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A systematic literature review of the prevalence, distribution, exposure, and human health risks of tire microplastics and the contribution of their physicochemically diverse properties

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A systematic literature review of the prevalence, distribution, exposure, and human health risks of tire microplastics and the contribution of their physicochemically diverse properties

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Abstract:

The history of synthetic plastics dates back to their first uses in 1907, continues with their expansion through the middle of the century with a diverse array of new polymers, and are so omnipresent today that many label this age of Earth the Plasticene Era. Tire microplastics (TMPs) have been increasingly identified as one of the environment's most bountiful types of microplastics (MPs). TMPs mainly enter the environment as tire-wear particles (TWPs) and recycled tire crumb (RTC). TWPs, in particular, have a high degree of variability, which impacts their distribution, degradation, and risk for adverse human health effects. This review will serve to provide an overview of the sources, distribution, and routes of exposure of TMPs, compile research and understand the mechanisms of physicochemical diversity and emission factors of TWPs, analyze their potential adverse effects on human health and the role TMP diversity plays in this risk, and will conclude by recommending solutions towards reducing TMP pollution and mitigating the impact on human health.

1. Introduction:

1.1 Background

1.1.1 Overview of Microplastics

The synthetic plastics industry dates back to its initial formation at the beginning of the 20th century. However, it wasn't until after World War II that the mass production of plastics began. Today, plastics have revolutionized industry and have made their way into every facet of manufacturing due to their convenience and low cost. From 2004 onwards, global plastics production doubled compared to the previous half-century (Rhodes, 2018). In 2020, the global plastics industry was valued at 580 billion dollars, and the growth is expected to accelerate over the next decade (Tiseo, 2021). With unchecked and ballooning use, a prolonged rate of biodegradation, and ineffective global recycling efforts, there is an alarming buildup of plastics in the environment. From the onset of mass production in 1950 to 2015, 79% of all used plastics have either been stored in landfills or released into the environment directly (Rhodes, 2018). Microplastics (MPs) are pieces of plastic that are less than 5 millimeters (mm) in one dimension, and nanoplastics (NPs) are pieces of plastic less than 1000 nanometers (nm) in one dimension (Gigault et al., 2018). Depending on how they are formed, MPs can be categorized as either primary or secondary. Primary MPs are created to serve a function, such as personal care products or industrial purposes. Secondary MPs result when larger plastics are weathered and fragmented. NPs are formed when MPs are fragmented even further, either biotically or abiotically. For example, polystyrene, the primary polymer in synthetic rubber, is particularly susceptible to being fragmented at the micro- and nano- scale via ultraviolet (UV) irradiation (Bottino et al., 2004). Dawson et al. (2018) showed how Antarctic krill could degrade MPs digestively into NPs and release them into the environment via fecal matter.

1.1.2 Overview of Tire Microplastics

While there are numerous sources of secondary MPs, micronized tire fragments resulting mainly from the wear and tear of car tires, called tire microplastics (TMPs), have been gaining recognition as a significant contributor. TMPs account for the second highest source of MPs released into aquatic ecosystems, at 28.3%, trailing only synthetic textiles. (Boucher and Friot, 2014). Furthermore, a UK report completed by Friends of the Earth found that TMPs were the second leading source of surface water plastic pollution from land-based sources (Friends of the Earth, 2018). A 2014 report published by the National Institute for Public Health and the

Environment rated tire wear MPs as prominent in the scale of emissions yet extremely difficult to replace or reduce, making the situation dire if the health of humans is being threatened. Furthermore, all TMP material can be suspended and mobilized by wind and traffic, allowing for quick and uncontrollable induction into the surrounding environment (Sommer et al., 2018).

1.1.2.1 Tire Wear Particles

The most prevalent forms of TMPs are tire wear particles (TWP), formed through the mechanical abrasion of car tires against the surface of roads. They are heteroagglomerates of tire tread, minerals, bitumen, and other particles/heavy metals from the road’s surface and may include elements from other traffic-related or environmental sources (Klöckner et al., 2021). It is important to note that various studies may label TWPs as tire and road wear particles (TRWP) or roadway particles (RP). Still, for this literature review, they will be blanketed under TWPs and are defined as previously stated. The size, shape, density, and other physicochemical characteristics of TWPs depend on several variables involved during their formation, including temperature, speed, road surface, and tire composition. There is a consensus that about 10% of the particles by mass are less than 10µm, with an average size of 65-80 µm (Pohrt, 2019).

The wear rate (W) of an automotive tire can be defined as the amount of mass lost (Δm) per total distance covered (d): $W=\Delta m/d$. Studies have shown that the typical automotive tire loses 1.4 kg of mass over a span of 50,000 km, resulting in a W value of 112 µg/m (Pohrt, 2019). The estimated global average of TWP emissions per capita is 0.81 kg/year. Additionally, it is approximated that the TWP contribution to the total global plastic pollution in the oceans is 5-10%, with an additional 1-10% contribution to airborne $PM_{2.5}$ concentrations.

1.1.2.2 Recycled Tire Crumb

Another significant source of TMPs from the environment is in the form of recycled tire crumb (RTC). RTC is crumb rubber manufactured from old, recycled automotive tires and truck scalp tires (Boyles et al., 2019). Tires are generally composed of 70% rubber by weight, with 15% being steel, 3% fiber, and 12% extraneous material. The process of manufacturing recycled tire crumb from end-of-life tires begins with ambient grinding, a multi-step process utilizing a series of machines that results in the separation of the rubber from the steel and fiber. There are two distinct grinding processes, one using granulation and the other using cracker mills. The granulation process generally results in coarser, rougher crumb rubber, while cracker mills can produce crumb rubber of reduced sizes, with further reduction in steel and fiber components (ScrapTire News, 2020). Furthermore, micro-milling, additionally called wet grinding, is a process that can create fine mesh crumb rubber with specific, clean, and consistent mesh sizes (ranging from as coarse as 40 mesh to as fine as 200+ mesh) (ScrapTire News, 2020).

The recycling of tires is a sound practice in that tires are not biodegradable and that approximately 1.5 billion tires are discarded every year across the globe, and nearly 300 million in the United States alone. For every recycled tire, 10-12 pounds of RTC is produced (ScrapTire News, 2020). RTC is utilized in civil engineering to produce T-blocks-concrete blocks containing RTC-and home decks, for road asphalt, in railroad structures, as artificial turf filling, athletic/cycling tracks, as mulch, for playgrounds, rubber pavers on stable floors and farms, and as road speed reducers. While recycling is favorable to leaving end-of-life tires in landfills or other waste sites, there are still environmental and potentially human health impacts due to RTC use.

1.2 Intended Purpose

Over the last few decades, MPs have become increasingly ubiquitous within the environment. They have been found within most living organisms, including the stool, placenta, fetus, tissue, and blood of humans. TMPs, considered MPs due to their synthetic polymer composition, have been identified as one of the major contributors to environmental MPs, particularly TMPs produced from tire wear on road surfaces (Sommer et al., 2019) (Wagner et al., 2018). However, the overall human health risks of TMPs are not well understood. While exhaust-related traffic emissions are currently regulated, non-exhaust-related emissions, including TWPs, are not.

Additionally, much needs to be understood regarding the physicochemical variations amongst TMPs and how these differences affect their distribution, human exposure, and human health effects. The literature review described in this proposal aims to provide an overview of the sources, distribution, and routes of exposure of TMPs, discuss and compile factors related to their physicochemical diversity, and analyze their potential human health effects and related mechanisms of toxicity to determine the varying risks associated with different TMP particles. Furthermore, the literature review will aim to determine the directions future research will need to take to fill existing gaps in the literature and will evaluate what the future looks like regarding TMP pollution and solutions for this growing issue. This review will do so by compiling and analyzing published scientific literature.

2. Methods

A broad assortment of literature was consulted to compile information regarding TMPs, their distribution, physicochemical diversity, and the risk they pose to humans. Research studies were necessary for each section of this review in that they provided data for the composition of TWPs and TMPs, factors contributing to their size, shape, chemical composition, deposition rate, prevalence and distribution within the environment, uptake and translocation within the body, and effects on humans and animals. In addition to these studies, global reports from the National Toxicology Program (U.S.), National Institute for Public Health and the Environment (U.S.), Friends of the Earth (U.K), Swedish Environmental Research Institute (Sweden), the International Union for Conservation of Nature, and more were utilized to provide relevant statistics, additional toxicological data, and potential future outcomes regarding TMPs.

To effectively compile relevant data, topics were taken from each subsection of this review and broken down into associated concepts, which were subsequently searched for in various databases, including Scopus, PubMed, Google Scholar, and ScienceDirect. As more knowledge was gained on multiple concepts, additional related ideas arose throughout the writing process. Other relevant research articles derived from articles found in the method mentioned above were also analyzed, and so on and so forth. Table 1 shows the key topics and concepts within each subsection. The concepts represent keywords and phrases that were searched within databases. If not searched directly, a varying iteration may have been searched instead to broaden the available data. Not all subsections required intensive database searching and are therefore not represented within the table. These subsections relied on previous subsections for data and depended on the author for insights. Figure 1 depicts a flow chart of the research process utilized for this literature review.

Section Number: Name	Topics	Concepts

1.1.1: Overview of Microplastics	• Synthetic Plastics Industry • MPs • NPs	• Plastics History • Plastics Global Production • Plastics Degradation & Distribution • Plastics Environment • Primary MPs • Secondary MPs • MP Distribution
1.1.2: Overview of Tire Microplastics	• TMP Overview	• TMP Prevalence • TMP Statistics
1.1.3: Tire Wear Particles	• TWP Overview	• TWP Prevalence • TWP Statistics • TWP Formation
1.1.4: Recycled Tire Crumb	• RTC Overview	• RTC Prevalence • RTC Statistics • RTC Uses • RTC Manufacturing • RTC Mesh Sizes • RTC Milling & Grinding • Crumb Rubber
3.1: Tires and Tire Tread	• Tire Composition • Tire Manufacturing • Tire Tread Composition	• Tire Rubber & Tread • Tire Structure • Synthetic Tire Rubber • Styrene Butadiene Rubber • Tire Filler • Tire Softening Agents • Tire Additives • Tire Vulcanization Agents
3.2: Tire Wear Particles	• TWP Composition	• TWP Encrustations • TWP Chemistry Mapping • SEM/EDX • ToF-SIMS • TWP Mineral Content • TWP Brake Wear Encrustation • TWP Organic and Inorganic Components • TWP PAHs • TWP VOCs & SVOCs
3.3: Recycled Tire Crumb	• RTC Composition	• RTC Chemistry Mapping • RTC Inorganics and Organics • RTC Properties • RTC VOCs & SVOCs

4.1.1: Force	• TWP Force • TWP Mechanics and Formation	• TWP Friction/Shear • TWP Abrasion/Abrasive Wear • TWP Abrasion Model • TWP Slip/Slip Angle • TWP Fatigue Wear • TWP Curving and Cornering • Lamellar Peeling • Hysteresis
4.1.2: Tire Composition	• Effects of Tire Composition on TWPs	• Tire Composition TWP Deposition • Tire Composition TWP Size • Tire Composition TWP Physicochemistry • TWP Rubber Microstructure • TWP Treadwear Grades • TWP Studded/Winter Tire • TWP Friction/Summer Tires
4.1.3: Temperature	• Effects of Temperature on TWPs	• Volatilization & Evaporation • Temperature TWP Deposition Rate • Temperature TWP Size & Morphology • Temperature TWP Ultrafine • Ultrafine Particles • TWP Ambient Temperature
4.1.4: Speed	• Effects of Speed on TWPs	• Speed TWP Deposition Rate • Speed TWP Size & Morphology • Speed TWP $PM_{2.5}$ & PM_{10} • Speed Limit TWP • Speed TWP Physicochemistry
4.1.5: Relative Humidity	• Effects of Relative Humidity on TWPs	• Relative Humidity TWP Deposition Rate • Relative Humidity TWP Size & Morphology • Wet Conditions TWP • Wet Conditions TWP Abrasion
4.1.6: Road Composition	• Effects of Road Composition on TWPs	• Road Surface Composition TWP Deposition Rate • Road Surface Composition TWP Size • Road Surface Composition TWP $PM_{2.5}$ & PM_{10}

		• Road Surface Composition TWP Ultrafine • Road Surface Variations • Asphalt TWP • Pavement TWP • Concrete TWP
4.1.7: Traffic Conditions and Behavior	• Effects of Traffic Conditions on TWPs	• Traffic TWP Deposition Rate • Traffic TWP Size & Morphology • Stop-and-go Traffic TWP • TWP Harsh Braking • TWP Acceleration • TWP Driving Behavior
4.1.8 Vehicle Type	• Effects of Vehicle Weight on TWPs • Effect of Vehicle Type on TWPs	• Vehicle Mass TWP Deposition Rate • Vehicle Mass TWP Size & Morphology • Vehicle Class TWP • Electric Vehicles & Hybrid Vehicles TWP • Electric Vs. Internal Combustion Engine TWP
5.1.1: Tire Wear Particles	• TWP Prevalence	• TWP Global Prevalence • TWP Prevalence Statistics • TWP Environmental Estimates • TWP per capita
5.1.2: Recycled Tire Crumb	• RTC Prevalence	• RTC Global Prevalence • RTC Prevalence Statistics • Artificial Turf Fields Statistics • RTC Industrial Use Statistics • RTC per capita
5.2.1: Tire Wear Particles	• TWP Distribution	• TWP Environmental Fate • TWP Routes of Distribution • TWP Markers/Indicators • TWP Organic Markers
5.2.2: Recycled Tire Crumb	• RTC Distribution	• RTC Environmental Fate • RTC Routes of Distribution • RTC Markers/Indicators • End-of-Life Tires
6.1: Inhalation	• TMP Inhalation Route of Exposure • TMP Inhalation Uptake and Translocation	• MP Systemic Absorption • Airborne MP Exposure • MP Uptake and Translocation • MP Size and Inhalation Exposure

		• MP Endocytosis • MP Physicochemistry Inhalation Uptake • TMP Inhalation Characteristics
6.2: Ingestion	• TMP Ingestion Route of Exposure • TMP Ingestion Uptake and Translocation	• MP Ingestion Mechanism • MP Uptake and Translocation • MP Rodent Ingestion • MP Physicochemistry Ingestion • MP Mesenteric Lymph Node
7.1: Overview of the Human Health Impact of MPs and NPs	• MP and NP Effects on Health-Overview	• MP/NP Mammalian Health • MP/NP Pathophysiology • MP/NP Mechanisms of Toxicity
7.2.1.1: $PM_{2.5}$	• TWP $PM_{2.5}$ Human Toxicity	• TWP $PM_{2.5}$ Composition • TWP $PM_{2.5}$ Toxicity Humans • TWP $PM_{2.5}$ Mechanism of Action & Pathophysiology • $PM_{2.5}$ Chemical Properties Toxicity
7.2.1.2: Ultrafine Particles	• TWP Ultrafine Human Toxicity	• Ultrafine Mechanism of Toxicity & Pathophysiology • Ultrafine Biological Systems • Ultrafine Human/Animal Studies • TWP Ultrafine Composition
7.2.1.3: Larger Particles	• TMP Coarse Particles Human Toxicity	• Coarse Particle Ingestion Toxicity • TMP Coarse Particle Toxicity • TMP Intestinal Leaching • Toxicity of PAHs • Toxicity of Carbon Black • TMP Morbidity/Mortality
7.2.2: Chemistry	• TMP Chemical Diversity Effect on Human Health	• Tire Composition TMP Chemistry • Studded Tire TMP Human Health • Road Composition TMP Toxicity • TMP Encrustation Toxicity • TMP Heavy Metal Toxicity • TMP PAH Toxicity • TMP Leachate Toxicity

		• TMP ROS/Inflammation
7.3: Effects of RTC on Health	• RTC Mechanisms of Human Toxicity	• RTC Human Ambient Exposure Pathway • RTC Ingestion • RTC Leachates • RTC Chemistry Toxicity • RTC Morbidity/Mortality • RTC Animal Toxicity Study

Table 1: Overview of sections, related topics, and specific concepts used to initiate database searches to obtain information for this literature review.

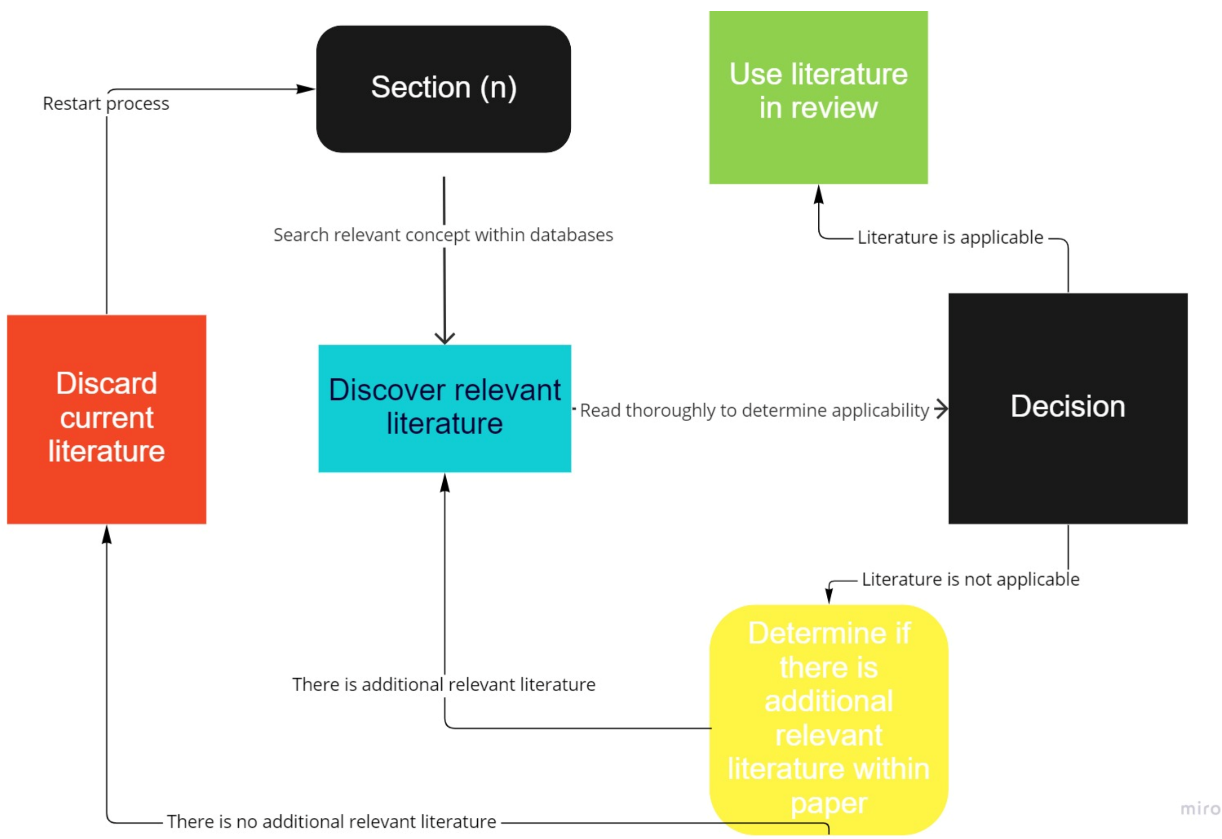

Figure 1: Flowchart illustrating database search process.

3. General Composition of Tires and Tire Microplastics

While many plastics are used globally, the broad assortment of plastic polymer products is generally derived from just six parent polymers: polyethylene, polyethylene terephthalate (PET), polypropylene, polyamide, polyvinyl chloride, and polystyrene.

3.1 Tires and Tire Tread

The tire manufacturing process is complicated and involves many components, steps, pressure, and heat. Various types of tires differ in their exact composition. For example, truck and winter tires contain a far more significant proportion of natural rubber than automobile tires. In general, however, it is approximated that, by mass, tires are composed of 40-60% natural and synthetic rubber/elastomers, 20-35% filler, 12-15% softener agents/process oils, 5-10% additives, 1-5% vulcanization agents, and 10-20% steel and textiles (Jekel, 2019) (Sommer et al., 2018). This breakdown is depicted in table 2.

Tire Component	**Potential Chemical Components**	**Mass Contribution (%)**
Rubber	Natural Rubber, Styrene Butadiene Rubber, Polybutadiene Rubber, Butyl Rubber	40-60%
Filler	Carbon Black, Silica, Single-Walled Carbon Nanotubes	20-35%
Vulcanizing Elements	Thiazoles, Peroxides, Sulfur, Tellurium, Selenium, and Nitro- and Azo- compounds	1-5%
Softener Agents/Process Oils	Organic Tars and Oils	12-15%
Additional Additives	Accelerators/Curing Agents (Sulphur Compounds, Zinc Oxides, Calcium, Lead, and Magnesium) Antiozonants (Hydrocarbon Waxes and Resins) Antioxidants (Amines, Diamines) Plasticizers	5-10%

	Preservatives Desiccants Processing Aids	
Steel and Textiles	Steel and Textiles	10-20%
Additional Trace Elements	Silicon, Aluminum, Calcium, Titanium, Sulfur, Cadmium, Selenium, and Potassium	Trace

Table 2: Breakdown of tire composition and related compounds by % mass.

Automotive tires were initially made from naturally occurring rubber, such as that from the Brazilian rubber tree. However, they are now composed of natural and synthetic rubbers. The synthetic rubbers used are most commonly styrene-1.3-butadiene rubber (SBR), an organic polymer consisting of styrene and butadiene polymers, but can also be polybutadiene rubber and/or butyl rubber (Wang et al., 2020). Hexamethoxymethylmelamine is a chemical used to crosslink the polymers. The tread of tires has traditionally been composed of these organic hydrocarbons with carbon black and Si as fillers. More recently, however, to increase the sustainable production of tires, black carbon fillers have increasingly been replaced by single-walled carbon nanotubes (Hilton, 2020). Vulcanizing compounds such as thiazoles, peroxides, S, Te, Se, and nitro- and azo- compounds are used with accelerators like Sulphur compounds, Zn oxides, Ca, Pb, and Mg. Various important chemical additives that may be added and fall under multiple categories in table 2 include organic tars and oils (softeners), halogenated cyanoalkenes, quinones, amines, diamines, calcium oxide, and phenols. Additionally, trace amounts of inorganic elements like Si, Al, Ca, Ti, S, Mg, Te, Cd, Se, Ti, and K may also be incorporated. The inner liner of tires is composed of butyl rubber and halogenated butyl.

While this is a passable breakdown of tire tread composition, studies have found hundreds of chemicals in tires, most of which are unknown and likely transformation products during manufacturing or use (Klöckner et al., 2021) (Müller et al., 2022). As discussed later, many of the compounds found in RTC and TWPs are leachable. While some are known (e.g., metals, phthalates, PAHs, Hexamethoxymethylmelamine, benzothiazole), many unknown compounds may be derived from tire tread that impact the environment and humans.

3.2 Tire Wear Particles

TWPs are generated due to the necessary friction between tire tread and the road surface during the rolling of the tire. As a result, TWPs are composed of elastomeric tire tread along with minerals and road encrustations embedded inside, with mineral and tread content each composing approximately half of the particles (Kovovich et al., 2021) (Unice et al., 2012). As such, all of the compounds from section 3.1 that compose tire tread may be present in TWPs. These particles generally range from <1 µm to 200 µm in diameter. Individual TWPs are challenging to identify and analyze since black particles due to carbon black-inherently interfering with spectroscopy. Scanning electron microscopy (SEM) and X-ray spectroscopy (EDX) are commonly used to analyze embedded minerals, vulcanization agents, and filler materials of TWPs (Kovovich et al., 2021). Additionally, while time-of-flight secondary ion mass spectroscopy (ToF-SIMS), a powerful technique for characterizing complex structures, hasn’t been commonly used, it can be helpful in identifying the inorganic and organic components of TWPs. Utilizing these techniques, the composition of various TWP samples has been analyzed in numerous studies.

Non-exhaust traffic emissions, to which TWPs contribute significantly, have substantial concentrations of heavy metals. Compared to tread particles, TWPs contain higher amounts of Si, Al, Ca, K, Mg, Na, S, and Fe, likely resulting from the encrustment of pavement or other wear surfaces (Kovovich et al., 2021) (Kreider et al., 2010). Additionally, brake wear can lead to

Fe, Cu, Zn, Ti, Mo, Mn, Ba, Sn, Pb, and W being encrusted within TWPs (Sommer et al., 2018). Furthermore, a study using on-road collection methods found the metals mentioned above and additional metals, including Sb, As, B, Ni, and V (Kreider et al., 2010). On the other hand, vulcanizing elements like Zn and S are lower in concentration in TWPs than in tread particles. Furthermore, fragments of SBR, like C_5H_5+ and C_7H_7+, can be found on the surface of TWPs, in distinguishable morphology, density, and co-localization with other compounds as compared to tire tread and other wear particles (Kovovich et al., 2021). Additionally, studies have shown that TWPs contain polycyclic aromatic hydrocarbons (PAHs) in amounts greater than in tire tread alone, indicating a significant contribution of PAHs to TWPs from non-tire sources. One such study, completed by Kreider et al. (2010), quantified PAH concentrations in TWPs utilizing thermogravimetric analysis followed by GC-MS. This study's authors have distinguished between TWPs and what they describe as roadway particles (RPs), defining TWPs as particles created through the interaction of road and tire. In contrast, RPs are defined as particles created through the interaction of road, tire, and the environment. For this literature review, RPs are synonymous with TWPs. After analyzing PAH concentrations in RPs compared to tire tread, the authors found a significant non-tire contribution of PAHs to the RPs, likely originating from fuel combustion products, asphalt, and exhaust. Kreider et al. (2010) discovered that some major contributing PAHs were phenanthrene, pyrene, benzo-a-anthracene, chrysene, and fluoranthene. However, there were at least a dozen additional PAHs found.

Additionally, A 2014 study determined that TWPs were a major source of environmental benzothiazoles, including the biocide 2-mercaptobenzothiazole, which was previously only determined to be a threat within occupational settings (Avagyan et al., 2014) (Zhang et al., 2018).

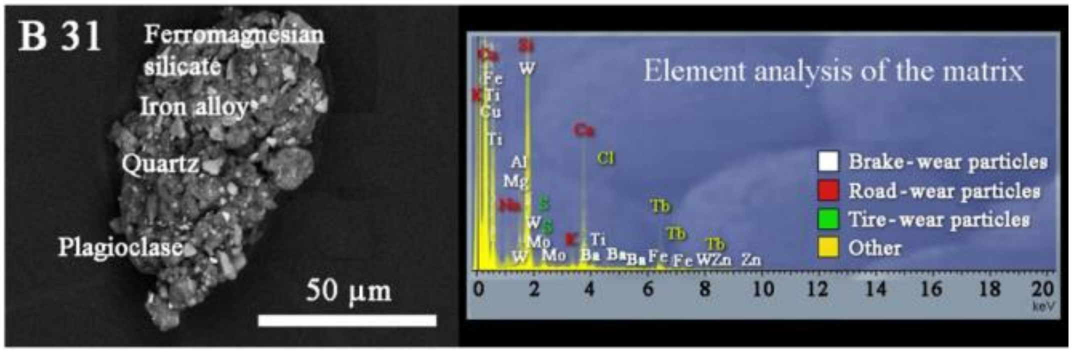

Figure 2: The left is a SEM image of a representative TWP taken from a federal highway. The right is an EDX diagram with 25 spectra from the same TWP with subsequent particle classification.

Note. From "Tire Abrasion as a Major Source of Microplastics in the Environment" by Sommer et al., 2018, *Aerosol and Air Quality Research*, 18(8), p. 2019 (https://doi.org/10.4209/aaqr.2018.03.0099).

A study by Sommer et al. (2018) utilized SEM/EDX to analyze representative TWPs from different roads in Germany. As shown in figure 2 (Sommer et al., 2018, p. 2019), one such TWP was wholly encrusted with large minerals, identified as quartz, plagioclase, orthoclase, calcite, gypsum, and barite, and metals, identified as Fe, Fe alloy, and Cu. Zn, Ti, Mg, Mo, W, S, and Cl were also detected.

While figure 2 is a good representation of TWPs and how they can be depicted using SEM/DEX, there is considerable variation in TWP composition. Important similarities, however, are generally ubiquitous and are therefore essential when identifying TWPs. These include an elongated or round shape, mineral encrustation, surface co-localization of (S + Zn/Na) ± (Si, K, Mg, Ca, and Al), and SBR fragments, including the co-localization of C_5H_5+ and C_7H_7+ (Kovovich et al., 2021).

More studies need to be completed to determine the prevalence of carbon nanotubules in TWPs or the environment due to tire wear. However, a release scenario predicted by Nowack et al. (2013) expects that there are carbon nanotubule-rubber composite emissions due to the abrasion of tire tread during everyday use and during the tire recycling process. The authors conclude that the release of carbon nanotubules is unlikely in all potential release scenarios except in manufacturing, tire use, and the mechanical stress of textiles.

3.3 Recycled Tire Crumb

A majority of the physical and chemical compositional studies of RTC are on the infill from synthetic turf fields due to the growing public health concern associated with recreational activities on such fields. As of 2019, there were over 12,000 artificial turf fields in the United States (Waidyanatha et al., 2019). With the assumption that a high volume of activities is being performed on each field, exposure to potentially harmful compounds is a prevalent concern.

A 2019 report completed by the National Toxicology Program on RTC from a crumb rubber lot determined that the sizes of the particles ranged from <1mm to 4mm using optical and scanning electron microscopy. Utilizing thermogravimetric analysis, the report determined that volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) made up a tiny proportion of the RTC. Additionally, polymeric material accounted for 29.9%, carbon black accounted for 37.1%, inorganics made up 7.7%, and extender oils such as paraffinic, naphthenic, or aromatic oils made up approximately 25%. Inorganics analysis was completed using inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma-atomic emission spectroscopy. Zn (1.68%), Si (0.932%), and Al (0.106%) were the inorganics found in the highest concentrations, with 13 other metals having concentrations of less than

0.1%. Headspace gas chromatography-mass spectrometry was used to identify and quantify the various concentrations of VOCs and SVOCs, which can be seen in the report (Boyles et al., 2019).

Furthermore, a study by Topçu and Unverdi (2018) gives a detailed breakdown of the different mechanical, physical, fresh state, and durability properties of RTC.

4. Physicochemical Diversity and Emission Rate of Tire Wear Particles

TWPs are formed and released due to the force between a tire and a surface. There are numerous variables that must be considered when determining the physical and chemical properties of TMPs, as well as the rate at which they are emitted. The composition of the tire, the temperature, the road's structure, the vehicle's velocity, and the way the tire is moving across the road all affect the size, shape, emission rate, and composition of TWPs. Interaction between the tire and the road itself alters the characteristics of the TWPs that are generated through the incorporation of heat, friction, shear, and material from the surface (Kreider et al., 2010). Therefore, depending on the environment surrounding the formation of TWPs, the nature of the TWP will vary, resulting in a significant degree of uniqueness, and therefore will distribute differently and have varying fates and impacts within biological systems.

4.1 Variables Affecting Physicochemistry and Emission Rate

4.1.1 Force

TWPs can be created through multiple mechanisms depending on the driving conditions. The primary mechanism for TWP generation occurs due to frictional shear forces, with shear force being defined as unaligned forces pushing one part of a body in one direction and another part of the body in the opposite direction, between the tire and the road interface during normal driving conditions. Frictional shear forces generally result in abrasive wear. The abrasive wear of tire tread occurs when there is frictional shear between a softer (tire tread) and a harder (road) surface. The important components of the frictional force in play are molecular adhesion and surface roughness. In this case, it is the softer material (tread) that loses material due to the relative roughness of the harder material and the adhesion between the tread and the road. Under normal conditions, abrasive wear caused by friction is the most common type of tire wear (Woo et al., 2022). Frictional shear forces resulting in abrasive wear are generally known to produce TWP of relatively large size, in the range of PM_{10} or greater (Kim et al., 2021). In general, the greater the force imparted on the tire, the greater the rate of deposition of TWPs.

A more extensive breakdown of forces impacting tires and therefore influencing the deposition rate of TWP is summarized by Pohrt (2019). Driving on straight roads can be described as a horizontal load and is impacted by resistive forces (F_{resist}). Resistive forces can further be broken down into inertia force ($F_{inertia}$), which applies to sections of road where there is frequent stopping and accelerating, slope force (F_{slope}), which applies to inclined roads, rolling resistance (F_{roll}), which applies to the force resisting the motion of the tire rolling on the surface, and aerodynamic drag force (F_{drag}), which is the force air imparts on the vehicle and is proportionately impactful at higher speeds. The math reveals that the most significant wear deposition rates likely occur during times of frequent acceleration and braking (e.g., traffic lights) and when cars are traveling at high rates of speed.

Furthermore, curving and cornering create an additional lateral load due to centripetal force (F_{cent}). The values for the F_{cent} during different road scenarios indicate significantly higher values than any horizontal load scenarios. A study by Turner et al. (1996) validates this math in that their simulated bench test results indicated that 63% of the total tire wear came from city driving even though it only accounted for 5% of the total distance driven (Turner et al. 1996). Nguyen et al. (2018) discuss an advanced abrasion wear model which effectively describes how the aforementioned load and forces result in the wearing of the tire and resulting deposition of TWPs (Nguyen et al., 2018). The mathematical model includes all factors that affect the abrasion of the tire, including the contact pressure, sliding velocity, flash temperature, frictional dissipation (calculated from the sliding velocity and the tangential stress), history of sliding, and the directional dependence. This model and others preceding it effectively describe side-slip under lateral acceleration and how they result in tire wear. Under normal conditions, abrasion, as defined by this model, is the most common form of tire wear. Tire slip angle, which is representative of the aforementioned cornering conditions that are important in creating frictional shear force, was studied by Park et al. (2018). As discussed, slip is an important mechanism of abrasion wear that can produce fine TWPs. The authors studied 0°-4° slip conditions and determined that 4° slip produced substantially more $PM_{2.5}$ and PM_{10} than 0° slip (Park et al., 2018).

It is important to note that while abrasion wear generally favors larger, coarser TWPs, micro-vibrations between the tire and the road surface can result in fine TWPs (Yan et al., 2021). The micro-vibration frequency is related to the tire tread's composition and modulus. For example, with increasing silica content, the modulus of the tread increases, and, subsequently, so does the micro-vibration frequency.

In addition to abrasive wear, tread fatigue wear, commonly characterized by lamellar peeling, curling, and/or rolling, is another notable contributor to tire wear. Similar to abrasive wear, fatigue wear is also caused by frictional shear force, however as opposed to the adhesive, harsher contributions of friction and the road surface, fatigue wear is caused by hysteresis friction (Moore, 1980) (Chang et al., 2020). In this way, fatigue wear occurs over time and is localized structural damage due to loading. When the load is higher than the fatigue strength of the tire, fatigue wear occurs. Fatigue wear is generally responsible for TWP of smaller sizes than abrasive wear and results in a milder, more continuous loss of material, but can be significant when considering long periods of rolling or sliding (Nguyen et al., 2018). A study analyzing type of tire, surface, and temperature effects on TWPs discovered that rolling wear, an aforementioned contributor to frictional fatigue wear, results in a marked increase in elastic deformation and produces a large amount of heat (Chang et al., 2020).

A final mechanism of TWP production results from volatilization. In this process, much finer TWPs are produced through the evaporation of volatile compounds. This mechanism will be expounded upon further in section 4.1.3.

4.1.2 Tire Composition

The composition of the tire is another important factor affecting both the physical and chemical characteristics of the resulting TWP. While an overview of tire tread has been given previously, the exact nature of tire tread composition is a trade secret and specifics are not known precisely. Regardless, the exact composition of the tire tread is important in considering the chemical profile of the resultant TWPs produced via different mechanisms. Overall, the type of tire, tread, and rubber compounds all have an impact on the wear of the tire.

It has been established that TWP emission is related to the tread rubber microstructure. Notably, the physical and/or chemical interactions between the nanofillers and the rubber polymers have an important effect on TWP emission. Silica, a widely used and environmentally conscious nanofiller (as opposed to carbon black), improves the static and mechanical properties of rubber. A 2021 study by Yan et al. determined that the composition and microstructure, specifically the concentration of silica in parts per hundred rubber (phr), of tire tread had discernable effects on both the size and deposition rate of TWP due to the ability of silica to increase the elastic modulus, or the measures an object's resistance to mechanical stress/deformation, and therefore increase the abrasion resistance of the rubber tread (Yan et al., 2021). To demonstrate the effectiveness of silica concentration in rubber composites on the amounts and size differentiation of emitted TWPs, the authors filled wheels with differing silica contents and ran them on an abrasion tester. The results of the experiment show that TWPs >1 mm accounted for the most significant proportion of the total TWPs emitted during the experiment. With increasing silica content, particles >1 mm decreased significantly, likely due to a reduced ability for cracks to propagate during the abrasion testing. Correspondingly, the total number of TWPs decreased as silica content increased due to the increase in elastic modulus or the resistance to the mechanical abrasion testing. Interestingly, their experiments demonstrated that as the silica content increased, the amount of fine tire wear particles (FTWP) also increased. They explain that with increased silica filler, there was an increase in silica aggregates, indicating that the silica-silica interactions overpowered the silica-rubber interactions. These aggregates were easily destroyed during abrasion, resulting in the production of the FTWP. The authors created and tested a modified version of the silica filler with slightly worse total TWP reductions but significantly improved FTWP reductions (Li et al., 2013).

Another study analyzed tire treadwear grades to determine their effects on PM emissions. The study used the uniform tire quality grade (UTQG) treadwear ratings and analyzed UTQG

250, 350, 500, and 700 tires. Important to note is that in the tires with UTQG 250, 350, and 500, most of the filler material was silica, with SBR and BR rubber, whereas in the UTQG 700 tire, the filler was 100% carbon black, with SBR, BR, and NR rubber polymers. Their laboratory experiments showed that PM emissions from UTQG 250, 350, and 500 decreased as the treadwear grade increased. Interestingly, the UTQG 700 tires, with different rubber and filler components, did not have the lowest PM emissions (higher than UTQG 350 and 500). In general, the higher the treadwear grade is, the stronger the rubber is, and therefore a reduction in PM emissions. While the UTQG 700 had proportionately less abrasive wear, there was likely an increase in fine particles due to an increase in fatigue wear from lamellar peeling, particularly at higher speeds (Woo et al., 2022). Overall, with a higher treadwear grade, tires have the benefit of reducing overall TWPs. However, there is a potential for an increase in fine TWPs in higher graded treadwear due to the particular configuration of polymer and fillers in the rubber.

Also, studded tires give rise to 60-100 times more particles than friction tires (Gustafsson et al., 2008). The type of tire used appears to be the most significant contributing factor in the size of ultra-fine particles that are released. Studded tires have been proven to drastically increase TWP emission and/or resuspension of already-generated particles. Sjödin et al. released a report in 2010 within which they analyzed PM_{10} concentrations after completing runs in a road simulator hall with three different tires: studded tires, Nordic unstudded winter tires, and summer tires (also unstudded) (Sjödin et al., 2010). Figure 3 (Sjödin et al., 2010, p. 26) shows the resultant mass concentrations for each of the three tires, where the cycle included 1.5 hours at 30 km/h, 1.5 hours at 50 km/h, 2 hours at 70 km/h, 1 hr at 70 km/h with a filter fan activated, finished with a stepwise reduction in speeds back to 0 km/h. As is depicted, the studded tires emitted remarkably higher PM_{10} particles than either of the other two tires. The results of their study also indicated that ultrafine particle production (30-50nm) only occurred during the tests with studded tires, indicating that their composition is responsible for finer particle formation. An additional study by Yiu et al. (2022) confirmed these results outside of laboratory simulations. In their research, taxi vehicles with studded tires generated 1.4 times more wear than those with all-season tires and three times more wear than those with summer tires. The difference in wear seen in these studies is likely due to the fact that studded tires have a higher proportion of natural rubber in their tread composition and have an increased tread depth. These characteristics result in softer tread with a lower modulus of elasticity which increases their affinity to wear via frictional abrasion.

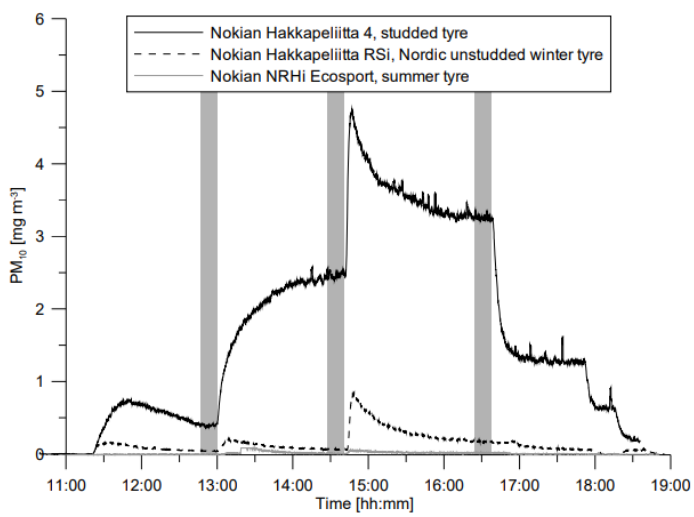

Figure 3: PM_{10} Concentrations in the road simulator hall after runs with studded winter tires, non-studded winter tires, and summer tires with speeds at 30 km/h, 50 km/h, and 70 km/h.

Note. From “Wear particles from road traffic - a field, laboratory and modelling study. Final report,” by Sjödin et al., 2010, *IVL Svenska Miljöinstitutet*, p. 26 (http://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-2719).

The size of submicron particles released as tire wear is at least partially dependent on the type and mixture of softening oils present in the tire. One study determined that 33% (by mass) of airborne wear particles had diameters less than 0.1 µm. A majority of these ultrafine particles had smooth appearances, indicating that their formation was associated with thermal or chemical generation, which will be expounded upon further in section 4.1.3 (Sanders et al., 2003).

4.1.3 Temperature

Temperature plays an important role in TWP characteristics, particularly particle morphology and diameter, and is significantly impacted by many of the other factors discussed in this section. One crucial factor involved in temperature is the speed of tire rotation. As discussed in section 4.1.1 and 4.1.5, speed is correlated with the amount of mechanical stress the tire experiences. More mechanical stress results in higher temperatures. The surface of the road also is important for temperature variations.

Importantly, volatilization at high temperatures and subsequent condensation of organic materials in the tire, including the rubber polymers, VOCs, and/or extender oils, can lead to the formation of ultrafine particles. The instantaneous heat flux caused by the generation of frictional heat between the tire and road surface during tire slippage likely causes the organic compounds, particularly the semi-volatile organic compounds in the tire tread, to vaporize and condense rapidly, forming these ultrafine particles. A study by Park et al. (2016) analyzed the effect of temperature and subsequent volatilization of tire tread. The authors heated tire specimens in a reaction chamber and analyzed the number concentration and size distribution of particles produced. Their experiments showed that increasing temperatures (from 130℃ to 350℃) resulted in an increased number concentration of particles. The volatilization reactions occurred at approximately 160℃ since the nucleation of tire fumes is initiated at this temperature. For all of the temperatures tested above 160℃, the size distributions were similar, with peak median diameters ranging from 50-60 nm. Additionally, the authors discovered that increasing the heating rate also increased the particle concentrations. In fact, the rate of heating was more consequential to the number of particles than the temperature itself (Park et al., 2016).

Ambient temperature also affects the amount and distribution of TWPs. Interestingly, Yan et al. (2021) showed that while an increased ambient temperature increased the total TWPs released, the proportion of fine TWPs decreased. The explanation for this trend is that higher ambient temperatures decrease the modulus of the tire tread and create a layer of lubrication on the tread. With a reduced modulus, there is a decrease in the frequency of micro-vibrations, as described in section 4.1.1, and therefore reducing fine TWP formation in favor of more coarse particles as a result of frictional shear (Yan et al., 2021).

Additionally, the shape of particles is also affected by temperature. Dahl et al. (2006) demonstrated particle size was a key determinant for temperature-related diameter changes. The authors used aerosolized TWPs from studded tires mounted on the road simulator and quartzite pavement and applied different temperatures to them with a thermodesorber. The selected particles had initial sizes of 40, 80, 160, 320, and 640 nm. The 40, 80, and 160 nm particles, which are near or at ultrafine size, were impacted by the thermal conditioning in that their diameters decreased linearly with increasing temperature, while the larger particles were unaffected. The authors hypothesize that the smaller particles (<200 nm) are mainly derived from the tire tread whereas the larger particles likely contain mineral grains (Dahl et al., 2006).

4.1.4 Speed

The previously mentioned study by Dahl et al. (2006) determined that speed was the greatest emission factor for TWPs compared to tire composition and road composition. The study results show that there weren't significant emissions factor discrepancies when comparing tire composition and surface composition at 50 km/h, whereas there were significant discrepancies between the 50 km/h and 70 km/h measurements.

An even more in-depth speed analysis was completed by Kim and Lee (2018). The authors used a road simulator and tested emissions and size distributions of TWPs at speeds of 50, 80, 110, and 150 km/h. Their results show that as the speed of travel increased, both the PM concentrations and the $PM_{2.5}/PM_{10}$ ratios increased. Furthermore, after 100 km/h the PM_{10} concentration stabilized, whereas the $PM_{2.5}$ concentration did not, indicating a transition from TWPs created via frictional shearing towards volatilization. Additionally, while the TWP mass concentration increased with increased speed, the TWP mass size distribution remained relatively unchanged (Kim & Li, 2018).

Additional studies have yielded comparable data. A Norwegian study by Hagen et al. (2005) found a reduction in coarse PM with a speed reduction from 72 km/h to 62 km/h. Another study done in Sweden found that particle mass concentration released behind studded tires in Stockholm at 100 km/h was ten times higher than at 20 km/h (Hussein et al., 2008).

Finally, speed is a crucial factor in releasing organic filler material and softening oils, with increasing speed raising the tire's temperature and releasing more material increasingly in the ultrafine particle range.

4.1.5 Relative Humidity

The amount of moisture in the ambient air also appears to have a noticeable effect on TWP characteristics. One study analyzed TWP generation under humidity conditions of 50%, 90%, and fully saturated wet conditions. Under drier conditions (50% humidity), the size of the TWPs was relatively large with elongated and granular characteristics. At 90% humidity, the TWPs were smaller and more dispersed. Under the wet conditions, the TWPs were even smaller, with a significant proportion of fine particles, indicating that water lubrication plays a vital role in forming fine TWPs. Additionally, SEM micrographs of the tread surfaces under different humidity conditions show that an increase in humidity is correlated with smoother tread surfaces, likely due to an increase in the presence of lubrication films. Mechanistically, these surfaces result in slighter curling of the tread surface and reduction in temperatures (and therefore thermal polymer degradation), resulting in rolling wear at lower temperatures and therefore a transition from abrasive wear towards fatigue wear. This supports the results indicating an increase in fine wear particles at increased humidity values (Chang et al., 2020).

4.1.6 Road Composition

The composition of the road surface is another significant factor that influences the characteristics and number of TWPs being emitted. The minuscule surface where the tire and road interface, particularly related to roughness and geometry, are important factors in considering frictional shear force. The chemical composition of particular TWPs is directly influenced by the material encrusted from the road surface. Asphalt concrete pavements, the most common type of road surface, consist of mineral aggregates, bitumen binders, sands, and fillers, whereas cement concretes are composed of coarse aggregates, cement, and sand (Lee et al., 2013). Furthermore, the rates of emission differ amongst different asphalt concrete compositions. For example, a study comparing TWP emissions from a dense asphalt concrete

(ABT) containing granite with a stone mastic asphalt pavement (ABS) containing quartzite determined that the ABT road emitted more wear particles into the environment (Gustafsson et al., 2018). The study did so by analyzing RTC particles and using them as representative material to study the TWPs in the environment. They also determined that the ABT granite particles had a 'flakier' appearance while the ABS quartzite particles were grainier. The size distributions, however, were similar for both kinds of roadway surface.

A different study showed that plain cement concrete (PCC) roads emitted up to 2 times more tire wear particles than Asphalt Rubber-Asphalt Concrete Friction Course (ARACFC) (Allen et al., 2006). Furthermore, it appears that the type of pavement topping is important for wear mechanisms. In a study by Anderson et al. (2006), Whitetopping and Superpave had more road wear over time than Micro/macro and modified class D pavement.

4.1.7 Traffic Conditions and Behavior

The degree to which TWPs are encrusted with dust and debris from the road is dependent on the traffic conditions. Stop-and-go traffic conditions result in a more complete encrustment of debris while more fluid conditions generally result in a partial encrustment. Furthermore, stop-and-go traffic conditions on urban roads produced more TWPs than stop-and-go traffic conditions on the freeway (Sommer et al., 2018).

Behavior is also an important factor regarding TWP emissions. Drivers who have a tendency to brake and/or accelerate harshly/abruptly generate more TWPs (Lui et al., 2022). The reason is that this kind of driving behavior creates more frictional shearing and heat. While the mechanism of abrasive frictional shear generates coarser material, the heat generated from this behavior results in volatilization and an increase in ultrafine particles as well.

4.1.8 Vehicle Type

A final factor influencing TWP emissions is vehicle type. Specifically, it is important to note that vehicle weight plays an important role regarding the force realized between the tire and the road surface. Increased vehicle weight is associated with increased concentration of particles released as a result of tire wear (Kim et al., 2022). A 2018 CEDR report compiled data on the emission factor (mg/vehicle km) for different kinds of cars with varying weights from various sources. The data shows that motorcycles (39-47 mg/vkm) had the lowest emissions factor for TWPs, followed by passenger cars (50-132 mg/vkm), light commercial vehicles (102-320 mg/vkm), buses (267-700 mg/vkm), and trucks/heavy commercial vehicles (546-1500 mg/vkm).

Type of engine also affects TWP emissions. A recent 22-month study by Liu et al. (2022) discovered that a hybrid powertrain vehicle generated 36% more tire wear than a similarly weighted vehicle with a traditional internal combustion engine. The powertrain vehicle produced more TWPs due to its ability to rapidly accelerate because of its instant torque, a feature of hybrid and electric vehicles. Previous studies have supported the notion that electric/hybrid vehicles, while rapidly becoming a solution for exhaust-related traffic emissions and related regulatory policies, may not significantly reduce PM emissions due to their impact on non-exhaust related emissions, notably TWPs (Timmers & Achten, 2016) (Beddows & Harrison, 2021). Regardless of torque, electric vehicles are notably heavier than their traditional counterparts. Timmers and Achten (2016) point out several examples of this notion, including the fact that the Ford Focus Electric is 219 kg heavier than its traditional counterpart, the Ford Focus hatchback, despite having nearly identical specifications. By comparing 9 such examples, they found that electrical vehicles were 24% heavier on average than their traditional counterparts.

4.2 Summary of Factors Influencing TWP Deposition and Physicochemistry

Table 3 gives a summary breakdown of the different factors influencing the physicochemistry of TWPs as well as their rates of emission.

Factor	Effect on Emission Rate	Effect on TWP size	Effect on TWP Morphology	Effect on TWP Chemical Characteristics
Abrasive Wear	• Increased abrasive wear increases emission rate. • Lateral load increases rate more than standard horizontal load. • Contact pressure, sliding velocity, frictional dissipation, slip, and directional dependence are all factors influencing the increase in emission rate.	• Frictional abrasion tends to produce larger, coarse particles. • Micro-vibrations can produce fine TWPs.		
Fatigue Wear	• Lamellar peeling, rolling, and curling result in a continuous, but mild release rate that is less significant than abrasion, but can become significant during long periods of rolling.	• Results in fine TWPs that are smaller than the abrasive wear mechanism.		
Tire Comp.	• Increased treadwear grade results in higher modulus of elasticity and a lower emission rate. • Increased silica filler content over carbon black results in a lower emission rate.	• Current silica filler results in an increase in fine TWPs while a modified silica does not. • Particular polymer and		• Tread composition is directly related to TWP composition: e.g., studded tires have

	• Studded winter tires have significantly higher emission rates than friction tires and all-season tires.	filler composition of high treadwear grades can result in increased fine TWPs due to lamellar peeling. • Studded tires emit more PM and ultrafine particles than other tires		more natural rubber • Type and mixture of softening oils present determine ultrafine particle concentration
Heat	• Increasing temperatures (from 130℃ to 350℃) results in a higher emission rate. • An increased rate of heat influx results in a much higher rate of emissions.	• Volatilization and evaporation at high temperatures results in ultrafine particle formation due to the combustion of volatile organics.	• The diameters of very fine and ultrafine particles subjected to heat decrease linearly while larger particles are unaffected. • Ultrafinene particles are spherical as compared to the common rod-shape of most TWPs	• Ultrafine particles generated by volatilization are generally composed of tire tread while larger particles show encrustment. This concept applies to all volatilization vs. frictional force emissions.
Speed	• Higher speeds significantly increase emission rate	• Increased speed increases the PM concentrations and the $PM_{2.5}/PM_{10}$ ratios. • Fast acceleration/braking can lead to heat influx and ultrafine particle formation		• High speeds impact the amount of oils/organics released and volatized.
Ambient Temp.	• Increased ambient temperature	• Increased ambient		

	increases the emissions rate	temperature results in more coarse particles and less fine particles		
Relative Humidity	• Increased humidity decreases the emission rate.	• Wetter conditions results in a transition to fatigue wear and therefore smaller particles.	• Drier conditions result in elongated and granular characteristics • Wetter conditions result in more round morphology.	
Road Comp.	• Cement concrete roads have a higher emission rate than roads paved with asphalt • Dense asphalt concrete results in a higher emission rate than open grade asphalt and stone mastic asphalt	• More ultrafine particles are found on roads meant for higher speed of travel	• ABT granite particles had a 'flakier' appearance while the ABS quartzite particles were grainier.	• The chemical constituents of particular TWPs are directly influenced by the material encrusted from the road surface.
Traffic Conditions	• Stop-and-go conditions result in a higher emission rate than non-traffic conditions • Stop-and-go traffic conditions on urban roads produce more TWPs than stop-and-go traffic conditions on the freeway.			• Stop-and-go traffic conditions result in a more complete encrustment of debris while more fluid conditions generally result in a partial encrustment.
Driving Behavior	• Drivers who have a tendency to brake and/or accelerate harshly/abruptly	• Heat generated from this behavior results in volatilization and an increase		

	generate more TWPs.	in ultrafine particles.		
Vehicle Weight	• Increased vehicle weight results in an increased emission rate.			
Engine Type	• Electric/Hybrid vehicle engines generate more torque, resulting in an increased emission rate than internal combustion engines.			

Table 3: Overview of different factors and their effects on TMP physicochemistry and emission rate. Empty cells indicate that the factor either isn't correlated with a change in that outcome, or the outcome has been described already for a different section and would be redundant.

5. Tire Microplastics in the Environment

5.1 Prevalence

5.1.1 Tire Wear Particles

TWPs make up a substantial proportion of non-exhaust traffic emissions. A comprehensive study done by Sommer et al. (2019), found that 89% of traffic-related non-exhaust PM was derived from traffic-related sources, with 39% from road wear, 33% from tire wear, and 17% from brake wear. The remaining 11% was from non-traffic-related sources (Sommer et al., 2018).

Regarding global prevalence, a review completed by Kole et al. (2017) gives a detailed breakdown of current national estimates of TWPs for The Netherlands, Sweden, Norway, Denmark, Germany, United Kingdom, Italy, Japan, China, India, Australia, USA, and Brazil. Notably, there are approximately 3,369,698 tonnes of TWPs emitted annually from these countries alone and an average of 0.95 kg emitted per capita each year.

5.1.2 Recycled Tire Crumb

Another way that TMPs can enter the environment is through RTC. Crumb rubber derived from end-of-life tires may be repurposed as turf in various recreational and sports facilities.

In Denmark, it is estimated that 380-640 tonnes/year are released from registered artificial football fields. From other RTC sources, there is approximated to be an additional 380-604 tonnes/year. Cumulatively, this contributes significantly to the total prevalence of TMPs in Denmark as it comprises approximately 20% of the total environmental contribution. (Lassen et al., 2015). In Sweden, the loss of RTC from artificial fields is approximately 2300-3900 tonnes/year, comprising 18-30% of the total environmental TMP burden.

5.2 Distribution and Environmental Fate

The distribution of MPs across the globe is remarkable. MPs have been found in and on every major continent and ocean, including the Antarctic marine and terrestrial systems, the summit of Mount Everest, and the Canary Islands (Herrera et al., 2018) (Miner et al., 2021) (Waller et al., 2017). MPs have also been found in deep marine sediment, in the atmosphere and in raindrops (Dris et al., 2015) (Wetherbee et al., 2019). The distribution of MPs is primarily impacted by anthropogenic and environmental factors. Over short ranges, anthropogenic effects have a dramatic influence on the density of MP distribution, but environmental factors like wind, waves, and rain have a more widespread role in the ubiquitous distribution of microparticles (Herrera et al., 2018).

5.2.1 Tire Wear Particles

The fate of TWPs is dependent on the mass concentration as well as the individual characteristics of each particle, including size and density (Kovochich et al., 2021). Coarse particles have differing physicochemical characteristics than fine and ultrafine particles. In addition to the many elements from the tread of the tire, they contain road, brake and traffic-related encrustations. The exact composition is determined by the variables described in the previous section. The largest TWPs are generally not transported very far and can be restricted to roadways. However, these particles may collect on the road and then wash into rivers, which is a major pathway of how MPs get into waterways. While TWPs are a main source of particulate traffic emissions, there is insufficient data on TWPs in the environment. A key challenge is determining ideal organic markers for TWPs to allow for quantification of TWPs in the environment. A 2021 study considered specificity, tendency of leaching, analytical sensitivity and precision, and stability during aging in order to determine an ideal marker. Their study resulted in the selection of N-formyl-6-PPD, hydroxylated N-1,3-dimethylbutyl-N-phenyl quinone diimine, and 6-PPD-quinone as candidates (Klöckner et al., 2021). Previous studies have used Zn as a tire wear marker but have since been questioned due to the numerous sources of Zn in the environment, including industrial activities, brake wear, automobile exhaust, lubricants, galvanized road furniture, and metallic barriers (Grigoratos and Martini, 2014). Another such marker that has been used is styrene-butadiene rubber. 70% of global styrene-butadiene rubber is used for tire manufacturing, making it a somewhat reliable tracer.

There are numerous fates for coarse TWPs after they are introduced on and around the road. Nearby receiving water is one such fate. Humidity, surface roughness, precipitation, and wind velocity are important factors determining what happens to the proportion of particles that are not cleaned off or trapped on the road. For example, storms and other precipitation events have been shown to induce a flushing effect, moving TWPs as road runoff and into receiving waters (Aryal et al., 2010). A UK study determined that 10-12% of the total pollution that enters receiving water is by highway runoff, a majority of which is TWPs and brake wear particles (Ellis and Mitchell, 2006). Various studies, using styrene-butadiene rubber, Zn, and benzothiazolamines, have found TWPs on the surface of the road, inside and outside tunnels, in the soil, 0, 8, 20, and 30 meters from the road, in snow, in road runoff, river water, wastewater effluents, sewage sludge, settling pond water, settling pond sediment, sediment, air, and plant milfoil (Saito, 1989) (Zeng et al., 2004) (Wik et al., 2008) (Fauser et al., 1999) (Fauser, 1999) (Ni et al., 2008). Compounds that are leached from TWPs are an important and potentially hazardous byproduct of TWPs dissemination into the environment. The predominant chemicals that are leached from TWPs are metals like Zn and additives like the halogenated cyanoalkanes, amines, phenols, calcium oxides, aromatic and aliphatic esters, mineral oils, and peptones (Yang et al., 2022).

Additionally, smaller TWPs contribute to the ambient ultrafine, PM2.5, and PM10 concentrations in the atmosphere. A 2019 study attributed 0.7% and 1.9% to the ambient PM2.5 and PM10 concentrations, respectively, while a separate, aforementioned study estimated that TWPs contribute 1-10% to airborne $PM_{2.5}$ concentrations (Panko et al., 2019).

An eloquent summary of these pathways into the environment is given by Kole et al. (2017), where the author illustrates two main courses for TWPs: transport by air and transport by runoff. While air emissions are more intuitive, transport by runoff is more involved. Rainwaters may flow directly into surface water, where they may ultimately reach the ocean and can accumulate in seafood and in sea salt. Additionally, runoff may reach wastewater treatment plants (WWTPs), where approximately 20% of particles larger than 20 µm reach the effluent streams and ultimately make it into surface waters (Magnusson & Wahlberg, 2014). A more involved description of these pathways is illustrated via flow diagram by Baensch-Baltruschat et al. (2021). Their discussion differentiates between urban roads, rural roads, and highways, and also places an emphasis on the TWP contribution to soils and the ecotoxicological consequences of this pathway. While non-airborne TWPs from rural roads and highways follow a similar route (runoff → runoff treatment plant → effluent → surface waters), urban roads TWP deposition results in a much more variable pathway, with multiple different mechanisms for entering surface waters as well as soil.

The age of the TMPs is another variable that impacts their fate in and effect on the environment. Wagner et al. (2022) reviewed this concept in terrestrial and freshwater ecosystems. While the paper primarily focuses on TWPs, RTC aging in the environment must also be considered. The authors describe how light and temperature are the initial aging mechanisms, and photooxidation, microbial degradation, mechanical stress, and leaching all result in continued aging that effects the physicochemical properties of TWPs. Biodegradation results in changes to the surface of the particles, increasing hydrophilicity and roughness. Mechanical stress can lead to the heteroaggregation of TWPs with other particles (through adhesion) or the breakdown of TWPs via weathering (Wagner et al., 2022).

5.2.2 Recycled Tire Crumb

The distribution of RTC is ubiquitous across the globe. Countries receive end-of-life tires from all parts of the world and convert them into RTC. Even though the EU has banned the placement of end-of-life tires in landfills, it is acceptable commonplace to grind them into RTC for global use.

Due to the outdoor nature of many of the facilities that use RTC (outdoor artificial sports fields, playgrounds, and on trails and walkways), it is exposed to the elements. Numerous studies have shown the diffusion of hazardous compounds present in crumb rubber into the air (Armada et al., 2021). Natural weathering and erosion processes disseminate RTC into the surrounding environment. As previously mentioned, outdoor artificial turf fields are a significant contributor to RTC in the environment. A significant percentage of RTC is released from these fields into the environment each year and must be replaced. This loss ends up in nearby soil and sewers, in the clothes of players etc. Many cities and related urban areas are located coastally, making the oceans a significant sink for RTC as it makes its way through the environment.

6. <u>Routes of Human Exposure</u>

The movement and distribution of polymeric NPs and MPs has been shown in mammalian systems and gives insights for how NPs and MPs distribute and what potential risks they may have in human bodies. The two routes of human exposure are through inhalation and ingestion. These routes will be discussed, and the mechanisms of uptake and translocation will be described briefly.

6.1 Inhalation

The most abundant exposure to TMPs occurs via inhalation of airborne particles. Compared to the GI tract, there is less available research on systemic absorption of NPs and MPs through the inhalation route of exposure. However, recent studies have demonstrated that there is a significant risk potential for airborne MP exposure, and MP fibers have recently been discovered in human lung biopsies, enforcing the need for additional research. (Cox et al., 2019). While a substantial portion of inhaled MPs end up in the gastrointestinal tract, the respiratory organs appear to be the main targets of the toxic effects of MPs and NPs (Lim et al., 2021). The alveolar surface area of the lungs is expansive, covering approximately 150 m^2. Fine PM, particularly particles smaller than 1 micrometer may breach the tissue barrier and permeate into the capillary blood system, and thus into systemic circulation. This uptake, however, is dependent on size, surface, and time (Thorley et al., 2014). For instance, charged surface moieties on particles may interact electrostatically with receptors on the cell membranes, increasing their uptake. Also, even at nano-sizes, the smaller a particle gets, the easier it can permeate due to the decreased energy required to uptake smaller particles and also due to the fact that smaller particles can diffuse passively through the membrane, whereas larger particles must rely on endocytosis alone (Thorley et al., 2014). Once taken up, it is more difficult, but possible for smaller particles to translocate through epithelial cells and reach systemic circulation.

6.2 Ingestion

No data are currently available on the potential for coarse TMPs to enter the human body via ingestion through the water supply or in the food chain. However, as elucidated in section 5.2.1, it is clear that TWPs reach the water supply and can be deposited into the soil. Additionally, RTC contributes significantly to the environmental burden of TMPs as described in section 5.2.2. Considering humans intake considerable MPs from sea salt, tap water, and shellfish, it is likely that TMPs contribute at least somewhat to the oral ingestion exposure route to MPs, which will therefore be elucidated here. The diffusion of particles through gastrointestinal mucus, to the enterocyte, and interaction with post-enterocyte cells is not only dependent on the physical characteristics of the particle but of the surface chemistry as well. For example, increasing hydrophobicity, anionic charge, and smaller size all increase a particle's capacity to translocate across the mucus barrier (Hussain, 2001). In a study where fluorescent polystyrene latex microparticles were orally administered to rats, qualitative and quantitative microscopy showed transmucosal uptake in all segments of the intestines primarily through villous tissue in and around the Peyer's patches as well as subsequent translocation of a fraction of the particles into mesenteric lymph nodes (Hodges et al., 1995). Peyer's patches are composed of a layer of M cells, under which lies the subepithelial dome, which contains macrophages and lymphocytes. This subepithelial dome acts as a cache for nonbiodegradable particles. A comparable rat study was done that showed only 10% of 60 nanometer polystyrene microparticles were recovered after oral administration. Furthermore, 60% of the absorbed polystyrene was taken up by the Peyer's patches, and a majority was in the large intestine (Hillery et al., 1994). A likely less important route of uptake for MPs in the gastrointestinal tract is through paracellular resorption, or persorption (Hussain, 2001).

7. <u>Human Health Impacts of Tire Microplastics</u>

7.1 Overview of the Human Health Impact of MPs

Overall, there is a large volume of research depicting the negative consequences MPs and NPs can have on mammalian systems. Animal studies have shown that pharyngeal aspiration of single-walled carbon nanotubes resulted in pulmonary inflammation resulting in fibrosis, granulomas, and functional respiratory deficiencies (Shvedova et al., 2005). In vitro and in vivo introduction of carbon nanoparticles showed that they accumulated in the cells' plasma membranes, resulting in increased alveolar macrophage number, activity, antigen presentation, and increased airway hyperresponsiveness (Ren and Huang, 2010). Long-term exposure to nanoparticles has been associated with serious damage to human lungs, including asthma, fibrosis, pneumothorax, and chronic bronchitis (Song et al., 2009). Polystyrene MPs increased the expression of TGF-b and TNF-a, fibrosis and inflammatory factors, compared to control groups (Lim et al., 2021). Furthermore, a study investigating the response of *Caenorhabditis elegans* to nanopolystyrene particles revealed that these particles decreased the encoding of insulin receptors (Shao et al., 2019). Polystyrene NPs have also been shown to negatively impact the innate immune system of fathead minnow (Greven et al., 2016). Additional studies have related the inflammatory responses/oxidative stress that MPs and NPs induce to developmental toxicity, neurotoxicity, and cytotoxicity (Lei et al., 2018) (Nobre et al., 2015). Not all of these adverse health effects may apply directly to TMPs due to their varying and complex chemical/physical characteristics, however, there have been numerous studies analyzing the health effects of TMPs or their constituent chemicals.

7.2 Effects of Differing Physical and Chemical TWP Characteristics on Health

7.2.1 Size

As described briefly in section 6.1, the size of a particle has a considerable effect on its uptake into cells and translocation throughout the body when inhaled, with smaller-sized particles resulting in increased uptake. While there are various sizes of TWPs, $PM_{2.5}$ and ultrafine particles result in the most well-known human health effects and will therefore be discussed more thoroughly. As discussed in section 4, there are numerous factors that contribute to the size of TWPs, with the following leading to more fine particle formation: micro-vibrations, stick-slip oscillations, increased degree of slip during cornering, fatigue wear as opposed to abrasive wear, increased silica filler content as it is currently implemented, higher graded treadwear due to the particular configuration of polymer and fillers, use of studded tires as opposed to friction tires, lower ambient temperature, increased humidity/water content, volatilization of organics, and increased speed of travel.

7.2.1.1 $PM_{2.5}$

There is a large body of research that indicates that particulate matter, particularly $PM_{2.5}$, has negative human health consequences, primarily through cardiovascular and chronic respiratory disease, and can additionally cause diabetes mellitus, birth defects, and other adverse health effects (Feng et al., 2016). PM_{10}, while less worrisome regarding adverse health outcomes, is associated with acute airway symptoms. TWPs contribute to the ambient $PM_{2.5}$ and PM_{10} concentrations. A review of $PM_{2.5}$ source attributions has determined that 25% of all $PM_{2.5}$ is from traffic-related sources (Karagulian et al., 2015). While a large proportion of this is from vehicle exhaust, many believe this proportion will shift towards non-exhaust sources as exhaust regulations change. The subsequent transition towards electric vehicles will add to the mass of vehicles, increasing the release of TWPs. While TWPs only contribute minimally to ambient urban particulate matter concentrations, the near-road $PM_{2.5}$ concentrations can increase by as much as 74% (Askariyeh et al., 2020).

Exposure to high levels of $PM_{2.5}$ has been linked to an increased risk for lung cancer and cardiovascular/respiratory morbidity and mortality. A 2015 study approximated that outdoor $PM_{2.5}$ contributed to 4.2 million deaths and 103.1 million disability-adjusted life-years (Cohen et al., 2017). Even at levels well below national guidelines, $PM_{2.5}$ has been shown to pose a risk to humans (Fann et al., 2011). Mechanistically, $PM_{2.5}$ exerts its toxic effects through intracellular oxidative stress, genotoxicity/cytotoxicity, metabolic activation, cellular viability, and inflammation (Feng et al., 2016). However, knowing the specific chemical/physical properties of specific $PM_{2.5}$ is important for determining its affinity for differing mechanisms of action, since the size, shape, surface chemistry, and composition can alter the interaction of the particles within biological systems. Unfortunately, the exact mechanisms and properties that make particles more or less toxic are poorly understood.

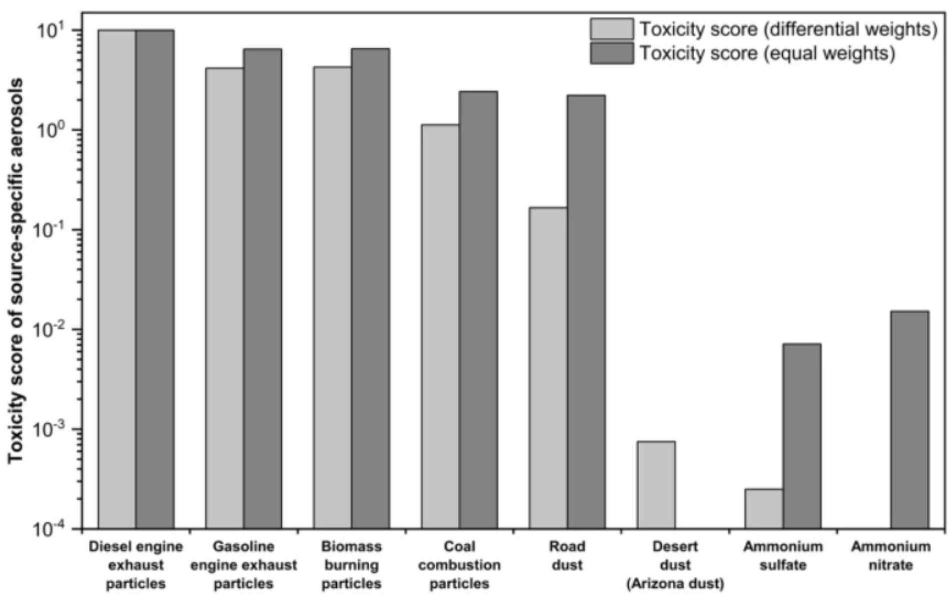

Figure 4: Toxicity scores for source-specific PM with differentially weighted endpoints and equally weighted endpoints.

Note. From "Differential toxicities of fine particulate matters from various sources," by M. Park et al., 2018, *Nature*, 8(1), p. 7 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6242998/).

A study by Park et al. (2018) studied the differential toxicities of $PM_{2.5}$ from different sources, as opposed to studying individual particles and chemical components (a virtually impossible task), by creating a weighted toxicity ranking system based on various biological and chemical endpoints including oxidative potential, cell viability, genotoxicity, oxidative stress, and inflammatory response. Taken from the study, figure 4 (Park et al., 2018, p. 7) shows that while road dust (of which TWPs are a major contributor) isn't quite as toxic as any of the $PM_{2.5}$ from combustion sources, it is significantly more toxic than any of the other non-combustion sources of $PM_{2.5}$. The authors found that $PM_{2.5}$ from the road dust samples primarily resulted in altered responses in oxidative potential, cell viability, oxidative stress, inflammatory response, and to a lesser extent genotoxicity caused by DNA damage. The chemical explanations for these particular endpoints will be elucidated in section 7.2.3. Due to the disproportionately high toxicity profile of TWPs in road dust as compared to other non-combustible $PM_{2.5}$, it is clear that traffic plays a critical role in enhancing the toxicity of fine particles (Park et al., 2018). It is not well understood how PM may accumulate in secondary organs and contribute to overall immune and cell health.

7.2.1.2 Ultrafine Particles

Since numerous studies have found ultrafine ($PM_{0.1}$) TWPs, the health effects of these particles must also be considered. Ultrafine particles cause even more pulmonary inflammation than $PM_{2.5}$ and are retained in the lungs for a longer period of time. The toxicity of ultrafine particles is associated with their physical/chemical properties. Overall, there is abundant literature on the health effects of ultrafine particles, with primary pathology occurring in the respiratory system, the cardiovascular system, and the central nervous system.

Ambient exposure to ultrafine particles has been associated with a cough, reduced peak expiratory flow, hospital admissions for people with asthma, increased clinical visits for respiratory disease, and increased pulmonary inflammatory markers. (Peters et al., 1997) (Klot et al., 2002) (Andersen et al., 2008). Mechanistically, ultrafine particles deposit in the centriacinar regions of the lungs where they may exacerbate asthma and COPD. Leikauf et al. (2020) summarize how ultrafine particles mediate their consequential pulmonary effects via induction of reactive oxygen species, the adaptive immune system, and the innate immune system.

Regarding cardiovascular disease, it appears that smaller particles produce worse disease states. Ultrafine particles promote and enhance early atherosclerosis due to their ability to synergize with proatherogenic mediators, leading to oxidative tissue damage. Additionally, ultrafine particles may lead to a reduction in the anti-inflammatory HDL function (Araujo et al., 2009).

Animal studies have shown that exposure to ultrafine particles has negative effects on the brain and its development. Due to their small size and subsequent ability to translocate, ultrafine particles may reach the brain within one day after inhalation (Schraufnagel, 2020). Specifically, a significant proportion of these particles may accumulate in the olfactory bulb, a pathway that avoids crossing the blood brain barrier (Oberdörster et al., 2004). In this way, ultrafine particles disrupt autonomic function, damage neural tissue, and increase sympathetic nervous system activity. Additional animal studies have shown a wide range of developmental effects of ultrafine particles, including learning, emotional behavior, function of neurotransmitters, motor activity, and performance (Kumar et al., 2013).

Furthermore, the hallmark amyloid plaque formations seen in Alzheimer's disease have been shown to be correlated with certain ultrafine particles. Specifically, particles with a copolymer structure (tire tread) and carbon nanotubules (found in tires as replacement for carbon black) are two main contributors to the nucleation of amyloid fibrils, allowing for their affinity to aggregate (Linse et al., 2007). Additionally, nano silica particles commonly produced from tire wear was found to be another potential contributor to Alzheimer's pathology. Mechanistically, nano silica are endocytosed by cells where they rapidly enter the nucleus. Similar to the aforementioned particles, the specific surface area of these particles allows for the fibrillation of amyloid proteins that later leads to the hallmark amyloid aggregates. (Hemmerich & von Mikecz, 2013) (Chen & von Mikecz, 2005).

7.2.1.3 Larger Particles

Larger, coarse particles are more likely to be ingested than fine particles, particularly $PM_{2.5}$ and ultrafine particles. To what extent TMPs reach the human GI tract is not well known, but it is likely that since both RTC and TWPs contribute to ambient environmental TMP concentrations, they are ingested to some degree. As mentioned previously, TMPs, as a form of MP, may be orally ingested by humans through drinking water, deposition onto food from the terrestrial ecosystem, sea salt, and consumption of aquatic organisms. The human health impact of MPs in general via this route is not well understood. However, it is probable that human health toxicity from TMPs via this route may be local or systemic. Systemic effects would be initiated by specific translocation mechanisms, as explained in section 6.2, however, they are not well understood at this time due to a lack of available research. It is likely that TMPs can cause acute inflammation in the intestinal lumen (Kole et al., 2017). Additionally, the leaching of toxic compounds locally into the intestinal lumen is also a concern. Potentially harmful leachates include PAHs, carbon black, and heavy metals.

TWPs measured in millimeters (up to approximately five) are on the larger end of MPs and have surface areas that are large enough to absorb surrounding pollutants. The potential for larger TWPs to absorb and serve as a reservoir for the bioaccumulation of organic pollutants is high (Mantecca et al., 2007).

7.2.2 Chemistry

Mechanistically, most studies are able to differentiate between the adverse physical effects that MPs and NPs have throughout biological systems and the toxicological effects from leachates, however for TMPs, particularly TWPs, it is difficult to make such distinctions due to the complex mixture of rubbers, chemicals, additives, road components, etc.

The type of road composition is an important factor when considering the toxic effects of resultant TWPs. Studded tire wear on paved road surfaces can induce inflammation in airways when inspired. However, the type of stone that is used in the pavement alters the level of inflammation (Gustafsson et al., 2008). Mylonite and gabbro had a far more pronounced inflammatory response (apoptosis and release of cytokines) in mice macrophages as compared to quartz, feldspar, basalt, hornfels, and syenite porphyry (Refsnes et al., 2006). Another study highlighted the difference in inflammatory effects in rats between a positive control sample of quartz with occluded surfaces as compared to quartz with fractured surfaces that were instilled intratracheally over 90 days. The occluded quartz resulted in a modest, transient inflammatory response while the fractured quartz resulted in a much more severe and persistent inflammatory response (Creutzenberg et al., 2008). Another study showed that regardless of road surface, TWPs induced the release of IL-6, IL-8, and TNF-α, but the intensity of response varied based on the type of road, with dense asphalt concrete containing granite having a more heightened response than stone mastic asphalt with quartzite (Gustafsson et al., 2008). A study by Grytting et al. (2021) demonstrated that respirable stone particles, like those found in fine TWPs, have differing cytotoxicity and pro-inflammatory effects on human airways using cell models. Specifically, the authors studied the effects of quartzite, anorthosite, rhomb porphyry, dacite, quartz diorite, and hornfels on HBEC3-KT (human bronchial) cells and THP-1 macrophages. While the pathophysiological mechanisms varied significantly, the quartzite, anorthosite, hornfels, and quartz were the most toxic. The authors suggest that the variability in effects is due to exact mineral compositions of each stone particle and related surface reactivity (Grytting et al., 2021).

The aforementioned toxicity endpoints of TWP $PM_{2.5}$ may be explained by the chemical constituents of the particles, as was described briefly. For instance, $PM_{2.5}$ from TWP in road dust may result in oxidative potential due to the presence of certain metals and PAHs. For example, the results from a study by Das et al. (2021) indicated Cd, Cu, Zn, and Pb in $PM_{2.5}$ were associated with inflammation as a result of increased cytokine production. A study by Crobeddu et al. (2017) correlated Cu, Zn, Sb, Pb, Fe, and Ni with oxidative potential in $PM_{2.5}$ samples as well as certain PAHs, including phenanthrene, anthracene, pyrene, indenopyrene, chrysene, and benzo(*a*)anthracene. As described in section 3.3, all of these metals and PAHs are commonly found encrusted in TWPs from various sources. Regarding oxidative stress as a result of reactive oxygen species (ROS), minerals encrusted within TWPs can induce the formation of ROS through multiple mechanisms, including binding to the cell surface, being engulfed by the cell, or by behaving as a carrier of metals and PAHs (Taira et al., 2020). Additionally, studies have shown that the presence of carbon (filler in tire tread), quinones (preservation additive in tread), and PAHs are associated with inflammatory responses and genetic toxicity (Liu et al., 2020).

6-PPD-quinone, mentioned in previous sections, has gained attention due to a recent study by Tian et al. (2020) that causally implicated the compound as the toxicant responsible for decades of acute deaths observed in coho salmon. 6-PPD-quinone has 38 known transformation products, and 32 of them were recently found in snow collected from urban roads (Seiwert et al., 2022). RTC, especially that from artificial turf fields, is another important source of 6-PPD and related compounds. It is unlikely that salmon are uniquely sensitive to the compound, and it is crucial that additional research is completed.

Leaching, which is also discussed in the following section (7.3), is an important, but scarcely understood mechanism for how many of the chemicals in TWPs exert their effect on the environment and subsequently humans. Multiple studies have shown that Zn in particular is a toxic leachate in water ecosystems (Gualtieri et al., 2005). Additionally, diphenylguanidine (used as a vulcanization agent), benzothiazoles (decomposition product), caprolactam (decomposition product), 2-mercaptobenzothiazole (vulcanization accelerator), 4-hydroxydiphenylamine (decomposition product), tributylamine (an impurity), dibenzylamine (vulcanization activator), N,N'-diphenyluria (vulcanization retarder), N,N'-dicyclohexyluria, and dimethylbutyl (antioxidant) were unequivocally identified leachables with a reference standard as determined by Müller et al. (2022). In the study, the authors also found 150+ other chemicals with lesser degrees of identification, although all had at the least an exact mass and isotopologue match to the reference list that they used. Benzothiazole and diphenylguanidine are considered toxic substances. The differentiation and secrecy of chemical formulations and additives of tire tread amongst different tire manufacturers leads to a lot of uncertainty about leachates and the potential for toxicity.

Regarding carbon black, a 2016 study by Ema et al. studied the reproductive and developmental toxicity of carbon black while Chaudhuri et al. (2018) analyzed its genotoxic effects. Carbon nanotubes, which are increasingly used in tires, have been shown to be embryolethal and teratogenic in mice, cause embryonic death and growth retardation in chickens, cause death and developmental arrest in zebrafish, and result in other genotoxic and developmental abnormalities in other animal studies (Ema et al., 2015).

7.3 Effects of RTC on Health

RTC that has been distributed into the environment may also have an impact on human health, with many overlapping potential health consequences with TWPs that was described previously. Primarily, RTC contributes to the global environmental burden of microplastics and as such may contribute to human health effects through established mechanisms in the water supplies and in the ambient environment. While there is a significant lack of human health studies on RTC, there is sufficient animal studies, particularly aquatic studies, that may be extrapolated to determine potential risk. Chemical additives in RTC have been shown to leach out in marine ecosystems and have detrimental effects on different aquatic species. Specifically, heavy metals, PAHs, aniline, and benzothiazole all leach from RTC to create a potent chemical cocktail (Halsband et al., 2020) (Halle et al., 2020). Additionally, if ingested, RTC has been established to have a longer gut retention time than other MPs, indicating a higher potential for harm in the ingestion pathway (Halle et al., 2020). In other aquatic species, not only leachates but the particles themselves caused acute mortality (Khan et al., 2019).

8. <u>Discussion and Conclusion</u>

8.1 Current Gaps in Research

A particularly large challenge that currently faces TMP research is the lack of harmony and standardization within the field. Analytically, there is a lack of reliable and representative chemical analysis methods. In the field, there isn't agreement upon tracer/marker compounds to reliably measure the distribution of TWPs within the environment. Another challenge that hinders analysis is the broad size ranges, shapes, and chemical compositions that TMPs can have (Ivleva, 2021). Not surprisingly, there is a lack of toxicity studies on TMPs and how their varying physicochemical properties may play a role in various diseases that are ubiquitous today.

A lack of standardization of tires and openness from tire manufacturers about exact chemical constituents of tread is a major factor leading to chemical diversity and morphological differences in TWPs. Additionally, among 192 countries across the globe, only 29% (44) have conducted research on MPs, limiting the scientific community's knowledge (Ajith et al., 2020). Additionally, there is limited research on the human health effects of TMPs, particularly through the oral ingestion route and through ultrafine particle inhalation exposure. Future research must consider the cumulative, exposomal conditions in order to understand the real-world risks of TMP exposure, and how these risks vary by region. Additionally, future health research must consider cofactors that may exacerbate TMP health effects, including, but not limited to smoking, drinking, and pre-existing conditions. Personal traits must also be considered in these evaluations, including age, sex, and race. Finally, future research must identify how the changing climate will affect the distribution, degradation, and exposure of TMPs to humans. There also lacks sufficient monitoring and field studies that investigate environmental concentrations of TMPs and how they degrade under various environmental conditions. Furthermore, there lacks modeling studies that estimate and predict the distribution, modes of transport, degradation, and retention of TMPs in the environment.

8.2 Recommendations for Future Solutions

In order to move forward, harmony and standardization need to be prioritized, particularly in regard to quantifying TWP pathways and the associated risks. Additionally, innovations to tire tread and RTC need to be expounded upon to reduce the release of TMPs into the environment and to reduce their potential for toxicity. Importantly, a more ideal and universal TWP tracer needs to be accepted in order to quantify the amount of TWP throughout the environment and better understand how they distribute so as to recognize differing routes of human exposure. Additionally, there needs to be more advanced ways in measuring real-world human exposure to TMPs in order to better assess the effects they may be having on human health.

While there still lacks specific clarity on the human health effects of TMPs, actions to mitigate potential effects should be taken out of an abundance of caution, including:

- Installation of state-of-the-art stormwater treatment systems and upgrades to existing ones.
- Improvement of runoff water treatment systems, particularly on highly trafficked roads and highways, or ones with significant stop-and-go traffic potential.
- Proper disposal of sewage containing road runoff materials.

- Increase in road maintenance.
- Optimization of road surfaces, particularly those with a higher incidence of TWP production in favor of surfaces like open-asphalt concrete, which have a reducing effect.
- Reduction in the use of studded winter tires.
- Innovation in the microstructure of tires, including an innovative two-step method for combined SBR with modified silica created by Li et al. (2013) and the reduction of friction and wear rate of Acrylo Nitrile Butadiene rubber (NBR) as imagined by Agrawal et al. (2016).
- Minimizing carcass stiffness in tires and combining that with maximum lateral flectional resistance of the tread in order to reduce the potential and degree of slide-slipping.
- Promotion of lightweight vehicles.
- Reduction in speed limits.
- Re-evaluation of stop signs and traffic lights to create conditions with less stop-and-go traffic.
- Optimization of automotive tires in regard to greater wear resistance while considering durability and safety.
- Creating legislative controls for traffic related non-exhaust emissions, which currently do not exist.
- Creating legislative controls for the currently ubiquitous use of RTC, particularly in external settings.
- Spreading awareness regarding driving behavior and the production and distribution of TWPs.
- Incentives for avoiding automotive transportation in favor of other methods of travel

- Incentives for self-driving cars, which can be programmed to drive in ways that reduce the wear and tear of tires.
- Reductions in the use of old tires, including recreational artificial turf, artificial reefs, and coastal protection barriers, and replacing these with suitable alternatives like cork. Increased initiatives for what to do with the everlasting influx of end-of-life tires.
- Discovering pro-ecological waste tire recycling methods, including low-temperature extrusion as specified by Wisniewska et al. (2022).

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Competencies Addressed:

Foundational Competency (1):

MPHF4: Interpret results of data analysis for public health research, policy or practice.

The purpose of this project is to create a comprehensive literature review on the diversity of tire microplastics and their varying effects on human health. Additionally, background information regarding microplastics, tire manufacturing, differing sources of tire microplastics, and the distribution of tire microplastics will be included to help the reader better understand the more pertinent information. To do so, mainly quantitative data from recent, relevant, peer-reviewed studies and papers will be pooled, interpreted, and discussed. The interpretation of these global, diverse studies will serve to give a better understanding of this complex topic that is growing in magnitude and recognition.

Concentration Competencies (3):

EOHMPH1: Analyze sources of exposure in the workplace and the environment that can cause health risks to humans or degradation of ecosystems.

The sources and distribution of tire microplastics in the environment are crucial components of this literature review. In tandem with considering the degree of human health effects that tire microplastics have, it is important to understand every aspect of how, when, where, and how much of these plastics enter into the ecosystem and in what ways they can reach humans. While tire wear particles represent the main source of tire microplastics, recycled tire crumb is also discussed in this review. Additionally, there are many factors affecting the sources and distributions of tire microplastics, particularly tire wear particles, that are analyzed in detail.

EOHMPH2: Examine exposures and pathways for environmental and occupational agents associated with human injuries and diseases.

In addition to the sources and distribution of tire microplastics, the potential routes of exposure will also be analyzed and discussed in this literature review. As tire microplastics distribute, they reach humans in various ways. This review examines how the physicochemistry of tire microplastics affects this distribution, what all distribution routes intersect with humans, how tire microplastics may be exposed into the human body, and what mechanisms are at play when determining the systemic distribution throughout the human body.

EOHMPH3: Compare and contrast specific symptoms and health outcomes associated with occupational and environmental exposures.

One of the main objectives of this literature review is compiling and examining the peer-reviewed literature on the toxicity of various tire microplastics. Due to the variety of tire microplastics and the various physical and chemical properties that they can have, this review focuses on how exactly tire microplastics exert their toxic effect and how differing physical and chemical properties can change their toxicity and mechanisms of action within biological systems, particularly focusing on human studies.

EOHMPH8: Examine information sources and public health indicators in occupational and environmental health.

An important competency for all literature review writing is the ability to examine information sources for relevant information. In this review, these information sources are primarily databases and relevant scientific journals. By completing comprehensive searches of these information sources, data for this review was compiled to get a clear picture of tire microplastics and their distribution through the environment and effects on human health.

Curriculum vitae (CV):

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Summary

An intelligent and assimilative graduate student with great people skills who is pursuing an opportunity to gain experience, learn, grow and improve the well-being of humanity and the environment.

Education

Texas A&M University
College Station, TX, 2015-2019
B.S. in Biomedical Science
Minor: Atmospheric Science
GPA: 3.7/4.0
Dean's List Fall 2015, Spring 2016
Sons of Norway Scholarship Recipient: 2016-2017
Rockwall Republican Men's Club Scholarship Selection (2x): 2015
Rockwall County A&M Club Scholarship Recipient: 2015-2017

University of Nebraska Medical Center
Omaha, NE, 2020-present
Master's in Environmental and Occupational Public Health
Current GPA: 3.8/4.0
Simmons Scholarship Recipient (4x): 2020-2021

Experience

Applied Practice Experience: Dallas Independent School District Environmental Health and Safety Department
Completed activities, projects, and job shadowing regarding asbestos policy, indoor air quality assessments, water quality testing, and project management
May 2022-August 2022

Study Abroad: Germany and Austria
Studied and received hands on atmospheric science experience, specifically regarding climate change, meteorology, outdoor air pollution monitoring, and environmental policy
May 2019-June 2019

Medical Shadowing: Baylor University Medical Center and Grace Clinic Rockwall
Shadowed in transplant surgery, radiology, interventional radiology, cardiology, and the clinic
December 2016- August 2017

Key Skills

MATLAB
IBM SPSS
Certified in Quality Improvement
Reliable
Fast Learner

Paid Employment

June 2019-May 2020
H-E-B-College Station, TX
Customer Service Associate.
May 2015-July 2017
Culver's - Rockwall, TX
Team trainer
Special Achievements: Newcomer of the Year (2015)