (b) shows TWP production for several countries (Lou et al., 2022).

Tire Rubber Physical and Physicochemical Characteristics

Tires manufacturing comes with various materials and layers with different compositions. Manufacturing tires involves mixing synthetic and natural elements under high heat and pressure, then rolling them into long sheets of rubber (EPA, 2019). The seven significant parts of tires include the outermost layer of tread, the sidewalls covering the body piles, the inflatable inner liner, steel belts, bead filler, and beads (US tire.org 2022; EPA, 2019). Tire production depends on natural resources to produce the yearly global demand for new tires. Therefore, synthetic rubber and elastomers are used alternatively to natural rubber in tire production (EPA, 2019). Tires composition includes "supportive filler materials; curatives like vulcanizing agents, activators, accelerators, antioxidants, antiozonants, inhibitors, and retarders; extender oils and softeners; phenolic resins and plasticizers; metal wire; polyester or nylon fabrics; and bonding agents" (EPA, 2019). The tire assembly occurs in layers of rubber and coated materials, and a steal belt is fastened to the tire tread, after which the tire is cured at temperatures ranging from 150 º F to 180º F to crosslink the tires' polymer chains (EPA, 2019). The composition of tires

Figure 2

Tire Composition



Note: Tire Composition for passenger cars and trucks (US tires.org., 2022).

depends on the type of vehicle, as shown in Figure 2; note that there is a higher percentage of antioxidants in passenger cars than in trucks (US tires.org, 2022). These chemical additives increase the tire's performance, and the tire lifespan of passenger cars is higher than trucks.

Today, tires are chemically enhanced by innovative technology to provide consumers with top-quality safety and performance measures. Table 1 provides an overview of the physiochemical properties of tire rubber to understand how TRWP impacts the environment. A thorough review of the physicochemical properties is vital when calculating the environmental fate of TRWP chemical leachates.

Table 1

Physiochemical properties of tire rubber microplastics

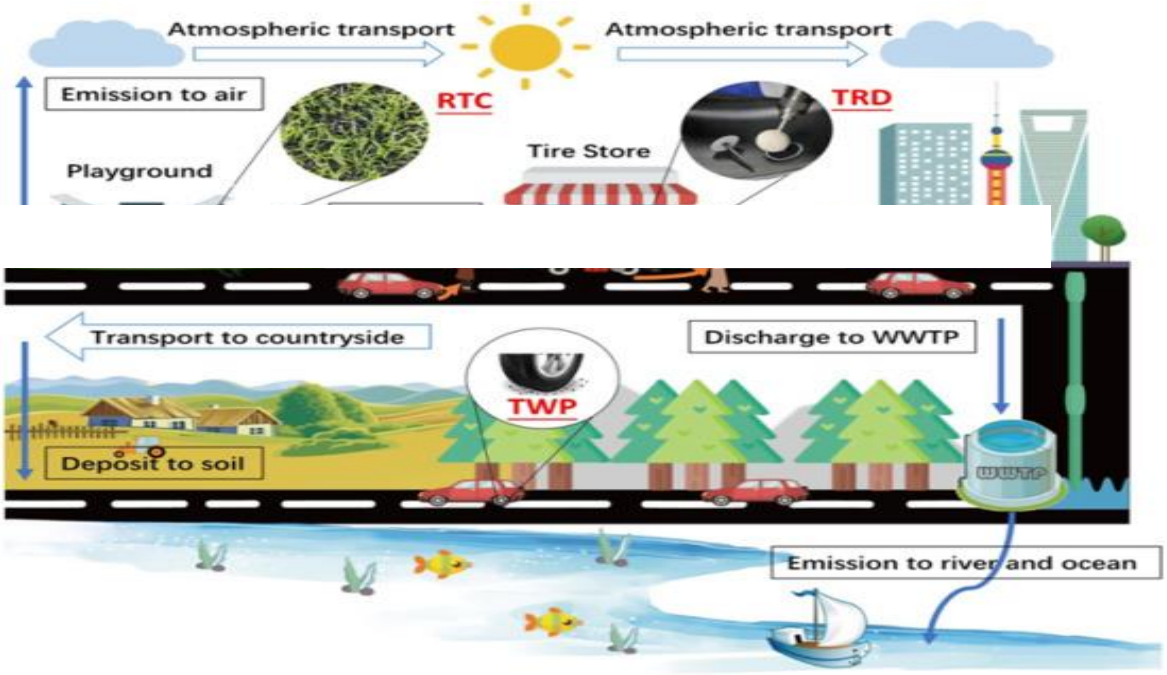
Parameter	Description	Reference
Materials	"Polybutadiene, styrene-butadiene, chloroprene-isoprene, polysulfide, carbon black, and silica"	Lou 2021; EPA 2019; Guzman 2013
Additives	"Mineral oils, thiazole, organic peroxides, nitro compounds, halogenated cyanoacrylate alkanes, amine, phenol, calcium oxide, aromatic and aliphatic esters, peptizer, zinc oxide, ZnO, sulfur, selenium, tellurium" and 6PPD.	Lou 2021; Gonzalez 2012; Johannessen 2022
Environmental Tire Pollutants found in Stormwater and roadway runoff	Fluoranthene, Chrysene, anthracene, polycyclic-aromatics, benzothiazole, 1-indanone, aluminum, 1-octanethiol, phenanthrene, anthracene, and aluminum, Zinc, Copper, Cadmium, 6PPD, DPG, and HMMM.	Muller 2020Halle 2021; Johannessen 2022; Lou 2021; Järlskog 2022

Tire Rubber Microplastics Sources to the Environment

Tire rubber microplastics enter the environment via its primary source of tire wear particles discharged to aquatic ecosystems via stormwater and roadway runoff. The secondary source of tire rubber microplastics to the environment comes from recycled tire crumb and tire repair-polished debris. Figure 3 displays the potential sources of primary and secondary tire rubber microplastic sources and their environmental fate once discharged. The recycled sources of tires are depicted in the top portion, and the primary ones are displayed at the bottom of

Figure 3.

Sources of Tire Microplastics to the Environment.



Note: illustrates TRWP sources, transport, and environmental sinks. Tire wear particles (TWP), recycled tire crumb (RTC), and tire repair-polished debris (TRD) (Lou et al., 2021).

Recycled tire sources manufacture tire crumb rubber for reuse as mulch, playground materials, and synthetic turf for sports fields (EPA, 2019). The two methods used to make tire crumb rubber are ambient and cryogenic (EPA, 2019). These processes create tire rubber particle sizes that range between 0.84 to 2.0 mm (EPA, 2019). In addition, the tire crumb rubber decomposes into particles with consistent measurements, whereas primary sources like tire road wear particles have a wide variety of particle sizes (Lou et al., 2021). For example, tire wear particles size ranges from a few nanometers to 265µm (Lou et al., 2021; Wagner et al., 2018). Recycled tire rubber crumb particles have consistent size ranges manufactured for specific purposes. Recycled tire rubber particles in the environment range from ≤0.063 to >4.75 mm (EPA, 2019). The smaller the tire rubber particle increases the surface area for leaching and absorption reactions, which is why the infill poses high human health concerns (Pennell et al., 2002). According to the EPA, as of 2019, there were 12,000-13,000 synthetic turf fields in the US and estimated that 12,00 to 1,500 new turf installations occur yearly. (EPA.org 2019). Recycled tire rubber pollution is an overlooked source of microplastics that continuously leach toxic organic chemicals and heavy metals into the air, soil, and water (Halle et al., 2020). Tire rubber crumb infill used in artificial turf is a crucial source of micronized tire rubber microplastics to the environment (Redondo-Hasselerharm et al., 2018). With that said, recycled tire crumb is a steady source of microplastic-sized tires to the environment.

Primary sources of Tire Rubber microplastics in the environment

The friction between the tire rubber and the road creates tire road wear particles (TRWP) and is the primary source of tire rubber microplastics in the environment (Mennekes et al., 2022; Lou et al., 2021; Wagner et al., 2018). TRWP concentrations accumulate on roadways and are dispersed to streams via stormwater runoff (Hiki et al., 2022). As we increase our global demand for personal vehicle use, the need for new tire production rises, thereby increasing the issue of TRWP accumulation in roadway dust (Lou et al., 2021). The number of roadways can indicate the amount of TRWP deposited to nearby streams based on roadway dust accumulation since over

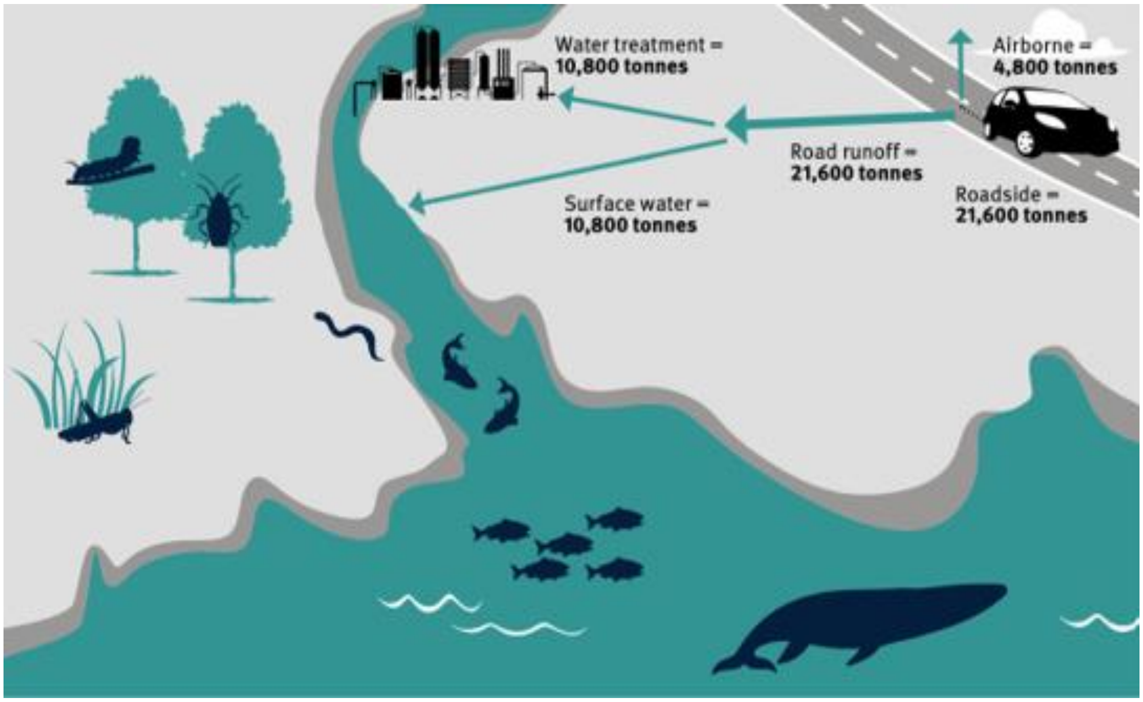
40% of TRWP deposited to roadways end up in surface waters (Hiki et al., 2022). The global production of TRWP annual release is estimated to be 6.15 × 10^6 tons per year using a world population of 7.59 billion (Mennekes et al., 2022; Lou et al., 2021; Wagner et al., 2018). The United States has the highest TRWP emissions per capita, estimated at 4.70 x 10^6 tons per year, due to our extensive transportation network with the most vehicles (Lou et al., 2021; Kole et al., 2017). Tire wear particles' environmental pathways are heavily dependent on localized factors such as road types and what types of regional stormwater infrastructure are in place. (Kole et al., 2017).

Tire Road wear particle (TRWP) transport, fate, and flow in the environment

The road environment is full of particles deposited and suspended by traffic, forming heterogeneous road dust (Järlskog et al., 2022). Non-exhaust emissions are qualified by the wear of the vehicle’s tires, brake pads, motor fluids, and road surfaces as a significant source of roadway pollution (Klockner et al., 2020; Järlskog et al., 2022). These non-exhaust emissions contribute 35 - 55% of total trafficking emissions (Klockner et al., 2020). Tire road wear particles (TRWP) account for up to 30% of these non-exhaust emissions (Klockner et al., 2020). TRWP are often hetero-agglomerates made-up of tire particles and other roadway particles such as minerals, chemical pollutants, and heavy metals (Klockner et al., 2020). The fate and transport of TRWP depend on the size of the particle. For example, the fine fraction TRWPs are easily suspended in the ambient air where inhalation poses human health hazards (Wagner et al., 2018). On the other hand, the coarse fraction of TRWP on the roadway is transported to nearby soils and surface waters (Wagner et al., 2018). The coarse fraction of TRWP poses eco-toxicity and human health challenges that are magnified through the food chain. Figure 5 shows the fate and transport of TRWP; once released to the roadways, approximately 90-95% of TRWP released to the road will be transported to nearby soils, streams, and water treatment facilities (Wagner et al., 2018; Baensch-Baltruschat et al., 2020).

Figure 4.

Fate and Transport of TRWP in the Environment



Note: illustrates the transport and fate of TRWP once emitted into the environment (Wagner 2018).

A study from Germany found that approximately 40% of TRWP are considered coarse particles that are transported from the roadway to nearby soils and streams (Järlskog et al., 2022). Furthermore, road dust total particle mass analysis has shown that samples collected adjacent to curbs contain up to 400 – 1240 g /m^2 (Järlskog et al., 2022). Whereas industrial sites in Korea found areas with high traffic volumes reported TRWP in road dust to be 334-1669 g/m^2 (Jeong et al., 2020; Järlskog et al., 2022). These sums are immense and require further investigation into the best way to monitor and measure TRWP pollution in the environment.

The size of the TRWP determines the transport. The smaller, finer particulate are more readily transported since they can be suspended in the air and remain suspended in surface waters

(Wagner et al., 2018). In contrast, the coarse larger TRWP are not transported as far and settle in soils and sediments where they degrade and release chemical leachates into their surrounding environment (Wagner et al., 2018). Road dust is a mixture of TRWP sizes with finer TRWP than roadside soils (Järlskog et al., 2022). Therefore, it is safe to say that TRWP found in road dust will have higher rates of co-contaminants due to TRWP's mixed composition of fine and coarse particles that undergo environmental reactions.

How TRWPs are Estimated

Almost all studies that estimate TRWP in the environment come from lab-simulated tests of tire wear (Mennekes et al., 2022). There are few real-world estimates of TRWP from the environment, so the current estimates are likely underestimated. Current studies on global estimates used a probability material flow analysis of tire rubber microplastic emissions to calculate tire wear particle emissions; this is done by multiplying the emissions factor of TWP in mg by the vehicle kilometers traveled (Lou et al., 2021; Verschoor et al., 2016). Traffic-related factors control the total amount of pollutants on the road. These traffic-related factors include transportation network structure, velocity, and the number of vehicles on the roadway (Markiewicz et al., 2017). The method used to estimate TWPs production goes as follows: (E) is E = Emissions Factor × Vehicle Km Travelled × number of the vehicle. EF assumes 100 mg/vehicle-km (Lou et al., 2021; Kole et al., 2017). The above equation can be adapted to estimate TWP emissions on a more regional scale to estimate the TWP emissions to stormwater. Other methods that identify tire wear microplastics include visual identification and a confirmation of the sample using gas chromatography-mass spectrometry (GC-MS) analysis looking for N-cyclohexyl-2-benzothiazolamine (NCBA) (Knight et al., 2020). This method is reliable in identifying the emissions of tire rubber microplastics to the environment. However, visual identification is essential in TRWP identification because the size of the tire rubber microplastics will determine the leaching capabilities of its known chemical contaminants (Knight et al., 2020).

Tire Road wear particle (TRWP) sizes and densities in environmental samples

TRWP particle size and distribution research has examined TRWP in environmental samples such as air, soil, sediment, water, and road dust (Baensch-Baltruschat et al., 2022). However, quantitative analysis of TRWP particle sizes and densities from ecological samples is still being determined (Wagner et al., 2018; Klockner et al., 2020). The primary quantitative analysis for tire wear contents in environmental samples estimates specific tire chemical or elemental markers (Klockner et al., 2020). These tire makers are degradation products of rubber polymers or elemental markers like zinc; other tire makers are organic constituents from chemical additives in tire production (Klockner et al., 2020). TRWP elastomer and chemical leachate contents provide reliable measurements for TRWP environmental release factors of cryogrind tire leachates. Wagner et al. (2018) compared three size ranges of TRWP to investigate tire wear particles aging of tire tread wear particles of milled tire particles, TRWPs from a road simulator, and road dust samples. Wagner et al. (2018) findings are listed in Table 3 below and detail the differences and commonalities in size, shape, density, and composition found among the different sample types from milled tire particles, road simulators, and road dust TRWPs.

Table 2.

Differences between milled TWP and TRWPs were generated from road simulation studies (Wagner et al., 2018).

Tire Rubber Particle	Density fraction	Composition
Cryogenically milled Tire Particles were Micro-sized and irregular shapes	1.2 g/cm^3	“No inorganic particle constituents from road dust, no asphalt components, 100% tire (tread) rubber. Chemical composition will depend on the age of the tires used for milling. Only tire tread should be milled” (Wagner et al., 2018).
Simulator TRWP’s and Environmental samples TRWP were Nano-sized to Micro-sized and elongated, with some irregular shapes	1.3-1.9 g/cm^3	“TRWPs contain inorganic particles from the road or road dust and organic TPs (tire tread only particles). The varying ratio of tire tread rubber and mineral particles is 50–80% tire tread rubber and 20–50% mineral dust from road surface). Contains transformation products formed by tire aging.” (Wagner et al., 2018)

TRWP found in Soils

Thomas et al. (2023) examined soil samples near the roadside and found TRWP size ranges of 5 mm to less than 1 mm in Ohio and Kansas. They estimated TRWP content to range between 800 to 1300 µg/g in Ohio; in Kansas, the TRWP content was estimated between 1,200 to 3,100 µg/g (Thomas et al., 2023). For the size range less than 1 mm, researchers found that in both Ohio and Kansas roadside soil samples, TRWP weight percentage ranges from 0.15 to 2.1%, and TRWP content is determined to depend on the locations and traffic (Thomas et al., 2023). Therefore, the presence and abundance of TRWP are dependent on traffic and urbanization rates as they indicate road use. Once TRWPs are transported to the soil, they degrade and leach out heavy metals and other co-contaminants from the roadway (Wagner et al., 2018). Therefore, soils tend to have larger TRWP than other environmental media, such as dust and water samples.

TRWP found in Road Dust

Road dust samples for TRWP and their chemical leachates have been more recently investigated due to 6PPD-quinone. Road dust comprises a variety of organic and non-organic particulates and is generally heterogenic in particle size composition (Baensch-Baltruschat et al., 2020). Kreider et al. (2010) assessed the interactions of car tires on concrete pavement, where they found a range of TRWP sizes between 4 and 350 µm, with most of the particles ranging from 5 µm and 25 µm. Aatmeeyata et al. (2009) studied air samples and found TRWP sizes that range ≥ 10 µm. Dahl (2010) used a road simulator to collect tire wear and tear from the wheel well and found particle sizes that ranged from 15 to 700 nanometers. Dahls et al. (2010) TRWP had a mean particle size diameter of 75 nm. Matthiessen et al. (2011) measured airborne particle concentrations from the vehicle's wheel well and found size ranges of 6 to 562 nanometers while driving. The same study highlighted that breaking produced a variation in the tire where particle emission sizes were between 30 and 60 nanometers (Matthiessen et al., 2011). The common theme in these studies' collection and particle sizes is that each collection method was by air sampling on and near tires on the roadway. Other studies analyzed TRWP from road dust samples and found that these particles on the roadway tend to be larger than the portion located in air samples and sediment samples (Klockner et al., 2020). Since dust can be collected into clumps off the roadway and dispersed into the air, TRWPs found in road dust pose a significant threat to human health and requires further research to understand its damages fully.

TRWP found in sediments and surface water

Water and sediment samples of TRWP are much scarcer in the literature. A few studies looked at TRWP when researching microplastic inputs to the environment. For example, Charleston Estuary, South Carolina, USA study found TRWP in subtidal and intertidal sediments and documented that TRWPs were abundant and widely distributed among sediment samples (Leads et al., 2019). The subtidal and intertidal samples contained TRWP size ranges between 63-149 µm (198 particles), 150-499 µm (94 particles), and size fraction ≥ 500 µm (19 particles) (Leads et al. 2019). The study highlights the fate of larger TRWP transported from roadways into marine and freshwater ecosystems that will end up in sediments. A review of urbanization drivers that directly impact the amount of TRWP entering urban streams is needed to understand how to mitigate the mounting issue of TRWP pollution in urban streams.

Urbanization of Streams: Connecting TRWP as a Physical and Non-point Source of Pollution to Urban Streams

Urbanization introduces diverse alterations in watersheds and presents many disruptions to streams' chemical, physical, and biological processes, negatively affecting stream biota (Booth et al., 2005). The mechanism that enacts these disruptions is replacing porous natural ground coverage with impervious surfaces like roads and buildings (Booth et al., 2005). The change of water inputs from stormwater and roadway runoff changes the velocity and abundance of water entering urban streams, resulting in stream channel erosion and degraded water quality (Booth et al., 2005). Point and non-point source contaminants impact urban streams' biodiversity, habitat function, and water quality (Booth et al., 2005; DOE, 2022). Tire rubber microplastics are a source of physical waste and non-point pollutants with known toxicological impacts on aquatic ecosystems (Muller et al., 2020). TRWPs carry co-contaminants of persistent organic pollutants like PAHs and benzothiazole derivatives, as well as heavy metals like zinc (Zn) and copper (Cu) (Klockner et al., 2021; Wagner et al., 2018). TRWPs also undergo photochemical degradation and environmental reactions with ground-level ozone, which emits harmful chemicals, leachates, and heavy metals into the air, soil, and water (Lou et al., 2021; Johannesen et al., 2022; Muller et al., 2020). One of these reactions occurs with tire additive 6PPD which pushes to the surface of the TRWP and reacts with ground-level ozone to create acutely toxic N-(1,3-dimethyl butyl)-N′-phenyl-p-phenylenediamine-quinone (6PPD-quinone), the casual toxicant for urban mortality syndrome observed in Coho salmon since the 1990s (Tian et al., 2021). TRWP emissions are a mounting problem that affects the health of our communities and aquatic environments.

Tire Road Wear Particles (TWRP's) toxicological effects are not limited to the environmental production of 6PPD-quinone. Instead, TRWP leaches and absorbs various persistent organic pollutants and heavy metals (Johannesen et al., 2021; Järlskog et al., 2022). TRWPs function as co-contaminant carriers of chemical toxins and biotic (pathogens, i.e., viruses and bacteria) from terrestrial environments to aquatic ecosystems (Lou et al., 2021). The transport of TRWPs into streams poses a significant threat to stream ecosystems because of co-contaminants carried from the roadway and stormwater runoff. The risks of URMS exponentially increase to 90% mortality for Coho salmon as the percentage of impervious land coverage reaches above 40% (Fiest et al., 2018). The expansion of the transportation network directly increases the inputs of motor vehicle pollutants like tire wear particles from roadways to streams where it toxifies urban streams (Fiest et al., 2018; Wagner et al., 2020). In Thurston County, WA, the population is expected to increase by 100,000 people by 2040 (TRCP, 2022). This means Thurston County has to make considerable efforts to ensure its stream ecosystems are not overrun by roadway runoff and motor vehicle pollution.

Urbanization drivers like stormwater runoff create stressors on stream ecosystems by altering environmental features that trigger a biological response such as URMS. Roadway and stormwater runoff is the main route of tire road wear particles (TRWP) transport to urban streams and surface waters (Wagner et al., 2018; Lou et al., 2021). The prevalence and abundance of TRWP emissions in urban streams make it necessary to measure TRWP emissions. To evaluate whether there was variation in the toxicity of TRWP, Halle et al. (2021) studied the effects of new versus old tires on the *Hyalella azteca* amphipod crustacean species. The result of the study determined that newer tires had higher toxicity effects than older tire particulates (Halle et al., 2021). The lethal impact of new tires on *Hyalella azteca* was estimated to be LC50 to be 364 ± 64 particles (0.19 ± 0.03 g L− 1) (Halle et al., 2021). Aged tire wear particles' lethal concentration was estimated at 3073 ± 211 particles (0.91 ± 0.06 g L− 1) (Halle et al., 2021). These study results provide a few insights; first, some species will take up TRWP as food; second, these animals can only take up so many particles before a lethal response; and third, TRWP degrades, and they have the potential to become less toxic. Tires becoming less toxic over time is not true of TRWP found in road dust and other environmental samples. For example, Järlskog et al. (2022) determined that road dust TRWP are highly absorbent polymers laden with roadway pollutants washed out into streams via runoff.

6PPD-quinones Environmental Production from TRWP

Identifying regions with increased TRWP inputs can highlight areas that require stormwater mitigation efforts to alleviate the toxic effects of 6PPD-quinone in urban streams. The spatial distribution of TRWP can indicate the potential abundance of 6PPD-quinone in the environment (DOE, 2022). The flow of TRWP once emitted to road environments has shown that TRWP is found in measurable quantities in air, soil, road dust, and surface water samples (Wagner et al., 2018). The chemical additives' reaction mechanism goes as follows: 6PPD within the tire particle pushes to the surface, reacting with ground-level ozone producing a byproduct called 6PDD-quinone (Tian et al., 2022). This reaction occurs at the interface of the particle surface due to 6PPD's chemical behavior, so over time, as the particle ages, its concentration of 6PPD decreases simultaneously as the particle increases 6PPD-quinone concentrations (Järlskog et al., 2022). Tire particles readily absorb toxins and minerals while on the roadway, where they become co-contaminate carriers.

The mechanism of the 6PPD surface reactively suggests that as the TRWP becomes smaller, it increases the available surface area for 6PPD to react and generate 6PPD-quinone. Studies also show that 6PDD-quinone can accumulate in tire rubber particles, enhancing tire rubber microplastic toxicity as it ages (French et al., 2022; DOE, 2022). This toxicity increase means that as tire rubber on roadways accumulates, it can become saturated in 6PPD-quinone because 6PPD-quinone sorbs to particles as it transfers through the environment. As TWP accumulates along the roadside, the particles become loaded with 6PPD-quinone and, during storm events, are washed into urban streams (DOE, 2022; French et al., 2022; Peter et al., 2022).

Point and Non-point Pollution to Urban Streams

Urban streams are subject to both point and non-point pollutants that change the water quality and introduce chemicals and heavy metals that negatively impact aquatic organisms. The point source of pollution in urban streams is the direct input of contaminants to marine systems via wastewater and stormwater effluent (Mallick et al., 2017). The same goes for tire rubber microplastics acting as an indirect or non-point source of chemical pollutants in urban streams. Urbanized regions tend to have higher ozone levels because of the number of vehicles and varying land use practices (Hiki et al., 2022). In addition, road dust samples show that 6PPD-quinone concentrations are higher on arterial roads than on roads with lower traffic volumes (Hiki et al., 2022). Therefore, identifying all the arterial roadways and their proximity to streams may indicate the amount of 6PPD-quinone contamination. Other factors that alter the effects of TRWP on urban streams include rain events and snow melts, which tend to carry large amounts of tire rubber microplastic chemical byproducts into streams (Peters et al., 2022; Johannessen et al., 2021). Road dust has been shown to have the highest TRWP chemical byproduct levels due to photochemical and ozone degradation (Hiki et al., 2022).

In the spring and summer, ozone levels naturally increase due to increased human activity, and the road dust accumulating in tire rubber microplastics increases the toxicity of 6PPD-quinone (Hiki et al., 2022). For example, Hiki et al. (2022) collected dust from arterial and residential roads in Tokyo, Japan, between May and October and recorded the highest levels of 6PPD-quinone were found between May to June, with 6PPD-quinone concentrations ranging from 35 to 47 ppb (Hiki et al., 2022).

Environmental Fate and Transport of 6PPD-quinone

Stormwater from roadways mobilizes TRWP chemical compounds and transports them into aquatic ecosystems (Johannesen et al., 2021). The lethal concentration of 6PPD-quinone needed to induce acute coho mortality response is 0.8 +- 0.16 µg/L (Tian et al., 2020). Stormwater runoff is a vector of toxic organic chemicals from TRWP into urban receiving waters. Environmental concentrations were estimated retrospectively and show that 6PPD-quinone is widespread, ranging from 0.3 to 19 µg/L (Tian et al., 2020). The widespread occurrence of 6PPD-quinone makes it toxicologically relevant and needs further investigation in quantifying surface water concentrations. The difficulty of establishing a lethal concentration for 6PPD-quinone comes from the fact that it is not commercially produced but made through the oxidation of a stabilizing rubber additive (Tian et al., 2020; Johannesen et al., 2021). Each year Pacific salmon journey to their natal streams; they travel through diverse waters impacted by various land practices and stormwater/roadway runoff inputs (French et al., 2022). Monitoring the environmental levels of 6PPD-quinone in Coho transit streams can provide vital parameters for the population modeling of Coho salmon.

Susceptible Species to Urban Runoff Mortality Syndrome

There is a stark difference in the susceptibility of Coho salmon relative to other salmon species for both 6PPD-quinone and stormwater/ roadway runoff. For example, a study tested the lethal tolerance of a commercial 6PPD-quinone on Coho and Chum salmon; the finding showed that Chum went unaffected, whereas the Coho salmon exhibited 100% mortality within 4-6 hours after exposure (McIntyre et al., 2021). Another study tested the susceptibility from collected stormwater runoff on four salmon species: Coho, Steelhead, Chinook, and Sockeye. The study found that stormwater/roadway runoff brings a caveat of toxins into freshwater streams and rivers that have acute mortality effects on Coho salmon (O. *kisutch*) and steelhead trout (O. *mykiss*) (French et al., 2022). Coho and steelhead trout show unique sensitivity to stormwater and roadway runoff; however, Coho showed the highest sensitivity displaying mortality with a 5% stormwater concentration exposure limit (French et al., 2022). Since tire rubber is the source of the 6PPD, the parent product of 6PPD-quinone, it is crucial to account for all tire rubber-related sources to gain insight into the prevalence and abundance of TRWP toxic effects on the environment.

TRWP can impact the food web through trophic interactions of tire particles and bioaccumulative chemical leachates (Ji et al., 2022). Both 6PPD and 6PPD-quinone have a bioaccumulative capacity and were found in the tissues of two fish species, the snakehead weever and the Spanish mackerel (Ji et al., 2022). Other research has shown that some benthic organisms will indiscriminately ingest TRWP, such as *Gammarus pulex* (Redondo-Hasselerharm et al., 2018). The estimated trophic transfers of tire particles for *G. pulex* were 4.7 x 10^{-9} for G. *pulex* (Redondo-Hasselerharm et al., 2018). This transfer implies that tire rubber may damage the food web and negatively affect human health. Furthermore, the ability of 6PPD-quinone to be retained in fish tissues means it accumulates and poses a risk for biomagnification (Ji et al., 2022). More research is needed to determine the 6PPD-quinones biomagnification factor to understand its environmental fate truly.

Human exposure to 6PPD-quinone

The risk of 6PDD-quinone is not limited to the issues of trophic interactions and URMS but also has implications for human health. For example, the main human pathway of exposure to 6PPD-quinone occurs via inhalation and dermal exposure (Zhang et al., 2022). As we know, 6PPD readily reacts with ozone to create 6PPD-quinone, which means people who live, work, and eat near regions of heavy vehicle use are at risk for inhalation exposure to 6PPD-quinone. At the same time, those who work in tire manufacturing, tire shops, and tire recycling centers are also at risk for exposure. Research shows that 6PPD-quinone tends to accumulate in coarse tire rubber particles, with the highest reported concentrations of 6PPD-quinone at 7.78-23.2 pg. m^{-3} (Zhang, 2022). The highest concentrations of 6PPD-quinone were found in areas with heavy vehicle or tire rubber-related locations (Zhang et al., 2022).

Human health exposures via inhalation have shown various distributions of 6PPD-quinone within the airway systems (Zhang et al., 2022). For example, the headspace airways have been shown to absorb approximately 89-91%; whereas the tracheobronchial absorbs approximately 3.2 -3.8%; and the Pulmonary alveoli has shown to take in up to 6.0- 6.9% (Zhang et al., 2022). More research is needed to understand the toxicological effects of 6PPD-quinone on humans fully. However, the human body takes up 6PPD-quinone via particle-bound inhalation, which has been traced through the airway systems; and has also been found to have trophic interactions. This means that 6PPD-quinone impacts may be more significant than expected since human pathways are mainly through touch, inhalation, and ingestion. This increases the need to mitigate TRWP from roadways before they are transported to streams and devise safety measures for workers in tire manufacturing, tire shops, and recycling centers. Very little is known about the consequences of human exposure, and more research is needed to understand how these multiple human pathways for exposure can limit human health. Since tire chemicals like 6PPD have been manufactured at grand scales, evaluating the potentially significant environmental and occupational injustices to those working in tire manufacturing and recycling centers is necessary. The environmental injustices of 6PPD-quinones impacts are not limited to workers but also tribes who depend on the salmon for their livelihood and cultural customs.

Importance of Salmon and Landscape Connectivity

Environmental injustice takes many forms. For example, salmon in Washington State is vital to the Native American tribes, their customs, and their culture. Unfortunately, over the last century, the salmon in Washington have faced unprecedented losses to their population from overfishing, barring of natal stream habitats, and chemical contamination of our fresh and saltwater ecosystems (Scholz et al., 2011). Washington has begun to prioritize salmon habitat rehabilitation to address these injustices and to provide reparations to the tribes of Washington. For instance, the fish passage barriers removal project in Washington works to remove/replace culverts and bridges that cut salmon off from the natal streams (State of Salmon, 2022). This project hopes to provide more spawning and rearing habitat for salmon. The project was asserted in 2007 the U.S. District Court tasked Washington State to order State to begin remediating the issue of fish passage barriers throughout Puget Sound; this was to provide salmon with their historic spawning grounds and safeguard the treaties made with the Native Americans at the time of Washington's statehood was established (U.S vs. WA 2013). Washington State and the Native American Tribes of Washington have long recognized that the rate of urbanization in Puget Sound has led to salmon habitat fragmentation (State of Salmon, 2022).

However, despite this acknowledgment, Washington State needed to do more to address the issue of fish passage barriers. This led the tribes to take further legal action with the United

States Superior Court, where they appealed the 2007 decision in 2013 for the timely removal of fish passage barriers (U.S. vs. WA 2013). First, Washington State needed to fully consider the urgency of saving salmon habitat due to limited funding for the project (U.S. vs. WA 2013). In the cross-motion judgment, the language references "the right to fish in accustom places" secured by Steven's treaties as a reason to grant the tribe's appeal for the timely removal of fish passage barriers (U.S. vs. WA 2013). Washington State and its residents are responsible for installing culvert/fish passage barriers. They, therefore, are responsible for providing mitigation and reparations to tribes for severing their native food supply of salmon. The United States vs. the State of Washington culvert injunction order required the State to assess, prioritize, and correct up to 90% of culverts/barriers within the injunction site by 2030 (U.S. vs. WA 2013). The injunction order is unique in that it requires habitat management as a way of complying with treaties and will likely function as a foundation for future court decisions. These two judgments are necessary for the State to allocate funds to connectivity projects, evidenced by the reluctance to fund projects before the injunction and the ticking clock set by the federal government.

Landscape connectivity for anadromous species like salmon is essential, and the fragmentation of its habitats results in the loss of biodiversity and decline of many species within Puget Sound (Cederholm et al., 2000). Salmon inhabit many environments within Puget Sound, from streams, rivers, and deltas, to the Salish Sea and the open ocean (Scholz et al., 2011). This means salmon pass through areas with varying aquatic ecosystems with various land use practices that negatively impact water quality. Land use management in Washington is now required to determine if the road crossings are necessary and, if so, choose a fish passage-friendly culvert design specific to the location (Barnard et al., 2013). With so much on the line for removing fish passage barriers, adapting green infrastructure in regions with roads that have increased TRWP inputs will provide safe urban habitats once the fish passages become available.

Tire Rubber Pollution in Washington State Aquatic Ecosystems

In Washington State, the most critical source of water pollution is stormwater and road runoff, with less than a third of our freshwater resources deemed fit for human use (DOE, 2022). Freshwater resources require stronger regulations of waste management practices and stormwater mitigation if we hope to reverse the many aquatics pollution events and daily loading of TRWP to Puget Sound and its tributaries. For example, in the 1970s, the Washington state department of Natural Resources placed over 500,000 waste tires in Puget Sound to create artificial reef habitats (Vargas, 2022). The project had hoped to consolidate the issues of mounting tire waste and aquatic habitat losses by using tires to create it. Unfortunately, over the last 50 years, these tire reefs have sprawled across the Puget Sound floor. The most recently highlighted tire chemical byproduct, 6PPD-quinone, is a chemical of emerging concern due to its widespread and poisonous products on marine life. With the discovery of 6PPD-quinone, the SCUBA Alliance group is addressing the failed restoration project through the location and removal of the 500,000 tires thrown in Puget Sound (Vargas, 2022). The removal process will take time to locate and coordinate the drives to remove the tire debris once found, but at least the issue is being addressed.

In 1990, Seattle initiated restoration projects to support Coho salmon by removing physical barriers to known spawning habitats, resulting in the observed Coho mortality syndrome (Lohse et al., 2008; Scholz et al., 2011). Ironically, these restored streams turned into ecological traps due to the removal of physical barriers that had prohibited Coho salmon from entering lethal urban streams (Scholz et al., 2011). As we move towards an increasingly urbanized Puget Sound, resource managers require new policies, processes, and technologies to mitigate the effect of stormwater runoff on urban streams. It is important to remember that even when a project to rehabilitate an ecosystem fails, many things can be learned from those failures. For example, we now know that tires are toxic to aquatic life, so using them to build habitats is not viable. Also, if we reopen streams for salmon in highly trafficked urban regions, there may be mortality responses.

Sometimes projects prioritize the costs and timeliness ahead of environmental concerns or permitting. Unfortunately, these business practices often come at the price of the ecosystem and human health. For example, in 2020, a significant tire rubber pollution event occurred on the Puyallup River resulting in a fish kill event for 7 ESA listed species (AGO, 2022). In the summer of 2020, the Electron Hydro dam illegally used synthetic field turf to make a temporary bypass channel during construction, placing approximately 2,400 sq. yards of artificial turf, which had up to sixteen to eighteen cubic yards of crumb rubber, into Puyallup River (AGO, 2022). Subsequently, the river overtook synthetic turf and polluted up to fourteen miles downstream with tire crumb rubber (AGO, 2022). Although the pollution event will have stretched much farther than the fourteen miles of the river, considering the chemical contamination from the tire crumb particulate has trophic factors, and the ability to remove tire crumb rubber from sediments is limited. The Dam owners now face millions in fines and cleanup costs but are also at risk of jail time for the illegal installation of synthetic turf (AGO, 2022). Each tire pollution-related event has taken an unmeasured toll on those affected aquatic ecosystems that have far-reaching impacts on the people who live and depend on these aquatic ecosystems.

Green Infrastructure (GI)

Although Washington State faces many challenges of tire rubber-related pollution, more efforts are being made to detail and understand how to minimize TRWP effects on aquatic ecosystems. The fate and transport of TRWPs determined that an estimated 21,600 tons per year go to wastewater treatment and surface waters, where it poses ecotoxicological and human health risks (Wagner et al., 2018). Research has shown that the green infrastructure approach is the best way to mitigate TRWP pollution in streams (French et al., 2022)

Green infrastructure should be a standard for all future land use planning to mitigate TRWP impacts on streams. GI provides an intermediate stage where stormwater is passed through to pull out unwanted roadway contaminants before its released into the receiving waters. The health of Puget Sound's watersheds, streams, lakes, and rivers are all at risk from TRWP, physical pollution, and chemical degradation. Globally in urban areas, stormwater and roadway runoff are the number one source of pollution in our freshwater and marine habitats (Wagner et al., 2018). Therefore, innovative green infrastructure is the only possible measure to help reduce the amount of TRWP entering urban streams through stormwater and roadway mitigation. Thurston County, Washington, has a variety of green infrastructure methods to reduce the amount of toxic stormwater and roadway inputs (TRCP, 2023). For example, researchers suggest catchment scale bio-retention systems could effectively remediate motor vehicle pollutants impacts in stormwater receiving streams (McIntyre et al., 2015).

Several types of green infrastructure are used in urban areas to prevent roadway and stormwater runoffs and adverse effects on streams. For example, *curb cuts* are spaces cut into parking lots to allow stormwater to move through a porous surface (IDEM, 2022). *Porous pavements* send stormwater and roadway runoff through layers of organic materials to mitigate toxins before entering streams such as rain gardens and retention ponds (IDEM 2022). *Swales* are GI similar to rain gardens but are usually much more extensive and treat significant amounts of stormwater (IDEM 2022). Finally, *street sweeping* mitigates TRWP and other road pollutants from entering urban streams (McIntyre et al., 2015). Street sweeping and bio retentions systems are the most effective GI for TRWPs and other motor vehicle pollutants in stormwater and roadway runoff.

Conclusions

Tire road wear particles are a significant source of microplastics to the environment and are a global issue that has yet to receive the attention it needs to be addressed. In Washington State, considerable efforts have been made to save salmon, costing the residents millions in restoring and remediating salmon habitats. However, land use practices like agriculture, timber harvesting, and urban development contribute to the loss and degradation of salmon habitats' water quality and negatively affect salmon life cycles (Fresh et al., 2004). These land-use changes alter the quality and quantity of available nutrients, water, sediment, and debris entering stream habitats (Fresh et al., 2004). Water and sediment quality directly impacts the longevity of a juvenile salmon's progression into adulthood (Chittenden et al., 2017). As we know, tire rubber is a significant source of chemical contamination to urban streams posing significant risks specifically to Washington's Coho salmon populations. Each stage of a salmon's life cycle is essential in Puget Sound's trophic food web; approximately 138 species depend on salmon's presence and abundance in Puget Sound (Cederholm et al., 2000). The rapid urbanization of Puget Sound and its tributaries and the growing dependence on its ecosystem services presents various environmental issues. In Puget Sound, Chinook, Steelhead, and Coho salmon are listed on the Endangered Species Act as endangered and threatened (State of Salmon 2022). A continuum of aquatic habitats, such as freshwater streams/tributaries, nearshores, estuaries, and the ocean, is vital to completing salmon lifecycles (Muir et al., 2012). In Washington state, road-crossing fish passages have increased with urban expansion, and, with that, the rates of habitat degradation from contaminants like TRWP have led to the loss of reliable salmon populations in Puget Sound.

To support more significant ecological goals for salmon in Washington, assessing the risk of TRWP in the streams is crucial. Especially those reopened for salmon to ensure the project's objective of providing more salmon spawning and rearing habitats are free of TRWP contamination. TRWP alone concerns the community's general health and the environment due to the many co-contaminate they absorb and transport. Unfortunately, in Washington, we have yet to fully address TRWP as a source of chemical contamination in our urban streams. By identifying regions most at risk for increased TRWP concentrations, we can adapt green infrastructure where it is most needed and limit the toxic effect of TRWP in aquatic ecosystems.

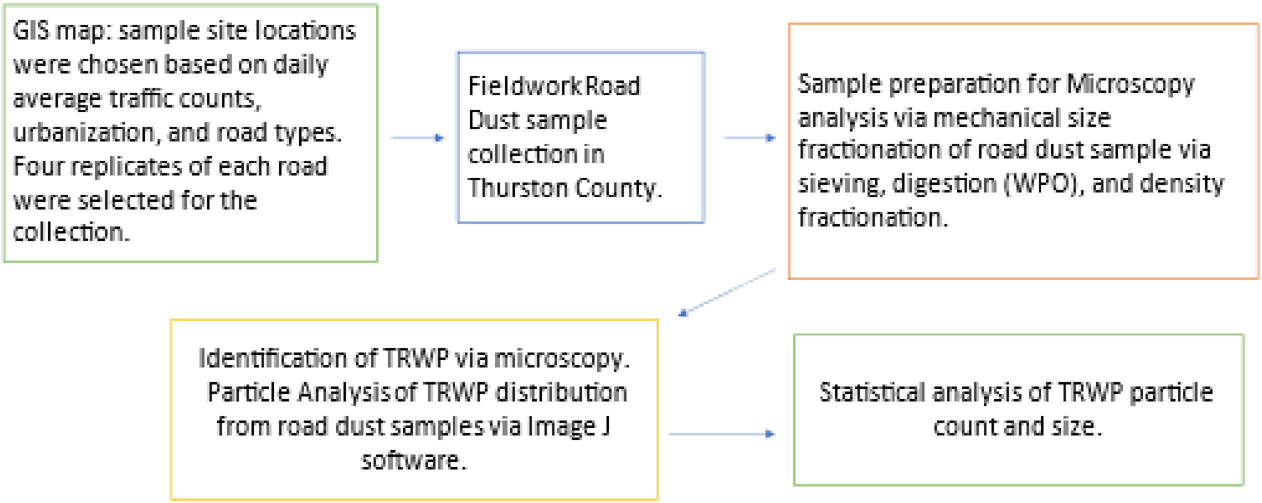
Identifying and quantifying tire road wear particles (TRWP) can indicate urban streams at risk for urban runoff mortality syndrome (DOE, 2022). 6PPD-quinone has one of the highest aquatic life toxicity ratings, with a lethal concentration of 95 ng/L (Tian et al., 2021). Several factors increase 6PPD-quinone inputs to urban streams, such as increased impervious land coverage, tire road wear particle concentration on the roadway, snow melts, and rain/storm events (French et al., 2022; Tian et al., 2021). Washington's Department of Ecology listed the evaluation of TRWP distribution size and quantities from roadways as a current knowledge gap in assessing and mitigating 6PPD-quinone (DOE, 2022). Therefore, the identification of the prevalence and abundance of TRWP emissions sources can function as an indicator of streams at risk for 6PPD-quinones toxicological effects. In addition, evaluating the spatial distribution of TRWP can provide insight into areas that need priority stormwater and roadway runoff mitigation. Several known factors influence TRWP emissions on roadways, such as speed limits, the topographical design of the road, and the ratio of new to used tires driving on the road (Gehrke et al., 2020). Therefore, understanding TRWP size and count can help researchers understand the extent of TRWP pollution.

Methods

Research questions: How does tire road wear particle (TRWP) size and count vary among road types (primary, secondary, residential, and rural) in Thurston County, Washington? The second question: Does the annual average daily traffic (AADT) count affect TRWP's count and average size? For both questions, the dependent variables are TRWPs count and size (area μm^2). The independent variables are road type for the first question and annual average daily traffic for the second research question. The research questions seek to understand if TRWP counts and sizes are similar among road types or dissimilar and if AADT plays a role in the distribution of TRWP sizes and counts. Figure 5 provides the methodology overview used in the study of TRWP in Thurston, county Washington.

Figure 5.

Overview of Methods



Studying tire road wear particles (TRWP), distribution in road dust requires an interdisciplinary approach utilizing environmental analysis methodologies, GIS, and image analyzing software, Image J. The above diagram shows an overview of the methods used to evaluate the distribution of TRWP in Thurston County, Washington. To assess TRWP particle sizes and distribution, road dust samples were collected from nineteen roads. The Thurston County Planning Office website provided the other datasets, road frequency, and zoning. The distinction of road type (primary, secondary, residential, and rural) will answer whether road type determines TRWPs' size and count. Four sample sites were chosen per road type to establish the distribution of TRWP in Thurston County. The four road types are categorized as follows:

- *Primary roads* are connected directly to the state's transportation system (I-5 and highways).
- *Secondary roads* are located in commercial and urban areas which connect to primary and residential roads.
- *Residential roads* are, by definition, residential, meaning regions where people live.
- *Rural roads* are classified as not urban and tend to have moderate to high speeds, with low residential and commercial areas (WDSOT, 2022).

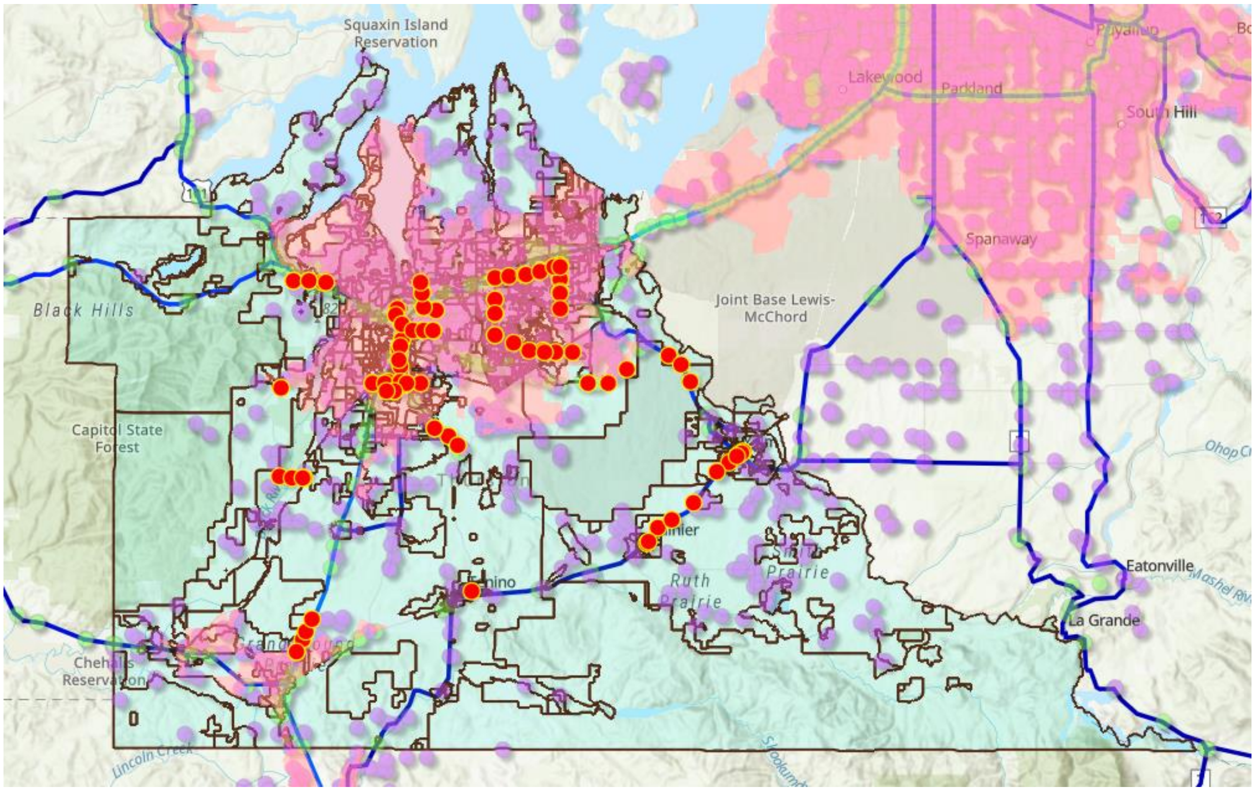
A GIS map of Thurston County's zoning, road networks, road frequency, and urban regions was developed to determine suitable sample locations for each road type. The study also used ArcGIS survey 123 to develop field assessment surveys for the safety protocols and the sample collection, which is elaborated on in the fieldwork section below.

Location of Study: Thurston County, WA

Thurston County, Washington, is located at the southern point of the Puget Sound. It contains six cities/towns (Olympia, Tumwater, Lacey, Yelm, Rainier, and Tenino). According to the Thurston County Planning Office, seventeen thousand traffic control signs and over one thousand streetlights have stormwater drainage and retention systems (2023). The transportation network is often considered the lifeblood of the local economy that connects Thurston County's approximately three-hundred-thousand residents with employment, services, and the ability to transverse in and out of the county (ThurstonCountywa.gov, 2023). Figure 6 shows the map of Thurston County, which displays the county's boundaries, State transportation network, urbanization, and traffic count. Four replicates of each road category were taken to represent Thurston County's TRWP distribution.

Figure 6.

Map of Thurston County Road Dust Sampling Sites



Note: Map of Thurston County zoning county green), state traffic network (blue lines), traffic count (purple dots), and urbanized areas (highlighted in pink). The red dot represents the sample locations for the study.

Road Dust Sample Collection Protocols

A risk assessment for safe sample collection was performed for each sample location. Factors considered in the risk assessment were road safety features that included: crosswalks, bike lanes, sidewalks, round-about, traffic lights, and school zones. These features were standard in urban areas, whereas the rural locations had little to no safety features. Road dust sampling protocols were similar to those the Environmental Protection Agency designed for collecting road dust near construction sites (EPA, 2020). Upon finding a safe location, a one-mile swath of road was analyzed at each site, collecting samples every half mile. The initial sample was collected at the zero-mile mark, moving approximately half-mile marks the second collection, and the one-mile mark was the third. All three samples were placed into one jar; road dust was collected via sweeping with an eighteen-inch width broom and dustpan; the collection was done on each side of the road, starting from the middle of the lane to the curb or edge of the road. As such, each road studied spans a distance of one mile with three collection sites.

Allowing a period of dry days before sample collection was necessary for road dust to accumulate on the roadway. Due to this requirement, sampling occurred on the 10th and 11th consecutive dry days, 1/30/2023 and 1/31/23, from 9 AM-3 PM, the lowest traffic times in Thurston County. The location was recorded at each sample site with the prepared ArcGIS 123 survey field assessments completed for each road collection.

Road Dust Sample Preparation and Separation of TRWPs

Evaluating tire road wear particles from road dust required homogenizing the sample, which includes drying the sample and mechanical size fractionation with a one mm custom-made wire sieve. The mechanical size fractionation was performed to help homogenize the sample for TRWP extraction from road dust. The road dust of less than one mm TRWPs was separated by Wet Peroxide Oxidation (WPO) digestion and density separation using NaCl which was adapted from NOAA (2015) protocol on microplastic separation from beach sand. Microplastics from environmental samples are measured between less than one µm to five mm (Kovochich, 2021)—

the range of TRWPs recovered by Jung (2022) measures consistently as less than one millimeter. Therefore, the TRWP size range evaluated for this study is between one mm and thirty micrometers (µm); the lower limit was arbitrarily set by the smallest mesh sieve size available. However, TRWPs may likely be smaller than the thirty µm due to their ability to cling to other larger road particles (Jung, 2022). After the mechanical size fractionation (i.e., the 1 mm sieve) of the road dust samples, three one-gram replicates were utilized to extract TRWPs from road dust samples. The extraction process consisted of digestion and density fractionation for each road.

Sample preparation process: Road dust samples were dried for twenty-four hours at 65 ºC to eliminate any water content and passed through a one mm sieve to remove large rocks or other debris (that could disproportionately affect the sample weight). Then, the content that passed through the sieve was directly transferred into beakers, which were weighed and stored for further analysis. Finally, the portion of TRWP collected from the above one mm fraction weight was recorded and then discarded.

The extraction and identification of TRWPs (i.e., material < 1 mm) had a three-step process; digestion to eliminate organic matter, density separation to separate TRWPs from road dust, and microscopic identification of TRWPs. Each replicate had one round of digestion using a Wet Peroxide Oxidation (WPO) reaction. The WPO reaction combined equal parts 0.5 M Fe(II) solution and thirty percent hydrogen peroxide with one gram of road dust for digestion (NOAA, 2015). The WPO reaction uses a heavy oxidizing agent to denature and dissolve organic materials within the sample (Rodrigues, 2019).

The density separation uses NaCl to increase the WPO solutions density and separates TRWPs from the materials left after digestion. Rodrigues (2019) suggested up to two doses of the WPO for TRWPs; however, since the replicates were weighed out at one gram, only one WPO dose was performed. The density fractionation step immediately follows the WPO. It uses ~ seven g of NaCl per 20 mL of the WPO solution left to increase the density (see Figure 6). The sample was left in the solution overnight to separate TRWPs. The calculated ranges of the replicate's density fractionation were between 1.4 and 1.5 g/cm^3. The float portion of each density fractionation was recovered by rinsing the sample with deionized water and pouring it through a custom-made thirty µm mesh sieve. The samples were then transferred from the top of the sieve using a metal spatula and rinsed into a labeled plastic cup with a lid for microscopic analysis. Leaving the sample suspended in a small amount of water for up to forty-eight hours made transferring sample contents from plastic cups to a viewing plate easier and avoided the loss of fine particles.

Figure 7

Digestion and Density Separation Lab Samples

Note: On the left is a picture of road dust samples in the cooling stage of digestion. The right shows samples in the density separation stage and heating the solution to dissolve salt (NaCl) to increase the density of the WPO solution.

Microscopic Identification of TRWP from processed replicate samples

The primary methods for TRWP's identification used visual, texture, shape, and color verifications as a guide. In addition, a dissecting microscope was used to identify TRWPs and then transferred to a glass slide, which was further examined with a compound microscope. The identification of TRWP is based on the morphologies in Figure 7 and listed in Table 3 below.

Figure 8.

Morphologies of TRWP (Jung, 2022)

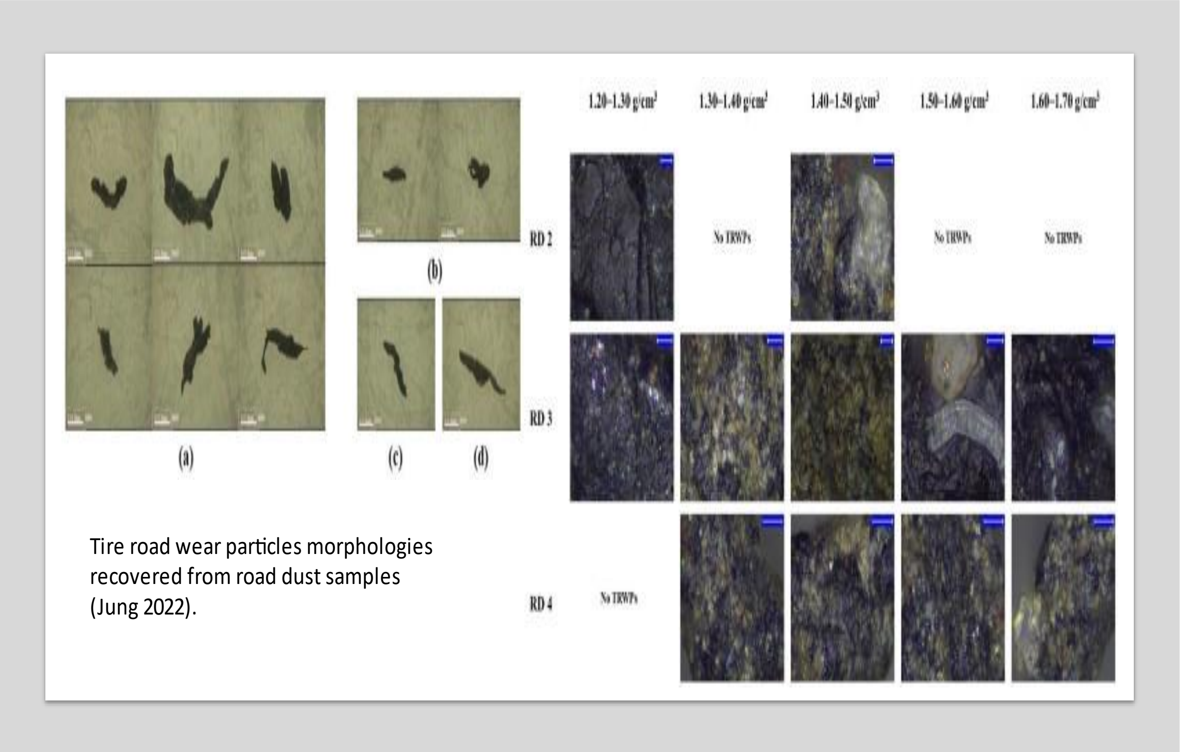


Table 3.

TRWP morphology and description (Jung, 2022; Leads, 2019).

TRWP morphology	**Description**
Color	Black or dark in color, sometimes brownish
Texture	Encrustation, rough surface, rubbery consistency, and malleable when manipulated with fine tip forceps.
Shape	Elongated or cylindrical

In total, nineteen roads were assessed for TRWPs, with three replicates performed for the TRWP extraction process (for 57 subsequent extractions). To identify the suspected TRWPs, a 30X dissecting microscope (Olympus SZ40) was used with a directed light and fine-tip dissecting tweezers to pick out suspected TRWPs then further verified using a 40X compound microscope (Omax DV5V). For each sample, a few particles were photographed with a compound microscope. After the sample TRWPs were verified using a compound microscope, the slide was placed onto a white piece of paper and photographed (Google Pixel phone) to use image analyzing software (Image J) to estimate particle count and size (μm^2) using Image J.

The analysis of road dust samples utilizes the weight-by-analysis method to identify TRWP; first, by isolating TRWPs through digestion and density separation; second, by visual identifiers confirmed by reference materials descriptions of TRWP's characteristics and morphology. The TRWPs were classified by density selection (1.4-1.5 g/cm^2) and visual markers. Density separation helped isolate the TRWPs from other particulates in road dust samples. However, various other particles were found in each sample, such as glass beads, paint particles, dirt conglomerates, some plant particles, minerals, and asphalt particles.

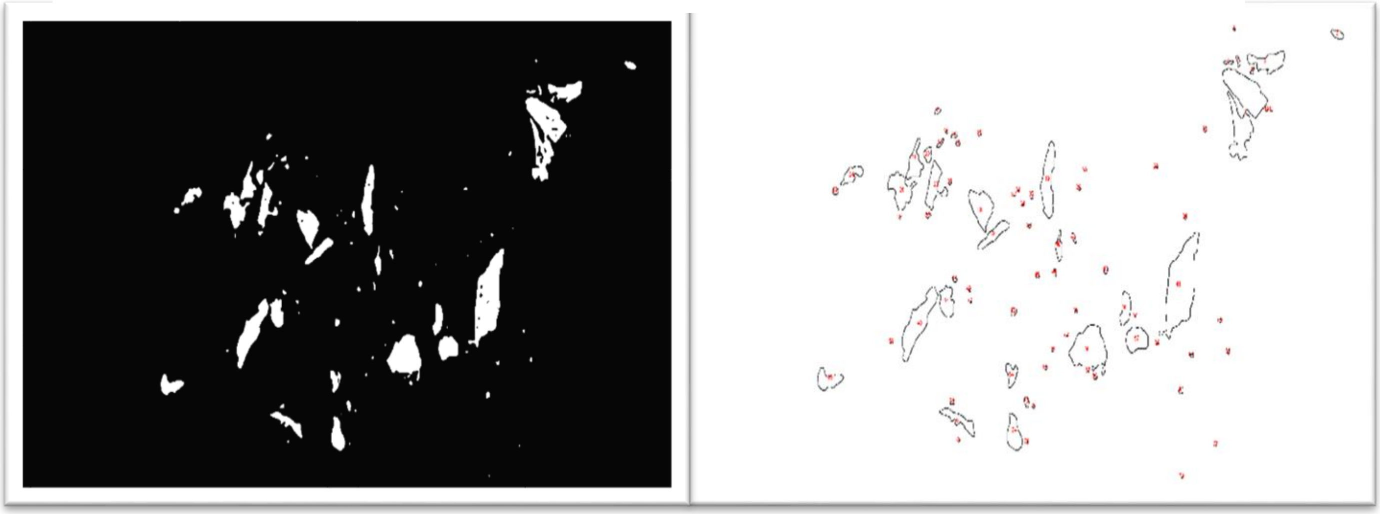
Image J analysis of TRWP particle sizes and distribution

Particle size distribution analysis is a highly desirable method in investigating TRWP particle sizes from road dust samples. Image J provides particle analysis by identifying the shape and dimension measurements and expressing them in pixel measurements (Igathinathan, 2008). To my knowledge, utilizing Image J software for analyzing environmental particles such as road dust is a new approach in TRWP analysis. Image J, a free-to-public software, has proven reliable, user-friendly, and used for various image analysis methods. Before beginning Image J analysis, the global scale must be set to measure photo particles based on the user's measurement (Rueden, 2017). For this step, the scale was calibrated by taking a picture of a known one µm measurement. The image J particle analysis method is based on the software "watershed analysis" in Rishis (2018). The photo of TRWPs was uploaded to ImageJ with the image settings adjusted to 8-bit; images were calibrated to estimate particle measurements in pixels/µm and report particle area sizes in micrometers squared. Finally, image J does some statistical analysis and assesses the sample distribution. It also saves a CSV file with all the particle analysis data generated by image J which was used in the statistical analysis. The TRWPs obtained from the extraction process were photographed and analyzed with Image J.

Note: displays one road replicate processed with image J for particle analysis. The left shows the stage after the photo is prepped and ready for particle analysis. The right shows the image produced post-particle analysis with each particle outlined, numbered, and measured.

Figure 9

Image J particle analysis (left) before particle analysis (right) post particle analysis numbered and outlined.



Statistical Analysis of TRWP Measurements (area µm^2)

The statistical analysis for this study used the data values generated by Image J and the annual average daily traffic (AADT) per road retrieved from the Thurston County Planning Office. The values given by image J were the recovered TRWPs count and the measured area for each particle (µm^2) for all TRWPs recovered from digestion and density separation. All roads were assessed for normality among TRWP measurements. A data transformation of the TRWP measurements was done using a natural log transformation. However, it was still not normally distributed. Nonparametric tests were run due to the small sample size. These non-parametric tests consist of a Wilcoxon/ Kruskal-Wallis with a post-hoc Dunn method ranks of all sums assessment. The Wilcoxon Kruskal-Wallis test determines if two or more populations are statistically different by ranking all values across each population. A post hoc test using the Dunn method to rank all sums for each road type was used to evaluate if there is a statistical relationship between the two or more populations or road types. These tests help indicate whether road types' TRWP counts are similar or dissimilar. A correlation test was done using a non-parametric Spearman's rho test to assess if AADT, TRWP count, and the average TRWP measurement per road showed any correlation.

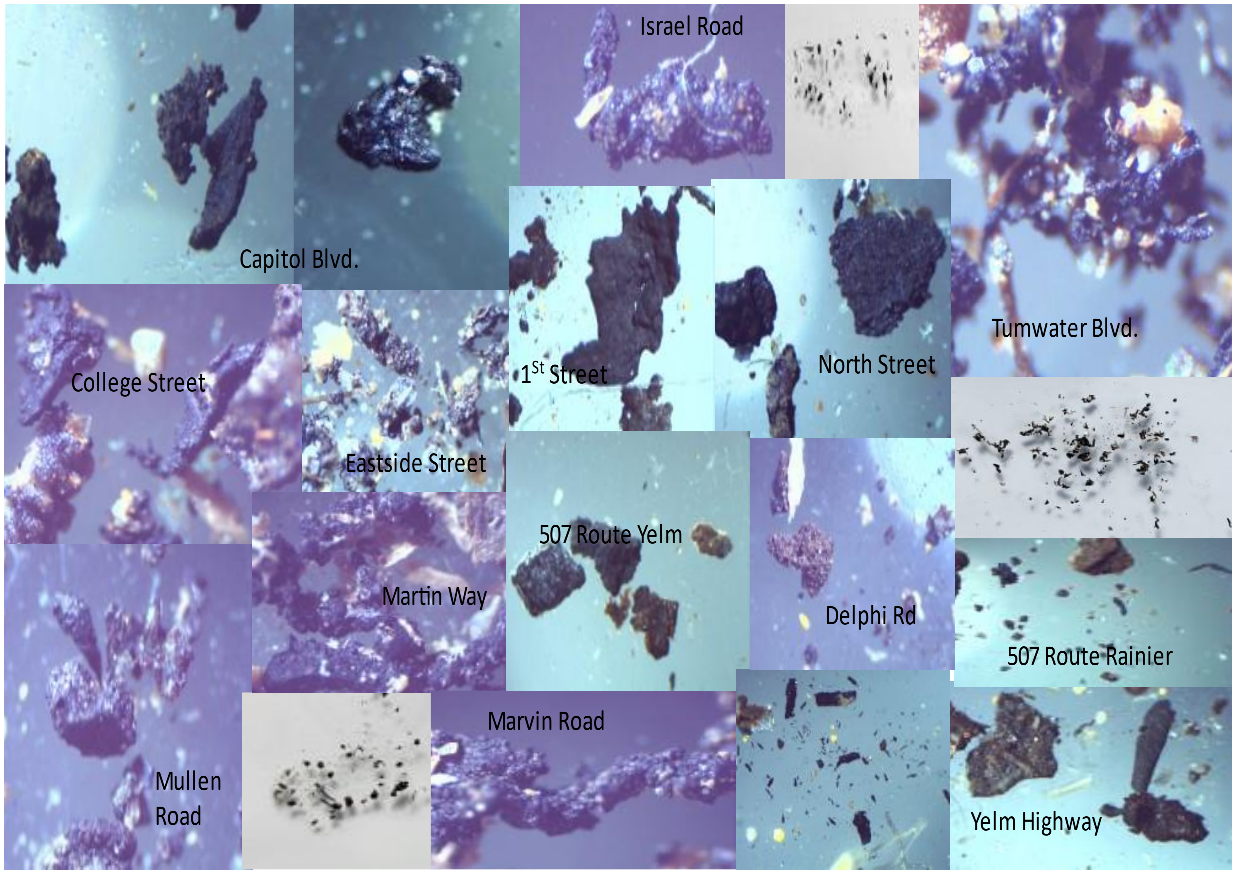
Results

Microscopy Identification and Image J analysis of Tire Road Wear Particles (TRWPs)

TRWPs were identified from all sampled roads in all replicate samples. Figure 5 shows the morphologies of the recovered TRWPs; some of the particles show how they are found as single free-floating particles or stuck in conglomerates with other road particulates. The tire pieces were distinct when looking at them under the microscope and shared the same features listed in previous studies (Jung, 2022; Leads, 2019).

Figure 10.

TRWPs recovered from road dust samples, and photos are identified by the name of the street from which they were sampled.



TRWP Count Results

When analyzing the particle count for each road, urban roads (primary, secondary, and residential) consistently had more TRWPs identified than rural roads (see Table 2). The range particle count for rural roads was from 45 to 408, with an average of 205 ± 173 mean average and standard deviation, respectively. The particle count for primary roads ranged from 112 to 1225, with a mean average count of 475 ± 441. For secondary roads, the range of particle counts is 298 to 4200; the reported mean TRWP count was 1493 ± 1741. Finally, the residential road TRWP count ranged between 87 to 707, with an average mean of 349 and a standard deviation ± 264. Figure 10 displays the distribution of TRWP count by road type and shows that secondary roads have the highest TRWP count compared to the other road types.

Figure 11.

Tire Road Wear Particles Counts by Road Type

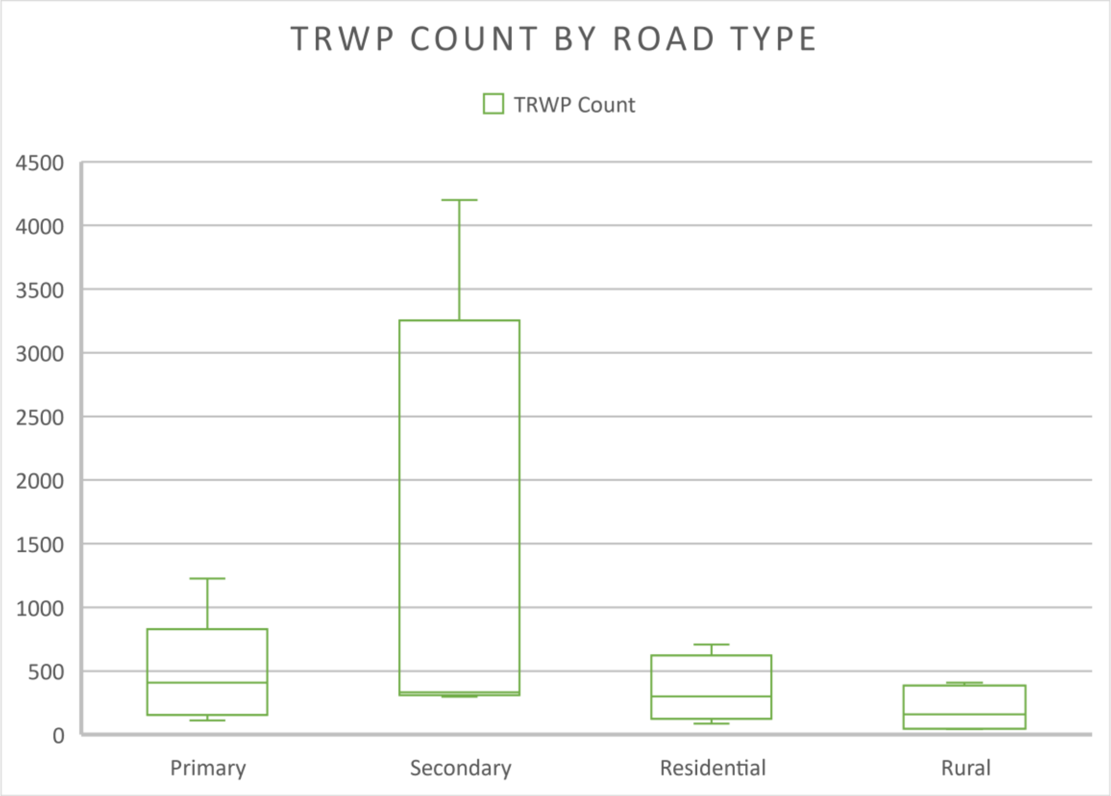


Figure 11 displays the particle count per road sampled. The figure shows Eastside Street, Olympia, contains the most TRWP, with 4200 tire particles collected from the three replicates processed and found mainly in conglomerates. The second road with the highest was College Street, Lacey, with 2309 TRWPs counted. Both roads are considered secondary roads and contribute to the highest TRWP counts in Thurston County.

Figure 12.

Distribution of TRWP count by sample site

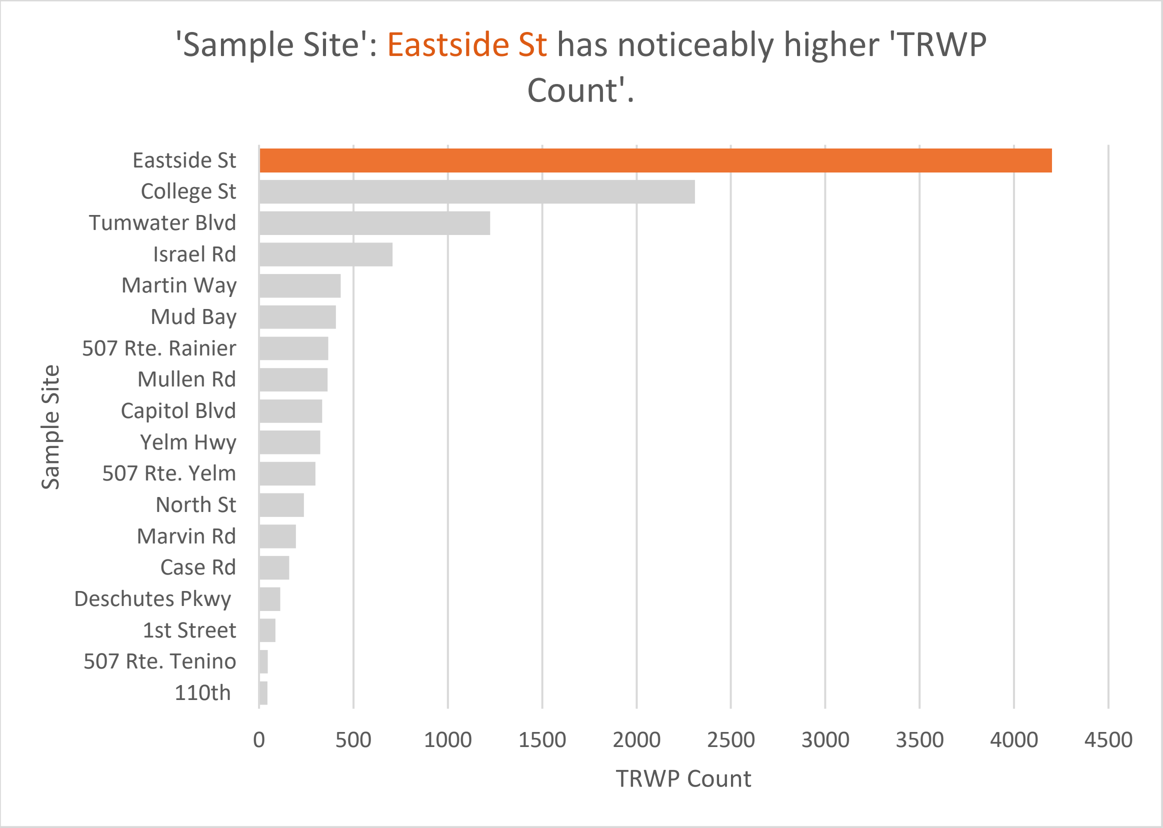


Table 4 displays the analyses of TRWP count; it gives the TRWP count per road, the estimated total TRWP counts in road dust samples, and the estimated TRWP per gram total dry weight of road dust. The yellow highlighted roads show the highest TRWP contributor to Thurston County roadways, and the white indicates the low TRWP counts and estimates.

Table 4

TRWP count data, and TRWP estimated counts per road sampled and TRWPs by grand dry weight (g).

Road Type	Sample Site	Road Dust dry weight (g)	TRWP Count	Total estimate TRWP per Road sampled.	TRWPs / gdw.
Primary	Mud Bay	38	408	5168	10.74
Primary	Tumwater Blvd	43	1225	17558	28.49
Primary	Martin Way	122	432	17568	3.54
Primary	Marvin Rd	86	196	5619	2.28
Primary	Deschutes Pkwy	64	112	2389	1.75
Secondary	Capitol Blvd	36	334	4008	9.28
Secondary	Eastside St	22	4200	30800	190.91
Secondary	College St	15	2309	11545	153.93
Secondary	Yelm Hwy	64	324	6912	5.06
Secondary	507 Rte. Yelm	51	298	5066	5.84
Residential	Israel Rd	82	707	19325	8.63
Residential	North St	103	237	8137	2.3
Residential	Mullen Rd	37	364	4489	9.84
Residential	1st Street	42	87	1218	2.07
Rural	507 Rte. Rainier	144	366	17569	2.54
Rural	507 Rte. Tenino	31	46	475	1.48
Rural	Case Rd	49	159	2597	3.24
Rural	110th	16	45	240	2.81
Rural	Delphi	42	408	5712	9.71

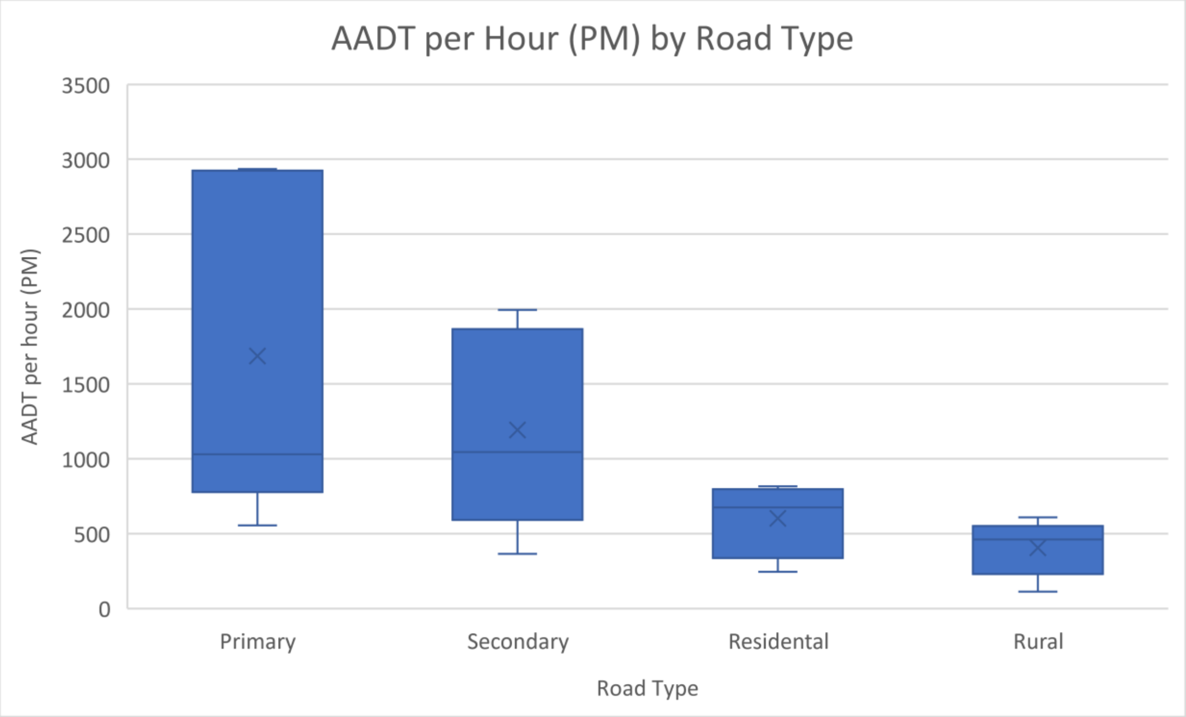
ADDT and TRWP particle count were weakly associated and insignificant (rho = 0.2115, p = 0.385). Furthermore, the correlation between ADDT and TRWP/gdw. was weak and not significant (rho = 0.1150, p = 0.6393). Finally, a nonparametric Kruskal-Wallis test with the

TRWP /gdw. and road type showed no significant differences among road types (Chi-squared = 4.2458, p = 0.2361). The conclusion of these tests all determined no significant relationship between ADDT and TRWP/ gdw. or TRWP count. There was no notable difference among road types for TRWP per gdw.

To further examine the relationship between AADT by road type, Figure 12 shows that Primary roads have the highest AADT counts per hour (PM), followed by secondary roads. AADT frequency is opposite to TRWP counts regarding primary and secondary roads, however, there was no statistical difference between road types.

Figure 13

Annual Average Daily Traffic (AADT) counts per hour (PM) by road type.



TRWP Measurement Results

The reported TRWP size range for each road type varied among road types and within replicate samples. For example, the range of TRWP sizes for rural roads varied from 1 μm^2 to 175 μm^2, whereas for primary, secondary, and residential roads, values ranged from. 1 μm^2 to 165 μm^2 , 1 μm^2 to 176 μm^2 and from 1 μm^2 to 175 μm^2, respectively. The residential roads' average TRWPs had the largest average mean size of the road types. Table 5 below reports the average TRWP size (μm^2) per road sample and the sampled roads' annual average daily road count.

Table 5.

Overview of Sample Sites in Thurston County, WA: Road type, Annual Average Daily Traffic (AADT), Average TRWP size, Standard deviation, Coefficient Variant, and TRWP count per road.

Road Type	Road ADDT per Hour (afternoon peak)	Average Area of TRWP (μm^2) found in a g of road dust	Standard deviation	CV %	Sample Site location
Primary	1029	4	13	325	Mud Bay
Primary	1001	10	15	150	Tumwater Blvd
Primary	2915	7	16	229	Martin Way
Primary	2934	8	62	775	Marvin Rd
Primary	555	12	19	158	Deschutes Pkwy
Secondary	1739	19	21	111	Capitol Blvd
Secondary	365	5	10	200	Eastside St
Secondary	1993	6	38	633	College St
Secondary	816	4	10	250	Yelm Hwy
Secondary	1045	6	9	150	507 Rte. Yelm
Residential	244	9	16	178	Israel Rd
Residential	614	13	22	169	North St
Residential	736	9	19	211	Mullen Rd
Residential	816	18	30	167	1st Street
Rural	494	6	14	233	507 Rte. Rainier
Rural	608	85	17	20	507 Rte. Tenino
Rural	347	20	37	185	Case Rd
Rural	112	27	33	122	110th
Rural	461	7	16	229	Delphi Rd

Unfortunately, due to the large CVs for each sample, no further analysis was conducted to assess the difference between mean particle size by road type or ADDT.

To conclude, the results of this study found that all roads contained TRWPs whose size ranges varied considerably for each road. By road type, the TRWP count showed that secondary roads had the most recovered TRWPs compared to the other road types. Spearman's rho correlation results showed no significant correlation between AADT, TRWP count, and TRWP/ gdw. These analyses provide limited answers to the research question of whether TRWPs count varies among road types. The answer is yes with uncertainty; TRWP counts vary amongst road types, but we cannot indicate what makes these differences occur. Furthermore, the study could not answer the second research question on whether AADT affects TRWP measurement due to the heterogenic nature of TRWP measurements from road dust samples. The results showed no significant correlation between TRWP count and AADT.

Discussion

Thurston County's TRWP's Differences Among Roads

Road types provide several factors that increase TRWP emissions to a roadway. For instance, primary and secondary road types have more congested areas and have higher rates of quick braking and aggressive driving, increasing tire wear and tear (Mian, 2022). At the time of sample collection, each road was assessed for stormwater drains and noted that all the urban roads had storm drains with straight-to streams marked on the gutters. RCW 35.78 details that Washington state cities and towns must adopt a uniform standard of road definitions (MRSC, 2023). This helped determine the differences between state, county, and city road types. Thurston County defines its road types based on functionality (TRCP, 2023(b)). Functionality refers to a road's usage needs and its urban or rural setting. For this study, road types were determined based on functionality and urbanization. Primary, secondary, and residential roads comprise urban road types, whereas rural roads are defined by low population and commercial zones (TRCP, 2022). The daily annual road counts are higher in urban areas when compared to their rural counterparts (WSDOT, 2022). More vehicles on roadways result in higher estimates of TRWP counts. Another aspect of the increased TRWPs to roadways is electric vehicles (EV), the increased vehicle weight results in more wear and tear on tires (Baensch-Baltruschat, 2020; Charbouillot, 2023). Thurston County has 2,264 registered EVs as of Spring 2021, and the estimate increases daily as more Thurston County citizens move toward EVs (TRCP, 2023(c))

Urban roads typically are more heavily trafficked and located in cities and townships (WSDOT, 2022). TRWP counts from secondary roads like Eastside Street and College Street contained the highest contributions of TRWP from all the road tested in Thurston County. From this study's field observations and mapping, these roads are located in dense urban regions and act as connectors routes from residential areas to the state’s transportation network. Based on TRWP counts, secondary and primary roads are the most significant contributor of TRWPs on the roadway and require targeted mitigation of TRWP.

The factors contributing to increased TRWP on secondary roads are the number of connector roads to secondary roads versus Primary roads (TRCP, 2023(a)). Also, secondary road traffic networks had more of a variety of road pavement materials, traffic patterns with multiple speed changes and school zones, and heavy traffic controls like lights, stop signs, round-about, and multi-lane roads (TRCP, 2023(a)). These factors are likely reasons for the increased rate of TRWP count on both College Street and Eastside Street, as these factors were present on both roads. The study shows that road type may be a determinant of TRWP count. However, further research is needed to examine features of the transportation network and their interactions with TRWP on roadways. For instance, secondary roads had a high variability in the TRWP counts, and the non-parametric tests showed road types with TRWP by gram dry weight had no significant differences among road types. This means that statistically, we cannot say road types strictly determine the abundance of TRWP distributions. However, with such a small sample size, this may not indicate the reality of TRWP abundance on the roadways when analyzing the relationship between road type and TRWP counts.

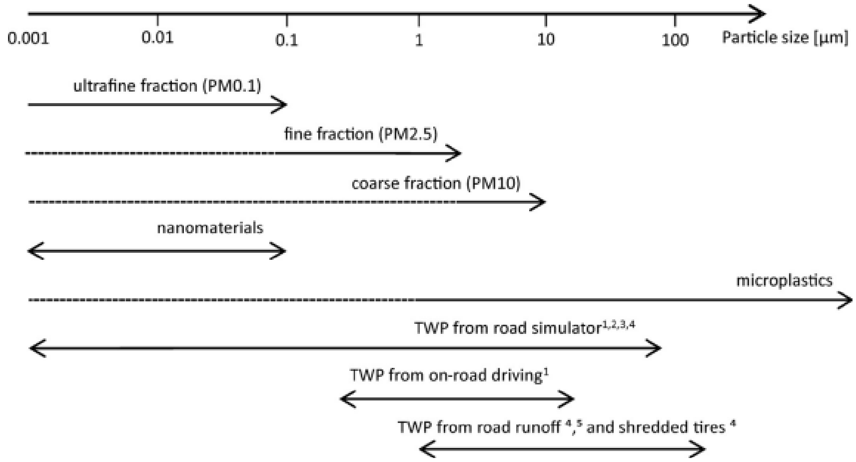
TRWP Morphologies

Environmental samples of TRWP have rarely been shown to be pure tire wear particles and are generally found in mixed compositions of tire wear particles and other road particles (Baensch-Baltruschat, 2020). The observations of TRWP from the microscopy analysis in this study showed that the dark elongated particles had very fine mineralization over the surface. The brownish/black TRWPs often had more extensive mineralization and stuck to other road dust particulates (glass beads, paint particles, plant particles, asphalt particles, etc.). They were similar to Jungs' (2022) and Leads' (2019) findings. A further chemical analysis would be needed to determine if the color difference in TRWP is a variation in the types of tires on the road or if aging / weathering plays a role in the decolorization of tire wear particles. Much TRWP comprises coarser heterogeneous particles released to the road's surface, soils, and aquatic environment (Baensch-Baltruschat, 2020).

From the results of this study, it is apparent that TRWPs exist in very fine (1 μm^2) to coarse TRWP (> 100 μm^2) on all Thurston County roads sampled. TRWP's limited information on real-world measurements has uniformly concluded that a better way to measure TRWP is needed for TRWP estimates (Mennekes, 2022). Approximately 90-95 % TRWPs are not air-borne particles (Mennekes, 2022; Baensch-Baltruschat, 2020; Klockner, 2019; Panko, 2013). The remaining 5-10% of TRWP emissions are emitted into the air and contribute to urban air pollution (Mennekes, 2022; Baensch-Baltruschat, 2020; Klockner, 2019; Panko, 2013). The transport and fate of TRWP are determined by the size of the particulate when emitted (Wagner, 2018). For example, fine particulates are released into the ambient air on roadways, and coarse particles remain on the roadway and are washed out with stormwater/roadway runoff. The morphology of TRWP makes them susceptible to absorbing other road contaminants, and as particles become smaller, they are more likely to hold contaminants like 6PPD-quinone (French, 2022).

Figure 14.

TRWP Measurement Range



Note: Tire Road wear particle size ranges from environmental samples and lab-simulated tire wear (Wagner, 2018; Kreider, 2010).

The size ranges in Figure 14 were established by lab-simulated tires' wear and tear, where researchers simulated road conditions and collected TRWP by collecting environmental samples of the air, soil, and water near roadsides (Wagner, 2018). The coarse fraction of TRWP transported to surface waters poses ecotoxicity and human health risks (Baensch-Baltruschat, 2020). The findings of this study TRWP measurement ranges were between the fine and microplastic fractions ($1 \mu m^2$ to $> 100 \mu m^2$). This means all sizes reported in this study pose ecotoxicity and human health risks to airborne and surface waters of nearby streams or rivers.

Image J for particle analysis

For this study, finding a way to count and measure all TRWP recovered from the extraction process was vital. Microscopy identifies TRWP morphologies, and to perform the particle analysis, the study utilized an image processing software (Image J) to count and measure TRWPs found in road dust samples. Image J has been used widely for various scientific studies, such as medical and agricultural research (Igathinathan, 2008; Rueden, 2017; Rishi, 2018). Image J was initially created in 1997 as an image processing software intended for the National Institutes of Health (Rueden, 2017). Since that time, image J has been vital in scientific study, especially in the life sciences (Arena, 2017). Other uses for image J include powder particles and cell counting, which is essential for many medical sciences (Igathinathan, 2008; Rishi, 2018). Other applications for Image J include seed counting and mineral counting for the American Agriculture Association (Rishi, 2018). In addition, the software has proven a helpful alternative in particle analysis when research expenses are low and require innovative approaches.

Image J is used in this study's particle analysis as an experimental technique for measuring and counting TRWPs. For this study, each image sample replicate of recovered TRWPs was analyzed three times to ensure that image J reported a consistent value. This ensured that the roads with high TRWPs, like Eastside Street and College Street, consistently reported the same values for each sample replicate processed. Another approach used in this study to ensure the values' validity was running more than one image of the sample replicate to ensure consistency in the data reported. Both strategies reported consistent values for each sample replicate processed and helped affirm that image J was viable for particle measurement and count.

TRWP distribution Implications to streams: Identifying regions with increased TRWP emissions

TRWP increases the risks of chemical and heavy metal loading to urban streams due to the particles' increased surface area and absorbent nature (Wagner, 2018; Lou, 2021). Furthermore, many streams in urbanized areas are at increased risk for urban runoff mortality syndrome due to higher rates of impervious surfaces within those regions (Mallick, 2017; McIntyre, 2015). In addition to the issue of impervious surface percentage is the emission of TRWP in congested traffic, which increases the dangers of poor stream habitat quality on susceptible species like coho salmon (French, 2022). TRWP implications for streams are heightened with the co-contaminants transported from the roadways to streams (Lou, 2021; French, 2022). The study aimed to see how road type affects TRWP input into urban streams by examining the quantity and measurements of TRWP on the roadways. These distinctions between road types can help determine streams' implications without chemically testing the water. However, further investigation of stormwater discharged into streams for TRWPs is necessary to follow up work, especially near roads with very high particle counts.

This study has identified roads with increased rates of TRWP counts by road type, which adds essential data to a highly underdeveloped area of research. In addition, TRWPs are annually released on scales that go unnoticed due to their microplastic nature (Mennekes, 2022; Baensch-Baltruschat, 2020). How do we move forward with habitat rehabilitation for susceptible species without providing environmental measurements of TRWPs found directly on the road? These measurements can be used to determine areas that need targeted mitigation of urban streams. Since TRWPs are retained easily within soils, bioretention systems make the particles inert (French, 2022). The other potential best form of mitigation is diluting stormwater and roadway runoff to avoid urban mortality response (French, 2022). TRWP's significant damage comes from the co-contaminants they carry to urban streams that foul the water and degrade viable habitats for salmon (Mennekes, 2022; French, 2022). This is why removing TRWP before it enters streams can reduce the number of toxins from the roadway that enter and degrade viable stream habitats.

Mitigation of TRWP's for Conservation and Rehabilitation of Susceptible Species

Stormwater mortality events have been mainly studied in Coho salmon regarding its lethal effects (French, 2022), and in the Thurston County Deschutes River, Coho runs are under threat (TRCP, 2023(b)). Recent studies have shown a variation in the susceptibility of urban runoff mortality syndrome and that dilution of stormwater effectively limits mortality response (French, 2022). Coho and Steelhead are highly sensitive to stormwater runoff, whereas Chinook, Chum, and Sockeye showed a stark difference in susceptibility compared to Coho and Steelhead (French, 2022). In Thurston County, the Coho salmon are considered vital markers of habitat health and function of the Deschutes River (TRCP, 2023(b)). Currently, three Coho salmon runs are located on the Deschutes River, all of which have faced exponential losses (TRCP, 2023(b)). The TRWP count from Deschutes Parkway was 112 particles, and when compared to other roads is not the greatest. However, other roads in the area tested, like Capitol Blvd and North Street, had much higher quantities of TRWP, and each had straight-to-stream drains on the roads tested. Therefore, the Deschutes River and its tributaries in Thurston County may likely be at risk for TRWP co-contaminant pollution.

The life cycle of Coho salmon in the Deschutes River is three years of migration runs; the brood year represents the year eggs are laid by adult spawners (TRCP, 2023(b)). Coho smolts migrate from the Deschutes River approximately two years after brood year (TRCP, 2023(b)). This means the most susceptible species to urban runoff mortality syndrome spend up to three years in the Deschutes River before migrating to the ocean. Unfortunately, juvenile coho salmon have shown the same susceptibility to 6PPD-quinone and stormwater runoff as the adult spawners for the syndrome were initially recognized (McIntyre, 2015; French, 2022).

Addressing the issue of green infrastructure not adequately placed in frequently trafficked areas presents an issue for habitat conservation and rehabilitation of susceptible species like Coho salmon. The U.S. Superior Court’s injunction order of 2008 determined that providing adequate and timely transitional habitats for salmon is necessary for the rehabilitation and conservation of the species (United States v. Washington, 2013). The same logic invokes WA states responsibility to provide historical salmon habitats mitigation of TRWP’s toxicological effects on urban streams in many reopened urban streams. Without this consideration, we have little hope for rehabilitating susceptible species like Coho salmon and Steelhead trout populations. The Puget Sound and its tributaries comprise the injunction area in the fish passage project and are also the most urbanized areas of Washington State (United States v. Washington, 2013; State of Salmon, 2022). Streams reopened for salmon are only assessed for fish passage, not for toxins that induce URMS. This poses an issue for these restoration and conservation efforts because these streams may not have adequate water quality or high toxic inputs that would result in urban runoff mortality syndrome events or Coho mortality syndrome.

From the results of this study, it is apparent that urban areas with heavy traffic also have more significant average TRWP emissions. The increased counts of TRWP have been attributed to aggressive driving; sudden stops and acceleration increase the friction of the wear and tear of the tire (Peters, 2023; Järlskog, 2020). Road types can function as a way to identify hot spots for TRWPs and the co-contaminants they carry to streams based on TRWP counts. It is daunting to approach the global toxic issue of tire rubber microplastic pollution, especially at the annual rate the environment currently endures. However, if we started our approach by turning road environments into semi-closed systems, where roadway and stormwater runoff goes through a transitional stage to catch or pull-out major road polluters like TRWP’s, there is hope. Tires are an essential function of everyday life; this study aims not to demonize tire companies for meeting consumers’ needs and federal regulation parameters needed for tire safety and performance but to provide awareness and real-world TRWP measurements and counts. Moreover, this study adds to a developing area of research that has become highly underdeveloped regarding the methodology and environmental measurements of TRWPs.

Limitations of this study

The major limitation of this study is the methodology, sample size, and no instrumental chemical identification was performed. The methods used for this study were created to find a way to estimate and measure TRWP distribution on the road. This study devised a method based on road dust collection near construction sites and extraction methods for microplastics from beach sand. The use of Image J for particle analysis has yet to be done for road dust before. However, the lack of conventional TRWP collection, identification, and measurement methods limited the studies' ability to homogenize the sample replicates processed. It may account for the wide variation in TRWP distribution per road. To evaluate the road for TRWP, this study recommends keeping each sample from the road separate instead of placing the whole one-mile road sample into one jar. Each replicate process showed high variation in the average mean for particle area, indicating the samples were not homogenized. This may be accounted for by three separate locations in the one-mile road being sampled. The road dust collections were placed into the same jar to represent the one mile sampled; however, from the study's results, this may not be the best way to represent TRWP on the roadway. Furthermore, the future methodology should assess how to homogenize the road dust after collection best so that the aliquot selected for future analysis is representative of the sample from which it was collected.

The sample size is another study limitation when determining a large region like Thurston County. Nineteen samples are a great start, but more is always better in the spatial qualification and quantification of environmental pollutants. The other limitation of this study is that no instrumental chemical verification was performed due to time constraints, and future research is highly recommended. The best form of chemical verification is hard to say since no routine methods are found in the environmental assessments of TRWPs. The most common methods used are the Inductively Coupled Ion Mass Spectrometer (ICPMS), Gas Chromatography-Mass Spectrometer (GCMS), and Fourier-transform infrared spectroscopy (FT-IR). The most common tire chemical markers researchers used to quantify TRWP's are Zn, HMMM, 6PPD, and polystyrene butadiene (Johannsen, 2022; Lou, 2021).

Conclusion

Investigating the environmental impact of TRWP on streams requires an interdisciplinary approach of tire science (manufacturing and chemical innovations), environmental chemistry, stream ecology, transportation infrastructure, policy, current stream rehabilitation projects in Washington State, and restoration conservation ecology. Each of these disciplines has a part in monitoring and orienting the public to the issue of TRWP impacts on streams and illuminating the public on the issue of tire rubbers' contribution to the global emissions of microplastics. The tire wear particles are emitted to the roadway through the abrasion of tires on the road, where they are weathered, aged, and become biofouled (Lou, 2021). Road dust poses as transitional media that transports TRWPs that become carriers of co-contaminates like 6PPD-quinone from roadways into urban streams via runoff. To address the mounting issue of TRWP pollution of urban streams, we would have to understand the transport and fate of TRWP. As well as how our transportation system can help define regions with increased risks of TRWP contamination of urban streams.

The finding of this study showed higher counts of TRWPs in road dust from secondary roads. Surface area μm^2 and particle count indicate two factors that determine the toxicity inputs of TRWPs to urban streams and require further investigation to define the distribution of TRWPs on roadways truly. However, surface area varied widely within each road, so additional analyses could not be conducted to see how road type or AADT affected surface area. Targeted green infrastructure approaches to TRWP's mitigation from streams are the best option to support more significant ecological restoration goals like the fish passage barriers removal project. Washington State has the initiative and duty to maintain a continuance of suitable aquatic habitats for salmon. The fish passage barriers project currently focuses on reopening stream habitats throughout Puget Sound (State of Salmon, 2022). However, there is no implicit consideration of whether these reopened streams are monitored for URMS-inducing toxins like 6PPD-quinone. This project provides vital information in a severely lacking field in the study of tire road wear particles. The study also provides vital information on TRWP's presence and abundance on the roadways in Thurston County. To conclude, secondary roads should be further assessed to mitigate TRWP since they had the highest contributions of TRWP found on Thurston County roads.

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