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Review

Where the rubber meets the road: Emerging environmental impacts of tire wear particles and their chemical cocktails

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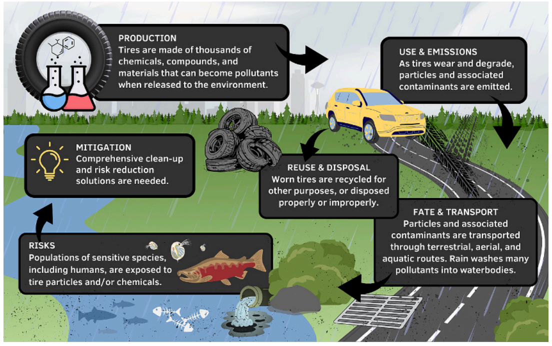
HIGHLIGHTS

- Billions of tires are produced each year and hundreds of millions of tires become waste.
- Tires are a complex source of pollutants including whole tires, particles, compounds, and chemicals.
- As they wear, tires emit pollutants *via* atmospheric, aquatic, and terrestrial pathways.
- Tire wear pollutants represent an environmental and human health risk.
- Comprehensive clean-up solutions are needed to reduce the risk of tire wear pollutants.

GRAPHICAL ABSTRACT



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ABSTRACT

About 3 billion new tires are produced each year and about 800 million tires become waste annually. Global dependence upon tires produced from natural rubber and petroleum-based compounds represents a persistent and complex environmental problem with only partial and often-times, ineffective solutions. Tire emissions may be in the form of whole tires, tire particles, and chemical compounds, each of which is transported through various atmospheric, terrestrial, and aquatic routes in the natural and built environments. Production and use of tires generates multiple heavy metals, plastics, PAH's, and other compounds that can be toxic alone or as chemical cocktails. Used tires require storage space, are energy intensive to recycle, and generally have few post-wear uses that are not also potential sources of pollutants (*e.g.*, crumb rubber, pavements, burning). Tire particles emitted during use are a major component of microplastics in urban runoff and a source of unique and highly potent toxic substances. Thus, tires represent a ubiquitous and complex pollutant that requires a comprehensive examination to develop effective management and remediation. We approach the issue of tire pollution holistically by examining the life cycle of tires across production, emissions, recycling, and disposal. In this paper, we synthesize recent research and data about the environmental and human health risks associated with the production, use, and disposal of tires and discuss gaps in our knowledge about fate and transport, as well as the toxicology of tire particles and chemical leachates. We examine potential management and remediation approaches for addressing exposure risks across the life cycle of tires. We consider tires as pollutants across three levels: tires in their whole state, as particulates, and as a mixture of chemical cocktails. Finally, we discuss information gaps in our understanding of tires as a pollutant and outline key questions to improve our knowledge and ability to manage and remediate tire pollution.

1. Introduction

Global dependence on tires produced from petroleum-based compounds, synthetic materials, heavy metals, and added chemicals, represents a persistent and complex environmental problem with only partial, and often-times ineffective, solutions. Used tires require storage space, are energy intensive to recycle, and end-of-life uses for tires (*e.g.*, crumb rubber, pavements, combusted tires) generally continue to release pollutants as particles or leached chemicals, or both. Tires are a significant source of highly mobile, persistent microplastics (Moran et al., 2021; Brander et al., 2021) that are a major component of pollutants in urban stormwater runoff (Wik and Dave, 2009). Furthermore, recent research has demonstrated that tires are a source of previously unrecognized chemicals, some are highly toxic to aquatic organisms, and many of which are currently unknown or poorly described (Tian et al., 2021a; Siddiqui et al., 2022; Cunningham et al., 2022). Production and use of tires generate a suite of heavy metals and other contaminants that can be toxic alone or as chemical cocktails, which represent combinations of elements novel to the Anthropocene (*sensu* Kaushal et al., 2020). Given that roads are ubiquitous in developed nations (Ibisch et al., 2016), cover extensive areas in urban ecosystems (Elmore and Kaushal, 2008), and that road construction and traffic are increasing worldwide (Meijer et al., 2018), the impacts of tires are vast and are expected to increase globally. Roads can represent hot spots of tire pollutants and effective pathways of pollutants to aquatic, terrestrial, atmospheric, and groundwater resources (Cooper et al., 2014; Sommer et al., 2018; Uliasz-Misiak et al., 2022).

Here we synthesize recent research and data about the environmental and human health risks associated with tire production, use, and disposal. We discuss gaps in our knowledge about fate and transport, as well as the toxicology of tire particles and leachates. We examine potential management and remediation approaches for addressing exposure risks across the life cycle of tires and associated contaminants. We consider tires as pollutants across three levels: whole tires, tire wear particles, and as a mixture of chemical constituents. Finally, we outline key questions to expand our knowledge and ability to manage and remediate pollution from tires.

2. The composition of tires

Tires are constructed of multiple, highly engineered components, including tread, belts, inner liners, and sidewall, each designed to meet performance characteristics that together create durable, strong, reliable, and safe tires (USTMA, 2018) which are the same properties that ensure the persistence of tire particles and tire materials in the environment. Tires contain myriad materials and chemicals, many of which are proprietary (Tian et al., 2021b). Tires typically use metal mesh or textiles for structure and rubber for all other components. Tire rubber consists of complex proprietary formulations that vary among brands, tire types, and tire components (Hüffer et al., 2019; Kreider et al., 2010; Selbes et al., 2015; Wagner et al., 2018; Chibwe et al., 2022). In general, tire rubber consists of synthetic and/or natural rubber (40–60 %), fillers and reinforcing agents like carbon black and silica (20–25 %), process or extender oils (12–15 %), vulcanization agents like Zn and thiazoles (1–2 %), and other additives such as preservatives and processing aids (5–10 %) (Wagner et al., 2018). Tires contain approximately 50:50 ratio of natural to synthetic rubber; passenger car tires contain more synthetic rubber, while truck tires more natural rubber, and heavy-duty vehicles tires contain little or no synthetic rubber (Grammelis et al., 2021). Tires contain thousands of chemicals, including those deliberately added, such as N-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine (6PPD, DTXSID9025114; CAS 793–24-8), contaminants in manufacturing feedstocks, such as polycyclic aromatic hydrocarbons (PAHs), and weathering or transformation products as tires age (Tian et al., 2021b; European Tyre and Rubber Manufacturer's Association, 2021; Kovochich et al., 2021). As a result, there is no standard chemical composition of tire wear particles. This creates challenges for monitoring and characterizing tire particles and tire-derived chemicals in environmental samples, for estimating tire microplastics fate, and for conducting ecotoxicology impact assessments. Determining the complete and quantitative chemical composition of tire rubber remains a critical research need.

3. Environmental and health impacts along the life cycle of tires

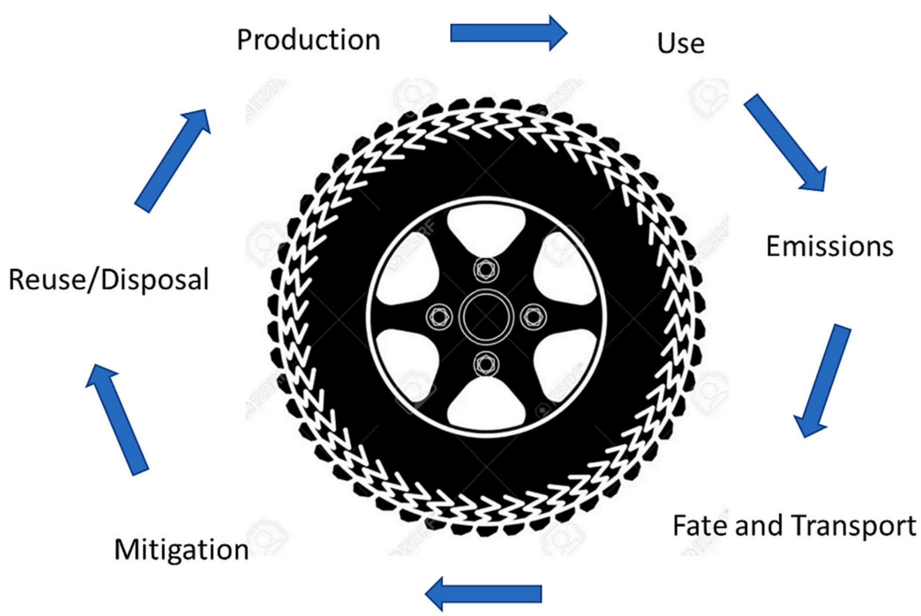
The life cycle of a tire can be characterized by stages including a) raw materials and production of the whole tire, b) transportation of the tire to a destination, c) use on a vehicle, and d) end of life management through downcycling into non-tire products or disposal (Dong et al., 2021; Trudsø et al., 2022). Here, we examine these stages as a continuum along the life cycle of a tire (Fig. 1) where tires and their components are produced and used. In the process, energy and resources are consumed while particles and elements are emitted and transported through the environment across various pathways (Trudsø et al., 2022). At points along those pathways, there are potential mitigation approaches to reduce environmental impacts including reuse or disposal, and, in some cases, recycling into new tires and tire related products. Manufacturing tires requires copious water and electricity and produces nitrogen oxides (NOx), benzene, and PAHs (Dong et al., 2021). Each tire life cycle stage has multiple impacts on climate and acidification from energy use and production of CO_2, ozone depletion, photochemical oxidation, and eutrophication from NOx production and use of PO_4^{3-} in manufacturing (Dong et al., 2021; Sun et al., 2016).

3.1. *Environmental and health impacts from the production of tires*

Global demand for automobile tires is large and growing. In 2019 alone, 3 billion tires were produced globally (Ruwona et al., 2019; Dong et al., 2021), an amount that, if stacked on top of one another, would reach *ca.* 675,000 km, nearly twice the distance to the moon. Recent tire production in the EU is about 335 million annually (Torretta et al., 2015), while tire production was about 300 million in the US (USTM, 2022) and about 800 million in China (Dong et al., 2021). Tire production begins with acquisition of natural rubber for the tread, textiles and steel for the cord and belts, and chemicals such as carbon black, silicon dioxide, and clay (Dong et al., 2021). A significant environmental impact of tire production is from the cultivation of natural rubber which involves clearing native, diverse forests for growing monocultures of rubber trees. This type of agriculture is an especially important cause of deforestation in Asia and Africa (Pendrill et al., 2022). High resolution maps of southeast Asia show that rubber tree cultivation accounted for at least 4 million ha of deforestation since 1993, 2 million ha of which was lost since 2000, including 1 million ha of rubber plantations that have been established in high biodiversity areas (Wang et al., 2023).

Combining tire components during production emits carcinogens and radioactive compounds (*e.g.* radon-222 and carbon-14), contributes to stratospheric ozone depletion, and requires massive consumption of water and electricity, and land in the form of extraction of minerals and fossil fuels, and water (Piotrowska et al., 2019). Combined, the various chemical components and the particles create chemical cocktails (*sensu* Kaushal et al., 2018, Kaushal et al., 2020, Kaushal et al., 2022) of heavy metals (*e.g.*, Zn), natural and synthetic rubber and plastics, hydrocarbons (*e.g.*, PAHs), and traces of other chemicals (*e.g.*, 6PPD) that can have negative effects on human health and the environment.

Manufacturing a single tire produces an estimated 243 g particulate matter to the air, 0.19 g NH_4^+ and 0.69 g suspended solids to the water (Sun et al., 2016). On average, 6 MJ of electrical energy, 45 L of water, and 0.02 kg of dissolvent are needed to manufacture one tire while



yielding 0.5 kg of waste (Piotrowska et al., 2019). Extrapolating from an estimated 3 billion tires produced annually, tire manufacture may produce as much as 729 million kg particulate matter, 570,000 kg NH_4^+, and over 2 million kg suspended solids annually, while as much as 104 billion MJ energy may be consumed along with over 70 billion liters of water though, water and energy consumption could be reduced through existing technologies, including high-pressure steam to shorten vulcanization time and recovery of waste steam (Sun et al., 2016). Using the Intergovernmental Panel on Climate Change (IPCC) methodology, each tire requires over 333,000 kg CO2 Eq during production while 2116 kg of CO2 Eq are recovered by recycling a tire (Piotrowska et al., 2019). Some tire manufacturers are striving to reduce their factory carbon footprint and/or exploring new tire designs with longer lifespan or which could be retread like industrial tires, thereby saving significantly on the amounts of materials required for production (https://www.motortrend.com/features/future-tire-technology/?id=applenews).

3.2. Environmental and health impacts from the use of tires

Significant ecosystem impacts are from tire emissions of carbon dioxide and sulfur oxides or nitrogen oxides, which are greatest during the use stage of the life cycle and a function of fuel use of the vehicle (Piotrowska et al., 2019). Tire wear during use results in tire wear particle emissions into the environment. Vehicle tire wear produces an estimated 1.2–6.7 kg of particles, or about 10–16 % of the weight of the tire, over the lifetime of the tire (Sun et al., 2016; USTMA, 2021). Tire wear and evolution of tire wear products may be exacerbated by the heavier weight and increased acceleration and torque produced by EVs (Zhao et al., 2019). Tire microplastics from synthetic rubber tires are a major contributor of microplastic pollution to the environment (Kole et al., 2017; Sieber et al., 2020; Siegfried et al., 2017). Measurable and sometimes significant amounts of tire particles have been collected in air, aquatic environments, and organisms (Baensch-Baltruschat et al., 2020; Leads and Weinstein, 2019; Siegfried et al., 2017; Tian et al., 2017; Werbowski et al., 2021; Wik and Dave, 2009). For example, untreated stormwater runoff samples collected from San Francisco Bay watersheds contained up to 15.9 tire particles/L, almost 50 % of all microparticles in these samples (Sutton et al., 2019; Werbowski et al., 2021). Globally, tires may be one of the top sources of microplastics to the environment (Boucher and Friot, 2017; Kole et al., 2017; Sieber et al., 2020), with a pollutant mass exceeding the total environmental emissions of other pollutant classes like pharmaceuticals and pesticides (Wagner et al., 2018).

Tire emissions generally relate to vehicle weight, tire size, and distance traveled, with larger heavier vehicles (trucks) emitting more than small light ones. Higher traffic speeds result in increased generation of tire particles (Wang, 2017; Pohrt, 2019; Kwak et al., 2013; Foitzik et al., 2018). Particle generation from any specific vehicle or in specific roadway segments can vary depending on driving speed or style (*e.g.*, urban stop/go *vs.* highway), road surface condition, type of contact (rolling *vs.* slipping) and temperature (Alexandrova et al., 2007; Knight et al., 2020; Kole et al., 2017). Based on relatively limited data, country-specific tire particle generation across size classes 10 nm to 1000 μm has been estimated to be as low as 0.23 kg/yr/capita in India to as high as 5.5 kg/yr/capita in the US due to its longer per-capita annual vehicle travel distances (Mennekes and Nowack, 2022; Baensch-Baltruschat et al., 2020; Councell et al., 2004; Wagner et al., 2018; Kole et al., 2017). Thus, approximately 1.7 million tons of tire wear particles are produced annually in the US based on 2021 population size. Where automobile and truck traffic are higher, production of particles may be significantly greater. Based on empirical and extrapolated data synthesized from Europe, Japan, China, Australia, Brazil, India, and USA annual global tire wear emissions, across size classes 10 nm −1000 μm, were estimated to be nearly 6 million tons (Baensch-Baltruschat et al., 2020).

Annually, about 800 million tires become waste material worldwide million tires (USTMA, 2020). The global annual production of waste tires is estimated to reach 1.2 billion tons by the 2030s (Liu et al., 2020). Others estimate that, globally, 1.5 billion tires are discarded annually currently with an expected to increase to 5 billion tires by 2030 (Grammelis et al., 2021). Generally, waste tires remain in the region of their production. For example, only 3.1 % and 5.7 % of waste tires are exported from the US (USTMA, 2020) and the EU (Sienkiewicz et al., 2012), respectively. Waste tires are often recycled into various products, including outdoor products with high potential to disperse tire particles or tire-derived chemicals into the environment (Dabic-Miletic et al., 2021). For example, the majority of waste tire use in California, USA includes burning for fuel, crumb rubber production, and integration in civil engineering applications (Table 1). Worldwide, the fate of tires is similar with most going into energy production or recycled (Table 2). Tires are often downcycled into microplastic-containing products like tire crumb and tire buffings. Used tire processors separate tire rubber from tire structural components (*e.g.*, steel belts) to produce various sized tire rubber pieces (Valente and Sibai, 2019) classified as buffings, ground, crumb, or aggregate, some of which contain or are entirely composed of microplastics. Products created from used tires include retreaded tires, tire-derived fuel, artificial turf infill, rubberized asphalt, shock absorption applications, landscaping mulch, playground and recreational areas, rubber-containing pavement seal coats, rubberized building and floor materials, railroad ties, and doormats (Dabic-Miletic et al., 2021). There are 12,000–13,000 synthetic turf fields in the US with 1200–1500 new installations annually (USEPA, 2019). Wear of turf fields, tracks, and other recreational areas where recycled tire crumb rubber is used can release tire microplastics into the environment (Wang et al., 2021).

4. Fate and transport

4.1. Cycling of tire particles in the environment

Studies of the fate and transport of tire microplastics and associated contaminants has been limited. A handful of studies have helped to characterize tire microplastics and affiliated leachate in the environment associated with urban runoff (Werbowski et al., 2021; Johannessen et al., 2021; Klöckner et al., 2020; Klöckner et al., 2021; Peter et al., 2018; Peter et al., 2020; Tian et al., 2021b). Data from Europe show that most of the mass of tire microplastics is deposited near roadsides, but that water and atmospheric pathways can move particles significantly farther (Baensch-Baltruschat et al., 2021; Evangeliou et al., 2020; Sieber et al., 2020; Sommer et al., 2018; Verschoor et al., 2016). Moran et al. (2021) conceptualized the sources and pathways of rubber particles to urban stormwater (Fig. 2).

Table 1
California waste tire use summary 2018*. Source: CalRecycle, 2019. *Includes material imported from out of state. Reprinted from Moran et al. (2021).

Use	Examples	Quantity (Metric Tons)
Combustion (export)	Burned at non-California facilities	130,000
Combustion	"Tire-derived fuel" burned at four California facilities	82,000
Landfill	Disposal, alternative daily cover	98,000
Reuse on vehicles	Used tires and retreads	82,000
Crumb/ground rubber	Rubberized asphalt pavement (60–67 %) Artificial turf infill (11–14 %) Mulch and ground covers (3–5 %) Molded & extruded products (19–20 %)	81,000
Civil engineering applications	Landfill structures, construction fill, vibration damping, and stormwater capture and treatment systems	4600
Other recycling	Unspecified	3100

Table 2
Fate of End of Life (Scrap) Tires in the United States and Europe in 2019. 76 % of scrap tires in the US are utilized in some fashion (not disposed of) and 95 % in the EU27 + NO+CH + RS + TR + UK. Sources: [1]USTMA 2019. U.S. Scrap Tire Management Summary. U.S. Tire Manufacturer Association. Washington, D.C. 20005. [2] European Tyre and Rubber Manufacturing Association (ETRMA). Press Release: In Europe 95 % of all End of Life Tyres were collected and treated in 2019. https://www.etrma.org/news/in-europe-94-of-all-end-of-life-tyres-were-collected-and-treated-in-2019/

Disposition (thousands of metric tons)	United States[1]	Europe[2] EU27 + NO+CH + RS + TR + UK	Notes
Civil Engineering and Similar Uses	333.20 (8.2 %)	112.95 (3.2 %)	USA: includes Steel, Reclamation Projects, Agricultural, Baled Tires to Market and Punched Stamped. EU: includes public works and backfilling
Recycling	987.92 (24.4 %)	1841.20 (51.8 %)	USTMA does not use Recycling category. Ground Rubber included in total here. For EU, includes granulation and additions to cement manufacturing.
Energy Production	1493.98 (36.9 %)	1428.82 (40.2 %)	EU: Cement kilns 75 % and 25 % Urban Heating and power plants
Exported	125.19 (3.1 %)		
Other	119.64 (3.0 %)		
Land disposed	616.89 (15.2 %)		
Unknown/stocks	372.84 (9.2 %)	165.16 (4.6 %)	
Total	4049.67	3555.61	Totals are from Source Tables

Abrasion by pavement during vehicle use creates small tire wear particles. After their initial release to the air, tire wear particles may travel short (1–10 m) to long (km) distances prior to deposition, often promoted by localized effects of high-speed traffic. Roadway-derived particles (including tires) may compose >80 % of all microplastic air deposition, (Brahney et al., 2021). Notably, inhalation of atmospheric particulate matter is a critically important mechanism of human exposure to tire rubber microplastics and tire-derived chemicals. Recent studies documented substantial contributions of tire rubbers and associated chemicals to atmospheric particulate matter phases and associated human exposure risks *via* inhalation (Cao et al., 2022; Johannessen et al., 2022a; Zhang et al., 2021; Zhang et al., 2022).

Particles, especially those deposited on pavements, may be resuspended, redistributed, or modified by vehicle traffic and environmental conditions. Vehicle tire abrasion grinds tire wear particles into pavement debris and soil, reducing particle size, encrusting particles with other road debris, and modifying particle shape (Kreider et al., 2010; Park et al., 2018) and chemical composition. Particles may also release tire related chemicals, including additive chemicals and their industrial and environmental transformation products, into air and water phases, or within biota that ingest particles (Peter et al., 2020; Tian et al., 2021b; Wagner et al., 2018).

For understanding particle transport, tire particles can be divided into three groups based on diameter: coarse (>2.5 μm), fine (<2.5 μm and > 0.1 μm), and ultrafine (<0.1 μm) (Wagner et al., 2018). Particle size governs transport distance, with fine and ultrafine particles most subject to long-distance aerial transport, depositing far from their sources (*e.g.*, the Arctic, mountain wilderness) (Brahney et al., 2021; Evangeliou et al., 2020; Thornton Hampton et al., 2022; Wagner et al., 2018). Larger particles >10 μm typically deposit close to the point of emission (Cadle and Williams, 1978; Fauser et al., 2002; Kreider et al., 2010; Wagner et al., 2018). Available particle size distribution data indicate that most tire wear particle volume (and therefore mass) is in the coarse fraction (particles >50 μm), which deposit quickly from the source, landing on or close to pavements. While no studies show the full range of particle sizes, most tire wear particles are fine and ultrafine (Alves et al., 2020; Cadle and Williams, 1978; Fauser et al., 2002; Kreider et al., 2010). The smaller coarse and larger fine particles (between 1 μm and 10 μm), can be entrained into the atmosphere through mechanical processes, such as from the intense turbulence generated by high speed vehicle traffic (Brahney et al., 2021) and have atmospheric residence times of 8 days (<10 μm; "PM10") to 28 days (<2.5 μm; "PM2.5") (Evangeliou et al., 2020).

Fine (<10 μm) and ultrafine (<2.5 μm) tire particles comprise only a small fraction of the total mass of tire wear particles. However, they compose a large fraction of the total number of emitted particles, and their surface area might make them important vectors for tire chemical transport beyond the immediate roadside area. This is particularly true for smaller organisms and/or sensitive life stages. Due to limited data addressing tire particles across the full particle size distribution and the lack of surface area measurements for each size fraction, the role and importance of air deposition in tire particle and chemical transport within and between watersheds remains largely unknown (Moran et al., 2021).

Ultimately, tire wear particles are incorporated into soils and surfaces, washed off outdoor surfaces with runoff (Field et al., 2000; American Society of Civil Engineers, 1998), or washed out of the air by rainfall or snow. Particle wash-off from impervious surfaces (*e.g.*, streets, sidewalks, roofs) is far more efficient than from permeable surfaces (*e.g.*, lawns, gardens, agricultural fields) (Field et al., 2000; Pitt et al., 2008). Estimates of the portion of tire wear debris that is washed off of urban outdoor surfaces into urban runoff are highly variable and likely a function of many system and condition specific variables; *e.g.*, 15–50 %, Wagner et al., 2018; 35 %, Blok, 2005; 80 %, Kennedy et al., 2002).

Modern urban and roadway drainage systems direct stormwater runoff directly (or indirectly *via* storm drains), untreated, into local water bodies. While tire particles may be temporarily retained in low points in stormwater collection systems under low flow conditions due to their density, turbulent flows during larger storm events will likely mobilize these particles and carry them into surface waters (Hoellein et al., 2019).

Tire particles may be washed by stormwater runoff into wastewater treatment systems. There are no current data on fate or volumes of tire particles specifically in wastewater treatment plants; however, data suggest that a high percentage of other microplastic particles transfer from the water into sewage sludge (Baensch-Baltruschat et al., 2021). Even with high removal rates, significant annual loadings of tire and road wear particles have been estimated in treated wastewater effluent in the UK (Parker-Jurd et al., 2021). Sewage sludge is typically incinerated, disposed of in landfills or spread on agricultural fields (Duis and Coors, 2016) where tire particles may remain in the soil or be mobilized and distributed by wind or by surface runoff to the aquatic environment (Duis and Coors, 2016; Baensch-Baltruschat et al., 2021).

Air transport and runoff may carry tire particles and associated chemicals into surface water drinking water sources (Johannessen and Metcalfe, 2022; Zhang et al., 2023). Drinking water treatment plants draw water from surface water, groundwater, and/or seawater, all of which may contain microplastics including tire particles (Collivignarelli et al., 2018). Drinking water treatment typically starts with screening and grit removal, followed by addition of alum to the raw water for coagulation, flocculation, and settling in tanks. Drinking water treatment plants are effective at removing small particles including 70–83 % of microplastics (<100 μm) with treatment by coagulation and membrane filtration showing high effectiveness (Nikiema and Asiedu, 2022; Pivokonsky et al., 2018). However, the level and types of drinking water treatment varies widely and effectiveness of drinking water treatment technologies to remove tire particles specifically is unknown.

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