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Tire crumb in the environment: a review on occurrence, fate and recent advances in detection and analysis

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Tire wear particles (TWPs) are increasingly recognised as a contaminant of emerging concern, owing to their toxic and omnipresent nature. Given these characteristics, it is imperative to discuss their occurrence and fate across different environmental matrices and critically examine the current state-of-the-art technologies utilised for their sampling, detection and analysis. This review provides a comprehensive overview of the physicochemical characteristics of TWPs, their occurrence, environmental fate, and detection methodologies. It further investigates the dominant methodological bottlenecks in the detection and quantification of TWPs across different environmental matrices, highlighting key challenges in their atmospheric and waterborne cycling, including inconsistent emission estimates, a lack of standardised protocols, and a limited understanding of transport and transformation processes. Our findings revealed that TWPs are ubiquitous across all environmental matrices; however, their transport and transformation remain poorly constrained due to variable density, aggregation, ageing and additive leaching behaviour, all of which complicate modelling efforts. In addition, we also concluded that despite rapid progress in spectroscopic, thermal and mass-based approaches, there remains no standardised, matrix-independent method potent enough for achieving simultaneous chemical specificity, particle-scale resolution, and quantitative recovery. Such findings emphasise the urgent need for harmonised analytical workflows and integrative studies linking physicochemical properties to environmental mobility and toxicity. This review thus establishes a conceptual framework for bridging analytical advances with environmental process understanding, an essential step towards reliable risk evaluation of tire-derived microplastics. It further offers essential insights to researchers, policymakers, and environmental professionals determined to better comprehend and alleviate the effects of tire wear particles on ecosystems and human health.

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1. Introduction

Over the last two or more decades, conventional microplastics (MPs) have become a contentious issue among the global scientific community. However, recently, the focus has shifted towards non-conventional MPs originating from the wear and tear, degradation, and recycling of tires, known as tire wear microplastics (TWMPs) or tire wear particles (TWPs).[1,2] TWPs are considered a prominent source of MPs in the environment[3–7] and an emerging environmental concern due to different types of harmful and hazardous chemical additives being added intentionally during the manufacturing process of tires.[8] According to a study by Giechaskiel *et al.*,[9] globally, TWPs contribute around one-third to half of the total unintentional MPs released into the environment, a significant portion of which ultimately ends up in terrestrial and aquatic ecosystems, and a smaller portion becomes airborne. Studies across different regions of the world have documented varying contributions of TWPs to the total MPs released from various sources, which is quite alarming. For instance, in China and Germany, the total share of TWPs in the overall annual MPs emissions is 27% and 30%, respectively,[10,11] while it has been reported that it is >50% in countries like Denmark and Norway.[12,13] On a global scale, nearly 3 billion tyres are produced annually, and almost 800 million tyres are discarded or abandoned as waste.[8] These figures underscore the significant and concerning prevalence of TWPs, highlighting their pervasive environmental contamination and stressing the need for understanding their occurrence and fate, effective analytical strategies for their quantification and detection in complex environmental matrices.

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The heterogeneous properties of TWPs, accompanied by characteristics like varying particle size, density, shape, texture, and elemental and chemical composition, make their analytical workflow challenging. As far as the current analytical methods are concerned, two methods exist currently: single particle analysis and bulk analysis methods.[14] Both groups encompass a considerable variation of methods, demanding different sampling[15–23] and sample pre-treatment methodologies[18,23,24] with different possible outputs, with the former focusing on the analysis of single TWPs[6,16,17,25,26] and the latter one on marker-based analysis.[24,27–39] The information, however, on the impact of TWPs on the identification and quantification of such pretreatment techniques remains limited or least understood.

Another significant aspect related to the TWPs in the environment is their fate. TWPs released from different sources may enter soil, water, and air[1,40,41] *via* different pathways and further interacting with various environmental biotic (micro-organisms, biofouling, eco-corona) and abiotic (interaction with mineral colloids, salts) components, or may undergo physical or chemical changes due to different physicochemical processes like UV radiation, temperature, redox changes, altering their fate and toxicity.[42]

Although traditionally examined from an environmental pollution perspective, tire crumb represents a complex soft matter system, a viscoelastic, multiphase polymer network composed of natural rubber, styrene butadiene rubber, butadiene rubber, carbon black, silica, and numerous additives.[43,44] This architecture imparts elasticity, energy dissipation, and deformation behaviour characteristic of Soft condensed matter,[45] governing its environmental fate through ageing, swelling, and oxidation that alter surface energy and hydrophilicity.[46] These transformations drive nanofragment formation and soft interfacial film generation *via* additive leaching and organic adsorption, yielding colloidal behaviours; aggregation, stabilization, and charge dynamics, consistent with DLVO and non-DLVO interactions.[47,48] Advanced spectroscopic, rheological, and microscopic studies (*e.g.*, quantitative NMR, TGA-GC/MS, cryo-EM, AFM) have revealed the multiphase viscoelastic microstructures and filler–polymer interactions of TWPs, bridging analytical environmental chemistry with soft matter characterization.[47,49] Consequently, tire crumb serves as a model environmental soft matter system where deformability, viscoelastic fracture, and colloidal stability dictate environmental transport and biological interactions, linking polymer physics and colloid science to the broader environmental implications of soft, deformable, and multiphase materials.[45,48,50]

Understanding tire crumb through this dual lens of environmental chemistry and soft-matter physics not only contextualises their transformation and transport but also informs methodological development for their detection and quantification. Accordingly, this review synthesises current progress in sampling, characterisation, and identifies key methodological bottle necks, and highlights the challenges underlying their atmospheric and aquatic cycling.

Although existing reviews and experimental studies have provided valuable insights into specific aspects of TWP research, such as generation mechanisms, compositional profiles, or individual analytical techniques, a critical synthesis that integrates these domains to identify overarching methodological and environmental knowledge gaps is still lacking. Particularly, ambiguities persist regarding the comparability of detection methods, the representativeness of sampling strategies, and the mechanistic understanding of environmental cycling. Therefore, this review aims to consolidate current advances and outline the central challenges that must be addressed to progress towards standardised quantification and risk assessment of TWPs.

Zahid Ahmad Ganie

Zahid Ahmad Ganie is an environmental researcher specialising in nanomaterials, micro/nanoplastics, and tire wear particles. His work focuses on elucidating the fate, transport, and toxicity of microplastics, particularly tire wear particles and their associated additives, as well as developing eco-friendly composite materials for their remediation. He is currently a JSPS postdoctoral fellow at the Graduate School of Global Environmental Studies, Kyoto University, Japan. His ongoing research integrates soft matter physics with environmental chemistry to advance the understanding of the transformation, ageing, and mechanochemical behaviour of tire-rubber-derived particles in real environmental systems.

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Amritanshu Shriwastav is currently an Associate Professor in the Environmental Science and Engineering Department at IIT Bombay, India. His current research focusses on the occurrence and fate of micro-and nanoplastics in environmental matrices, and development of suitable remediation strategies.

This review is structured based on the discussions concerning the key challenges governing the atmospheric and aquatic transformation and ultimate fate of TWPs. It further critically analyses questions such as dominant methodological bottlenecks in the detection and quantification of TWPs across diverse environmental matrices, and ultimately suggests on how future research can integrate detection, modelling, and toxicity assessments to develop a unified environmental framework. By systematically addressing these knowledge gaps, this review aims not only to summarise the current state of knowledge but also to highlight emerging directions for analytical innovation and interdisciplinary collaboration, ultimately providing a roadmap for future research directions on tire-derived microplastics in environmental systems.

By identifying key research priorities and proposing future directions, we aim to inspire interdisciplinary collaboration among scientists, policymakers, and industry stakeholders to address the growing challenge of TWP pollution. Only through concerted efforts can we mitigate the environmental and health risks posed by TWPs and move toward a more sustainable and resilient future.

2. Characteristics of TWPs

2.1 What exactly constitutes a tire

A simple tire is a complex makeup of numerous components that impart different types of properties to it. Tires consist of major makeup components like tire tread, nylon overlay, steel belts, sidewall, body piles and inner liner, which are made from rubber, nylon fibres, bead wires and additives as shown in Fig. 1.[1,12,51,52]

A perfect mix of all these components makes strong, durable, safe and reliable tires.[54] In addition to this, a wide range of compounds and constituents, many of which are exclusive to manufacturing companies, different brands, and types, may also be added to tires during their manufacturing.[52,55–59] The major component of tires is tire rubber, and the two most common types of rubber used in tires are styrene butadiene rubber (SBR) and natural rubber (NR), which comprise the butadiene and *cis*-1,4-polyisoprene components, respectively. Generally, rubber polymer makes up to 50% of the tire tread, and apart from this, different reinforcing and softening fillers contribute to 20–25% of the tire weight, respectively.[51,60] Numerous types of performance enhancer additives like carbon black, activator like Zinc-Oxide (ZnO), softener (stearic acid), vulcanizers and antioxidants like *N*-(1,3-dimethyl butyl)-*N*′-phenyl-*p*-phenylenediamine (6PPD), polyaromatic hydrocarbons (PAHs), are added to the tires to enhance their wear and tear resistance and increase their life on the roads.[1,8,51] For instance, carbon black is added to the tires with the motive of enhancing and reinforcing their anti-ageing properties due to UV radiation, and similarly, ZnO is used as an activator to promote rubber cross-linkage during the synthesis process.[61] Such properties not only ensure the longevity and persistence of tires but also the TWPs generated from these tires in the environment. In addition, the manufacturers may tune tire manufacturing and its properties according to the vehicle it is designed for and the season of the vehicle's operation.[1] In conclusion, no standard makeup composition for tires exists; it may vary from country to country. Table 1 summarises the typical composition of tire tread and the functional roles of major components.

Tires across different regions or conditions undergo weathering or disintegration, making it challenging to identify and characterise the released TWPs and leached-out additive chemicals in the environmental samples, making it difficult to understand their distribution, morphology, fate, and ecotoxicological risk.

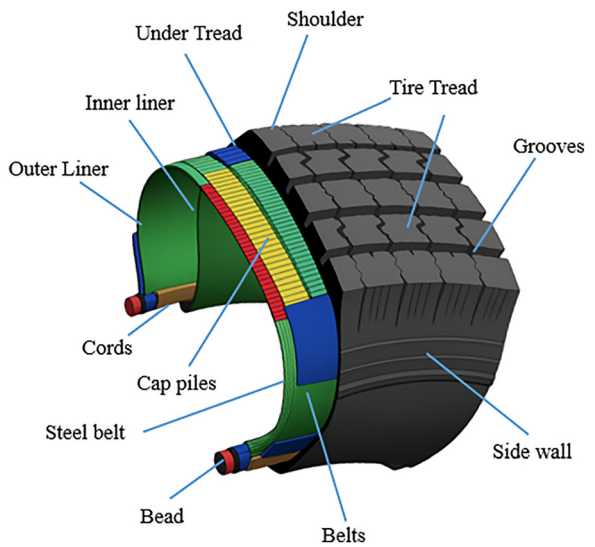

Fig. 1 Components of a tire. Adapted from ref. 53 IOP Conference Series: Earth and Environmental Science, licensed under CC BY 3.0, copyright 2020. Changes have been made to the original figure.

2.2 Generation and physical properties of TWPs

TWPs are generated from the mechanical interaction between tires and road or runway surfaces through two primary mechanisms: abrasive wear (mechanical grinding by road texture) and fatigue wear (thermal and structural degradation from repeated deformation).[63,64] Abrasive wear produces large, elongated fragments, whereas fatigue wear generates smaller, spherical particles.[64,65] There are numerous intrinsic and extrinsic factors that influence and control the generation of TWPs. Intrinsic factors include tire tread design and rubber formulation. Higher treadwear-grade tires, characterised by dense cross-linking, emit more fine particles (<10 μm) due to dominant fatigue wear, while low-grade tires emit larger fragments *via* abrasive wear.[64] Tire tread depth also affects wear rate; deep patterns and soft rubber compounds, as in winter, increase wear, especially under cold conditions.[66,67] Enhancing the wear resistance of winter tires is therefore essential for emission mitigation in colder climates. Extrinsic factors include vehicle characteristics, road conditions, and environmental factors. Heavier vehicles such as electric and hybrid vehicles, exert greater load on tires, resulting in higher TWP emissions (72 mg per vehicle per km for hybrids *vs.* 53 mg per vehicle per km for

Table 1 Different tire components with their mass percentage and functional roles

Component	Mass fraction (%)	Examples/details	Function	Ref.
Base polymers	40–50	Natural rubber (polyisoprene), synthetic rubber (SBR, BR)	Provides elasticity and structural integrity	6, 11 and 62
Fillers	30–35	Carbon black, silica (SiO_2), calcium carbonate ($CaCO_3$)	Reinforces mechanical strength and durability	6, 11 and 62
Softeners	~15	Oils and resins	Improves flexibility and processability	6, 11 and 62
Vulcanization agents	2–5	Sulfur (S), zinc oxide (ZnO)	Facilitates crosslinking to enhance elasticity and resilience	6, 11 and 62
Additives	5–10	Antioxidants (amines, phenols), preservatives (halogenated cyanoalkanes), desiccants (CaO), plasticizers (aromatic/aliphatic esters), processing aids (mineral oils)	Enhances stability, aging resistance, and workability	6, 11 and 62
SBR content in passenger tires	~11	Styrene-butadiene rubber	Common synthetic rubber component	11 and 30
SBR content in heavy-duty tires	Low to none	Styrene-butadiene rubber	Typically excluded from heavy-duty tire formulations	11
Polymer content in tread	~50	Various polymers	Indicates microplastic potential in TRWP	11
TRWP composition	Variable	Tire and road wear particle aggregates	Mixture of rubber, road debris, and other particles	11

conventional vehicles).[67,68] Road roughness enhances abrasive wear, while moisture reduces friction and favours fatigue wear.[64] Climate conditions, such as high temperatures and aridity, accelerate fragmentation through rubber brittleness.[69,70] Driving behaviour (acceleration, braking, and cornering) further increases wear.[71,72] Recent machine learning analyses suggest that widespread electric vehicle adoption could elevate non-exhaust emissions, emphasising the continued relevance of TWPs even in low-emission transport futures.[73]

The physical characteristics of TWPs, including size, morphology, density, and composition, govern their environmental fate, mobility, and detection.[1,11,74–76] Particle size is a critical determinant of TWP transport and deposition. TWPs typically range from nanometres to hundreds of micrometres (0.1–100 μm),[77,78] exhibiting bimodal distributions that correspond to distinct wear mechanisms.[79,80] Coarse fractions (PM10) tend to settle in soils and road size dust, while fine and ultrafine fractions (PM2.5 and PM0.1) can remain airborne, though only 0.1–10% TWPs ≤PM10 become suspended.[81,82] Ultrafine TWPs are often subjected to high temperature thermo-chemical processes at the tire–road interface.[83]

Environmental factors and road–tire interactions contribute to the heterogeneous morphology of particles. TWPs occur as granules, fibres, or droplets and are rarely pure rubber; they are often mixed with mineral and road dust components.[6,84–87] Studies confirm that the composite nature of road material contributes substantially to micro- and sub-micron TWP fractions.[75] For instance, Bae *et al.*,[88] reported that abrasion rates are higher on concrete than on asphalt pavements, yielding TWPs primarily within 63–500 μm. Similarly, Zhong *et al.*,[44] found that ultrafine particles (<10 μm) accounted for approximately 95% of total TWPs generated in laboratory wear tests. Field-collected TWPs average around 126 μm by number and 220 μm by volume.[89] Density of TWPs also plays a major role in environmental partitioning. Pure tire rubber exhibits densities of 1.1–1.2 g cm^{-3}, but environmental TWPs commonly range from 1.25–1.85 g cm^{-3} due to encrustations of pavement, soil, and debris.[77,90–94] High-density particles settle rapidly, accumulating in sediments, while lighter ones or less encrusted particles remain suspended and mobile in the water. Only ultrafine fractions are capable of re-entrainment between aquatic and terrestrial compartments.[90,95]

Overall, the physical diversity of TWPs, arising from varied generation mechanisms and environmental conditions, complicates their detection and toxicity assessment. Standardised measurement protocols and understanding how environmental factors alter TWP characterisation remain key research priorities.

3. Distribution and fate of the TWPs and additive chemicals into the environment

TWPs and their additives are ubiquitous in almost all environmental compartments, from soil, sediments and water to air.[80,96–101] Table S1 shows the presence of TWPs and their additives reported by different studies in different environmental compartments. The demand for manufacturing tires is ever-increasing. Almost 2.47 billion tires were sold across the globe in the year 2023 alone,[102] an amount, if stacked upon one another, would make a distance roughly 1.6 times the distance to the moon.

According to the European Tire and Rubber Manufacturers' Association (ERTMA), approximately 300 million tire units were sold across the European Union in 2023.[103] US Tire Manufacturing Association (USTMA) confirmed the tire shipments of 331.9 million units in 2023, with an expected rise to 335.7 in 2024.[104] China alone produced approximately 1.19 billion units in 2024, up by 9.2% compared to the previous year.[105] World's largest populated country India produced over 217 million tires

in year 2024.[103] Owing to such huge production numbers, the global per capita production rate of TWPs has been documented as 0.23–1.9 kg per year, contributing to nearly 12% of total tire mass that's being transferred to the environment,[32] making them ubiquitous in soil, freshwater, marine water, sediments and atmosphere.[1] Studies related to the fate and transport of TWPs and the additive chemicals in the environment are scarce; nonetheless, in the past 2–3 years, studies have begun to emerge.[19,106–110] From the European subcontinent, studies related to the TWPs have mostly documented the persistence of TWPs in the road dust, despite the fact that water and atmospheric pathways can move particles farther.[4,40,51,111,112]

The abrasion of vehicle tyres due to wear and tear on the concrete or asphalt road pavements leads to the generation of TWPs, which, upon their initial release, may travel a shorter distance in meters or a longer distance in kilometres before they deposit. This transport of TWPs is facilitated by localised effects of high-speed traffic. The atmospheric road particulate matter, including tire particles, contributes to more than 80% of all atmospheric particulate deposition.[113] This atmospheric fraction is one of the major sources of human exposure *via* inhalation, which has been recently documented by many studies.[96,114–116] Vehicle traffic and environmental conditions may assist in the resuspension, redistribution and modification of the TWPs that are deposited on road pavements. The abrasion and pressure due and shear forces of vehicle tyres further grind the generated TWPs into pavement debris and soil, modifying their shape, size and chemical composition[57,117] and further encrusting them with the other road debris. Moreover, there is also a possibility of the release of the additive chemicals and their environmental and industrial transformation products into the surrounding environment or into the body of organisms inhaling or ingesting them.[52,55,118]

TWPs are primarily dispersed into the environment through air transport and runoff. These particles are mainly generated in urban areas due to road traffic, where they become integrated into road dust or suspended in the air as vehicles move.[6] Due to factors such as wind and gravity, a significant portion of TWPs tends to settle along the roadside.[119] Studies have shown that the concentration of TWPs is highest within five meters from the road, with roadside soils serving as key accumulation zones.[4] Fine TWPs are often carried into the atmosphere and dispersed by air currents, while larger particles tend to remain on road surfaces and are later transported by rainwater into soils, groundwater, or surface waters.[120] Environmental forces such as rain, wind, and ocean currents drive the migration of micro- and nano-sized TWPs.[1,4,120] These particles may travel through the air, flow into rivers and soils *via* surface runoff, or eventually reach marine environments.[121] Fig. 2 illustrates the transport of TWPs in the environment. A remaining portion of TWPs can be retained in environments such as wastewater treatment facilities, with estimates suggesting that about 50% of the TWPs entering environmental systems eventually accumulate in oceans.[121,122]

As mentioned earlier, the size of TWPs plays a critical role in their transport. For the sake of understanding the TWP transport, the size of TWPs is generally categorised into three size fractions: ultrafine (<0.1 μm), fine ($<2.5->0.1$ μm), and coarse (>2.5 μm).[52] When we talk about particle transport, particle size can't be overlooked. Ultrafine and fine particles have usually been linked with longer transport distances far away from their source (*e.g.*, the Arctic, mountain wilderness),[52,111,113,123] while

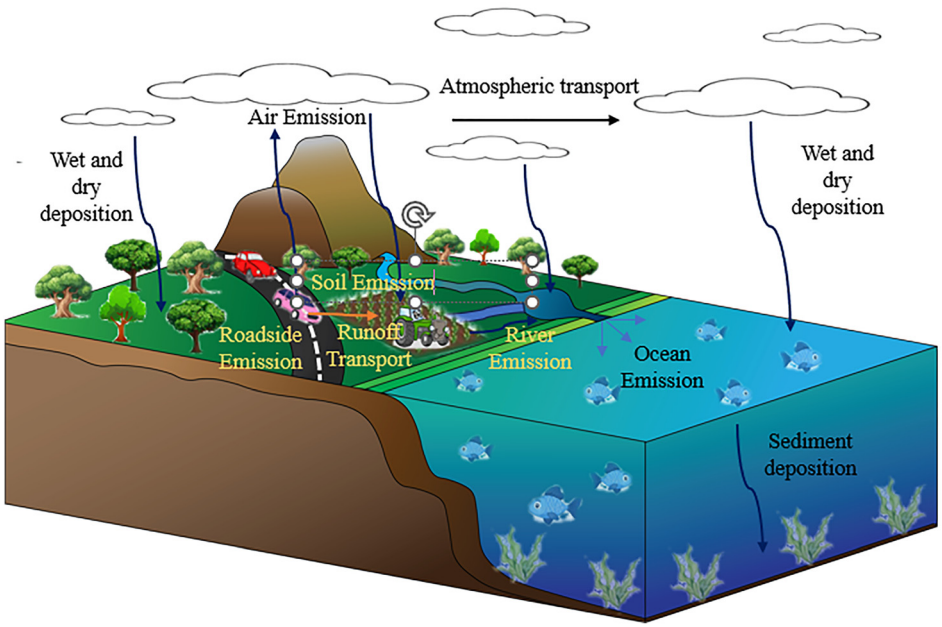

Fig. 2 A detailed overview of the emission and fate of TWPs in the environment. Adapted from ref. 96 with permission from Elsevier, licensed under CC BY-NC 4.0, copyright 2024. Changes have been made to the original figure.

the coarse ones don't transport to the longer distances, usually settling in the nearby road dust or on the pavement surface[57,119,124] close to their emission sources. Most of the available studies on particle size distribution indicate that most of the TWP volume is usually in the coarse fraction with particle size >50 μm, which are known to deposit rapidly upon their generation from the source. While it is quite surprising to see that hardly any of the studies currently show the complete range of particles, especially the fine and ultra-fine fractions, which are most abundant[57,124–126] and prone to long-range transport and inhalation by humans and other organisms. Such particles readily tend to become entrained in the atmosphere[127,128] due to the intense turbulence generated by vehicular traffic,[113] with their atmospheric residence time varying from 8–25 days.[111] Though fine and ultrafine particles comprise a smaller mass of the total emitted TWPs, their number can be significantly higher than the coarse ones, and their properties, like higher surface area, may make them potent vectors for other chemicals, like additives and may help in their transport over longer regions in the environment. Such particles may also aid in carrying such chemicals into the bodies of smaller and sensitive organisms.[8] Due to the data insufficiency regarding the size distribution and surface area measurements of each fraction, the significance of air deposition in the transport of TWPs and associated chemicals between watersheds remains poorly tacit.[112]

The long-range transport of fine and ultrafine TWPs is not only empirically observed but also mechanistically expected from first-principles particle transport physics. As particle size decreases, several soft-matter and physico-chemical mechanisms fundamentally shift transport behaviour across atmospheric and aquatic compartments. Some of the key mechanisms responsible are as follows:

(1) Reduced gravitational settling of smaller TWPs as explained by Stokes law

For spherical TWPs of $< \sim 50$ μm, in the Stokes flow regime, the settling velocity scales as $V_s \alpha d^2(\rho_p - \rho_m)$. Thus, a decrease in diameter from 10 μm to 1 μm reduces the settling velocity by two orders of magnitude, enabling longer atmospheric residence times or downstream transport in aquatic systems.[129]

(2) Increased influence of Brownian motion and turbulent diffusion

Brownian diffusion becomes dominant over gravitational forces and inertial settling for the smaller-sized particles, eventually increasing the dispersion length scale and reducing deposition efficiency. Turbulent eddies in the atmosphere and the water column can transport these particles far beyond local emission sources.[130]

(3) Lower aerodynamic entrainment thresholds

Smaller particles, which may also include fine TWPs, possess low terminal fall velocities and can be entrained or resuspended by very weak shear stresses.[131,132]

(4) Enhanced atmospheric lifetime due to slow dry deposition

Sub-micron particles fall within the ''accumulation mode gap,'' where both Brownian and impaction deposition processes are inefficient, extending atmospheric lifetimes from hours to days or weeks.[133]

(5) Colloidal stability in aquatic systems

At the nano- and microscales, electrostatic repulsion (DLVO effects), steric stabilisation from oxidised polymers, and the presence of natural organic matter act to prevent aggregation, maintaining particles in suspension and facilitating downstream transport.[134,135]

(6) Lower inertia leads to advection-dominated transport

Smaller particles like fine TWPs possess a lower Stokes number, meaning they closely follow fluid streamlines instead of settling or depositing.[136] This allows micrometer and nanometer-sized particles to be transported long distances in rivers, stormwater flows, estuaries, and marine currents.[137]

Together, such mechanisms indicate that long-range movement of fine TWPs is not merely an empirical observation but a predicted outcome of particle physics, colloidal behaviour, and atmospheric/aquatic transport theory.

Once the TWPs are formed or generated from the tires, the particles eventually reach washed-off outdoor surfaces and soils, along with the runoff,[138,139] or from the air, are washed out due to precipitation in different forms. Field *et al.*[138] and Pit *et al.*[140] have reported efficient runoff from impermeable surfaces like streets, pedestrian walks and side roofs compared to permeable ones like lawns, gardens and agricultural fields. The portion of tire wear debris that is washed off urban outdoor surfaces into stormwater runoff varies widely, likely due to numerous systems and condition-specific factors, with reported values ranging from 15–50%,[52] 35%[141] to as high as 80%.[142] Stormwater runoff may also wash away TWPs into the wastewater treatment facilities. It has been observed that local water bodies are fed by modern urban and roadway drainage systems that receive stormwater directly.[8] TWPs may be retained temporarily in the lowest points of stormwater collection systems,[143] due to low water flow and high density of TWPs, but during high flow and turbulent storm water events, they may be resuspended into the water and may be ultimately carried into surface water systems.[144] Though numerous studies have reported the fate of conventional microplastics in the wastewater treatment plants, highlighting their transfer from water to sludge,[122,145–147] studies regarding the fate of TWPs are scarce. Sewage sludge is applied to agricultural soils,[148] which may lead to mobilisation of TWPs in soil or distribute them by wind or surface runoff to the aquatic environments.[40]

TWPs and associated chemicals may be carried into the surface drinking water sources *via* air transport and surface water runoff.[100,149] The feed sources, like surface water or seawater, that supply water to drinking water treatment plants may contain microplastics, including TWPs.[150] Though drinking water treatment plants may remove 70–80% of microplastics (100 μm) with effective technologies like membrane filtration, the types and levels of treatment plants vary widely, and their effectiveness in removing TWPs is still very poorly known.[8]

Benzothiazoles, polyaromatic hydrocarbons, vulcanisers, antidegradants, antiaging chemicals, aromatic and paraffinic oils, formaldehyde, styrene butadiene rubber and metal ions like zinc[24,27,84,119,151] are the chemicals that have been known

to get leached or released from tyres in the environment. Although tire particles are relatively durable over time, the processes of manufacturing and ageing alter their chemical additives, leading to the formation of complex mixtures of tire-related pollutants in the environment.[62,118,152,153] Such pollutants are eventually transported to the nearby urban ecosystems by urban runoff.[62,118,153–155] Moreover, the TWPs released to soils, roadside dust and surface water continue to release additive chemicals, which are eventually taken up by the living organisms. Numerous chemicals or additives, or transformation compounds known or related to tire manufacturing or TWPs have been highlighted by earlier studies.[156]

The fate of TWPs released to the air may be highly complex. City settings contain a mix of tire-derived pollutants along with various traffic-related contaminants such as nitrogen oxides and ozone produced by photochemical smog.[156] In the atmosphere, volatile substances and particles are created by evaporation and subsequent condensation of semi-volatile organic compounds, which react with atmospheric species, such as OH radical, ozone and oxides of nitrogen under UV light. These interactions may lead to the production of cancer-causing, harmful nitrosamines formed when oxides of nitrogen react with molecules containing amine groups derived from tire particles.[149,157] Additional tire additive chemicals that may affect atmospheric transport include 2,2,4-trimethyl-1,2-dihydroquinoline (TMQ), 4,4′-dithiodimorpholine (DTDM), and tetramethyl thiram disulfide (TMTD); however, their environmental behaviour and movement remain largely unclear.[157] The harmful tire additive chemicals like 6-PPD quinone and 4-aminodiphenyl amine (4-ADPA) were detected in the air samples taken at a distance of 5–30 meters from the road with concentrations estimated as 2.90 ng L^{-1} for 6-PPD quinone and 1.14 ng L^{-1} for 4-ADPA indicating a possible risk to both human health and other organisms.[158] Although exposure levels are generally greater near roads, the atmospheric lifetime of tire particles lasting up to 28 days allows tire-related chemicals to disperse over long distances, leading to contamination in far and remote areas.[111]

Numerous chemical properties and system-specific factors influence the magnitude of leaching of the additive chemicals from TWPs. Such factors majorly comprise hydrophobicity, diffusivity, polarity, structure, properties of tire material, *e.g.*, chemical composition, surface alterations, ageing/weathering related alteration, particle surface area and size, and location and binding interactions of the chemical to the tire matrix.[156] Moreover, factors within leachate generation systems impact the boundary conditions for mass transfer and thermodynamic equilibrium. These factors include the liquid to solid ratio during mixing conditions, temperature, and the characteristics of the water phase, such as pH, salinity, presence of co-solvents, organic matter or infinite sink scenarios. Due to the influence of these variables, concentrations of the specific chemicals in the leachate can vary significantly between studies. For instance, variations in temperature or turbulence or flow have been shown to notably affect the toxicity of tire leachate.[159] High molecular weight hydrophobic compounds like polyaromatic hydrocarbons and 6PPD have been reported to sorb to natural sediments.[160] Moreover, the leaching of metallic ions like zinc has been observed to increase in acidic conditions and fresh water due to the direct impact of pH and ionic strength on the solubility of metal ions.[58,161,162]

It has been reported that the chemicals in tire wear leachate may undergo reactions and transformations.[156] Although transformation products are commonly determined in laboratory experiments, interpreting the temporal changes in these complex mixtures and accurately mimicking the environmental conditions in the lab are challenging. Many studies report leachate concentrations and sometimes calculate an aqueous loading (μg of a chemical per gram of tire in a solution), which considers the mass of a tire and liquid-to-solid ratio used during leachate generation (expressed as μg per L × g tire per L). However, this measure doesn't reflect the total mass of chemicals present in the system, which depends on both the tire mass and chemical concentration within the rubber phase. For studies that provide the solid phase concentration (μg chemical per gram of tire), it is possible to calculate the fraction or percentage of chemical leached into the solution by dividing the chemical amount in the solution by the solid phase concentration and multiplying it by 100, as reported by Mayer *et al.*[156] Environmental ageing and weathering of tire material can reduce the amount of leachable chemicals like benzothiazole,[160] making certain organic compounds such as *N*-cyclohexylbenzothiazole-2-sulfenamide (CBS), *N*-(1,3-dimethylbutyl)-*N*′-phenyl-1,4-phenylenediamine (6-PPD), and 1,3-diphenylguanidine (DPG) less reliable as markers of tire pollution in environmental samples.

4. Ageing and environmental transformation of TWPs

Right from the beginning, when TWPs are generated from the tires on the road surface, the environmental factors like light and temperature influence their ageing and transformation in the environment.[163] After the generation, TWPs are transported to the different environmental compartments, including roadside dust, atmosphere, soil and water, due to atmospheric dispersion or rain and stormwater. Soon after their transportation, processes like photooxidation, ozonation, additive leaching and degradation due to microbes start to initiate and finally they may end up in the sewer and aquatic systems (Fig. 3).[8] A further mechanical shear stress due to environmental factors enhances the breakdown of particles, but at the same time, aggregation may also occur. In the water systems, the inorganic and organic constituents in TWPs may leach additives into the surrounding environment. The fine fraction of TWPs in the atmosphere is transported along with the wind, and eventually, the volatile organic components in them may evaporate. TWPs in the environment are relatively stable and persistent, but as mentioned above, they may undergo numerous physical and chemical changes under the influence of processes like phototransformation, oxidation/reduction, hydrolysis, biotransformation and

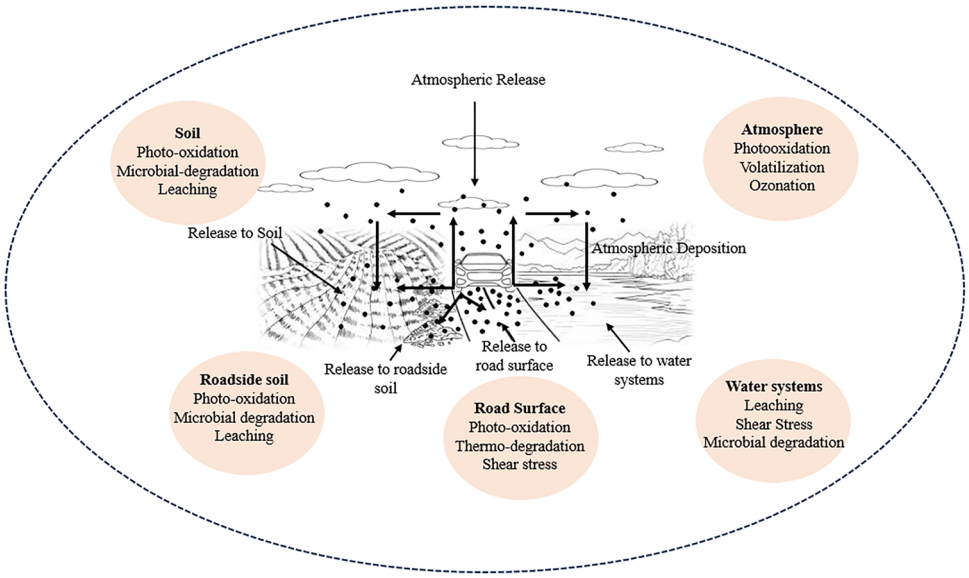

Fig. 3 Diagrammatic illustration of the ageing reactions TWPs undergo after release into different matrices and ultimately reaching water systems. Adapted from ref. 163, licensed under CC BY 4.0, copyright 2021. Changes have been made to the original figure.

mechanical degradation.[52] Tire rubber may undergo cracks and crazing because it is susceptible to ozonolysis or oxidative cleavage of C═C double bonds present in it.[164] Tire particles may also undergo thermal degradation due to high temperatures up to 60 °C reached on the asphalt paving.[165] A handful of studies have currently analysed the effect of weathering on the physical properties of TWPs, with most of them focusing on bulk tire material or conventional microplastics.

The specific surface area of TWPs is significantly impacted by photoaging, which facilitates chemical release from TWPs. A study by Fan *et al.*[166] showed a 55-fold increase in the surface area of tire wear particles collected from a recycling facility, compared to 13-fold increase in the surface area of conventional polypropylene microplastics. Another study by Zhang *et al.*[167] also reported an increase in the specific surface area of differently sized TWPs upon exposure to UV-C for 60 days. Concerning this differential amplification in the specific surface area of TWPs compared to conventional MPs, it is explained by the heterogeneous elastomer composition of TWPs as discussed earlier. TWPs contain carbon black, silica, oils, sulfur crosslinks, and metal oxides, unlike conventional MPs, which are chemically homogenous polymers. Upon environmental ageing, TWPs undergo photo-oxidation, thermo-oxidative chain scission, desulfurization, leaching of plasticisers/oils, and exposure of embedded fillers, which generate deep microcracks, voids, and porous domains.[163] This exposure and partial detachment of carbon black and silica aggregates substantially increase micro- and nano-scale roughness, thereby enhancing the overall surface area. In contrast, conventional microplastics primarily undergo surface-layer oxidation without significant internal fragmentation, due to their semi-crystalline, hydrophobic structure, resulting in only a modest increase in their surface area.[168] TWPs display orders-of-magnitude higher surface physical restructuring, making this behaviour mechanistically expected for rubber-based composites. Despite this mechanistic understanding of why TWPs age more aggressively than conventional MPs, there remains a substantial knowledge gap regarding how prolonged weathering, microbial colonisation, and biochemical degradation further modify the physicochemical properties of TWPs, which eventually influence not only particle morphology and fragmentation patterns but also the release of associated contaminants, surface reactivity, and bio-eco-toxicological behaviour.

Additive leaching and transformation is one of the other major concern related to the life cycle of tire material. Tire additive chemicals may be released from the surface or inside of the tire, TWPs and undergo transformation and degradation in the gaseous or dissolved phase after their release from the polymer matrix. Reactions like thermo-oxidation, photo-oxidation, ozonolysis, biodegradation, shear stress and hydrolysis are the common ones that influence such transformation or degradation processes.[169] Processes like hydrogen abstraction, radical formation, oxygen addition and formation of ketones and carbonyls like polar functional groups may also occur, leading to an increase in the chemical polarity of the TWPs in the environment post weathering.[170,171]

TWPs may be transported to the receiving waters along with stormwater or road runoff on a rainy day. In such environments, processes like photooxidation, ozonolysis and thermal degradation may decrease due to low oxygen availability, low temperature and attenuation of light and turbidity with depth in water but at the same time after coming in contact with water, the dominant transformations in TWPs due to the leaching of additives, hydrolysis and microbial degradation, may increase many folds. As a result, such additive chemicals may be carried to nearby water systems, including sewers, treatment facilities, *etc.*, where they have already been reported by many studies.[100,149,172,173] Weathering-associated transformation of

tire wear additive chemicals may sometimes drastically transform their chemical nature and signature, which may eventually alter their toxicity in the environment. One of the prime examples is the transformation of *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine (6-PPD) to *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine quinone (6-PPD-quinone). 6-PPD-quinone is a transformation byproduct of 6-PPD, which is used as an antioxidant[153,174,175] in tires during their manufacturing process. Upon reaction with ozone, 6-PPD transforms into 6-PPD quinone, which is one of the highly toxic compounds that have been proven by numerous studies.[176–179]

In conclusion, the environmentally driven leaching and transformation of tire additives are governed by fundamental polymer degradation chemistry, diffusion process, and the contrasting oxidative-hydrolytic conditions of terrestrial and aquatic environments. These transformations not only mobilise additives far from their sources but also generate new, often more toxic transformation products, with 6-PPD-quinone serving as the most prominent example. Understanding these underlying mechanisms is therefore essential for predicting the environmental fate, transport, and ecological impacts of TWP-associated chemicals.

5. Environmental compartments of concern

5.1 Airborne TWPs in the atmospheric particulate matter

Non-exhaust vehicular emissions, especially TWPs, are significant sources of atmospheric particulate matter (PM).[128,180] Although only 0.1–10% of total tire mass becomes airborne,[86,181] their small size, chemical complexity, and toxicity make them a global concern. TWPs predominantly occur within respirable fractions PM10 and PM2.5.[11,182]

Estimates suggest that road transport contributes about 10–15% of ambient PM10,[183] with tire wear accounting for roughly 0.3–4.5% (which is 5–31% of the road transport contribution).[184] Source apportionment studies show tire contributions of 5–6% to ambient PM10 and 0.1–0.4% to PM2.5 near heavy traffic zones.[185] National reports show similar results; *e.g.*, Germany (3.1% PM10, 4.6% PM2.5),[186] the UK (4% PM10, 2% PM2.5),[187] and South Korea (3–7%).[188] Similar values are observed in Switzerland (1.8–10.5%)[16] and China (6.6%).[189]

Deposition rates near highways range from 100 to 30 particles cm^{-2} day^{-1}, equivalent to 7.8–2.8 mg m^{-2} day^{-1}.[190] TWPs have also been detected in remote marine air (35 ng m^{-3}) and even in spider webs used as passive collectors.[191,192] Overall, TWPs contribute modestly by mass but significantly by number to urban and roadside PM, emphasising their role in non-exhaust air pollution.

Although airborne TWPs form only a modest fraction of PM10–PM2.5 mass, they dominate particle numbers because of the tribochemical, thermomechanical, and aerodynamic behaviour of vulcanised rubber. At the tire–road interface, intense shear, cyclic loading, and flash temperatures drive tribochemical fragmentation, producing thin films, fibrils, and microfragments rather than large chips, while carbon-black/silica fillers create stress concentration points that favour submicron particle detachment.[57,86,193–195] Rubber's low density means that for a given emitted mass, a far larger particle volume and number is generated compared to mineral or metallic debris.[193] Its viscoelastic nature dissipates energy and suppresses brittle fracture, inherently biasing emissions toward particles of $\leq$10 μm.[86,194] Thermal softening (80–120 °C) and filler-reinforced micro-domains further promote fine-scale tearing instead of coarse fragmentation.[193] Road dust inclusions act as micro-cutters, enhancing abrasive efficiency and increasing the yield of fine wear particles.[196] After emission, oxidative and photochemical ageing, driven by ozone cracking, UV-induced chain scission, and thermo-oxidative embrittlement, lead to secondary fragmentation, shifting particle sizes into respirable fractions.[163] Their irregular, porous morphology yields low settling velocities and long atmospheric residence times, enabling transport far beyond roadways.[197] Collectively, these physicochemical processes explain why TWPs contribute modestly to mass but disproportionately to atmospheric particle number concentrations.

5.2 TWPs in aquatic systems

Quantifying TWPs in aquatic environments is challenging due to the lack of standardised analytical protocols.[198,199] Current methods include optical microscopy, spectroscopy, and advanced techniques such as TED-GC/MS and LDIR imaging.[200–202]

Globally, TWPs have been reported in runoff, snow, and sediments, with the highest levels in industrialized regions. Concentrations reach up to 44 749 particles L^{-1} in Swedish runoff and 14 500 mg L^{-1} in Norwegian snow.[19,203] Sediment concentrations range from 7515 particles kg^{-1} in U.S. urban bays to 240 g kg^{-1} in German wetlands.[204,205] TWPs are largely absent from Antarctic ice but have been detected in Greenland (3.2 μg L^{-1}), suggesting potential long-range transport.[206]

Their black carbon content ($\sim$30%) enhances light absorption and may accelerate snow and ice melt, contributing to positive climate feedbacks.[207,208] TWPs are particularly abundant in runoff channels, constructed wetlands, and estuaries; hotspots linked to vehicular activity.[198,209,210] However, data from lakes, rivers, and oceans remain sparse. Harmonized monitoring protocols are urgently needed for reliable global comparisons.

TWPs enter aquatic systems primarily through stormwater transport, where high runoff shear stress mobilises freshly generated particles from road surfaces.[57,211] Their intermediate density promotes suspension in turbulent flow, enabling rapid downstream transport into drains, rivers, and estuaries.[212] Hydrophobic elastomer matrices and embedded fillers exhibit strong adhesion to organic-rich sediments, which explains their high accumulation in depositional zones such as wetlands and estuaries.[213,214] Fine TWPs are preferentially mobilised due to low settling velocities, whereas coarser fragments remain near road edges or storm drains.[129] Ageing processes, such as oxidation, plasticiser leaching, and surface embrittlement, alter density and wettability, thereby enhancing fragmentation and

redistribution in water bodies.[163] High concentrations in snow arise from the efficient scavenging of airborne TWPs, which are later released during a meltwater pulse and their carbon black content enables strong solar absorption, leading to localised heating and accelerated melting of snowpacks where they accumulate.[215] Long-range atmospheric transport and subsequent wet deposition explain detections in Greenland despite low regional emissions.[111] Spatial hotspots near urban infrastructure reflect traffic density, drainage design, and hydraulic retention times in engineered systems. Overall, hydrodynamic transport, particle–surface interactions, atmospheric deposition, and physicochemical ageing jointly control TWP behaviour in aquatic environments.

5.3 TWPs in soil and sediments

TWPs accumulate in soils through atmospheric deposition, surface runoff, and sewage sludge application.[216] Concentrations decrease with depth, remaining mostly in surface layers where they are retained by soil structure.[217] Measured levels range from 155–15 898 mg kg^{-1} (SBR-based) and 413–44 812 mg kg^{-1} (Zn-based) near roads.[34]

While traffic intensity often predicts TWP levels, local conditions such as drainage and soil type can override this influence.[80] TWPs also alter soil physical and microbial properties, affecting pH, aggregate stability, respiration, and nitrogen cycling.[218,219] Elevated emissions of CO_2, N_2, and N_2O linked to TWP exposure suggest potential roles in greenhouse gas fluxes and soil fertility decline.[219] Despite these findings, knowledge on terrestrial TWP ecotoxicity and standardized detection methods remains limited.

Although TWPs accumulate in soils and sediments through atmospheric deposition, surface runoff, and sewage sludge application, their fate is influenced by several physical and environmental processes that determine their distribution, retention and ecological effects.[11] TWPs delivered by runoff or deposition tend to remain in surface soil layers because their relatively low density and hydrophobic/elastic nature reduces downward mobility, and because soil pore-space structure physically traps irregular rubber fragments. Field studies have reported high concentrations in roadside soils near roadsides, which decrease with distance and depth as particles become more diluted through soil mixing and wind/rain deposition gradients.[220]

In addition to physical entrapment, TWPs also affect the soil's physicochemical and microbial properties. Laboratory experiments conducted across 59 diverse soils demonstrated that TWP addition altered water-stable aggregate stability, soil pH, microbial respiration, and decomposition rates, with the magnitude and sign of the effects strongly modulated by soil texture, bulk density, and land-use intensity.[218] These results highlight that local soil characteristics, not just proximity to traffic, strongly influence how TWPs behave in terrestrial systems. Moreover, recent bioretention-column experiments have shown that TWP exposure can disrupt nitrogen removal processes. After prolonged TWP contamination, nitrification and denitrification rates declined, the organic matter content changed, and emissions of greenhouse gases were altered, indicating potential impacts on soil fertility and nitrogen cycling.[221]

In summary, a combination of delivery (deposition, runoff, and sludge), physical trapping (soil structure, density, and porosity), and soil-dependent interactions (texture, density, and microbial activity) controls TWP accumulation in soils and sediments. The resulting high concentrations near the roadside and changes in soil function underscore the urgent need for more standardised direction methods and broader ecological assessments of TWP fate in terrestrial ecosystems.

5.4 TWPs in biota

The widespread presence of TWPs and their additives poses toxicological risks to both aquatic and terrestrial organisms. Evidence of ingestion and accumulation has been reported in species including fish, mussels, and benthic invertebrates.[11,89,222,223] Unice *et al.*[224] confirmed TWP uptake in sediments and organisms near high-traffic zones, indicating potential for entry into food webs.

Leachates from TWPs contain toxic compounds such as 6-PPD-quinone, which causes acute salmon mortality.[225,226] Nano-sized TWPs (<1 μm) and leachates exhibit higher toxicity than larger particles, impairing growth, reproduction, and swimming behaviour in model organisms like *Brachionus plicatilis*.[227] While data on direct trophic transfer of TWPs are limited, studies on microplastics suggest this is plausible.[228–230]

Chronic exposure to TWPs and their transformation products may disrupt food webs, harm the health of organisms, and introduce persistent contaminants into higher trophic levels. Ongoing research on bioaccumulation, sublethal effects, and improvements in detection methods is crucial for assessing ecological risks.

TWPs enter organisms primarily through ingestion and adsorption, driven by their small size, organic content, and resemblance to natural food particles. Filter feeders and suspension feeders (*e.g.*, mussels, rotifers) unintentionally take up TWPs during feeding, as particles fall within their ingestible size range (1–100 μm) and accumulate in digestive tissues.[231,232] Once internalised, gut surfactants and enzymes solubilise embedded additives, releasing bioactive chemicals that become bioaccessible in digestive fluids.[233] Nano-sized TWPs cross epithelial barriers more readily *via* endocytosis or paracellular transport, enabling tissue penetration and cellular uptake.[232] Additionally, hydrophobic rubber surfaces adsorb environmental pollutants, acting as vectors that deliver co-contaminants to organisms.[234]

Chemical transformation products, especially 6-PPD-quinone, enter biota through both dissolved-phase diffusion and particle-associated exposure, causing acute toxicity in fish.[235,236] Benthic organisms ingest TWPs during sediment feeding, as TWPs accumulate in depositional zones and are retained in gut tracts.[3] Together, these mechanisms cause bioaccumulation, oxidative stress, behavioural impairment, and reduced growth and reproduction, indicating that TWPs act as both physical particulates and chemical carriers within food web.[237]

Across all compartments, TWPs demonstrate cross-media transport, chemical persistence, and biological reactivity. Nonetheless, quantitative assessment is hindered by inconsistent analytical methods. Developing a unified framework that includes generation mechanisms, physicochemical transformations, and behaviour in compartments is essential to better understand global fluxes and inform mitigation policies. The strategic priority is to develop harmonised monitoring and mechanistic models linking emission, partitioning, and exposure across air, water, soil, and biota.

6. Detection and identification methods

Detection of TWPs in the environment is challenging, requiring high sensitivity and selectivity to accurately measure their concentration in the samples, particularly when sampling sites are located far from emission sources. The detection of TWPs is often hindered by complexities like the matrix effect due to the presence of organics, making the detection process more cumbersome, specifically when dealing with lower or sensitive concentrations. For these reasons, the sampling methods, analytical protocols for TWPs differ totally from the methods and protocols used for the analysis of conventional microplastics or other organic contaminants in the environment. Moreover, the analytical procedures for determining TWPs vary depending on the environmental matrix being studied.

Numerous techniques have been employed to generate, collect and analyse TWPs. However, obtaining accurate measurements remains challenging due to the complex physicochemical properties of TWPs and the difficulty in distinguishing them from background and interfering particles.[238] At this growing stage of TWP research, the influence of various factors such as testing conditions (real world roads *vs.* laboratory setups), vehicle or tyre type, collection methods (suction pump *vs.* adhesive surfaces), sampling location and tube length remains poorly understood and inconsistently reported. As a result, identifying the most reliable and standard methods for TWP measurements is still uncertain. Continued experiments and refinements of techniques will be essential to determine the most effective approach or combination of methods. For the determination of TWPs in different environmental matrices, the analytical procedures that may be followed or implemented may depend on the characterisation and analysis of the tire rubber itself or different types of additives (both organic and inorganic) used as markers, added during the tire manufacturing process to improve their performance or are produced unintentionally during the production process.[52] These additives may include elements like Zn, S, Sr, Pb, Cr, As, Ni *etc.* or organic compounds like polyaromatic hydrocarbons (PAHs), benzothiazoles sulphonamides (BTZ), diphenyl guanidine (DPG), hexamethoxymethyl amine (HMMA) or *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine (6PPD) *etc.* and their secondary degradation of transformation products like 6PPD quinone.[239] Numerous sophisticated analytical instruments have been utilised to detect and analyse tire rubber itself or different types of organic or inorganic additives, including but not limited to ICP-OES, FTIR, Py-GCMS, LC-MS, TED-GC-MS, *etc.*[34,240–242] in different types of environmental matrices. Recently, machine learning (ML) and artificial intelligence (AI) have also emerged as promising tools for determining and analysing TWPs and their additives in complex environmental matrices.[243–247] In the following sections, we will discuss all these analytical techniques in detail and also point out the potential analytical challenges and gaps that need further improvement or where additional research needs to be carried out.

To determine the concentration of TWPs in the different types of environmental samples, like soil, water, biota and air, the key or potential markers used are styrene butadiene rubber or nylon rubber. In addition to this, different types of additive markers can also be used, as we already discussed before. However, for a marker to be selected for the analysis or detection of any target contaminant, different criteria points should be met before choosing a marker to analyse a particular target contaminant, like TWP.[77] The first criterion that should be met is that the marker should be present in all the parent material, tyre, irrespective of the manufacturing process or the manufacturer's company or industry. The second characteristic feature of the marker should be that it should not leach easily from the parent material in any type of environmental condition. Moreover, there should be no transformation in the marker compound irrespective of the residence time or duration of the parent tire material in the soil, water or air. Furthermore, the marker should be specific to the parent tire material and not come from the traffic-related ambient environment like particulate matter, brake dust, surface runoff or roadway particles. In addition, the marker should be present in a significantly higher concentration than the analysis matrix, such as soil water, air, dust, biota *etc.* Finally, the most crucial criterion is detecting the marker quickly from the analytical perspective. The selected or chosen marker should be analytically accessible by standard detection methods, with higher precision, accuracy, and sensitivity when reasonable analytical efforts are made.

The accurate quantification of TWPs across various environmental matrices, including road dust, water, sediments, air, and biota, requires harmonised sampling and extraction strategies. However, methodological heterogeneity remains a significant obstacle to inter-study comparability. Sampling protocols differ considerably depending on site characteristics, particle size range, and target compartments, often resulting in variable recovery and contamination risks.

In road dust and sediments, mechanical and vacuum-based samplers (*e.g.*, vacuum cleaners, spatulas, and grab samplers) are commonly used to recover deposited TWPs.[17,20,23,37,248–252] Dry sampling ensures high recovery efficiency, whereas wet collection helps elucidate runoff dynamics but can lead to the leaching of organic additives.[251] In aquatic environments, grab and pump-based methods enable surface and columnar sampling,[20,253–260] but the heterogeneity of suspended *versus*

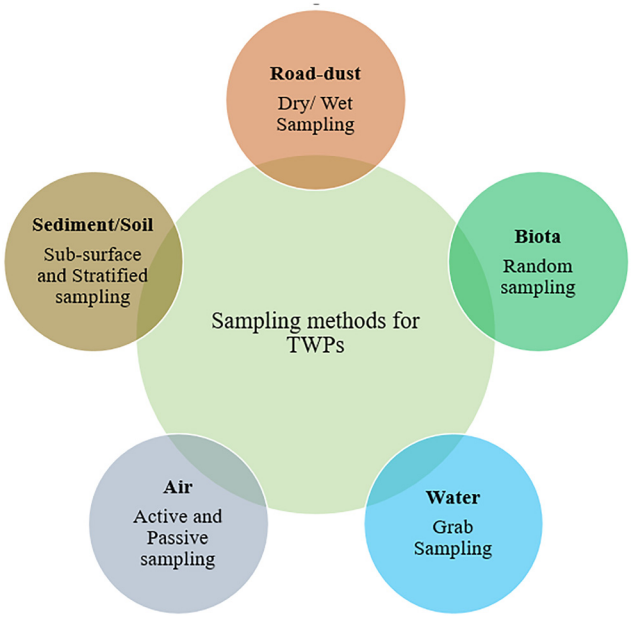

Fig. 4 Diagram representing the sampling methods used for sample collection across different matrices.

settled fractions introduces uncertainties. The use of Niskin bottles and automated samplers is increasing for depth-specific collection, while snow and microlayer sampling have recently emerged as proxies for studies of seasonal and surface exposure.[19,261,262] In sediments, tools such as Van Veen and Ekman grab samplers, as well as corers (gravity, piston, or vibrocorers), are preferred for assessing vertical TWP distribution and accumulation history.[129,263–271] Yet, sediment disturbance, limited depth resolution, and particle distribution remain challenges.

Airborne TWPs are collected *via* active filtration (*e.g.*, quartz, Teflon, or Al_2O_3 filters) and passive deposition (*e.g.*, tree bark, adhesive surfaces), each with trade-offs between capture efficiency and selectivity.[82,272–278] In biota, hand-picking and netting (*e.g.*, trammel or seine nets) are used for organisms such as fish, mussels, and earthworms;[89,258,279–282] however, contamination control and depth-specific sampling are often overlooked.

Extraction strategies vary with matrix complexity. Clean matrices (air, snow) require minimal treatment, while complex matrices (sediments, biota) demand multistep purification. Density separation using NaI or sodium polytungstate (ρ = 1.8–1.9 g cm^{-3}) remains the most common approach,[199,249] though salt interface and incomplete separation persist.[283,284] For organics-rich matrices, chemicals (H_2O_2, HNO_3, Fenton's reagent) or enzymatic digestion (protease, lipase and chitinase) is applied,[18,285,286] albeit with risks of polymer degradation. Biological tissues are often digested with KOH or NaClO to preserve TWP structure.[89,279,282] Alternative methods, such as magnetic separation[287–289] and pressurised liquid extraction,[290,291] show promise for selective recovery but lack standard validation. Extraction steps, such as centrifugation and filtration, may also bias particle count or integrity.[285–289,292–295] Hence, developing matrix-optimised and minimally invasive extraction workflows is vital for reliable TWP quantification.[296,297] Fig. 4 shows sampling methods used for sampling across different environmental matrices for TWP analysis.

A detailed comparative overview of the existing sampling and extraction methods across various matrices is provided in Table 2.

Despite progress in developing matrix-specific methods, a lack of harmonised sampling and extraction protocols remains a major obstacle in TWP research. Variability in recovery efficiency, contamination control, and digestion selectivity impedes cross-study comparability. The adoption of standardised workflows integrating contamination control, validated density media, and non-destruction digestion techniques will be critical for producing robust, reproducible data sets and enabling reliable mass balance and fate modelling of TWPs in the environment.

Table 2 Summary of the comparative overview of the existing sampling and extraction methods across various matrices

Matrix	Sampling techniques	Extraction/pretreatment methods	Advantages	Limitations/challenges	Ref.
Road dust	Vacuum cleaners, wet/dry samplers, brooms, spatulas	Air drying, sieving, density separation (NaI, $ZnCl_2$)	Simple, cost-effective, high surface recovery	Cross-contamination; loss of volatiles; leaching under wet sampling	17, 37, 203, 249–252, 298 and 299
Water/ runoff	Grab sampling, telescopic tools, submersible pumps, Niskin bottles, robotic samplers, snow corers	Filtration, centrifugation, density separation (NaI, $ZnCl_2$), organic matter removal	Captures suspended and dissolved phases; adaptable to flow	Variable depth profiles; clogging; incomplete recovery	19, 20, 253–255, 258, 259, 261 and 262
Sediments/ soil	Scoops, Van Veen grab sampler, Ekamn dredge, piston/gravity/ vibrocorers	Density separation, enzymatic/chemical digestion (H_2O_2, Fenton's)	Enables temporal/ spatial profiling; large volume	Sediment disturbance; incomplete organics removal; polymer alteration	18, 20, 129, 263, 265, 268 and 300–302
Air	Active: filter based (quartz, Teflon, Al_2O_3); passive: bark collectors, adhesive films	Direct filter analysis (FTIR, Raman, TD-GC/MS)	Captures respirable particles, long-term monitoring possible	Low efficiency for <1 μm particles; filter re-entrainment; substrate interference	82, 269–274, 276, 278, 303 and 304
Biota	Hand-picking, fishing using trammel/seine nets, electrofishing	KOH/NaClO digestion, freeze-drying, tissue extraction	Allows trophic transfer assessment	Risk of cross-contamination; incomplete digestion	89, 258, 279–281 and 305

7. Analysis of tire wear particles

Following the extraction of tire and road wear particles, their analysis presents several challenges, primarily due to inadequacies of current methods, which are often optimised for traditional microplastics. Detecting and quantifying TWPs at concentrations typically found in the environment requires highly sensitive techniques. However, many such methods are either prohibitively expensive or require specialised instruments that are not widely available.[286] The choice of an analytical method largely depends on the specific objectives of the study, whether it's to assess particle size, morphology, elemental or organic composition, mass, or particle count.

Understanding both the physical and chemical characteristics of TWPs is essential, as these properties influence their environmental behaviour and potential toxicity. Importantly, TWPs span a wide size spectrum, ranging from nanoscale to several millimetres in size. No single technique can comprehensively analyse this entire range. As a result, integrating approaches combining multiple complementary methods are often required to accurately characterise TWPs and determine their mass-based concentrations.[306] Tools such as microscopy, spectroscopy, thermal analysis and most recently, machine learning and artificial intelligence have been commonly employed for this purpose.[115,245,307] A schematic overview of all the current analytical techniques is given in Fig. 5, and a description and summary of the currently existing analytical techniques, along with their advantages and disadvantages, is given in Table S2.

8. Challenges and limitations

8.1 Analytical challenges

The diverse characteristics of TWPs, including their size, shape, density, texture, elemental and chemical composition, create analytical challenges and complicate detection and classification workflows. Analysing TWPs in complex aqueous matrices is critically challenging due to their heterogeneous composition, making them difficult to identify and isolate from other particulate matter, like road dust, brake wear particles and other microplastics. For instance, black microplastics and carbonaceous materials from combustion sources may have similar infrared absorption bands or thermal degradation profiles to TWPs. This similarity may further complicate the application of common techniques like TGA and FTIR, which rely on specific thermal or spectral signatures for identification of the analyte of interest. Such types of complications can be observed even with advanced and highly informative instruments like Py-GCMS, due to the presence of similar pyrolytic products from other rubber or plastic materials.[14] Compound-specific markers, *viz.* styrene butadiene rubber pyrolysis products or zinc as a tracer, along with chemometric approaches, can improve selectivity for TWP detection in complex matrices.[308] Sometimes, ML-assisted classification to differentiate TWPs from other particulate matter can also help in improving selectivity.[245] In order to achieve reliable source apportionment, accurate quantification and risk assessment of TWPs in environmental samples, enhancing selectivity is always pivotal.

Another challenge faced during the TWP analysis is the detection sensitivity of the analytical methods, owing to the trace level concentrations of TWPs in the collected samples such as soil, air, water and sediment. Detection of TWP markers like styrene butadiene rubber, normal rubber, carbon black, zinc and various other additives at environmentally relevant concentrations may be challenging due to the signal suppression or interference from co-existing substances like road dust, organic matter, other microplastics or inorganic particles like dust and soot. Environmentally relevant concentrations of TWPs in samples produce weak or overlapping spectral signals in techniques like FTIR or Raman spectroscopy, which makes it challenging to differentiate them from the background noise.[309] Similarly, techniques like Py-GC/MS or TGA can be used to identify TWP-related thermal or chemical signatures when there is a low particle load or masking by other material. Integrating diverse analytical methods can improve detection consistency by combining the assets of each technique, for instance, the structural specificity of spectroscopic tools (*e.g.*, FTIR, Raman) with the chemical sensitivity of thermal or mass spectrometric approaches (*e.g.*, Py-GC/MS,

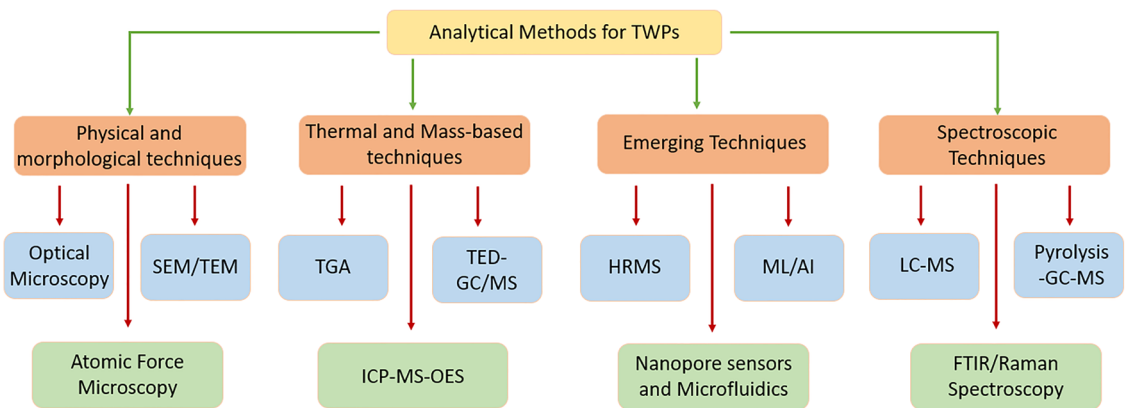

Fig. 5 A schematic overview of all the current analytical techniques for the detection and analysis of TWPs and additive chemicals.

TGA-MS), thus refining the identification and quantification of TWPs even at trace levels in complex environmental matrices.

For sensitivity improvement, the methods or procedures like pre-concentration, selective extraction or signal enhancement strategies (*e.g.*, surface-enhanced Raman scattering) may be helpful.[310,311] Furthermore, the integration of ML may prove handy in amplifying detection capabilities by recognizing subtle patterns in complex datasets. It is very essential to have a high sensitivity for the assessment of environmental contamination with higher accuracy, as it is pivotal for evaluating regulatory thresholds and tracking the fate and transport of TWPs in the ecosystem. Without adequate sensitivity, the risk of underestimating TWP-associated environmental risk and health impacts remains at the forefront.

As TWPs in the environment are rarely found in isolation, the effects from the matrix they are present in (soil, dust, sediment, water, air, organic matter) may create analytical challenges in the detection, quantification, and identification of TWPs. There can be physical interference as the TWPs in the matrix may resemble the matrix constituents in size, shape, and morphology, hence, it may be visually or instrumentally difficult to distinguish the particles. Chemical interference may be due to the compounds present in the matrix that suppress or enhance chemical signals during the analysis using spectroscopy or FTIR analysis, leading to inadequate quantification or misidentification. Instrumental contamination may be possible due to complex matrices resulting in fouling or memory effects, especially during spectroscopic analysis, which may hamper sensitivity or reproducibility. Sample preparation for TWPs is always labour-intensive and error-prone as the extraction and purification processes in complex matrices is always challenging.

8.2 Lack of standardized protocols

One of the major challenges currently faced by researchers during TWP research is the lack of a standard protocol for identification and analysis. Currently, there is hardly any harmonised or universally accepted protocol or method for sampling, extraction, identification and quantification of TWPs. This is one of the biggest challenges in this research field, leading to data inconsistencies and limited comparability of the generated data. Inconsistencies in sampling methods, extraction procedures, identification methods, quantification metrics and reference materials exist, limiting reliability, accuracy and comparability of the results. This underscored an urgent need for international standardisation to advance both research and regulatory monitoring.

8.3 Differentiation from other microplastics and particles

Another major challenge faced during TWP analysis is to differentiate them from other microplastics and particulates due to their overlapping physical and chemical characteristics, especially in complex matrices like road dust, sediments, water and soil. Differentiating TWPs from other microplastics and particulates is pivotal in the context of source identification, risk assessment, and control of pollution. Numerous factors like similar composition of TWPs with other rubber and microplastic particles, overlapping morphology with soot, char or degraded plastic fibres, high carbon black content making spectral differentiation difficult, environmental alteration and lack of unique markers make it difficult to distinguish them from other microplastics and particulates.

To accurately and promptly differentiate TWPs from other microplastics and particulates, there is a need for the integration of multiple analytical techniques, such as SEM-EDX, Py-GC/MS, and ML-assisted classification. Such methods may effectively help to overcome limitations in visual, chemical and spectral similarity.

8.4 Advancing analytical strategies to enhance the detection and characterization of TWP

Analytical approaches for TWP research must evolve towards methodologies that are harmonised, multimodal, size-inclusive, and chemically explicit. Existing studies still rely on highly heterogeneous procedures for sampling, isolation and identification, resulting in datasets that are difficult to compare and insufficient for quantitative exposure or risk assessment. Below, we outline how current limitations can be addressed and how emerging technologies can be leveraged more efficiently.

In the TWP research, one of the major obstacles is the inconsistency in sampling across different matrices, which leads to inter-study variability. Differences in sampling volumes, mesh sizes, filters, and reporting units hinder meta-analysis. Moreover, the absence of certified reference materials for TWPs prevents adequate method validation. To address this challenge, we recommend developing matrix-specific standard operating procedures, common reporting matrices, and reference materials that represent both pristine and environmentally aged TWPs.

In addition to the above recommendations, there is also a need to shift to the multimodal, interoperable workflows as a single technique can be incompatible to completely capture the complexity of TWPs, heterogeneous polymer blends, weathering states, additives, and encrusted road dust. To achieve this shift, we recommend the publication of end-to-end multimodal workflows, one of the most important future directions in TWP research, which integrates multiple complementary techniques into a single, standardised pipeline, from sample collection to reporting. Such workflows are emerging in the microplastic research but are still largely missing for TWPs, which are more complex, compositionally different, and prone to misclassification.

Moreover, submicron and nano-sized TWPs dominate number concentrations but their detection remains challenging. We recommend the inclusion of method detection limits for the nano-sized fraction using advanced techniques such as atomic force microscopy-infrared spectroscopy (AFM-IR), optical photothermal infrared spectroscopy (O-PTIR), nanoparticle tracking analyser (NTA), single particle-ICP-MS, and surface enhanced Raman scattering (SERS), and incorporating nanoplastic-specific controls. Furthermore, chemical monitoring of additives and transformation products generated from

Tire wear organics (TWOs) in the environment should be targeted as they have already been proven to be toxic. Mass-based techniques such as LC-MS/MS should be utilised for their precise quantification in order to integrate their analysis into TWP workflows.

We further recommend the creation of machine learning and automated classification-assisted open-access TWP spectral and imaging libraries to improve classification accuracy for complex TWPs.

Lastly, real-time monitoring of TWPs in the air should be conducted. This can be achieved by co-locating Single Particle Aerosol Mass Spectrometry (SPAMS) instruments with FTIR/Py-GC/MS pipelines. Additionally, certified reference materials should be developed, and inter-laboratory studies should be promoted. For this, we recommend the development of certified reference materials covering various polymer chemistries and the implementation of international round-robin studies. Table 3 summarises all the recommendations, highlighting analytical gaps with the potent solutions and benefits.

9. Future perspectives and research needs

9.1 Harmonization and standardization of methods

As TWP research has gained momentum over the last decade or so, due to the significant contribution of TWPs to microplastics and associated health risks, it is highly pivotal to develop unified protocols for reliable data production, data reproducibility, and data comparison across studies, regions, and regulatory bodies. Data standardisation in TWP research is one of the key aspects that need to be examined. Enhanced and adequate data standardization may ensure comparability across studies, data integration and quality assurance of the already generated data. Moreover, there is also a need for harmonisation in the key areas in TWP research, like techniques utilised for sampling of TWPs in varying environmental matrices, currently utilised techniques and procedures in particle extraction and isolation, methods used for analysis, reference material, and data reporting.

There is a need for interlaboratory comparisons to validate proposed protocols and assess interlaboratory variability. Moreover, the development of field-deployed methods is also crucial, as it may help simplify methods for application in daily environmental monitoring or citizen science initiatives. Technology integration is also needed with harmonisation and incorporation of artificial intelligence, automation and high-throughput screening methods to streamline workflows and reduce human error.

In conclusion, for advancing TWP research from isolated academic studies to scalable environmental monitoring and regulation, standardisation and harmonisation are of key importance. The scientific research community should focus on multidisciplinary collaboration, create, validate, accessible and globally harmonise protocols supporting both scientific discovery and policymaking.

9.2 Field-deployable high-throughput methods

Field-deployable high-throughput methods can play a crucial role in the advancement and progress of TWP research. Especially when environmental monitoring demands real-time, scalable, and economically efficient approaches. Need for the field deployable analytical instruments that can be directly operated at the site, *e.g.*, roadside, urban runoff, aquatic systems, is highly needed. Such methods may ensure high throughput with minimal manual intervention when it comes to the analysis of a large amount of data. Current methods in the TWP research are highly laborious, non-field deployable, and have low throughput. Working towards the advancement of field-deployable, high-throughput methods may enable real-time monitoring of pollution hotspots with precise temporal resolutions and spatial mapping. They can also play a critical role in regulatory compliance, public risk assessment, and source apportionment. Moreover, they may help in bridging the gap between lab-based analysis and real-world environmental monitoring. The road map in Fig. 6 illustrates the future perspectives and research needs in TWP research.

Focus should be shifted towards the development of portable analytical instruments like FTIR/Raman spectrophotometers and sensors with molecular imprinting polymers, ensuring specific recognition of rubber-related polymers.

Table 3 Highlights of all the analytical gaps with the potent solutions and benefits

Analytical gap	Emerging analytical solution	Benefit	Ref.
Lack of harmonized sampling and QA/QC	Standardized SOPs; matrix-specific protocols; CRMs	Improves comparability, reduces uncertainty	77, 312 and 313
Limited detection of <20 μm TWPs	LDIR, FPA-FTIR, automated FTIR imaging	High-throughput chemical identification	314 and 315
Bulk quantification lacks specificity	Pyrolysis-GC/MS; TED-GC/MS	Polymer and additive specific quantification	14 and 316
Sub-micron and nano-TWPs undetected	AFM-IR, O-PTIR, NTA, SP-ICP-MS, SERS	Access to <1 μm fraction; improved size resolution	16, 317 and 318
Misclassification of aged/mixed TWPs	Machine-learning classification models	High accuracy, reduced subjectivity	16 and 319
Poor temporal resolution in air studies	Single particle aerosol mass spectrometry (SPAMS) and real-time aerosol mass spectrometry	Captures emission dynamics and events	115, 189 and 320
Lack of TWP reference materials	TWP-specific certified reference materials; round-robin inter-lab tests	Enhances validation and reproducibility	14

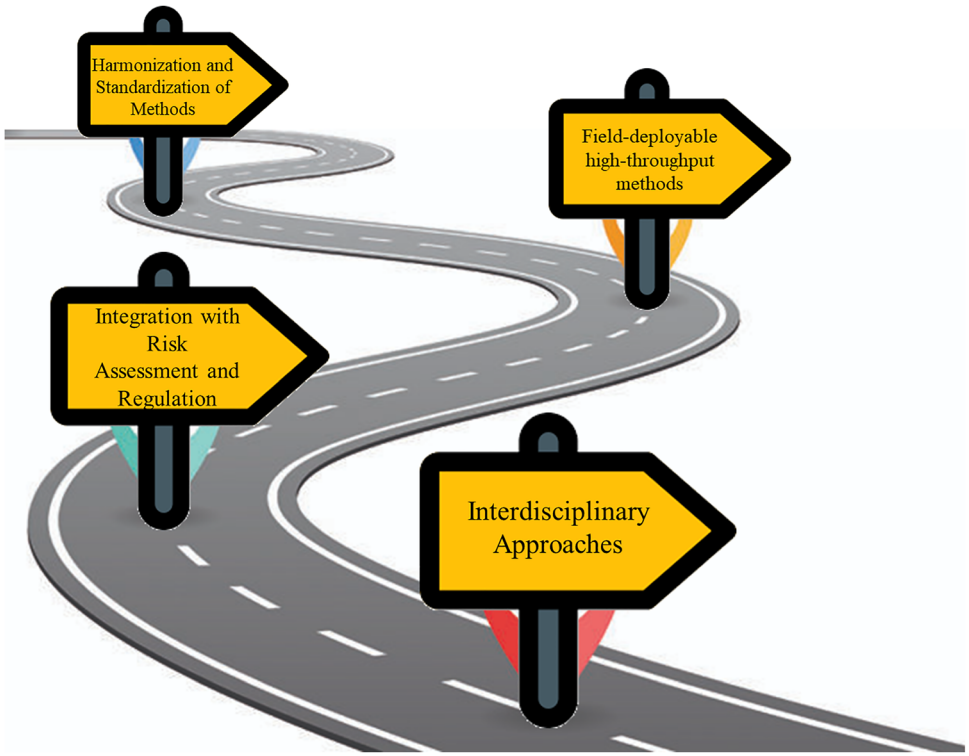

Fig. 6 Future perspectives and research needs to be focused on in future TWP research.

Nanosensors and microfluidic detection methods should be explored more and more, and the integration of ML and AI with the currently existing techniques should be ensured. Investment in sensor innovation and data integration technologies with standardisation will be pivotal in enabling scalable, robust and universally implementable TWP monitoring systems. Future research must stress and focus on the multidisciplinary collaborations, ML integration and sustainably-focused design to meet the growing environmental challenges posed by TWP pollution.

9.3 Integration with risk assessment and regulation

In the TWP research, one of the crucial future directions for ensuring the successful translation of scientific findings into actionable policies in order to safeguard the environment and human health is the integration of TWP research with risk assessment and regulation. Despite numerous pieces of evidence of the ubiquity and potential toxic nature of TWPs and their additive chemicals,[96,162,321,322] they remain largely unfettered due to inadequate data on their exposure pathways, ecological and health risks. In order to bridge this gap, interdisciplinary efforts are needed to align analytical research with regulatory frameworks and risk assessment methodologies.

Currently, there are numerous gaps that hinder the regulation process, which include but are not limited to a lack of exposure data, toxicity uncertainty, source apportionment challenges, and no regulatory limits. There is a growing need for linking analytical data with risk models, ensuring that research evolves beyond detection and quantification to include fate, transport, bioavailability, and dose–response relationships. To learn about the potential impacts of TWPs and their additives under real-world conditions, standardised data must be fed into risk assessment models in a timely manner. There is also a need for long-term ecotoxicological tests and studies on different environmentally sensitive species, by mimicking real-world aquatic, terrestrial and airborne exposure scenarios in order to reveal the risk posed by TWPs or their leached or additive compounds. Policy-driven monitoring frameworks should also ensure the establishment of threshold levels or environmental quality standards for TWPs. This may require universally acceptable data sets and leads from public health and global environmental agencies like the WHO, USEPA, *etc.* Integration of TWP generation with its life cycle and emission inventories will promote regulatory planning and help in mitigation strategies. The development of integrated platforms as decision support tools that may ensure the combination of analytical data, ML, and GIS-based models may help point out pollution hotspots, assess risk, and prioritise policy interventions.

9.4 Interdisciplinary approaches

In order to develop a comprehensive understanding of the environmental and health impacts of the TWPs and their additive or leached out compounds, there is a need for an interdisciplinary approach combining the analytical studies of TWPs and compounds with their toxicological studies. At present, most of the studies related to TWPs focus either on their detection or toxicity in isolation. Integrating both these fields may be insightful from the context of understanding

exposure-risk relationships, mechanistic toxicity, and overall environmental behaviour, which are pivotal in informed risk assessment and regulatory decision framework. Interdisciplinary approaches may further help in linking the composition of TWPs to their toxicity. For instance, analytical techniques like Py-GC/MS, FTIR and SEM-EDX may help in the identification of harmful additives like PAHs, benzothiazoles, quinones, zinc, *etc.*, which a toxicologist can then study for bioavailability and mode of action. Moreover, such approaches may also help in understanding realistic exposure scenarios by generating environmentally relevant particle suspensions, which can be later used for exposure tests. Furthermore, advanced analytical techniques like those omics-based ones can be coupled with chemical characterization to identify the actual cause of toxicity or biological effects. Interdisciplinary collaborations may also foster the development of standardised and reproducible test materials for thorough toxicity studies. Such collaborations may also authenticate accumulation or uptake observed in toxicology studies, while toxicological results can prioritise which particle forms or chemicals must be focused on in environmental monitoring.

9.5 Critical physical chemistry challenges in TWP research

Despite recent progress in analytical detection, several fundamental questions in physical chemistry remain unresolved in TWP research. These fundamental challenges limit our ability to accurately characterise TWPs, understand their environmental transformations and integrate findings into exposure and risk models. Key areas requiring deeper physical chemistry investigations include:

9.5.1 Mechanisms involving thermo-mechanical generation of TWPs. The real-time generation of TWPs is a complex interplay of frictional heating, viscoelastic deformation, oxidative stress, strain-induced crystallisation, and mechanical abrasion. The fundamental gaps in this area that should be addressed include investigations comprehending the effects of temperature gradients and frictional heating on polymer chain scission. In addition, investigating how strain-induced crystallisation affects the fragmentation of tire rubber is what needs to be understood. Moreover, comprehending how different traditional formulations, such as styrene-butadiene rubber, butadiene rubber, and nylon rubber, affect mechanochemical reaction pathways and understanding the contribution of shear-assisted radical formation during tire–road contact, demands investigation. For the development of effective predictive source models and the design of future low-emission tyre materials, a deeper molecular-level understanding is essential.

9.5.2 Interfacial chemistry at the tire–road interface. This nanoscale reactive environment, where the tire meets the road, experiences localised temperatures ranging from 150 to 200 °C, accompanied by strong mechanical shear forces acting within microseconds. Additionally, minerals, metals, and organics in the surrounding dust participate in heterogeneous catalysis. In this environment, certain key questions need to be addressed, including how prevalent road mineral elements, such as quartz, calcite, and asphalt binders, interact with elastomer chains during tribochemical wear. In addition, understanding the role of interfacial adhesion and surface energy mismatch in determining particle size distribution, as well as comprehending the role of silica- or carbon-black-rich microdomains in the TWP detachment behaviour, is vital and demands further investigation. These encompass the base surface chemistry and soft-matter problems, having a direct implication on the formation rates of TWPs.

9.5.3 Segmental dynamics and phase heterogeneity in elastomer composites. As far as tire rubber is concerned, it is a multiphase, as well as microphase, polymer network, including dynamic domains of butadiene-rich elastomeric phases, styrene-rich blocks, natural rubber crystalline regions, and embedded carbon black and silica aggregates. Regarding these dynamic domains, critical questions that remain unanswered are how segmental dynamics and glass transition temperature heterogeneities influence crack initiation and propagation. Moreover, other unanswered questions include how the mechanical stability and weathered particle chemistry of TWPs is impacted by additive migration, including antioxidants, fillers, oils, *etc.* To probe such soft-matter processes, advanced techniques are required, including AFM-IR, O-PTIR, nano-dynamic mechanical analysis, and broadband dielectric spectroscopy.

9.5.4 TWP transformation pathways and ageing kinetics in the environment. As discussed earlier, TWPs undergo oxidation, ozonolysis, hydrolysis, and biodegradation; however, the reaction kinetics associated with these processes remain poorly understood. In this case, key unknowns include the kinetic rate constants and activation energies for the oxidative ageing of SBR, BR, and NR in the natural environment, as well as the rates at which functional groups, such as carbonyls, quinones, and sulfoxides, form. Moreover, how particle hygroscopicity, density and colloidal stability is altered by environmental ageing and the dominant ageing mechanisms in aquatic, atmospheric and terrestrial environmental compartments also remain unknown. Such parameters are vital in determining the fate, stability, transport and toxicity of TWPs and remain poorly comprehended.

9.5.5 Thermodynamics and kinetics of tire additives and leachates, including their partitioning. As discussed earlier tire formulations contain antioxidants, oils, vulcanisation agents, stabilisers, *etc.*, which may interact with water, organic matter, biofilms or tire rubber itself, after leaching. Currently, there exist gaps concerning the thermodynamic models that can better help in understanding the partitioning of such additives with different biotic and abiotic components of the environment. Additionally, there is limited information available regarding the kinetics of slow diffusion through crosslinked rubber matrices, as well as the roles of swelling, sorption enthalpies, and polymer–solvent interactions. There is also a gap in the prediction of time-dependent release of toxic compounds, including 6PPD and 6PPD-quinone. These discussed gaps should be assessed as they are critical for risk modelling and assessment.

9.5.6 Colloidal behaviour of TWPs in aquatic systems. The behaviour of TWPs in aquatic systems is typically colloidal, but their aggregation, dispersion and settling in such environments remains poorly understood. In this context, some critical open questions include investigations related to the zeta potential analysis of pristine and aged TWPs across realistic pH and ionic strength conditions. In addition, studying the impact of biofilm formation on the stability and hydrophobicity of TWPs, and understanding how DLVO and non-DLVO forces control the TWP aggregation in the presence of clay, humics or conventional microplastics. Moreover, the questions addressing the impact of weathering on van der Waals interactions and the Hamaker constant of TWPs have been largely unexplored and remain open. Deciphering and comprehending this knowledge is crucial for developing transport models that can better explain the fate and behaviour of TWPs.

9.5.7 Understanding the morphology and thermodynamic stability of ultrafine TWPs (<1 μm). The formation pathways for ultrafine particle forms, including thermal decomposition, condensation, volatilized organics and mechanochemical degradation, remain unclear. In this context, some key outstanding questions that demand attention include understanding the factors and parameters that govern the growth and nucleation of nanoscale TWPs, the nature of the particles (amorphous or semi-crystalline), and their thermodynamic stability in air and water. As ultrafine particles dominate the airborne toxicity of TWPs, addressing such gaps is crucial.

10. Conclusion

The current review focused on the occurrence, environmental fate and recent advances in the detection and analysis of TWPs found in different environmental matrices. The prevailing knowledge, as summarised from this review, concluded that TWPs are heteroaggregates comprising tire and road-related material with diverse shapes, sizes, densities, morphologies and chemical compounds present in almost all environmental compartments. These traits of TWPs further complicate their identification and quantification in the complex environmental matrices. Concerning the fate of TWPs, their interaction with diverse biotic and abiotic components dictates their fate in the environment. The environmental ageing process, influenced by processes like thermal degradation, photooxidation, ozonolysis, shear stress, and biodegradation, is pivotal in influencing their overall properties. Currently prevailing analytical tools and techniques are insufficient in comprehending the fate of TWPs in the environment and detecting them across complex aqueous matrices. Hence, we endorse the advancement of a standard harmonised method and analytical instrumentation that may ensure the quality and reliability of future studies.

The atmospheric and aquatic cycling of TWPs remains poorly constrained due to significant methodological and conceptual gaps. In the atmosphere, uncertainties in emission factors, limited detection of ultrafine particles, and a lack of standardised source apportionment approaches impede accurate estimation of airborne contributions. In aquatic environments, the absence of harmonised sampling and pretreatment methods, coupled with the influence of aggregation, density variation, and ageing, complicates quantification and modelling. The scarcity of long-term field data and integrated atmospheric–hydrological models further limit our understanding of their transport, deposition, and remobilization. Addressing these challenges will be essential for advancing mechanistic models and risk assessments of tire-derived microplastics. Nevertheless, the sampling procedures across matrices may vary; preserving consistency and reliability during the sampling practices is vital. Integrating different currently existing analytical techniques like microscopy, spectroscopy, with ML/AI may help better identify, quantify and characterise TWPs in complex matrices and enhance selectivity. To achieve a consistent source apportionment and accurate quantification and risk assessment of TWPs in environmental samples, enhancing selectivity is always essential. Field-deployable high-throughput methods can play a crucial role in advancing and progressing, particularly when environmental monitoring demands real-time, scalable, and economically efficient approaches. In conclusion, advancing our understanding of TWPs demands a multifaceted and interdisciplinary approach that bridges analytical chemistry, environmental science, and toxicology. Generating standardised methodologies, refining analytical precision *via* technological amalgamation and incorporation, and aligning scientific efforts with regulatory frameworks are vital steps towards precisely assessing the environmental and health risks of TWPs. Such harmonised efforts will not only augment and supplement the reliability, consistency and comparison of upcoming research but also sustain the progress of informed, science-based policies and guidelines destined to alleviate the effects of TWPs on ecosystems and human well-being.

Author contributions

Zahid Ahmad Ganie: writing original draft, review & editing. Amritanshu Shriwastav: review and editing, supervision.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5sm00823a.

No primary research results, software or code have been included and no new data were generated as part of this review.

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