Beyond The Exhaust: The Rising Environmental and Pathological Toll of Tire Wear Particles

Saddab Ansari[1], Deepali Kulkarni[2]
[1]*Student, Marathwada Mitramandal College of Engineering, Pune*
[2]*Professor, Marathwada Mitramandal College of Engineering, Pune*

Abstract*—Tire wear particles (TWPs) are recognized as a dominant yet overlooked contributor to global microplastic pollution, representing a chemically complex "cocktail" of synthetic rubber, heavy metals and over 200 distinct additives. This review synthesizes current research on TWP generation via stick-slip motion, environmental transport and multi-trophic biological impacts. We highlight the "First Flush" phenomenon, where a lethal chunk of pollutants, specifically the transformation product 6PPD-quinone (N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine), is discharged into the aquatic systems within the initial 30 minutes of storm events. Biological studies reveal a dual-action threat of TWPs, physical obstruction in filter-feeders and severe subcellular stress in sentinel organisms like Eisenia andrei, shown by significant inhibition of catalase (CAT). Additionally, a global biomonitoring has confirmed the presence of tire associated chemicals like benzothiazoles (BTH) in human urine, raising concerns about respiratory distress and systemic toxicity. Finally, this review identifies critical research gaps in standardized quantification process and emphasizes on the urgent need for high-flow filtration technologies to prevent the damage by "First Flush".

***Index Terms*—Tire wear particles, microplastics, 6PPD-quinone, First Flush, oxidative stress, ecosystem engineers, pathological toll, trophic transfer.**

I. INTRODUCTION

Tire wear particles are generated due to the friction of tire with the surface below it, usually roads. The rubbing between the tire and the road leads to release of micro-scale particles from the tires into the surrounding air environment. This process is called tire abrasion. Tire wear has an elongated, fiber-like morphology ("sausage-like" shape) and ranges from 2 micrometer to 20 micrometer (Giechaskiel et al. 2024; Tian et al. 2017). TWPs were later classified as microplastics in a research article by Mr. Pieter Jan Kole (Kole et al. 2017). Microplastics are typically described as solid, water insoluble, polymer-based materials less than 5 mm in size with a low degradation rate (Verschoor et al. 2016; Boucher and Friot 2017). Current definition of microplastics is satisfied by TWPs and puts it in the category of microplastics. As argued by Sundt et al. (2014), Magnusson et al. (2016) and Kole et al. (2017). While modern classification as microplastics is relatively recent, the physical shedding of rubber through tread surface abrasion has been a subject of engineering concern for over five decades (Dannis 1974). However, TWPs are not entirely rubber, tires are made up of a complex mix that includes polymeric material (natural rubber, synthetic rubber), fabric, fillers (like carbon black), softeners, vulcanization agents and other additives.

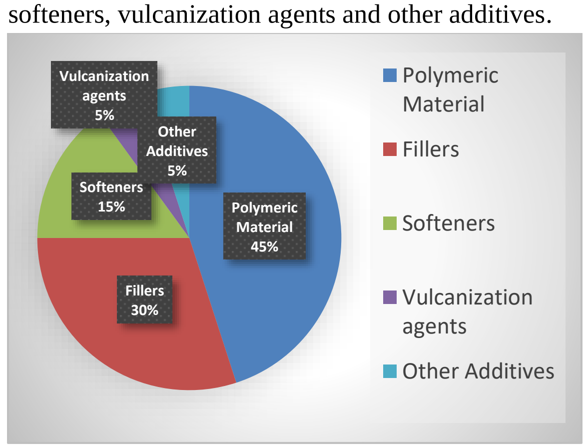

FIGURE 1: CHEMICAL COMPOSITION OF TIRE. (INSPIRED BY JOHANNESSEN ET AL. 2022)

As illustrated in Figure 1, the tires consist of softeners, additives and polymers which can cause some pathological harm to all the living organisms. Different researches show adverse effects of tire wear particles on smaller organisms like earthworms, shrimps and many more. To tackle these problems, understanding tire pollution and tire abrasion becomes essential.

II. GENERATION OF TIRE WEAR PARTICLES

Tire abrasion is caused due to slippage during vehicle acceleration and braking as the tire maintains grip with road (Liu et al. 2025). This grip maintained by tire with road is then known as stick-slip motion, where rubber treads block deformation and intense friction (Ishii et al. 2025). This is often characterized as a relaxation phenomenon, where the rubber vibrates and oscillates as it loses contact with the road, these releases high-frequency energy and sheds material in process (Ishii et al. 2025). The material generated by the process of tire abrasion and deformation is then known as tire wear particles. TWPs are polydisperse in nature, hence they show a wide range of sizes. The lower the slippage, the less is the deformation in treads and hence, less abrasion (Liu et al. 2025). The findings indicates that aggressive driving behaviors and high traffic areas such as bottlenecks are responsible for higher tire pollution (Gnecco et al. 2005; Essel et al. 2015; Munari et al. 2017). As braking and slipping is the main reason for TWPs formation, driving on less traffic roads, which reduces the frequency of applying brakes, saves the tire and decreases the amount of TWPs formed (Knight et al. 2020; Tian et al. 2017). This behavior is often reflected in visible skid marks on roads, especially near the speed breakers, because the skid marks are formed by slippage of tires leading to tiny fragments of tire wears stick to the road. It is observed that at PM_{10} (particulate matter with aerodynamic diameter of 10 micrometers or less) much higher number of particles are present compared to those at $PM_{1.}$ Showing that only about 3% of the total TWPs were actually fine PM_1 size (Amato et al. 2009). This suggests that most TWPs remain within the coarse particulate fraction itself with only a small proportion occurring in the fine PM_1 range (Amato et al. 2009).

III. FACTORS AFFECTING GENERATION OF TWPS

Long high-speed rides or braking at higher speed converts the kinetic energy to thermal energy. Due to this thermal energy, the temperature often becomes high enough to decompose the material of tire (Chan et al. 2004). This is also the reason why sports cars require tire change more frequently than regular passenger cars. Some studies show that new tires have more abrasion rates, as the excess material and sharp edges easily get shed-off (Sommer et al. 2025). Also, in two-wheeled vehicles (like mountain bikes), rear tires exhibit significantly higher abrasion, because they bear the brunt of propulsion forces directly (Sommer et al. 2025). Studies on the number of particles at PM_{10} released by various vehicles, shows that the weight of the vehicle plays a vital role in the formation of tire wear (Amato et al. 2012). Comparing the amount of TWPs at PM_{10} released by a regular passenger car to a heavy-duty vehicle like truck, show that a truck produces 20 times the TWPs than that of a passenger car (Amato et al. 2012). Some researchers have also observed that the size of a particle depends on the velocity of the vehicle, i.e., higher vehicle speeds tend to produce smaller TWP fragments and vice-versa (Tian et al. 2017).

IV. CHEMICAL COMPOSITION OF TWPS

Unlike standard consumer microplastics, TWPs are considered ‘chemical chameleons’ because their toxicity is driven more by the diverse leachates of additives than by the polymer beads themselves (Wagner et al. 2018). Tires are primarily made up of Styrene-butadiene-rubber (SBR) or styrene-butadiene polymer (SBP) (Liu et al. 2025). Usually the filler (~12%) is made up of Carbon black. Carbon black here, acts as the structural reinforcement and provides significant adsorption properties (Johannessen et al. 2022). Due to their high carbon black content, tire wear particles can actually adsorb other urban pollutants like Toluene and Xylene from aqueous solutions (Alamo-Nole et al. 2011). During vulcanization of tires, a huge volume of Zinc oxide (ZnO) or Zinc sulphide (ZnS) is added, which makes up for about 1% of the total weight of the tire (Adamiec et al. 2016). Modern tires also consist of silica for higher performance (Liu et al. 2025) and about 200 distinct inorganic and organic additives designed to help improve durability and elasticity of tires (Johannessen et al. 2022). Tires contain up to 5-10% specialized additives like hexa methoxy methyl melamine (HMMM) and the antioxidant 6PPD (Johannessen et al. 2022). 6PPD (Figure 2a) is an essential additive for tires, however, it often reacts with the environment to form highly toxic compounds like 6PPD-quinone (Figure 2b) (Johannessen et al. 2022).

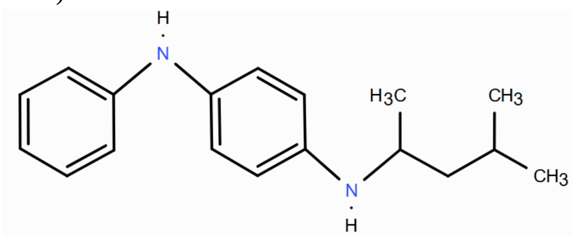

FIGURE 2A. CHEMICAL STRUCTURE OF 6PPD

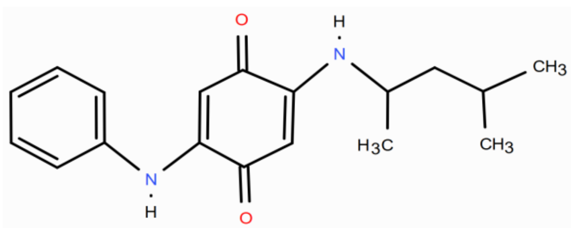

FIGURE 2B. CHEMICAL STRUCTURE OF THE TRANSFORMATION PRODUCT 6PPD-QUINONE

TWPs are not composed solely of tire rubber but often contain high concentration of road dust enriched with metals like zinc, copper and iron (Amato et al. 2009). Such high concentration of chromium and zinc are often used as an identifier for tire wear and these are also termed as "finger-prints" for tire wear (Almeida-Silva et al. 2011). In 2011, An urban tunnel in Lisbon, Portugal was used to take multiple readings of tire wear particles, the research concluded that there is a very high concentration of Zn, Sb, As, Br, Co and Sc in the TWPs (Almeida-Silva et al. 2011).

V. MODE OF TRANSPORTATION OF TWPS

TWPs are primarily generated on roads, and they account for about 90% by volume of the "Super-coarse" (> 10 µm) airborne particles near highly frequented roads (Sommer et al. 2018). Roads are the primary source of atmospheric microplastics, and is estimated to be up to 84% in some regions (Brahney et al. 2021). TWPs gain the necessary kinetic energy for atmospheric resuspension through a combination of physical 'kicking' from mechanical tire movement and the powerful upward force of turbulence induced by the vehicle itself, making the TWPs airborne (Brahney et al. 2021; Rausch et al 2022). Without these two forces combined, the TWPs would have just stayed on the road as a thin layer. Once airborne, these TWPs enter a global cycle similar to biogeochemical flows, allowing them to be transported far from their actual origins (Rausch et al. 2022; Cadle and Williams 1978; Brahney et al. 2021).

Most of these TWPs end up falling on nearby ground. In a study conducted by Knight et al. (2020) It was observed that the soil just below A38 bridge, United Kingdoms, had the highest abundance of TWPs in the surrounding area. The accumulation of the TWPs happens because the air sweeps the airborne TWPs formed on the busy A38 bridge (Knight et al. 2020). TWPs contain many harmful chemicals, like Zinc, which can affect the health of organisms living there, like earthworms. The microplastics entering the environment may seem insignificant at first; however, the annual emission of car tire dust in Germany alone is estimated at up to 110,000 tons (Lackmann et al. 2022).

Recent field assessment conducted across the tributaries of the Charleston Harbor Estuary, Winyah Bay and South Carolina, showed that TWPs are the second most abundant microplastic particle type collected during the study, constituting 17.1% of the total microplastics identified (Gray et al. 2018). However, in certain 'hotspots' characterized by high traffic density and direct bridge runoff, TWPs were the most dominant pollutant, making up over 90% of the total microplastics particles at those specific sites (Gray et al. 2018).

VI. TWPS IN RIVERS, LAKES AND OCEANS

According to Gray, Leads and Weinstein (2018), tire wear particles represent a major component of the microplastic burden in estuarine environments. A significant chunk of microplastics in water bodies is caused due to rainstorms. Increasing urbanization has replaced natural, pervious landscapes with impervious surfaces such as concrete and asphalt, preventing the natural filtration of particulates into the soil (Aryal et al., 2010). Therefore, tire wear particles and associated nutrients accumulate on road surfaces until they are mobilized by stormwater. These pollutants are then transported via drainage systems into canals, rivers, and ultimately, marine environments (Kazour et al., 2019).

Researchers have observed that around 50% of the total pollutants get washed off and discharged into the drainage system within the first 30 minutes of a water event; hence, the first 30 minute is the most crucial in order to save the marine environment (Aryal et al. 2010). the phenomenon where a highly concentrated "lethal pulse" of accumulated pollutants is washed off impervious surfaces (like roads) during the beginning of a storm is called the 'First Flush'. The peak toxicity is observed in the first 30 minutes of rainstorm event; however, the toxicity may last multiple hours (Aryal et al. 2010; King et al. 2025). Hence, filtering the stormwater thoroughly for that period can remove over 50% of the total pollutants (Aryal et al. 2010). This research invited many attempts and newer research on the 'First Flush' phenomenon. As observed by King et al. (2025), the first 30 minutes aren't just "dirtier" but are also chemically more lethal. Research on 6PPD-quinone (The chemical that kills coho salmon; Figure 2b) shows that its concentration peaks almost perfectly with the 'First Flush' (King et al. 2025), meaning that the most toxic "pulse" of tire chemicals hits the water all at once, and it still goes on for a very long duration. Hence, to avoid it we need filters that would work for the entire duration of rainfall, which is very difficult (King et al. 2025).

As highlighted by Boogaard et al. (2015), existing stormwater treatment systems are often ineffective at capturing the fine-fraction particulates (<63 µm) that carry the highest pollutant loads, with removal efficiencies frequently falling below 50% during peak flow conditions. TWPs exhibit polydispersity and hence, have a wide range of different sizes (Sommer et al. 2018). Usually, coarse particles (> 100 µm) get settled quickly near the roadside or in drains, however, fine-fraction particulates (<63 µm) stay suspended in runoff water, hence they are not only more likely to be transported into streams, rivers and oceans, but they also carry a disproportionately high pollutant load due to their increased relative surface area compared to larger chunks of TWPs (Sommer et al. 2018; Boogaard et al. 2015).

VII. EFFECTS OF TWPS ON MARINE ORGANISMS

The entry of TWPs into marine ecosystems represents a dual-action threat that combines physical obstruction with acute chemical toxicity. Unlike traditional microplastics, TWPs is dual-natured: they act as a physical obstruction when ingested by filter-feeders, while simultaneously releasing complex leachate of additives and transformation products, like 6PPD-quinone (King et al. 2025). These particles settle in estuaries or other water bodies. Hence, they become available to a wide range of marine life, ranging from primary producers like microalgae to high trophic level species. In the base of marine food web, primary producers like microalgae suffer significant physiological impairment when exposed to TWPs. According to Cunha et al. (2020), TWP leachates can reduce algae growth by up to 47%. Additionally, the increase in antioxidant enzymes such as catalase (CAT) acts as an essential biochemical signal of oxidative stress in these organisms, indicating that they are reacting to the complex mixture of chemicals released by TWPs (Cunha et al. 2020).

Beyond primary producers, filter-feeders represent a critical point of entry for TWPs into the marine food web. Organisms such as the blue mussel (*Mytilus edulis*) and various species of grass shrimp are more prone to this threat, due to their non-selective feeding strategies (Kazour et al. 2019). These organisms cannot distinguish between organic edible food and microplastics, leading them to often consume microplastics, including TWPs. Research indicates that when these semi-synthetic fragments are ingested, they can scratch the inside of the digestive tract and create a condition of 'false fullness' or 'false satiety', where indigestible rubber occupies space in the gut and reduces the intake of real nutrients (Gray et al. 2018; Kazour et al. 2019). Such physical damage not only harms the health of the affected organism but also allows the associated toxins such as zinc and 6PPD-quinone to move up the food web through trophic transfer to higher-level predators (Johannessen et al., 2022; King et al., 2025).

The biological risk of TWPs is especially severe for higher-trophic-level species such as teleost fish, where chemicals released from tire particles can cause serious systemic effects. A well-documented case is Urban Runoff Mortality Syndrome (URMS) in Coho Salmon (*Oncorhynchus kisutch*) (King et al. 2025). King et al. (2025) showed that during heavy rainfall and storm-water events, 6PPD–quinone can accumulate to lethal levels, leading to rapid death within a few hours of exposure. Recent toxicology studies have expanded this threat to include other salmonids, such as Brook Trout (*Salvelinus fontinalis*) and Rainbow Trout (*Oncorhynchus mykiss*), which also exhibit significant mortality when exposed to tire-derived leachates (Brinkmann et al. 2022; USGS 2025). Furthermore, the effects of this contaminant reach lower trophic levels, as evidenced by significant physiological impairment and mortality in aquatic crustaceans, indicating that 6PPD-quinone poses a systemic hazard to the entire aquatic community (Hiki et al. 2021). In addition to these acute effects, sub-lethal exposure to tire-derived metals and organic additives has also been associated with developmental neurotoxicity and cardiovascular impairment in fish embryos, showing that the biological impacts of TWPs can affect organisms across multiple life stages (Johannessen et al. 2022; King et al. 2025). Different metals present in TWPs show different effects on marine species; like Zinc (Zn) is known as a neurotoxin for aquatic invertebrates because excessive zinc interferes with neuronal ion channels and enzyme activity in the nervous system (Adamiec et al. 2016). Similarly, Lead (Pb) and Cadmium (Cd) have endocrine-disrupting potential. These metals interfere with hormone signaling pathways, block them or alter the receptor activity, leading to neurological and behavioral impairment, which may contribute to mortality under high exposure (Amato et al. 2009; Johannessen et al. 2022). Overall, the combined effects of ingestion and long-term chemical exposure show that TWPs are not just a risk to individual species but a continuing source of ecological disruption across entire aquatic food webs.

VIII. EFFECTS OF TWPS ON TERRESTRIAL ORGANISMS

While aquatic impacts are widely documented, terrestrial ecosystems represent a primary and potentially dominant sink for the TWPs. In Germany alone, annual emissions are estimated at 110,000 tons (Lackmann et al. 2022), much of which accumulates in roadside soils via atmospheric deposition or stormwater wash-off (Knight et al. 2020; Aryal et al. 2010). A global study confirms that terrestrial environments have become a massive, unintended reservoir for these particles. It is now estimated that global soil loading rates for tire wear are reaching as high as 6.1 million metric tons annually, positioning land as the ultimate sink for tire-derived microplastics (Büks and Kaupenjohann 2020; Rillig et al. 2021). Within the soil systems, earthworm functions as key ecosystem engineers, improving soil fertility and structural stability through their bioturbation activities like feeding, moving or burrowing (Lackmann et al. 2022). Lackmann et al. (2022) studied the terrestrial impact of TWPs using the earthworm *Eisenia andrei* as a model organism. Findings indicate that exposure to real-world concentrations of tire abrasion causes significant subcellular stress, even when acute mortality is not observed (Lackmann et al. 2022).

Research by Lackmann et al. (2022) reveals that while these concentrations do not cause immediate mortality or avoidance behaviors, they do trigger gradual changes in oxidative-stress biomarkers, most notably a decrease in catalase (CAT) activity after 28 days. Although antioxidant enzymes such as CAT may initially increase under stress, prolonged exposure to TWPs can overwhelm cellular defenses, leading to enzyme inhibition and reduced antioxidant capacity (Lackmann et al. 2022). Additionally, the high metallic contents in tires containing over 11.7 g/kg of zinc suggest that TWPs act as a significant source of heavy metal contamination in terrestrial ecosystems (Lackmann et al. 2022). These cellular or molecular level damages (like enzyme inhibition and oxidative stress) are important because they act as early warning signs. In the future, the overall health of soil-living organisms (worms, microbes, insects, etc.) may be harmed, especially in areas of high vehicle-traffic.

IX. EFFECTS OF TWPS ON HUMAN HEALTH

Urban air monitoring has confirmed that tire-related debris constitutes a measurable percentage of the total respirable mass in metropolitan environments, directly contributing to the daily particulate burden on city dwellers (Panko et al. 2013). The ecological consequences of tire wear are profound and well-known, however, the unique chemical composition of TWPs also brings a significant pathological risk to human health. Humans get exposure of TWPs primarily through inhalation of airborne particulates, where the fine $PM_{2.5}$ fraction can enter deep into the pulmonary system (Amato et al. 2009). This finding was later backed by a study Tetley (2023) and Tan et al. (2023) at Imperial College London, highlighting that these micro-scale tire fragments are not only respirable but may cross the air-blood barrier, potentially triggering systemic inflammatory responses beyond localized respiratory distress. Beyond respiratory impairment, the presence of over 200 distinct additives and heavy metals, such as Zinc (Zn) and Lead (Pb), raises concerns regarding systemic toxicity and endocrine disruption through both ingestion and dermal contact pathways (Johannessen et al. 2022; Adamiec et al. 2016).

Recent biomonitoring research has confirmed that humans are actively absorbing and metabolizing chemicals directly associated with tire and rubber production. A global study by Asimakopoulos et al. (2013) detected benzotriazole (BTR) and benzothiazole (BTH) derivatives in human urine samples across seven countries, including the U.S and India. BTR and BTH are both key components of rubber materials and corrosion inhibitors. Estimated daily intake (EDI) doses for these compounds can reach several tens of micrograms per day (Asimakopoulos et al. 2013). Additionally, in some regions, BTH was found in 100% urine samples, highlighting the danger (Asimakopoulos et al. 2013). It is observed that, once these chemicals enter the body, they undergo complex metabolic transformations, such as hydroxylation through cytochrome P-450 enzymes, though the long-term effects of these metabolites are still being investigated (Asimakopoulos et al. 2013).

The pathological toll of TWPs extends beyond just simple irritation. 1H-benzotriazole (1H-BTR) is classified as a suspected human carcinogen, while other BTH derivatives have been linked to mutagenicity (mutation in DNA) in microorganisms and cancer risk in industrial workers (Asimakopoulos et al. 2013). Common BTH derivatives found in tire rubber are also known as 'dermal sensitizers'; these can potentially cause allergic reactions upon skin contact with road dust (Asimakopoulos et al. 2013).

X. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the rising environmental and pathological toll of tire wear particles, significant knowledge gaps remain. Foremost among these is the lack of standardized analytical methods for TWP quantification in soil and sediments, which complicates global monitoring. (Boogaard et al. 2015). Lack of a clear analytical distinction between TWPs and road-wear particles further complicates environmental quantification. While soil is a 'dominant environmental reservoir', research on soil only accounted for 3.8% of microplastic publications between 2004 and 2018 (Lackmann et al. 2022). Furthermore, while acute toxicity is well-documented in specific sentinel species like earthworms or salmon, the long-term effects on reproductive health and the potential for human exposure via trophic transfer or bioaccumulation remain unexplored (Asimakopoulos et al. 2013). One essential research gap is the development of high-flow filtration capable of capturing fine particulates of 'First Flush' (King et al. 2025) and the engineering of non-toxic tire chemical alternatives to avoid the use of toxic chemicals, like 6PPD-quinone (King et al. 2025). Addressing these gaps is essential for transitioning from only observations to active environmental protection.

XI. CONCLUSION

The rising environmental and pathological toll of tire wear particles (TWPs) represents a rapidly emerging focus within microplastic research, shifting the focus from traditional consumer plastics to abrasion generated pollutants. Present review has synthesized recent findings to show that TWPs are not merely "road dust" but chemically complex entities comprising a mixture of synthetic rubbers, carbon black fillers, and over 200 distinct organic and inorganic additives. As vehicles travel across urban landscapes, the resulting "stick-slip" motion and relaxation phenomena generate a polydisperse range of fragments that enter the global biogeochemical flows through both atmospheric resuspension and high-velocity stormwater runoff.

The evidence presented underscores a multifaceted, dual-action threat to biological systems. From the inhibition of primary production in microalgae to the acute mortality of salmonids, TWPs disrupt multiple levels of the aquatic and terrestrial food webs. Studies on soil ecosystem engineers like *Eisenia andrei* prove that even at environmentally relevant, non-lethal concentrations, TWPs induce significant oxidative stress and enzymatic changes, such as the inhibition of Catalase (CAT) activity. Beyond ecological disruption, biomonitoring data discussed in the present review, specifically the detection of benzothiazoles and benzotriazoles in human urine globally confirms that the 'pathological toll' extends into the human body. These findings, coupled with the identification of 1H-benzotriazole as a suspected carcinogen, underscore potential long-term risks regarding respiratory irritation, carcinogenicity, and endocrine disruption.

The phenomenon of the 'First Flush' highlights a critical technological bottleneck. While the scientists have identified the 'lethal pulse' of chemicals such as 6PPD–quinone during initial storm events, current infrastructure remains largely ineffective at capturing the fine-fraction particulates (<63 µm) that carry the highest pollutant loads. Moving forward, it is essential to prioritize the standardization of detection methods. Addressing the tire wear crisis is no longer a localized road-management issue, but an ecological and public health necessity required to protect the lives of both terrestrial and marine ecosystems.

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