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Tire emissions during the use phase of tires – current and future trends†

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The ongoing energy transition, marked by notable advancements in electric vehicles, presents new challenges related to tire emissions. In addition, these emissions and their distribution may be affected by other future trends like prolonged heat periods and an increase in stormwater events, which are both related to the ongoing climate change. An understanding of future trends and robust data on tire emissions during the use phase that inform these trends is essential for evaluating the potential environmental impact and implementing effective mitigation strategies even today. In this structured literature review current and future environmental exposure pathways of tire emissions during vehicle use including particulate tire wear, leachables and volatiles are discussed. A total of 502 publications between 1985 and 2024 were reviewed, resulting in a conceptual exposure model (CEM) for tire emissions during the use phase. Analytical tools are discussed and a proposal for a fit-for-purpose analytical methodology is adapted from microplastic research to inform the CEM of tire emissions. This concept follows a tiered approach covering exploratory, screening, mass, single particle, and chemical analysis of environmental samples with dedicated analytical methods and quality assessment criteria for each tier. Further, the current state of knowledge on factors controlling tire emissions is assessed to determine whether sufficient information is currently available to predict future emissions from tires during use. In conclusion, knowledge needs that need to be solved for a predictive environmental assessment of tire emissions during the use phase are identified.

Environmental significance

The ongoing energy transition, marked by notable advancements in electric vehicles, presents new challenges related to tire emissions. These emissions may additionally be affected by other future trends like climate change and related changes of weather conditions. An understanding of future trends and robust data on tire emissions that inform these trends is essential for evaluating the potential environmental impact and implementing effective mitigation strategies even today. Therefore, this manuscript presents a structured literature review of current exposure pathways of tire emissions during vehicle use including particulate tire wear, leachables and volatiles. In recent literature, particulate tire wear emissions as well as leachables are discussed most frequently while volatiles are not yet in the focus of tire emissions. Further, a fit for purpose tiered analytical approach is developed, and it is discussed how future trends may affect tire emissions. Based on this thorough and structured literature analysis, knowledge and data gaps are identified, which need to be considered in research for prospective impact assessment of tire wear emissions. This manuscript provides a comprehensive overview of the current knowledge on how different trends may affect tire emissions.

1 Introduction

Attention to tire emissions was first raised in the 1970s with initial publications focused on gas and particle wear emissions from automobile tires.[1,2] The presence of particulate tire emissions in the environment was estimated by determining tire ingredients, such as Zn[3,4] and benzothiazoles.[5] Tire emissions are not limited to particle release; volatile compounds and dissolved compounds, known as leachables, may also be released from the tires during use and from emitted particulate tire wear. With increasing attention on plastics in the environment, comparably high emission loads of particulate tire wear, and reports on adverse effects of tire derived chemicals on biota, tire emissions returned to the research spotlight.[6–8] Values of 1.1 and 1.3 million metric tons per year have been estimated for the U.S. (2010 reference year) and Europe (2014 reference year), respectively.[9] A much smaller emission rate of 0.13 million tons for the year 2020, however, has been estimated for China[10] illustrating the challenges of interpreting published estimates. Since China has more vehicles than in the U.S. or Europe, it appears that the lower amount is attributable to applying the factor of 0.033 g per passenger tire from Kole *et al.*

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(2017)[11] as if it were (1) per vehicle quantity, and (2) using a passenger tire emission factor to represent both passenger and truck tire emissions. In comparison, an average estimate of 0.053 million tons per year for South Korea that accounted for vehicle weight and distance traveled (2020 reference year) appears to be more closely proportionate to the U.S. and European estimates.[12] Not surprisingly, questions regarding the accuracy of particulate tire wear emission estimates have been raised,[13] suggesting that the comparison of future estimates can be refined through global harmonization efforts. As a result of the collective research, progress was made not only in acquiring invaluable knowledge but also in regulatory requirements. For example, in Europe, the implementation of Euro 7 now includes tire wear resistance.[14]

The ongoing energy transition, marked by notable advancements in electric vehicles, presents new challenges related to tire emissions. For instance, particulate tire wear emissions are considered as non-exhaust emissions, which further include brake wear and pavement abrasion. While electric vehicles do not produce tailpipe emissions, non-exhaust emissions are expected to increase due to higher weight and greater acceleration compared to fossil-fuel driven vehicles.[15] It is also crucial to understand how particulate tire wear emissions may be influenced by the change of weather conditions due to climate change in terms of their generation, distribution and fate.[15]

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Weather patterns and road conditions may impact the emission because increased precipitation and extreme weather events can deteriorate road surfaces more quickly or necessitate more frequent braking and acceleration.[15] A temperature change is expected to influence chemical and/or biological degradation of particulate tire wear and tire leachables.[16] An understanding of future trends and the data on tire emissions that inform these trends is essential for evaluating the potential impact and implementing effective mitigation strategies.

A comprehensive understanding of the environmental impact of these emissions requires data and knowledge on the types of emissions, their quantities, properties, distribution and fate in the environment. Previous studies suggest that particulate tire wear occurs in the environment as tire and road wear particles (TRWPs). TRWPs are heteroaggregates formed during driving due to the friction between the tire tread and the road pavement surface. They consist of a mixture of particles originating from tire tread, road pavement, brake systems, and mineral particles deposited on the road.[17–19] Volatile emissions may occur directly from tires during use or from particulate tire wear, often triggered by elevated temperature.[20] Leachable emissions can occur directly from tires when roads are wet or from particulate tire wear.[21] Measured and modeled estimates of TRWPs and leachables have been documented in different environmental media.[22–26]

A key step in the risk characterization of tire emissions to the environment is the preparation of a conceptual exposure model (CEM).[27] The CEM offers insight into the underlying mechanisms of emissions generation, the environmental media that may be affected, and the potential exposure of relevant entities and the pathways through which this exposure may occur. To predict changes of the CEM due to *e.g.* change of weather conditions and mobility transformation, robust and fit for purpose analytical methods are needed and the emissions as well as environmental fate processes need to be understood.

Therefore, the purpose of this study is (i) to summarize possible environmental exposure pathways of tire emissions, (ii) to recommend characterization and measurement methods of tire emissions which are useful in field sampling of tire emissions, (iii) to compile the current state of knowledge on factors controlling tire emissions, and (iv) to evaluate whether sufficient information is currently available to predict future emissions from tires because of changes in *e.g.* mobility, tire formulations, climate change, and urbanization. In conclusion, knowledge needs are identified that are required to be solved for a predictive environmental assessment of tire emissions.

2 Method applied for this structured literature research

The literature search was conducted using the online database Web of Science (WoS) and PubMed, covering publications from 1985 to January 2024, with continuous updates until November 2024. We focused on peer-reviewed literature as well as grey literature, including white papers and reports. The list of keywords is provided in the ESI (Table ESI.1 keywords).† All literature items were pre-screened based on their title to identify false positives that did not cover a relevant topic of this literature review. Eventually, each item from the revised list was tagged to predefined topics covering all relevant themes of particulate tire wear emissions, leachables, and volatiles. The themes include measurement methods, emission characteristics, parameters affecting tire emissions, and exposure pathways, climate change, and vehicle electrification. Items were also assessed for quality to ensure they contained relevant and reliable information for the literature review. The quality criteria include: (i) journal type: peer-reviewed journal; grey literature (only reports with a clear origin); information on author and publisher provided, (ii) methodology: complete description of the sampling and analytical methodology available, (iii) data, results: literature contains extractable data/results and data evaluation is comprehensible.

3 Results and discussion

3.1 Classification of available literature

A total of 502 publications were identified for the search terms of the structured literature review using WoS and PubMed as research databases, following the removal of duplicates and false positive hits (Table ESI.2 literature list†). These publications were then reviewed and, based on their abstract, classified according to their relevance to topics related to tire emissions including particles, leachables, and volatiles: (i) analysis methods, (ii) emission characteristics, (iii) exposure pathways, (iv) parameters affecting tire emission, (v) changes of tire emissions related to electric mobility, and (vi) changes of tire emissions related to climate. The highest number of publications was found for particulate tire wear emissions and their characteristics (Table 1). In the ESI† the publications are further divided into primary literature (406 publications), publications with original data and those that can be used to generate original data, and secondary literature (96 publications), such as review articles (see ESI.3,† Table 1).

3.2 Nomenclature for tire emissions used in this study

Tire emission nomenclature in the literature is not harmonized. This may lead to misunderstandings of results and creates an additional challenge regarding comparability of data. In this structured literature review the nomenclature used from previous studies was evolved as summarized in Table 2. The nomenclature differentiates between direct tire emissions and tire-originated emissions which are formed and observed in the environment.

3.3 Conceptual exposure model for tire emissions

The potential for tire emissions to be released and transported during tire use can be described using the CEM provided in Fig. 1. The CEM starts from the left with the source and leads to primary receptors as well as potential receptor pathways on the right. The CEM in Fig. 1 was developed based on available information from the literature (see ESI.3† Table 2), showing proven exposure pathways with solid arrows, proposed exposure

Table 1 Number of publications identified during the systematic literature review subdivided into the six topics

Topic	Total	Particulate tire wear emission	Leachables	Volatiles
Overall	502	369	187	17
(i) Analysis method	158	129	59	7
(ii) Emission characteristics	213	160	48	10
(iii) Exposure pathways	223	154	81	1
(iv) Parameters affecting tire emission	114	114	0	1
(v) Changes related to climate	14	13	2	0
(vi) Changes related to electric vehicles	20	19	2	0

Table 2 Definition of the nomenclature used in this structured review on tire emissions based on Halle *et al.* (2020)[28] and further developed by Wagner *et al.* (2024)[29]

Terminology	Definition
Tire emissions during the use phase	All materials which are released from the tire during driving as a result of the abrasion process including particulate, dissolved and gaseous entities *e.g.* compounds (direct emission)
Particulate tire wear (TWP)	Material from tire tread which is released in particulate form during the wear process covering a broad size range from nanometer to micrometer. The abbreviation TWP refers to particulate tire wear (direct emission)
Leachables	Dissolved compounds which can be released from tires (direct emission) and from TRWPs (indirect emission)
Volatiles	Gaseous compounds which are vaporized during the use from tires (direct emission) and from TRWPs (indirect emission)
Tire and road wear particles (TRWP)	Heteroaggregates consisting of particulate tire wear and mineral particles located at the surface of the road pavement (direct emission)
Airborne tire emissions	It is a sum parameter including gaseous and fine particulate matter like PM10-fraction (direct and indirect emissions)
Particulate matter ≤10 μm (PM10)	All particles with a diameter of 10 μm or less of any particle type

pathways with dashed arrows and proposed receptor pathways with dotted arrows. While there is already a substantial body of knowledge on the exposure of leachables and coarse particulate tire wear emissions (>PM10), the exposure of volatiles and fine particulate matter, for example PM2.5 and PM10, remains to be elucidated (compare Table 1 and Fig. 1 dashed lines). No literature showing the direct exposure of humans to tire emissions was found but it is assumed that primary exposure pathway for humans will be *via* inhalation, as soil, sediments and surface waters are not directly consumed. However, humans may be subsequent receptors if consuming *e.g.* exposed plants or fish. Accordingly, this literature review aims to synthesize existing knowledge on the subject of particulate tire wear and leachable emissions, while also identifying areas where further research is required with respect to volatile and fine particulate matter exposure.

The CEM is also useful to depict changes of exposure due to altering boundary conditions *e.g.* increased proportion of electric vehicles on the total number of vehicles. To establish a comprehensive CEM and to predict its changes due to adapted boundary conditions, it is necessary to employ analytical tools.

3.4 Characterization and measurement of tire emissions

Assessment of tire emissions first requires identifying clearly structured research questions and setting operational definitions of the quantities being measured.[30] This first step is often described as the problem formulation, which can be described as the process of articulating questions and determining how they might be answered. Depending on the questions, analytical tools for particulates, leachables and volatiles may be more or less relevant; however, all share in common the existence of limitations or required assumptions needed to translate marker measurements to tread wear or TRWP mass amounts. Some factors contributing to measurement uncertainty have included assumptions of compositional and size temporal stability, overall average composition, and specificity in the matrices where the marker is applied.[30]

Accurate and precise environmental measurements of tire emissions and amount in environmental matrices will be essential in assessing climate impacts, given the complexity of competing fate processes and unknown future innovations as a consequence of climate change adaptation. From the available literature most of the analytical publications on tire emissions investigated method development for particulate tire wear emissions (79.1%) while 37.3% focused on leachable compounds and 1.9% on volatiles.

Barriers to the harmonization of environmental measurements of polymeric particles have included the high cost and extended analysis time required to achieve the sensitivity, specificity, and repeatability historically expected in regulatory

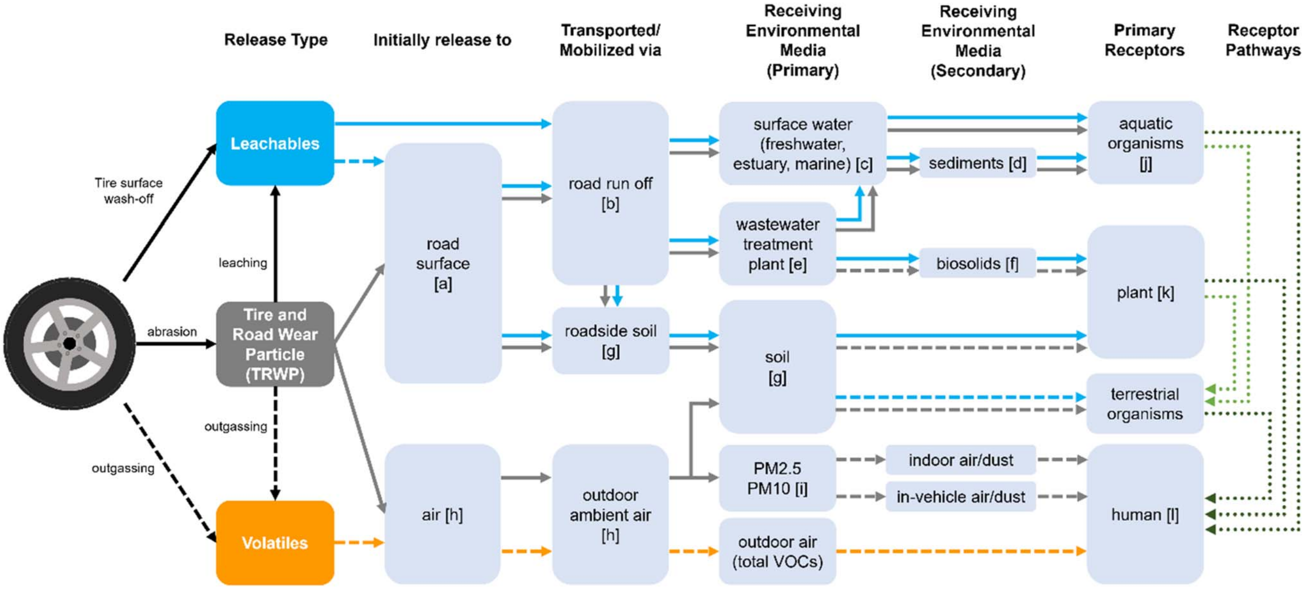

Fig. 1 Conceptual Exposure Model (CEM) for tire emissions during vehicle use. The arrow color corresponds to the release type and indicates their specific distribution in the environment (grey – TRWP; blue – leachables; orange – volatiles). A dashed arrow indicates a potential but not yet verified distribution pathway and a green dotted line arrow indicates a potential but not yet verified receptor pathway. For all references [a–l] see ESI.3† Table 2.

analyses of anthropogenic environmental releases. Rødland *et al.* (2023a)[30] recently conducted a comprehensive review of TRWP measurement method capabilities, limitations, and knowledge gaps. Overall, the survey found wide variation in single-particle and mass-based (or bulk) methodologies, with relatively few methods having been evaluated for accuracy and precision. The available methods for TRWP measurement identified by Rødland *et al.* (2023a),[30] supplemented by additional studies identified in the present review, can be informatively classified by adapting Coffin's (2023)[31] three-tier framework to include categories of exploratory (Tier 0), screening (Tier 1), mass quantification (Tier 2), single-particle (Tier 3), and refined chemical-specific characterization (Tier 4) (Fig. 2).

Mass-based TRWP and chemical methods (Tiers 2 and 4, respectively), which can also differentiate amounts by size classes with appropriate sampling methods, are the most suitable for addressing questions related to quantitative exposure assessment and long-term trends associated with climate change. The analytical chemistry concepts of accuracy, precision, laboratory control, spike recovery, and blank analysis are most readily applied to these study types, making them the preferred methods for contributing a pragmatic operational definition of environmental particulate tire wear emissions or levels within regulatory risk assessment and mitigation programs.

Exploratory (Tier 0), screening (Tier 1), and single-particle analysis (Tier 3) methods are important for the development of health and climate conceptual models. For prioritization and understanding of fate mechanisms related to health and climate trends, respectively, these tiers are less suitable. This is because they either lack the accuracy and precision necessary to detect subtle changes or rely heavily on weight-of-evidence judgments in the interpretation of the results. For example, density-based zinc methods and conventional GC/MS methods for organic compounds are placed in Tier 1 rather than Tiers 2 and 4 due to the incompatibility of important tire-tread constituents with gas chromatography[32] and the presence of significant environmental sources of zinc from road and other transportation structures.

TRWP measurements will benefit from consistent, harmonized study designs and robust as well as fit for purpose analytical methods. This is consistent with analytical recommendations for microplastics which were originally developed by Cowger *et al.* (2020).[33] Adapting the recommendations of Cowger *et al.* (2020),[33] the most relevant reporting categories for TRWP laboratory procedures include materials and equipment, quality assurance and quality control (QA/QC), sample preparation, and principle of identification (Fig. 2). Within QA/QC, key reportable attributes include accuracy (positive controls as noted by Cowger *et al.* (2020)),[33] precision (error propagation and replicates as noted by Cowger *et al.* (2020)[33]), limit of detection, and blank controls (including laboratory contamination mitigation).

Important sample preparation considerations include the use of recognized calibration standards (including polymers, deuterated internal standard, TRWP and CMTT), particle separation (by density or size), and sample cleanup. Recommendations for minimum reporting requirements for each tier in Fig. 2 are presented in Table 3. Studies in Tiers 0 and 1 are most suitable for local or regional assessments due to their less stringent protocol requirements, whereas studies in Tiers 2, 3, and 4, which satisfy the identified reporting elements, are informative for global trend analysis. This scheme illustrates

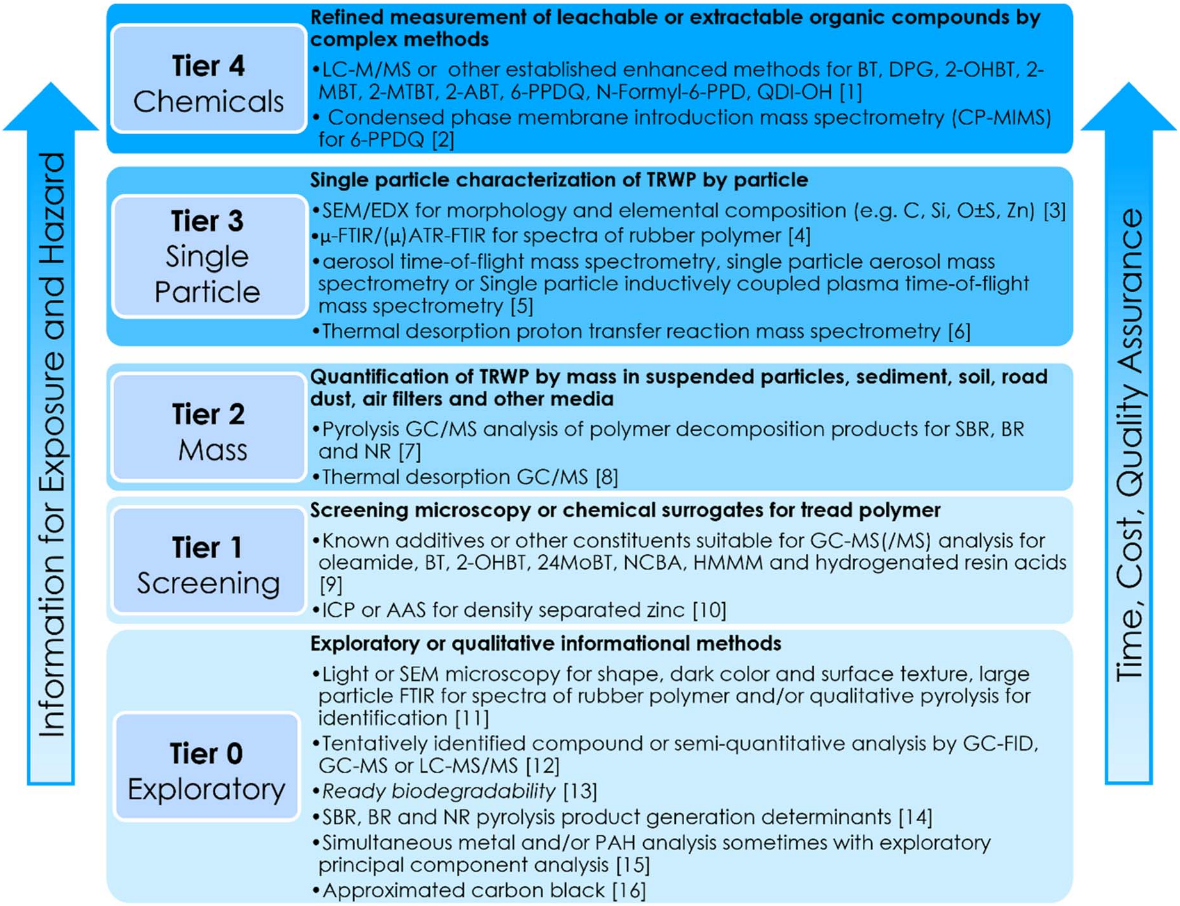

Fig. 2 Tiered characterization scheme for TRWP analytical methods; for all references [1–16] listed in this figure see ESI.3† Table 3.

a systematic approach to balancing expense, time, and the level of information needed for climate and health risk management.

Currently, thermal decomposition *via* thermal desorption or pyrolysis methods, paired with fragment detection by GC/MS, is the most frequently studied approach.[30] The py-GC/MS method appears to be the most suitable for prospective climate trend analyses due to the availability of ISO technical specifications covering air, soil, and sediment (ISO/TS 20593 and ISO/TS 21396), along with several more recent studies that address refinements to improve accuracy and precision for the development of international standards. Studies reporting on py-GC/MS measurements are summarized in Table 4, with an indication of the reporting elements from Cowger *et al.* (2020)[33] that were included. Notably, many of the studies utilized an internal standard and provided at least some information regarding method accuracy and precision.

While most of the studies have focused on near-road soil or dust samples, py-GC/MS methods have also been reported for

Table 3 Proposed conceptual scheme for reporting TRWP measurement results[a]

	QAQC					Sample preparation			Geographical scope
Study type (Tier)	Accuracy	Precision	Reference standard	Detection limit	Blank control	Particle separation	Sample cleanup	Internal standard	Scale
Exploratory (0)	.	.	.	.	●	○	○	.	Local or regional
Screening (1)	.	.	○	○	●	○	○	○	Local or regional
Mass (2)	●	●	●	●	●	○	○	○	Global
Single particle (3)	●●	●●	●	●●	●	○	○	○	Global
Chemical specific (4)	●●	●●	●	●	●	○	○	○	Global

[a] ● Always required. ●● Always required and may require appreciable resources for refinement. ○ Required when applicable. . Sometimes required depending on the aim or method.

Table 4 Overview of elements reported in published py-GC/MS measurement studies

					QA/QC					Sample preparation			Media				
Study	Measured entity	Target polymer[b]	Marker compounds[c]	Analytical equipment[d]	Method accuracy	Method precision	Calibration standards	Detection limit	Blank control	Particle separation	Sample cleanup	Internal standard[e]	Near road soil/dust	Surface water or retained solids	Aquatic sediment	Air	Other
Chae *et al.* (2021a)[35]	Truck tread	BR, NR	M-5, 6	I-2		●	●										Tread polymer
Chae *et al.* (2021b)[36]	TWP	NR	M-5, 6, 8, 9	I-3		●	●						●				
Chae *et al.* (2022)[37]	PM-2.5 & 10	SBR/BR	M-5, 6, 7, 8, 9, 10, 11, 12	I-2, 5												●	Rubber
Chae and Choi (2023)[38]	Rubber	NR	M-6, 8	I-1, 3		●	●										Rubber
Goßmann *et al.* (2021)[39]	Tread	SBR/BR, NR	M-5, 6, 13, 14	I-1			●	●	●	●	●	S1	●		●		Mussel, marine salt
Jeong *et al.* (2023)[40]	PM10	SBR/BR, NR	M-5, 6, 7, 8	I-7			●									●	
Jung and Choi (2022)[41]	TRWP	SBR, BR, NR	M-5, 6, 8, 9	I-3						●	●		●				
Jung and Choi (2023)[42]	Rubber	NR	M-6, 8	I-1													Marine salt
Kim *et al.* (2022)[43]	Road dust	SBR/BR, NR	M-5, 6	I-7									●				
Miller *et al.* (2022a)[44]	TWP	SBR/BR, NR	M-5, 6, 11	I-2, 3	●	●	●	●	●		●	S4			●		
Miller *et al.* (2022b)[45]	TRWP	SBR/BR, NR	M-5, 6, 11	I-3	●	●	●	●	●			S4					
More *et al.* (2023)[46]	TRWP	SBR/BR, NR	M-5, 6, 11	I-1	●	●	●	●	●		●	S4		●	●		
Mun *et al.* (2022)[47]	TRWP	SBR/BR, NR	M-5, 6	I-1, 4	●	●	●	●				S3				●	
Panko *et al.* (2013)[48]	TRWP	SBR/BR, NR	M-5, 6	I-2	●	●	●	●	●			S4				●	

Table 4 (*Contd.*)

					QA/QC					Sample preparation			Media				
Study	Measured entity	Target polymer[b]	Marker compounds[c]	Analytical equipment[d]	Method accuracy	Method precision	Calibration standards	Detection limit	Blank control	Particle separation	Sample cleanup	Internal standard[e]	Near road soil/ dust	Surface water or retained solids	Aquatic sediment	Air	Other
Panko *et al.* (2019)[49]	TRWP	SBR/BR, NR	M-5, 6	I-2	●	●	●	●	●			S4				●	
Parker-Jurd *et al.* (2021)[50]	Tread	TRWP	M-15	I-3			●	●	●					●			
Rødland *et al.* (2022)[51]	Tread; PMB[a]	SBR/BR, SBS	M-1, 2, 3, 4	I-1	●	●	●	●	●			S1	●				Roadside snow
Rødland *et al.* (2023b)[52]	TRWP	SBR/BR	M-1, 2, 3, 4	I-1	●	●	●	●	●			S2	●				
Rosso *et al.* (2023)[53]	TRWP	SBR/BR, NR	M-5, 6	I-3	●	●	●		●		●		●				Storm water
Unice *et al.* (2012)[54]	TRWP	SBR/BR, NR	M-5, 6	I-2	●	●	●	●	●			S4	●		●	●	
Unice *et al.* (2013)[55]	TRWP	SBR/BR, NR	M-5, 6	I-8	●	●	●	●	●			S4	●		●		
Woo *et al.* (2022)[56]	PM-2.5 & 10	SBR/BR, NR	M-5, 6	I-6			●					S4				●	
Youn *et al.* (2021)[57]	TRWP	SBR/BR, NR	M-5, 6	I-1		●	●	●					●				

[a] PMB = polymer modified bitumen. [b] Target polymer: BR = polybutadiene rubber, NR: natural rubber, SBR: styrene–butadiene rubber, SBS: styrene–butadiene–styrene. [c] Marker compounds: M1 = benzene, M2 = α-methylstyrene, M3 = ethylstyrene, M4 = butadiene trimer, M5 = vinylcyclohexene, M6 = dipentene, M7 = butadiene, M8 = isoprene, M9 = styrene, M10 = 2-phenylpropene, M11 = 4-phenylcyclohexene, M12 = 3-phenylcyclopentene, M13 = cyclohexenylbenzene, M14 = 2,4-dimethyl-4-vinylcyclohexene, M15 = benzothiazole. [d] Analytical equipment: I1 = microfurnace pyrolyzer with GC/MS, I2 = Curie point pyrolyzer with GC/MS; I3 = resistive (filament) pyrolyzer with GC/MS, I4 = protocol based on ISO/TS 20593, I5 = low volume particulate matter sampler with 47 mm filter, I6 = PM2.5 and PM10 cyclone with an unspecified pyrolysis instrument based on ISO/TS 20593, I7 = unspecified pyrolysis instrument with GC/MS. [e] Internal standard: S1 = deuterated polystyrene, S2 = deuterated polybutadiene, S3 = not reported, but methods reference ISO/TS 20593, which specifies deuterated isoprene and deuterated polystyrene–polybutadiene, S4 = deuterated isoprene and deuterated polystyrene–polybutadiene.

aquatic sediments, the PM2.5 and PM10 fractions of air, and surface water suspended solids (Table 4). Future applications of the method to biota would represent a useful additional mass-based measure when combined with appropriate sample pretreatment and cleanup. The Tier 2 pyrolysis methods, which meet the reporting guidance of Cowger *et al.* (2020),[33] should provide accurate and precise operational definitions of TRWP mass, useful for determining concentration in media as well as flux rates at specific locations and times. These pyrolysis estimates can be supplemented by the refined chemical-specific methods in Tier 4, which also meet similar accuracy, precision, and reporting objectives.

To date, no standardized test method has been developed to characterize tire emissions, making it challenging to assess the impact of changes in tire and vehicle technology. The harmonization of standard procedures for sample collection, laboratory measurement, quality assurance/quality control (QA/QC) and reporting of microelastomer and microplastic particles in environmental emissions and samples has consistently been emphasized as a priority for meaningful integration of exposure and hazard data to characterize and manage potential risks.[31,33,34] However, there has been very little discussion of the TRWP measurement methods that would be most useful in field sampling of TRWP or constituent concentrations intended to longitudinally characterize the effects of climate change innovations or environmental conditions on TRWP emission rates.

3.5 Particulate tire wear emissions

3.5.1 Generation and properties of tire and road wear particles

3.5.1.1 Generation. TRWPs are generated during driving through the contact between the tire tread and the road surface. The exact wear process of the tire is complex and includes fatigue wear, friction wear, adhesion wear, and chemical erosion wear,[58] with friction and fatigue wear considered as the main mechanisms.[59] Friction wear occurs when a rough surface (road) slides over a softer one (tire), producing cuts and cracks in the softer one (tire). Fatigue wear refers to the formation of subsurface cracks produced by cyclic high stress during a rolling movement. Over time, these induced cracks grow and result in particles separating from the tire tread surface.[60] However, particulate tire wear does not occur independently; it typically occurs in conjunction with road surface wear.[9,58] As a result, pristine tire wear particles have not been observed in the environment, but rather conglomerates consisting of a particulate tire wear core encrusted with particles originating *e.g.* from road surface, along with other vehicle-related particles such as brake wear particles, tailpipe emission particles, and natural particles like soil.[17,61]

Generally, a particulate tire wear contribution of 50 wt% to the TRWP heteroaggregate mass is assumed.[25,62–66] Surprisingly, a review of the references cited by those studies for this TRWP composition revealed that all traced back to only one study: Kreider *et al.* (2010).[18] Their reported TRWP composition of 50 wt% particulate tire wear and 50 wt% minerals refer to particles collected with an on-road test vehicle and a collected size range of 0.3–100 μm. Yet, other studies have reported different TRWP compositions. Klöckner *et al.* (2021)[67] reported a 75 wt% particulate tire wear contribution in tunnel road dust samples (<1 mm) and attributed the higher content to the fewer secondary particle sources inside a tunnel. While Jung *et al.* (2022)[41] did not report specific numbers, they observed an increase of particulate tire wear content with the decrease in TRWP particle size (fractions 63–106 μm, 106–212 μm, 212–500 μm) collected from road dust near a bus stop. Sommer *et al.* (2018)[17] observed two types of particles in their study, particulate tire wear particles with less than 50 vol% encrustation and with more extensive encrustation. They even report TRWP particles with a particulate tire wear content of 90–94 vol% for TRWP particles >40 μm. However, it should be noted that they stated their composition in vol% while the other studies refer to wt%. Yet, those three studies showed, that the particulate tire wear contribution is very variable depending on the size fraction and sampling site. Hence, it is astonishing that the assumption of a general 50 wt% particulate tire wear contribution is often considered as a fact and even referenced in the ISO norm,[66] while no other study could be found in our literature review that observed such a TRWP composition. Awareness has to be raised to this potential misconception and studies are needed for addressing the contribution of particulate tire wear particles to TRWP for different size fractions and different sample types. This apparently variable conglomeration and the resuspension with road dust can lead to enormous differences in the physicochemical properties of TRWP, making it difficult to define universal parameters. Therefore, property distributions, as is done for microplastics, are provided.[67] Information on TRWP properties related to e-mobility would be necessary to predict the distribution and impact of particulate tire wear emissions in the environment for future scenarios.

3.5.1.2 Particle size, density and shape are affected by wear conditions. The size distribution of the generated particles ranges from a few nanometers to several hundred micrometers.[9] However, considerable variations in the size distribution exist depending on factors such as vehicle speed, driving conditions, tire composition, and road surface as well as the experimental setup and study conditions. For example, Kovochich *et al.* (2021)[68] determined a size distribution range of 11–1588 μm (average mass concentration of 506 μm) in sediment samples, but a range of 8–315 μm in tunnel dust samples (average mass concentration of 94 μm). Kreider *et al.* (2010)[18] found the TRWP size to range between 5 μm and 220 μm, with a size peak at 75 μm, which aligns with the findings of ref. 69–73. However, studies investigating smaller size fractions reported a maximum particle abundance in the 2–5 μm range,[29,74–77] highlight the existence of particles in the <10 μm fraction.

The particle[62] density of environmental TRWPs ranges from 1.5 to 2.2 g cm^{-3}.[41,63,78] However, the density decreases with increasing particulate tire wear contribution to the TRWPs, which should be considered, especially when analyzing tunnel dust samples.[67]

The predominant reported TRWP particle shape is elongated, with an average aspect ratio of 0.64,[18,68,73,76] though spherical and irregular particles have also been observed.[76,77] In the <10 μm fraction a higher abundance of spherical particles has been reported.[79]

3.5.1.3 Chemical composition varies and future trends may not be predicted currently. The chemical composition of particulate tire wear is complex due to the high proportion of additives and transformation products in the original tire tread material. It is estimated that approximately 40–60% of a tire is rubber, 20–35% filler, 12–15% process oils, 5–10% textile and metal net, 5–10% additives, and 1–2% vulcanization agents.[9] Because the tire tread is the tire component which is in contact with the road pavement its chemical composition is crucial for understanding the chemical characterization of the tire wear emissions. Recent studies provide insights into its chemical composition with respect to elemental content and content of organic substances. For instance, the metal content of tire tread from various types of tires was reported recently.[80–82] Differences in the metal content of tire tread and tire side walls were also reported.[82] A few studies describe the composition of organic chemicals in tire tread as well.[21,83–86] With the shift toward more sustainable products, so-called "green" tires are available on the market. However, the composition of a limited number of "green" and conventional tires, covering inorganic elements such as Al, Ca, Cd, Cr, Fe, Mg, Na, Pb and Zn, as well as organic compounds like 1,3-diphenylguanidine (DPG), *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine (6-PPD), *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine-quinone (6-PPDQ), hexa(methoxymethyl)melamine (HMMM), 2-hydroxybenzothiazole (OHBT), and 2-aminobenzothiazole (ABT), did not show significant differences compared to conventional tires.[85] The same study showed differences in the natural and styrene–butadiene rubber composition of tires for different seasons. Currently, no studies have been conducted to directly compare tires used for electric vehicles with those designed for conventional vehicles. However, due to different performance characteristics, *e.g.* lower rolling resistance to improve energy efficiency and lower noise, the chemical composition is expected to vary. To conduct an impact assessment that considers potential changes in tire composition, more specific and systematic data on the chemical composition of current and future tires would be necessary.

3.5.2 Parameters affecting particulate tire wear emissions. To predict future changes in tire emissions, it is essential to understand the emission process and the parameters that control particulate tire wear emissions. No information on specific parameters affecting emission of volatiles and leachables was found. The emission of particulate tire wear, in terms of both particle mass and properties, is influenced by several parameters, which can be grouped into four main categories: vehicle parameters, road parameters, tire parameters, and environmental parameters (Table 5). However, these parameters cannot be considered independent due to their overlapping and mutual influences. As a result, it is challenging to assess only one parameter and directly apply study results from test tracks (under controlled conditions) to real-world driving conditions. Additionally, most studies focused on the PM10 fraction rather than the entirety of particulate tire wear emissions, raising questions about whether the findings can be directly applied to other size fractions. Also, it must be noted that not all studies differentiated between the particle types in the analyzed PM10 fractions; thus, the fraction does not solely correspond to particulate tire wear emissions but may include other particles such as road wear particles, brake wear particles and resuspended matter depending on the experimental setup. Hence, the question is raised if an observed increase or decrease in PM10 emissions can be directly translated to particulate tire wear emissions. Current developments regarding harmonization of abrasion test/emission factors will support future assessments of the abrasion properties of tires. Yet, the qualitative correlations between parameters and particulate tire wear emissions/PM10 are consistent, allowing for the derivation of trends.

3.5.2.1 Vehicle parameters. Vehicle parameters comprise driving speed, longitudinal force, lateral force, and vehicle load. Driving speed is the most extensively studied influence parameter, with a positive correlation consistently observed between speed and emitted particle number. While the majority report their findings qualitatively for particulate tire wear emission[77,87–90] or PM10 emissions,[58,79,91–94] Kupiainen and Pirjola (2011)[94] reported a 30% PM10 emission increase for each 10 km h^{-1} step from 40 to 60 km h^{-1}. Additionally, for the PM10 fraction, Schläfle *et al.* (2024)[91] identified a shift towards smaller particles on average with increasing vehicle velocity.

During accelerating and braking events, a longitudinal force is generated that acts on the tire, increasing the frictional power between the tire and the road surface.[79] Since formation of particulate tire wear is partially based on friction wear processes, the increased frictional power leads to a higher particulate tire wear emission factor.[58,72,79,91,95] Most studies observed that braking maneuvers result in higher emission values compared to acceleration maneuvers. However, this may be attributed to the limited acceleration potential of the test stands or vehicles.[58] While no specific emission values were reported, Kim and Lee (2018)[77] observed an exponential increase in particle numbers during braking maneuvers. Additionally, Feißel *et al.* (2020)[96] found the PM10 mass concentration increased by a factor of four during emergency braking events (longitudinal force of 8 m s^{-2}), and Schläfle *et al.* (2024)[91] reported a 35-fold increase in particle mass emissions and a 15-fold increase in particle number emissions at a longitudinal force of ±4 kN. Nevertheless, it is not feasible to establish a general emission increase factor depending on the longitudinal force, due to the superimposition of the driving speed influence.

In addition to the longitudinal force, a lateral force acts on the tire during cornering maneuvers. The lateral force also increases the particulate tire wear[77,89] and PM10 emission mass[58,72,79] and has been identified as exerting a more pronounced impact on PM10 emissions than the longitudinal force at identical acceleration values.[58,79] No specific investigations into the impact on the size distribution have been conducted. However, Hesse *et al.* (2022)[58] reported an increase in particle number concentrations (PM10) in the 2–3 μm and <1 μm size ranges with increasing acceleration values, although the particle size range only changed slightly. The impact of

Table 5 Description of parameters which affect PM10 and particulate tire wear emissions ($\leq$10 µm). It has to be noted that the experimental design and the particle types and size fractions investigated differ. Thus, no direct comparison of the studies is possible, but the qualitative results were consistent allowing for general conclusions listed here. Ambiguous study results are highlighted

Category	Parameter	Description	Influenced by changing weather conditions	Influenced by a change towards e-mobility
Vehicle factor/driving style	Driving speed	• Particulate tire wear emission[77,87–90] and PM10 emission[58,79,91–94] increase with increased driving speed • Average particle size of the PM10 fraction decreases with increased speed[91]	No	No
Vehicle factor/driving style	Longitudinal force (accelerating/braking event)	• PM10 emission increases with increased longitudinal force[58,72,79,91,95] • Influence depends on driving speed: lower longitudinal force at higher driving speeds yields the same PM10 emission factors as high longitudinal force at low driving speed[79]	No	Yes
Vehicle factor/driving style	Lateral force (cornering)	• Particulate tire wear emission[77,89] and PM10 emission[58,72,79] increase with increased lateral force • Highest emissions during superimposing driving scenarios of cornering and simultaneously accelerating/braking[58,79]	No	No
Vehicle factor/driving style	Vehicle load	• Particulate tire wear emission[77,87] and PM10 emission[91] increase with increased vehicle load if tire inflation pressure remains constant • Examination in conjunction with tire inflation pressure	No	Yes
Road	Road profile	• No direct influence • Road profile defines number and intensity of corners, brake/accelerating events and driving speed[58,79,97] • Particulate tire wear emission and PM10 emission depend on the traffic situation[58,97] • Superimposition and variability of parameters make it impossible to rank rural, urban and highway sections according to their EF	No	No
Road	Road surface texture	• Particulate tire wear emission[59] and PM10 emission[92,93,98] increase with increased roughness • Average particle size of particulate tire wear emission increases with increased roughness[59]	Yes	No
Road	Road surface type	Ambiguous data: • Particulate tire wear emissions are lower for asphalt pavements compared to concrete pavements[100] • No significant change in particulate tire wear emission observed comparing concrete and asphalt pavements[99]	Yes	No
Tire	Inflation pressure	Ambiguous data: • Particulate tire wear emission decreases with increased inflation pressure[88] • PM10 emission increases with increased inflation pressure[91] • Examination in conjunction with vehicle load	No	No

Table 5 (*Contd.*)

Category	Parameter	Description	Influenced by changing weather conditions	Influenced by a change towards e-mobility
Tire	Tire composition	• Order based on their particulate tire wear emission: studded > winter > all-season > summer tire[92–95]	Yes	No
Environmental conditions	Humidity	• No data on particulate tire wear or PM10 emission change • Average particle size of particulate tire wear emission (<10 to >400 μm) decreases with humidity increase[59]	Yes	No
Environmental conditions	Temperature	Ambiguous data: • Particulate tire wear emission[88,99] and PM10 emission[95] increase with increased temperature (summer and winter tires tested) • Particulate tire wear emission (<18 μm) gradually decreases with temperature increase (custom-made tire material)[87]	Yes	No

lateral force cannot be determined separately, and the highest PM10 emission values are reported for combined driving scenarios, such as cornering with simultaneous acceleration or braking.[58,79]

An increase in vehicle load at constant tire inflation pressure results in a more deflected tire and an increased contact area between the tire and the road surface. In conjunction with this increased contact area, Schläfle *et al.* (2024)[91] observed a proportionally increased PM10 emission, consistent with the findings of Kim and Lee (2018, particulate tire wear)[77] and Yan *et al.* (2021, particulate tire wear).[87] Furthermore, Kim and Lee (2018)[77] determined that the impact of increased load is even more pronounced during braking or accelerating events due to the greater longitudinal forces acting on the tire to achieve the same accelerating/braking rate. However, no impact on the size distribution of the particulate tire wear was observed.

It is necessary to examine the vehicle load parameter in conjunction with tire inflation pressure: if tire inflation pressure is adjusted according to the load, the impact of both parameters on particulate tire wear emissions may be diminished or even canceled out. While insufficient inflation pressure aligns with the reported results of an increased vehicle load, excessively high inflation pressure would reduce the contact area between the tire and the road surface, resulting in higher shear stress. However, the impact of tire inflation has been inadequately studied, and the reported results are contradictory. While Li *et al.* (2012)[88] observed a decrease in particulate tire wear emissions with increased inflation pressure, Schläfle *et al.* (2024)[91] observed an increase, which may be attributed to the fact that the overall PM10 concentration was assessed rather than the particulate tire wear emissions alone. Thus, further research is needed to assess the impact of vehicle load and tire inflation pressure on particulate tire wear emissions.

While it is difficult to assess the impact level of each vehicle parameter, two studies tried to rank their investigated parameters. Hesse *et al.* (2022)[58] found that vehicle load had less impact on the PM10 emissions compared to vehicle speed and the lateral and longitudinal forces. In contrast, Kim and Lee (2018)[77] found a more pronounced impact of vehicle load than driving speed. This contradictory observation is attributed to the different experimental setups and the difference in particle types analyzed. However, with the change toward e-mobility, the vehicle load parameter may become more relevant in the future, as increased vehicle weight could lead to higher particulate tire wear emissions. More studies that investigate different parameters under the same experimental conditions and compare their individual impact on particulate tire wear emission mass are needed to enable a reliable evaluation of these parameters.

3.5.2.2 Road parameters. The road parameters identified to influence the particulate tire wear emissions are the road profile/section, the road surface texture and road type. However, the road profile/section does not directly influence particulate tire wear emissions but rather defines the intensity and frequency of the primary parameters, such as driving speed, accelerating/braking maneuvers, and cornering maneuvers. While vehicle speed is higher on highways compared to rural and urban roads, leading to increased particle emissions, urban and rural sections are characterized by a greater number of cornering and braking/acceleration maneuvers.[58,79,97] This superimposition and unknown impact levels of each parameter make it difficult to rank and evaluate road sections based on their particulate tire wear emission values. Additionally, the specific characteristics of each road profile make comparisons even between roads of the same type challenging.

Moreover, the traffic situation impacts the determination of emission values. For instance, Hesse *et al.* (2022)[58] found the lowest PM10 emission values on highways compared to rural sections because the test was carried out at night when traffic density was low, resulting in constant driving speeds and minimal accelerating/braking maneuvers. In contrast, De

Oliveira *et al.* (2024)[97] conducted their sampling campaign during the day at higher traffic densities, leading to more accelerating, braking, and overtaking maneuvers on the highways. Consequently, the highest PM10 emission values were observed on highways and ring road trips, which were accompanied by higher speeds. Furthermore, the study evaluated the contribution of particulate tire wear emissions to the PM10 emissions, and the highest content was found in highway samples, followed by suburban, urban, ring road and rural samples. However, no direct correlation between PM10 emissions and observed tire weight losses was found. The missing correlation is attributed to differences in the road dust content on the streets, its resuspension during the driving experiments and thus different dilutions of the emitted particles with previously deposited and then resuspended particles. Highest tire weight losses were observed on highways (0.029 g per km per tire) compared to urban and ring roads (0.011 g per km per tire).[97] However, higher local PM10 emission values were observed for both studies in urban roads due to sharp interchanges and roundabouts.[58,97]

Another parameter to consider when comparing road sections is the potentially differing road surface texture. Road surface texture is defined by its sharpness and coarseness, which directly influence the contact area between the tire and the road surface.[90] A smooth surface results in even pressure distribution, while a coarse surface reduces the effective contact area but increases contact pressure at the texture peaks.[58] Consequently, friction force increases, leading to greater tire and road wear in the investigated <10 μm fraction. This was confirmed by ref. 92, 93 and 98. However, these studies did not specifically evaluate particulate tire wear emission, instead assessing total PM emissions.

Chang *et al.* (2020)[59] focused on particulate tire wear emissions, determining that friction wear predominates on coarse road surfaces, while fatigue wear dominates on smooth surfaces. Since fatigue wear results in smaller particle sizes, smooth surfaces would lead to higher PM10 particulate tire wear emissions. However, no specific emission factors were reported, and the transferability of their results is questionable due to the use of sandpapers of different mesh sizes as asphalt imitations. Further studies are needed to examine the particulate tire wear portion of PM emissions in order to accurately assess the impact of road structure on particulate tire wear emissions.

The road surface texture is also defined by the type of road surface as concrete roads have a higher roughness than asphalt roads. However, the influence of the road type on particulate tire wear emissions is inadequately studied. Only two studies comparing emissions on concrete and asphalt roads were found.[99,100] Alexandrova *et al.* (2007)[100] found 1.2 to 2 times higher particulate tire wear emission (<10 μm) for portland cement concrete compared to an asphalt rubber friction course surface. On the other hand, Miech *et al.* (2024)[99] could not observe a significant difference in emission factors for a diamond-ground concrete surface and asphalt rubber friction course surface. More studies investigating the influence of different road types on particulate tire wear emissions are needed.

Based on these study results, even though different experiment designs and methodologies were utilized, it can be concluded that high traffic volume, high maneuver density, and rough road surface structure are associated with increased PM10 (ref. 58, 79, 92, 93 and 98) and particulate tire wear (<10 μm)[58,59,97] mass emissions. However, the variability and overlapping influence of road parameters make it difficult to define a general impact level on particulate tire wear emission values. Instead, individual values under specific test conditions must be determined for each road section to evaluate their respective impact on particulate tire wear emissions.

3.5.2.3 Tire types. Tire manufacturers have developed different tire types for various seasons to ensure optimal tire performance in respective weather conditions. As a result, studded, winter, summer, and all-season tires have been created. Winter tires are generally softer than summer tires, while all-season tires fall between the two, and studded tires resemble winter tires but with metal or ceramic studs.[101] When examining their corresponding particulate tire wear emissions, uniform study results rank the tires from highest to lowest emission as follows: studded > winter > all-season > summer tires.[92–95] The average PM10 emission mass for summer tires was found to be two times lower than for all-season tires and four times lower than for winter tires.[95] Studded tires emitted 2.0–6.4 times more PM than winter tires.[92] However, each study examined the total PM10 fraction, not specifically particulate tire wear emissions. Therefore, the increased PM emissions of studded tires compared to winter tires are primarily attributed to increased road wear.[92] Whether particulate tire wear emissions are also increased remains to be determined.

3.5.2.4 Environmental conditions. The influence of ambient temperature on particulate tire wear emissions has been demonstrated by Li *et al.* (2012),[88] Miech *et al.* (2024),[99] Schläfle *et al.* (2023)[95] and Yan *et al.* (2021).[87] While Li *et al.* (2012)[88] based their findings on a theoretical model that indicated increased particulate tire wear emissions with higher temperatures, Schläfle *et al.* (2023)[95] conducted an emission study on winter, summer, and all-season tires at 5 °C and 25 °C using an internal drum test bench. The emission order remained the same, with summer tires always emitting lower PM10 values than winter tires regardless of the temperature. However, different emission trends were observed. Higher ambient temperature led to slightly higher emissions for summer tires and lower emissions for winter tires. That said, the sampling of total PM and the focus on the PM10 fraction limit the validity of the results. Since winter tires are softer, an increase in particle size is assumed. Therefore, the reduced particulate tire wear emissions at higher temperatures may be misleading, as more particles larger than 10 μm might have been emitted but were not considered.[95] Miech *et al.* (2024)[99] determined a decrease in particulate tire wear emission (<10 μm) in highway PM10 samples during the winter season which corresponded to 29.1 °C cooler ambient temperature than in summer. In contrast, Yan *et al.* (2021)[87] observed that there was a gradual decrease in fine particulate tire wear emissions (<18 μm) with an increase in ambient temperature (25 °C, 45 °C, 65 °C) under laboratory conditions using a custom-made tire tread material. However, the extent to which these findings can be extrapolated to real-world conditions remains to be elucidated.

Besides temperature, rain impacts particulate tire wear emissions, as the friction between the tire and the road decreases when the road surface changes from dry to wet conditions.[98] Even an increase in humidity may result in the formation of smaller particle sizes, as observed by Chang *et al.* (2020).[59] However, wet pavements may decrease resuspension and rain droplets may remove airborne particles from air.[102]

In addition to this direct impact, humidity also indirectly affects particulate tire wear emissions. For good tire grip under wet conditions, the road surface texture must have a coarse structure to allow water drainage[98] and reduce the risk of aquaplaning. A coarse road surface, however, is correlated with higher particulate tire wear emissions.[59]

3.6 Leachables from tires and particulate tire wear

The majority of additives present in tires and their transformation products are not covalently bound to the rubber polymer.[21] Consequently, these substances can be released either directly from the tire or from the emitted particulate tire wear during precipitation events or when tire wear particles reach surface waters; compare Fig. 1. Environmental studies assessing the distribution and fate of these tire leachables mainly focused on a few specific substances. The most frequently detected tire leachables included tire additives dibenzylamine, dicyclohexylurea, DPG, diphenylurea, HMMM, 2-mercaptobenzothiazole, tributylamine, and the known transformation products benzothiazole-2-sulfonic acid, 2-methylthiobenzothiazole, phenylguanidine, and 6-PPDQ. Apart from tributylamine and dibenzylamine, the environmental occurrence of these substances has been well documented, with reported concentrations ranging from ng L^{-1} to μg L^{-1} in surface waters, stormwater runoff and wastewater.[25,26,103–106]

However, screening studies of tire leachates have revealed over 150 organic substances that could potentially be emitted from tires.[21,83] Of these, 60% remain unidentified.[21] Moreover, Weyrauch *et al.* (2023)[16] demonstrated that the environmental ageing of TRWP results in significant changes to the leachate composition, shifting from parent compounds to transformation products. Yet, the identification of potential transformation products and their environmental occurrence remains limited to a few well-known tire leachables, including HMMM,[103,107] 6-PPD, and 6-PPDQ.[108] Additionally, changes in the original tire composition will affect the tire leachate composition. Currently, tire manufacturers are engaged in the development of new vehicle tires that are designed with the objective of enhancing sustainability and reducing environmental impact addressing lower fuel consumption and lower wear rates and reduced CO_2 emission during manufacturing, especially by replacing fossil-based materials with biobased or recycled materials. Such tires are promoted as being "eco-friendly", "green" or "sustainable". However, data on "green" tires are limited,[85] and no data on tires used for electric vehicles are currently available. Furthermore, the impact of electric trucks on truck tire emissions remains unknown, as no investigation into this area has yet been conducted.

Two additional factors complicate the determination of the emission factors for each tire leachable. While some leachables are known to be exclusively used in tires (*e.g.*, 6-PPD and DPG[109]), others, such as HMMM, have multiple sources besides tires.[107] To evaluate the impact of changes in tire composition or particulate tire wear emission on the emission factor, it is essential to assess emission levels from other sources as well. Furthermore, the emission dynamics of each tire leachable require assessment. While untreated road runoff represents the primary entry pathway into the hydrosphere,[110] in addition to stormwater and wastewater treatment plant effluents, Johannessen *et al.* 2022[104] observed different emission dynamics for DPG and 6-PPDQ. It was found that DPG persists in the liquid phase after emission, whereas 6-PPDQ is prone to sorption.[108] Therefore, it is essential to assess the emission dynamics of each tire leachable, as these will directly affect their environmental distribution, fate, and, consequently, their environmental impact.

3.7 Volatiles from tires and particulate tire wear

Depending on the compound properties, emissions from the tire may occur as gases. Volatile emission data during the manufacturing and the recycling process of rubber exists.[20,111,112] A study in a truck tire manufacturing facility indicates alkanes, aromatics, and oxygenated volatile organic compounds as dominating gaseous tire emissions.[113] Only one study by Williams and Cadle (1978)[2] investigated volatile tire wear emissions (hydrocarbons) besides particulate tire wear emissions (separated into sedimentary >30 μm and airborne PM <30 μm) for different driving conditions. While no specific driving parameters were varied, different driving conditions and scenarios, such as cold starts, steering maneuvers, accelerating maneuvers and high-speed driving, as well as their combinations were investigated and compared. For all test conditions, sedimentary particulate tire wear (>30 μm) emissions were the predominant emission type and the highest percentage of total tire wear emission for airborne particulate tire wear (<30 μm, 4–12 wt%) and hydrocarbon emission (6–13 wt%) was found for the high-speed test (88 km h^{-1}). Interestingly, the emission rate of gases and airborne PM was found to be nearly independent of the wear rate and accounted for 1–20 wt% of the total emission. Additionally, Cadle and Williams (1979)[1] reported volatile emissions (hydrocarbon and sulfur compounds) of 2.4 mg per kg per vehicle and particulate tire wear emissions (0.01–30 μm) of 2–5 mg per kg per vehicle. Generally speaking, data on gaseous emission is sparse and data gaps regarding volatile emissions during the use of a tire persist.

4 Impacts of climate change and e-mobility on the conceptual exposure model

Future changes of tire emissions and exposure may be attributed to changes in mobility and tire technology including formulation, legislation, and distribution pathways. Mobility changes may be influenced by the transition towards electric vehicles and increased urbanization. Distribution pathways of tire emissions can be affected by factors such as changing weather conditions. In order to capture these changes and predict the development, fit for purpose analytical tools and exposure measures are needed.

4.1 Needs and development of analytical methods for tire emissions

The aforementioned lack of harmonization in standard procedures results in various reported emission factors due to differences in sampling systems, particle measurement systems, test cycles, or reporting units. The sampling system poses a major problem due to significant variations in sampling efficiency. Hesse *et al.* (2022)[58] determined a sampling efficiency of 40% at 30 km h^{-1} and only 10% at 60 km h^{-1}, with overall efficiency decreasing as particle size increases. Most studies focused on the PM10 fraction rather than the entirety of TRWP emissions, raising questions about whether the findings can be directly applied to other size fractions. Tier 2 and Tier 3 methods are needed to enable a comprehensible exposure assessment and to identify long-term trends.

Tire emissions have been characterized using either emission factors (EF) or material flow analysis (MFA). As described by Mennekes and Nowack (2022),[13] EF are derived as the mass release of tire tread per tire or vehicle and distance driven, while MFA uses data related to import, export, production, or tire collection numbers, along with assumptions regarding the weight lost during the tire's service life. It has to be noted that the EF only refer to the mass loss of the tire and not to the mass of the heteroaggregate TRWP found in the environment. The reported range of emission rates per tire varies from 5 to 80 mg km^{-1},[114] depending on the severity of the driving conditions, with median values around 20–30 mg km^{-1}. Full vehicle tire abrasion rates range from 53 to 1500 mg per vehicle per km, depending on the vehicle type (passenger car, light duty truck, or heavy duty truck/bus) and driving conditions.[19,115]

Tire emission estimates have been calculated at the regional and country level with highly variable results depending on the method used (EF or MFA) and the experimental studies conducted to estimate mass loss.[11] In a study of European country level estimates, Mennekes and Nowack (2022)[13] reported that particulate tire wear emissions ranged from 54 000 metric tons per year to more than 130 000 metric tons per year, with per capita emissions ranging from 0.9 to 2.5 kg per year. The authors' critical review of the published literature revealed that very few of the published emission estimates are based on measured data, and more than half of the measured data is over 50 years old.

In addition to total mass emissions, estimates of size-fractionated EF for airborne particulate tire wear emissions have been made. The most common size-fractionated EF for particulate tire wear is the PM10 EF, with estimates ranging from 0.1 to 11 mg per vehicle per km in the primary literature.[116] PM10 EF <0.1 have been reported in the literature; however, there is uncertainty based on comparability of the tire type that was tested[117] or the testing apparatus did not represent a real world pavement.[76,77] The maximum reported PM10 EF of 13 mg per vehicle per km was first published in the secondary literature by Lükewille *et al.* (2001);[118] however, its actual origin is unclear. Similar to total mass emissions, the wide variation in the PM10 EF can be attributed to the different methods used to calculate emission rates, including derivation from emission inventories, receptor modeling, and statistical models using source profiles, as well as direct measurements from road simulator laboratories, asphalt paved test tracks, roadway tunnels, and roadside air sampling campaigns using various chemical markers.[115,119] Additional variables within those methods include the consideration of single tire types *versus* mixed fleets, pavement type, and driving conditions.

4.2 Shift toward electric vehicles will affect particulate tire wear emissions and possibly exposure pathways

As the relevance of exhaust emissions declines due to the transition of fossil-based traffic to electric transportation, the relative significance of non-exhaust emission increases.[120] Emission scenarios for airborne particulate tire wear predict a future increase, largely due to the increased weight of electric vehicles.[121–123] Yet, this proposed increase is based on model calculations and the results of Foroutan *et al.* (2025)[123] predicting a 17-fold increase in total particulate tire wear emission are questionable, as they are based on the MOVES4 model by the U.S. Environmental Protection Agency (EPA). Saladin *et al.* (2024)[116] have shown in a critical literature review that the tire wear PM10 emission factor used by the EPA is overestimated due to misunderstanding and misquotation of primary literature. Only Woo *et al.* (2022)[124] performed an experiment with different test vehicles and showed a 1.2 times higher tire tread loss for the electric vehicle compared to gasoline and diesel internal combustion engine vehicles due to its 20% heavier weight. Conversely, brake wear may decrease due to factors such as regenerative braking and the prevalence of autonomous driving.[125,126] While the estimates of emission factors are based on computations referring to few actual measurements and two major assumptions, the future electric vehicle fleet will be heavier and electric vehicles have higher torque, the development of the tire emissions depends on many more factors. Tires of electric vehicles differ from conventional vehicles in several ways. Because electric vehicles are often heavier than conventional cars due to their heavy batteries, the tires must have a higher load capacity. To maximize the travel range of electric vehicles, the tires are designed to have a lower rolling resistance. Additionally, the immediately available high longitudinal force of electric vehicles may lead to higher particulate tire wear emission rates and therefore, special rubber compounds are used that are more resistant to abrasion. Also, because electric cars are quieter, tire noise is more noticeable. Therefore, low-noise tires are often used to increase driving comfort. Lastly, tires designed for electric cars are often narrower and have a special tread pattern to minimize rolling resistance and maximize fuel efficiency.[120,121,127] These aspects have been investigated with respect to tire performance and no original data was found during this structured literature research which depicts the changes in particulate tire wear emissions during the electrification of the vehicle fleet. In addition, emission factors also depend on driving style influenced by driving assistant systems which may counteract the higher torque of the engines and composition of the vehicle fleet. Finally total emissions may be impacted by total traffic. The future development of automobile traffic is still expected to increase globally; however, there are likely regional differences and the global socio-economic development may quickly shift resulting in less traffic of heavy cars. Hence the commonly represented conclusion that electrification of the vehicle fleet will result in an increase of particulate tire emissions is not substantiated by the available data and knowledge and the discussion should include more of the relevant aspects.

4.3 Effects of climate change on tire emissions, distribution pathways and exposure

Empirical evidence directly linking particulate tire emissions and climate change is limited, given the complexity of isolating specific factors with broader environmental changes. However, a few studies and observations can hint at possible relationships, even though they may not directly establish causation. Climate change may have both direct and indirect effects on tire emissions. Direct impact could include changes in environmental conditions such as temperature, which may affect particulate tire wear, and changes in emission pathways due to extended dry periods and stormwater events.[15] Indirect effects may result from changes in the vehicle fleet (e-mobility) and tire types (fewer winter tires, more summer tires for Central European regions).

Several publications were found discussing seasonal variations in tire emissions, focusing on differences between winter and summer emissions. Kang and Kim (2023)[128] reported an increase in TRWP concentration in road dust by approximately 7.6–24.2% in summer compared to winter conditions in Cheonan City, Republic of Korea. Srimuruganandam and Shiva Nagendra (2012)[129] showed that in Chennai city, India, the 24-h average ambient PM10 and PM2.5 concentrations were significantly higher in winter and monsoon seasons than in the summer. Sadiktsis *et al.* (2012)[130] investigated differences in the chemical composition of winter and summer tires. An increase in stormwater events is expected to lead to more combined sewer overflows, resulting in increased particulate matter emissions, as demonstrated for microplastics.[131] Barbosa *et al.* (2023)[132] proposed the development of novel viscoelastic road pavement bituminous mixtures that offer an opportunity for increased on-road capture of microplastics and heavy metals concurrent as temperature trends rise. Zhou *et al.* (2023)[133] applied machine learning techniques to study the effects of various climate scenarios and socioeconomic conditions on emissions estimates in China from 2008 to 2018. Yan *et al.*[87] reported a gradual decrease in the emission of fine particulate tire wear with an increase in ambient temperature. Interestingly, the authors concluded that particulate tire wear emission decreased with increases in temperature and precipitation due to changes in vehicle utilization and behavior. Yet, Schläfle *et al.* (2023)[95] and Li *et al.* (2012)[88] observed an increase in particulate tire wear and PM10 emissions with higher ambient temperatures. Together the results of these studies were inconsistent, likely due to differences in methodologies emphasizing the importance of harmonized tire emission measurement methods capable of generating datasets that are "fit for purpose" in program evaluations related to climate change adaptation, environmental health, and public health. Overall, while there is a reasoned basis for linking climate change to particulate tire wear emissions through temperature effects, changes in precipitation, and altered traffic patterns, direct empirical evidence specifically focused on this relationship is relatively sparse. This gap highlights a potential area for future research as the implications for both air quality and climate mitigation strategies are significant.

5 Conclusions

As a consequence of the transition towards electric vehicles and weather changes which are related to climatic change, there has been a need to consider how tire emissions will be affected by these changes. The results of this research demonstrate that tire emissions while vehicle driving predominantly result in the formation of TRWPs. Additionally, constituents of tires may leach from the tire directly or from the emitted TRWPs when in contact with water, for example, during rain events. Information on volatile emissions during the use phase is currently unavailable. To assess exposure to tire emissions and ultimately assess their relevance and predict future changes, it is necessary to employ suitable sampling and analytical methods for particulates, water, and airborne matter. With a view to developing a targeted analytical workflow, a tiered approach was adopted from microplastics and proposed here, taking into account the different analytical questions involved in exposure assessment. The tiered approach allows for an overall assessment of tire emissions, encompassing all three types of emissions: particulates, leachables, and volatiles. To understand and accurately predict the occurrence of these emissions in response to changing environmental conditions, it is essential to gain a comprehensive understanding of the underlying process and to parameterize it accurately. Hence, the following knowledge and data gaps were identified:

- Robust analytical workflows to quantify emissions including particulates, leachables, and volatiles.
- Process understanding of the emission process including wear and its quantification aiming at a mass balance during changing formation conditions, and.
- Data on volatile emissions from tires and from particulate tire wear during vehicle use.

This data can then be incorporated into predictive computational models of the emission process and exposure, which will facilitate the evaluation of the impact of potential changes *e.g.* due to e-mobility and climate change on tire emissions. This, in turn, will support the development of targeted and efficient mitigation strategies, including the optimization of material and product design as well as the implementation of regulatory actions.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

The authors declare the following facts which may be considered as potential conflicts of interest: Kathrin Müller, Julie Panko, Kenny Unice, and Stephan Wagner report that partial financial support was provided for the research by the Tire Industry Project, which is a part of the World Business Council for Sustainable Development, Switzerland.

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