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Risk assessment of tire wear in the environment – a literature review†

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Tread wear emission inventories, uncertainty about the future development of the emissions and observed adverse effects of tire constituents in the environment have raised the need for an environmental risk assessment of tire wear emissions. While progress has been made in exposure and hazard assessment of tire wear emissions in the environment, the complexity of tire wear emissions creates some challenges which are not yet overcome. For instance, there is no universal agreed risk assessment framework for tire wear emissions. It was proposed that existing frameworks, for example for microplastics, be adapted to tire wear emissions because there are similarities between particulate tire wear emissions and microplastics, *e.g.* particulate material with a polymer backbone. The review discusses whether these are applicable for tire wear emissions and proposes adaptations. It provides a comprehensive assessment of exposure and hazard data for tire wear emission and reveals needs and data gaps for environmental risk assessment of tire wear. Based on the available exposure and hazard data sets a low risk prioritization of particulate tire wear emissions in aquatic and terrestrial environments was estimated. Risk prioritization of leachables from tire emissions is not yet possible due to inconsistent hazard data sets. It was found that for environmental risk assessment, insufficient consistent exposure and hazard data is available. It is suggested to develop clear harmonization guidelines how exposure and hazard studies should be designed. Such guidelines should be developed between all relevant stakeholders covering the entire product life cycle.

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Environmental significance

This structured literature review concludes with a risk prioritization of environmental compartment with respect to particulate tire wear emissions and leachables from tire wear. The review reveals also data and knowledge gaps that must be addressed in order to facilitate a comprehensive risk assessment of tire wear emissions. These needs include data and knowledge regarding exposure and hazard of tire wear emissions for marine environments and more specifically exposure and hazard data of leachable tire chemicals and their transformation products. Furthermore, it proposes a series of possible adaptations of microplastics risk assessment frameworks that could be employed in the context of tire wear emissions.

1 Introduction

As reported by the International Organization of Motor Vehicle Manufacturers, in 2024 global vehicle production reached approximately 92.5 million units.[1] The average lifespan of a tire is approximately four years, or 50 000 kilometers. During this period, the tire undergoes a loss of approximately 10% of its mass. This equates to a reduction of between 1 and 1.5 kg for a tire weighing between 7 and 12 kg, or an average wear per vehicle of approximately 120 g per 1000 km.[2,3] For example, it is estimated that approximately 500 000 tons of tire wear is generated in the EU on an annual basis.[4] How these mass generation rates will evolve during the ongoing electrification of the vehicle fleet is not yet known. Tread wear emission inventories, uncertainty about the future development of the emissions and observed adverse effects of tire constituents in the environment have raised the need of an environmental risk of tire wear emissions.[5–7]

The characterization of environmental risk is a process for estimating the probability of an adverse outcome or event due to pressures or changes in environmental conditions resulting from human activities. Risk is determined by incorporating

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knowledge of both the hazard and exposure potential and involves several steps, including (1) problem formulation, (2) exposure assessment, (3) hazard assessment and dose–response, and (4) risk characterization. Problem formulation defines the scope of environmental risk characterization by specifying the affected environmental compartment and potential harmful effects. The risk is determined based on a comparison between the hazard and the exposure assessment.[8,9] There is no universal agreed risk assessment framework for tire wear emissions. It has been suggested to adapt existing frameworks for instance for microplastics[10–13] to tire wear emissions because there are similarities between particulate tire wear emissions and microplastics, *e.g.* particulate material with a polymer backbone. Risk characterization of tire wear emissions may include particulate but also volatile and dissolved emissions so called leachables.[14] Therefore, there is a need to discuss the applicability of the existing microplastic risk assessment framework and consider the possibility of making adaptations.

This structured literature review summarizes available risk assessment concepts for microplastics and assesses whether these are applicable for tire wear emissions and suggests adaptations of these concepts toward tire wear emissions. Subsequently a comprehensive assessment of exposure and hazard data for tire wear emission is carried out and the needs and data gaps for environmental risk assessment of tire wear are identified. Based on the available exposure and hazard data a risk prioritization for freshwater, terrestrial and marine environments is done. The structured literature search was done from 1980 to 2024. Ultimately, the present study explores the question of whether environmental risk assessment of tire

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wear emissions is already possible and formulates most pressing research needs in this field.

2 Adaptation of the risk assessment concepts for microplastics to tire wear emissions

2.1 Risk assessment concepts for microplastics

In the past decade, ecological assessments of microplastics have consisted of particle mass or number exposure concentration measurement studies aimed at determining nature and extent in aquatic, terrestrial and airborne exposure settings. While progress has been made on the problem formulation and the general scheme (Table 1), a global consensus has not been agreed on the critical elements of a robust regulatory risk assessment framework.[11] Nonetheless, the proposed frameworks include (1) consideration of problem formulation, (2) exposure assessment, hazard assessment and (3) the integration of hazard and exposure to characterize the risk (Table 1). Differences exist in the terminology and approach in frequently cited frameworks that have been proposed for regulatory risk assessment (Table 2). The four main concepts proposed for microplastic risk assessment to date are based on this stepwise assessment requiring exposure and hazard data but differ with respect to information inputs.

The International Council of Chemical Associations (ICCA) proposed an environmental risk assessment framework (ERA) which would identify species and compartments of concern using exposure, fate, and hazard studies for a wide range of polymer types with diverse physicochemical properties[15] resulting in a high number of tests. The concept by Koelmans *et al.* is based on polymer-specific probability density functions (PDF) which reflect the diverse microplastic properties in the environment[10,16] and the identification of most sensitive species towards the heterogeneous polymer mixtures. This approach may not allow systemic identification of drivers for adverse effects. A third approach, the microplastics management framework, categorizes microplastics concentrations and applies tiers for mitigation actions.[17] A fourth concept uses a relative level of concern based on summed categorical hazard such as none, low, moderate, elevated, or high which are based on a harmonized exposure and hazard testing protocols.[18] All concepts have in common that they focus on the particulate nature of the microplastics, but chemical additives are not included despite some of them are for instance endocrine disruptors, *e.g.* bisphenol A or phthalates and nonylphenols.[19]

2.2 An extended risk assessment framework for tire wear emissions needs to cover particulate tire wear emissions and leachables

Among the proposed frameworks in Table 2 none can be directly applied to tire wear emissions because (i) physicochemical and morphological differences exist between particulate tire wear emissions and microplastics and (ii) both particulate and chemical hazard are relevant for tire wear emissions while microplastic concepts focus only on assessment of particles. The PDF approach by Koelmans *et al.*[10] represents the most flexible approach because it accounts for the heterogeneity of the physical and chemical properties of these materials. It is also comprehensive and consistent with modern ecological risk assessment principles incl. quantitation of uncertainty (Tables 1 and 2). Similar to microplastics, the uncertainty of exposure and hazard data from tire wear emissions remains high and needs to be reduced to draw reliable conclusions. For a tire wear risk assessment framework, the exiting microplastic framework may be complemented by specific aspects of chemical compounds, so called tire leachables and their transformation products, as tire wear particles may act as a source for these chemicals. As revealed by this

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Table 1 Overview of the multidimensional regulatory risk assessment scheme and emphasis on ecologically relevant metrics (ERM) proposed by ref. 10 and 20

Scheme element	Step 1: Problem formulation	Step 2: Exposure and hazard	Step 3: Risk assessment
Question	What is the protection objective?	What is the effect mechanism?	What is the risk?
Outcome	Preliminary hypotheses about past or future ecological effects	Selection of exposure (A) and dose–response metrics (B)	Risk for each assessed toxicological and/or ecological effect mechanism
Concepts	● Exposure pathways	● Exposure metric and profile	● Continuum (*e.g.* distribution of sizes)
	● Ecological or toxicological effect	● Effect metric and profile	● Acceptable dose distributions
Considerations	● Harmonization	● Mass and surface area	● Bioavailable fraction
	● Quality assurance and control	● Volume and aspect ratio	● Probability density function

literature review, leachables from tire wear emissions are most susceptible to adverse effects. Therefore, an extension of the risk assessment of microplastics towards methodologies for leachables including transformation products is required.

Because a risk assessment is conducted for a specific geographical scale and mostly for a specific site, it precludes the drawing of general conclusions regarding the risk of tire wear emissions. However, a discussion on available data and information regarding the three steps of the regulatory risk assessment scheme depicted in Table 1 for tire wear emissions is possible.

Table 2 Comparison of four proposed environmental risk assessment frameworks

Framework	Contributors	Key first tier inputs	First tier outputs	Higher tier assessment	Data needs	Reference
International Council of Chemical Associations (ICCA) symposium summary of a proposed conceptual model	Scientists from academia, industry and government attending ICCA symposium	Fate; physio-chemical properties; harmonized effect studies (physical and cellular effects); exposure and dose–response modeling	Compartments and species of concern; screening-level risk characterization; identification of data needs to address uncertainty	Refined risk characterization based on mesocosm, field studies, mixture toxicity, and/or species sensitivity distributions	Research on method development and use to strengthen data quality	15
Development of default polymer-specific probability density functions (PDF)	Lead by scientists at Aquatic Ecology and Water Quality Management Group, Wageningen University & Research[a]	PDFs for particle width, width to length ratio, area, specific surface area, volume and mass distributions	Screening-level alignment of monodisperse effect threshold with polydisperse environmental exposures for risk characterization	Authors suggest conceptual workflow be used refine the generalized PDFs and exponent values	Mechanism of adverse effects for freshwater, marine and terrestrial toxicological or ecological endpoints	10, 16 and 21
Microplastics management framework (MPP) developed by Microplastics Health Effects Workshop experts	International scientists participating in Sothern California Coastal Water Research Project (SCCWRP) workshop	Particles per liter or mass (mg per liter) in water scaled operationally defined as particles sized 1 to 5000 μm	Management tier or level of concern based on concentration for food dilution and tissue translocation **Tier 1** (no concern); **Tier 2** (low; monitoring); **Tier 3** (moderate; study sources); **Tier 4** (elevated; mitigation); **Tier 5** (pollution control)	Freshwater and aquatic species were merged to derived tiered thresholds of concern; data for taxa specific to geography and habitat, if available, would refine the assessment	Evaluation of the assumption that mechanisms influence toxicity more than habitat; thresholds for sediment	17
Bucci and Rochman (BR)	Scientists at Department of Ecology and Evolutionary Biology, University of Toronto	Categorical dimensions of shape, polymer type, size and ecosystem water quality	Relative level of concern based on summed categorical hazard such as none, low, moderate, elevated or high	Metaanalyses of literature or future toxicity tests to inform risk management in line with objectives and risk tolerance	Harmonized exposure measurements and ecotoxicity testing	18

[a] Researchers from Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (Germany) and Department of The Built Environment, Aalborg University (Denmark) contributed to the development of particle-specific PDFs.

3 Risk assessment of tire wear emissions in aquatic and terrestrial environments

3.1 Step 1: Problem formulation

In step 1 the protection objective is defined and preliminary hypotheses about past or future ecological effects are set. This includes the geographical scale of the risk assessment; does it assess a local site or a region, continent or even globally. Endpoints of adverse effects and test organism are to be defined as well; classics are growth or mortality or other end points which may be related to chronic effects or effects on cellular level, metabolisms or on population scale.

With the compilation of the release and distribution pathways of tire wear emissions during vehicle use, relevant exposure pathways and affected environmental compartments are identified. These pathways have been described earlier.[22,23] Tire wear emissions during vehicle use comprises particulate tire wear emissions, leachable constituents and volatile or semi-volatile organic chemicals. While the emission pathways and exposure routes of particulate tire emissions and leachables have been studied in more detail, there are substantial knowledge and data gaps for the emission of volatiles.[24] The main distribution pathways of leachables and particulate tire emissions is *via* terrestrial and aquatic compartments and thus, considered as relevant environmental exposure routes. While air is considered as a transport pathway of airborne particulate tire wear emission eventually being deposited in terrestrial and aquatic compartments, it is only considered as relevant exposure route for human health assessment but not ecological risk assessment.[22]

Many microplastic researchers have acknowledged that the largest testing uncertainty is the lack of representativeness of the test material because most microplastic testing has been conducted with particles of the pristine polymers rather than present in the environment. Hence, the pristine microplastics lack many of the plastic additives. Compared to tire wear emissions microplastics are expected to contain an even higher diversity of additives due to the very broad range of applications and the required material properties while the mass concentration of additives in rubber is comparably high; up to 60%.[25] Representative test materials for tire wear emissions may include particulate materials mimicking tire and road wear particles (TRWPs) and dissolved compounds representing typical leachable composition. Ideally the test material for hazard and fate studies should mimic the heterogeneity of the environmental tire wear emissions including physical and chemical properties *e.g.* size, density, and chemical composition, including transformation products.[26] For instance, it was observed that aging of particulate tire wear results in changes of the toxicity of the leachates; leachates from pristine tire wear particles were more toxic compared to leachates from aged tire wear particles.[27] Although the tire wear emission researchers use some type of surrogate for TRWP, the test material is highly variable including particles from laboratory generated TRWP,[28,29] manual abrasion from the tire surface,[30–32] commercially produced recycled crumb rubber,[33] both of which may be further ground to a specific size range, and more recently, a standardized cryogenic milled tire tread (CMTT) mix.[34] Additionally, there is an appreciable difference in test system designs with respect to particle size, concentration of tire particles used either directly or from which leachates are prepared (100 to >100 000 mg L^{-1}), duration of leaching time, temperature at which the leachate is created, and aging of the particles.[35–38] Test material representing a tread compound mix of tire leachables, including their transformation products, needs to be defined for the exposure assessment of the entirety of tire leachables. As for now leachates are produced mostly from pristine tire materials or laboratory aged tires either using organic extraction agents or water-based extraction protocols while environmental material rich in TRWP has not been used to generate representative leachable composition.[39]

3.2 Step 2A: Exposure assessment in relevant environmental compartments

A structured literature search was conducted of relevant scientific publications using Web of Science and PubMed as research database to identify exposure and hazard measurements of particulate tire emissions or leachables in terrestrial and aquatic environmental compartments. In total 327 publications were reviewed, and 130 publications were found stating exposure or hazard concentration data for tire wear emissions (Table 3). Exposure data for freshwater environments (38 items) was reported more than four times as much as for marine (11 items) and terrestrial environments (10 items). There were also more literature hits for leachables compared to particulate tire wear emissions. Additionally, data for road dust, treatment systems, storm water and snow (other) were compiled as they may act as source and entrance pathways for tire emissions into natural environments.

3.2.1 Concentrations of particulate tire emissions are overall consistent despite high uncertainties in the quantitation methods. Most data were found for road dust, one of the initial receiver media of particulate tire wear emission, and the different road dust origins can be rank from lowest to highest concentration as follows: rural < industrial = urban < tunnel (Table 4). The mean concentration ranges between several thousand to tens of thousands mg kg^{-1}, while maximum concentrations of over 100 000 mg kg^{-1} are reported for urban and tunnel road dust.[40,41] For roadside soil as primary environmental receiving media, a mean concentration of several thousand mg kg^{-1} is reported but can even reach up to 52 720 mg kg^{-1}[42] and thus, are in the same range as for road dust. For the aquatic compartment as receiving media, storm water is considered as main distribution pathway, indicated by the mean concentration of particulate tire wear emission in the two-digit mg L^{-1} range.[43] Due to dilution and further transformation and removal processes in the receiving water compartments two order of magnitude lower concentrations are reported for the river water column and sea water column.[2] For example, the particulate tire emission is eventually deposited in the sediment (secondary environmental receiving media) after

Table 3 Number publications found during the structured literature review for exposure and hazard data of particulate tire wear emissions and tire leachables

Topic	Total	Freshwater	Marine	Terrestrial	Other
Overall	130	68	27	21	43
(i) Exposure data of particulate tire wear emission	31	10	3	5	20
(ii) Exposure data of tire leachables	49	28	8	5	21
(iii) Hazard assessment data of particulate tire wear emission	29	16	6	8	1
(iv) Hazard assessment data of tire leachables	32	23	11	4	1

reaching the aquatic compartment.[29] The reported river sediment concentrations range from several hundred to thousand mg kg^{-1}, with exception of the results of Goßmann *et al.*[25] which are significantly lower reporting only 0.05 mg kg^{-1} on average. This uncertainty is usually explained with different sample locations, sampling methods, as well as analyses methods.[3,44] This may also be true for the reported high concentration in lake sediment employing Zn as marker.[45] Barber *et al.*[46] adapted the Zn-based tire wear detection method and yielded more comparable results for the same samples analyzed once employing Zn as marker and once employing styrene–butadiene rubber (SBR), butadiene rubber (BR) and natural rubber (NR) pyrolysis products as marker. For sea sediment the authors reported concentrations in the low hundred mg kg^{-1} range, while again the results of Goßmann *et al.*[25] for sea sediment are significantly lower reporting the overall lowest concentration in any compartment. As this concentration is one order of magnitude lower than the authors reported river sediment concentrations, the concentration of particulate tire wear emission in sea sediments is assumed to be the lowest. Yet, further studies of lake and sea sediments are needed to verify these results.

The observed high concentration variations within one sampling compartment may be attributed, among other things, to the conditions at the different sample locations of each study. The formation of particulate tire wear emissions depends on several influencing parameters such as vehicle speed, road profile/section, road surface, tire types and more.[47–52] Thus, urban road dust samples from Beijing, China,[53] from Seoul, Republic of Korea[54] and from Leipzig, Germany[45] are difficult to directly compare. Furthermore, differences in the analysis method increase the variation as eleven different markers were used to determine the particulate tire wear concentration using average content of marker compounds in tire tread. Interestingly, the mean concentrations in urban road dust are one order of magnitude higher if organic marker compounds are employed compared to polymer markers (compare Table 4). While these differences indicate a potential bias, no general conclusion can be drawn about the marker suitability and if concentrations are overestimated or underestimated, respectively.

3.2.2 Exposure data of tire leachables is dominated by a few tire chemicals. Over 200 potential leachables emitted from tires or particulate tire emissions have been identified[30,76] but only for a few selected compounds such as *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylendiamine (6PPD) and its transformation product *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylendiamine quinone (6PPD-Q), 1,3-diphenylguanidine (DPG), hexa(methoxymethyl)melamine (HMMM), benzotriazole and benzothiazole derivatives has their environmental occurrence and distribution been reported (Tables 5 and S1†). Among the assessed compounds 6PPD-Q is studied the most (38 publications) followed by DPG (20 publications) which is detected most frequently and is reported with the overall highest concentration of 0.3 mg L^{-1} in storm water.[77] The highest concentrations in environmental media are reported in general for each compound in storm water, ranging from ng L^{-1} to μg L^{-1}, as it acts as transportation media for leachables.[77–81] Additionally, for roadside snow, high concentrations are detected due to the accumulation of particulate tire emissions in the snow and the resulting continuous leaching of the particles.[77,82] Thus, snow melt water must also be considered as relevant mobilization and transportation media for leachables. The same is true for tunnel wash water. While it does not represent an environmental compartment, it acts as a potential source and entrance pathway, reporting concentrations of several μg L^{-1}.[83,84]

In the receiving compartments, freshwater concentrations in the ng L^{-1} range are reported and lowest concentrations are reported for marine water due to the dilution effect and other fate processes *e.g.* transformation, breakdown and possibly sorption processes. Thus, also higher concentrations for freshwater sediment are reported reaching up to 801 μg kg^{-1} for HMMM and 619 μg kg^{-1} BTR,[85,86] while for marine sediment one-digit μg kg^{-1} concentrations are reported. Yet, data on sediment concentrations for each compound are limited as mostly only one study assessed those (Tables 5 and S1†). Soil as receiving media is studied the least and concentrations of up to mg kg^{-1} are reported with the highest concentration of 4.1 mg kg^{-1} for DPG.[87] Especially for the terrestrial receiving media and sediments a more comprehensive data set is needed for a reliable exposure estimation and thus a risk characterization of leachables.

Another consideration in the exposure and thus risk characterization is the uncertainty about the known and unknown leachables. While the presented exposure data are needed for a risk characterization of each compound, no defined exposure measure for the risk assessment of tire leachables exists.

Table 4 Reported concentrations of tire wear particles in various environmental and anthropogenic matrices using different chemical markers. The data refers to the tire tread component of TRWP particles

Sampling compartment	Marker	Mean	Min	Max	Unit	References
Terrestrial						
Roadside soil	SBR	3347	179	18 700	mg kg^{-1}	55 and 56
	SBR/BR	3900	200	20 000	mg kg^{-1}	29
	SBR/SBS/BR	9381	3700	20 067	mg kg^{-1}	42 and 57
	Zn	8400	475	52 720	mg kg^{-1}	55
Road dust						
Urban	SBR	5683	4050	7000	mg kg^{-1}	45
	SBR/BR	3580	2270	4950	mg kg^{-1}	58
	SBR/NR	1294	105	6813	mg kg^{-1}	59 and 60
	SBR/BR/NR	2666	1500	4500	mg kg^{-1}	54
	BT	35 400			mg kg^{-1}	61
	Bonded sulfur	23 400	10 400	48 600	mg kg^{-1}	53
	24MoBT	17 000	5000	124 000	mg kg^{-1}	40 and 41
	NCBA	34 000	2000	78 000	mg kg^{-1}	40 and 41
	Oleamide	28 958	18 250	42 750	mg kg^{-1}	62
	Zn	4017	3350	4700	mg kg^{-1}	45
Rural	SBR/BR	510			mg kg^{-1}	58
Industrial	SBR/NR	7645	860	20 660	mg kg^{-1}	59 and 63
	SBR/NR	59 748	38 037	87 472	mg kg^{-1}	60
Tunnel	SBR/SBS/BR	62 900	8650	186 500	mg kg^{-1}	64
	24MoBT	70 600	7725	210 700	mg kg^{-1}	41
	NCBA	67 100	14 404	203 600	mg kg^{-1}	41
	Zn	57 500	55 000	60 000	mg kg^{-1}	65
Tunnel wash water	SBR/SBS/BR	16.7	4.9	34.6	mg L^{-1}	64
Aquatic						
River						
Sediment	SBR/BR	1036	13	31 508	mg kg^{-1}	29 and 66
	SBR/BR/NR	250	70	1150	mg kg^{-1}	67
	SBR/SBS/BR	0.05	0.01	0.07	mg kg^{-1}	25
	24MoBT	900	429	3900	mg kg^{-1}	40 and 41
	NCBA	3500	530	7300	mg kg^{-1}	40 and 41
	Zn	611	0.9	2560	mg kg^{-1}	67
Water column	SBR/BR	0.38	0.004	9.2	mg L^{-1}	66, 68 and 69
	SBR/BR/NR	0.01	0.004	0.03	mg L^{-1}	67
Lake						
Sediment	SBR	52.1	0.075	172.9	mg kg^{-1}	45 and 70
	Zn	20 000			mg kg^{-1}	45
Sea						
Sediment	SBR/BR/NR	202	103	361	mg kg^{-1}	46
	SBR/SBS/BR	0.002			mg kg^{-1}	25
	Zn	179	73.5	522	mg kg^{-1}	46
Water column	SBR/NR	0.0008			mg L^{-1}	46
	SBR/SBS/BR	0.002	0.0006	0.007	mg L^{-1}	71
Storm water	SBR/BR/NR	4.06	0.01	12.2	mg L^{-1}	72
	24MoBT	43.9	0.64	164.8	mg L^{-1}	40 and 41
	NCBA	34.0	2.23	171.7	mg L^{-1}	40 and 41
Roadside snow	SBR/SBS/BR	2090	0.11	14 500	mg L^{-1}	57 and 73
Treatment system						
Sedimentation basin						
Sediment	SBR	34 300	950	95 000	mg kg^{-1}	45 and 74
	SBR/BR	24 400	2611	374 300	mg kg^{-1}	66
	Zn	53 900	190	240 000	mg kg^{-1}	31 and 45
Water column	SBR/BR	1	0.20	15.1	mg L^{-1}	66
gully pot						
Sediment	SBR/BR	6700	305	188 700	mg kg^{-1}	66
	SBR/SBS/BR	26 800	5900	76 800	mg kg^{-1}	57 and 64
	STA + FTIR	43 100	800	149 600	mg kg^{-1}	75
Water column	SBR/BR	1.9	0.44	27.8	mg L^{-1}	66

Table 5 Reported concentrations of TRWP related leachable compounds in various environmental matrices. For concentration data of further TRWP related leachable compounds refer to Table S1. 6PPD *N*-(1,3-Dimethylbutyl)-*N*′-phenyl-*p*-phenylendiamine, 6PPD-Q *N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylendiamine quinone, HMMM hexa(methoxymethyl)melamine, DPG 1,3-diphenylguanidine

Analyte	Sample	Mean	Min	Max	Unit	Reference
6PPD	Freshwater	28.0	0.27	163	ng L^{-1}	89–92
6PPD	Marine water	2.65	0.02	6.37	ng L^{-1}	93–95
6PPD	Storm water	36.7	<0.04	907	ng L^{-1}	78, 81, 91, 92, 96 and 97
6PPD	Snow	329	65.6	784	ng L^{-1}	82
6PPD	Freshwater sediment	51.4	0.14	468	μg kg^{-1}	85, 90, 98 and 99
6PPD	Marine sediment	2.87	<0.02	11.1	μg kg^{-1}	93, 94 and 98
6PPD	Soil	182	3.03	1290	μg kg^{-1}	97 and 100
6PPD	WWTP influent	10.6	1.10	59.0	ng L^{-1}	101 and 102
6PPD	WWTP effluent	5.94	0.30	15.0	ng L^{-1}	101 and 102
6PPD	Tunnel wash water	21 554	1743	91 200	ng L^{-1}	83
6PPD-Q	Freshwater	76.6	0.05	2850	ng L^{-1}	68, 89–92 and 103–115
6PPD-Q	Marine water	3.47	0.02	16.3	ng L^{-1}	80, 93–95 and 109
6PPD-Q	Storm water	733	0.002	5580	ng L^{-1}	77, 78, 80, 81, 91, 92, 96, 97, 103–105, 109 and 115
6PPD-Q	Snow	217	4.43	756	ng L^{-1}	77, 82, 96 and 107
6PPD-Q	Freshwater sediment	8.72	<0.30	46.0	μg kg^{-1}	85, 90, 98 and 116
6PPD-Q	Marine sediment	2.10	0.02	4.88	μg kg^{-1}	93, 94, 98 and 116
6PPD-Q	Soil	206	0.85	939	μg kg^{-1}	97, 100 and 117
6PPD-Q	WWTP influent	28.3	1.90	470	ng L^{-1}	91, 101, 102 and 118
6PPD-Q	WWTP effluent	8.78	1.10	37.0	ng L^{-1}	84, 91, 101 and 102
6PPD-Q	Tunnel wash water	1048	49.5	3440	ng L^{-1}	83 and 84
HMMM	Freshwater	365	0.30	2260	ng L^{-1}	68, 89, 110, 111, 114 and 119–122
HMMM	Marine water	11.5	<0.22	57.0	ng L^{-1}	80, 94 and 115
HMMM	Storm water	1681	0.2	11 548	ng L^{-1}	78, 80, 81 and 96
HMMM	Snow	3311	1110	8419	ng L^{-1}	82 and 96
HMMM	Freshwater sediment	6.40	<0.03	801	μg kg^{-1}	85
HMMM	Marine sediment	0.27	0.09	0.57	μg kg^{-1}	94
HMMM	WWTP influent	7.87	<1.60	23.1	ng L^{-1}	123
HMMM	WWTP effluent	39.4	<1.60	83.2	ng L^{-1}	123
HMMM	Tunnel wash water	13 129	2214	18 629	ng L^{-1}	83
DPG	Freshwater	139	0.50	1894	ng L^{-1}	68, 77, 91, 110, 111, 113, 114 and 119–121
DPG	Marine water	7.65	0.28	93.0	ng L^{-1}	80, 93, 94 and 115
DPG	Storm water	34 098	0.29	364 250	ng L^{-1}	77, 78, 80, 81 and 91
DPG	Snow	5912	15.8	14 196	ng L^{-1}	77 and 82
DPG	Marine sediment	0.15	<0.12	2.07	μg kg^{-1}	93 and 94
DPG	Soil	1100	15.0	7600	μg kg^{-1}	87
DPG	WWTP influent	1086	73.0	3570	ng L^{-1}	91 and 101
DPG	WWTP effluent	123	58.2	296	ng L^{-1}	91 and 101
DPG	Tunnel wash water	29 561	2674	63 086	ng L^{-1}	83

Furthermore, several transformation products have been identified for the leachables and some still potentially being unknown, which need to be considered. Therefore, it is necessary to define a representative compound mix of tire leachables, including their transformation products, for the exposure assessment of the entire range of tire leachables. To generate such a representative compound mix there is a need for focused data on the assessment of vulcanization and decomposition products of additives, such as potential environmental weathering products of unknown and variable composition of functionally important classes of chemicals, such as amine antioxidants. An illustration of a previously unknown weathering product is 6PPD-Q, which has been identified as a decomposition of 6PPD formed during its intended function of protecting tire tread from oxidative attack.[79] Subsequently, a broad collection of studies necessary to inform risk management of this environmentally formed product have been initiated[88] and it is currently most studied tire leachable.

3.3 Step 2B: Hazard assessment of tire wear emissions

3.3.1 What are relevant endpoints for hazard assessment of tire wear emissions? There are no agreed upon methods for testing the ecotoxicity of particulate tire emissions, however like microplastics, researchers have investigated effects from both direct exposure of organisms to the particles and exposure to leachates created from the particles. Many microplastics researchers have concluded that the relevant endpoints for direct particle exposure is food dilution, wherein part of the organism diet is replaced by the microplastics and creates a false sense of satiation and reduce nutrient ingestion, as well as translocation of microplastics across epithelial barriers which may induce tissue inflammation and oxidative stress.[17] A wide range of particle size is considered for food dilution (1–

5000 μm), but a more limited particle size is considered for tissue translocation (1–83 μm).[124] For these impacts, test systems have included acute and chronic exposures, and the endpoints evaluated included those at the organism (*e.g.* mortality, body mass, body length, fecundity), tissue (*e.g.* Hepatic and gonad somatic index), cell (*e.g.* cell density and morphology) and sub-cell (*e.g.* metabolism indicators including glutathione *S*-transferase and superoxide dismutase activity and endocrine indicators like estradiol to testosterone ratio) levels.[17]

For exposure to microplastics leachates, no common relevant endpoints have been proposed, which is also the same for particulate tire emission leachates. Endpoints measured for tire particle leachate studies include mortality, growth, reproduction, population increase or decrease, hematological changes, and gene expression. The leachate research studies indicated that the effects from particle leachate are associated with the chemical composition of the particles themselves and are highly variable depending on the test material, age, and leaching conditions.

Mixture toxicity for chemicals associated with tire emissions is assessed when using particulate tire emissions and its surrogates because particulate tire emissions is itself a mixture comprised of the tread compound (a mixture of polymers and additives from different tires) and roadway particles (asphalt, minerals), as well as vehicle-related particles (brake wear particles, tailpipe emission particles).[125] As such, studies of particulate tire emissions rather than its base polymers provide the most realistic test material for investigation of the ecological hazard properties because the chemical mixture is inherently assessed. Given the difficulty in producing particulate tire emissions in the laboratory, cryogenic milled tire tread (CMTT) particles are the next best surrogate test material at the moment. If environmental materials rich in TRWP such as tunnel road dust may be a better surrogate test material has not been evaluated yet.[26]

3.3.2 Hazard data exists predominantly for freshwater and terrestrial organisms. The ecological hazard of particulate tire wear emission has been assessed directly through exposure of organisms to the particles directly or indirectly through exposure to the leachates prepared from the particles. Particle exposure data have been presented in 29 studies (Table 3) to a total of 27 different terrestrial, aquatic and sediment dwelling organisms, involving many different test designs. Acute and chronic exposure for freshwater, marine water and terrestrial dwelling organisms have been investigated, while for freshwater sediment and marine sediment dwelling organisms only chronic exposure tests were performed (see Fig. 1). The most common endpoints investigated were those associated with organism level effects including mortality (67% of studies), growth/development (10% of studies), and reproduction (23% of studies). Only two studies were identified wherein subcellular effects were evaluated for acute freshwater exposure and include various gene expressions (midge *Chironomus riparius*[126]) and antioxidant enzyme levels (water flea *Daphnia magna*[127]).

Most aquatic toxicity tests of particulate tire wear emission were carried out for acute and chronic exposures of freshwater organisms, with mortality and reproductive endpoints of *Daphnia magna* being the most studied. Other acute exposure studies have assessed mortality of invertebrates (*H. azteca*, *A. aquaticus*, *C. riparius*), growth for algae (*P. subcapitata*), mortality of amphibian (*S. tropicalis*), and mortality and reproduction in fish (*P. promelas*, *D. rerio*). All the of the available LC50 or EC50 values exceed 10 mg L^{-1} except for the amphibian *S. tropicalis*.[128] For chronic studies of the freshwater organisms, the data are more scattered with some hazard values less than 10 mg L^{-1}. In general, studies for *D. magna* report no effect to mortality after chronic exposure to particulate tire emission but effects to reproduction at concentrations between approximately 1 to 10 mg L^{-1}.[129] Growth was impacted in green algae (*P. subcapitata*) at ~31 mg L^{-1} (ref. 129) and mortality was observed in the amphibian *S. tropicalis* and on zebrafish (*D. rerio*) after chronic exposure to particulate tire emissions.[128,129]

The toxicity of particulate tire wear emission in freshwater sediment organisms has also been well studied under chronic exposure conditions including mortality for amphibian (*R. sylvatica*), as well as seven invertebrate species (*G. pulex*, *Tubifex*, *C. riparius*, *C. dilutus*, *H. azteca*, *L. variegatus*, *A. aquaticus*) and reproduction for *L. variegatus*. All of the no observed effect concentrations (NOECs) for mortality or reproduction in these organisms are greater than 1000 mg kg^{-1}. There are no studies identified on the acute toxicity of particular tire wear emission in freshwater sediment organisms.

In addition, one study evaluated freshwater fish *in vitro* toxicity of tire wear particulate emissions (as CMTT) in rainbow trout gill (RTgill-W1) and gut (RTgutGC) cell lines.[130] Cell metabolic activity, membrane integrity, and lysosome integrity were assessed after 24 hour exposure to CMTT or thermooxidized CMTT particles to assess the effect of particle aging on toxicity. In both cell lines, metabolic activity was the most sensitive endpoint. Further, aged CMTT was less toxic in both cell lines. The EC50s for metabolic activity were 2023 mg L^{-1} RTgill-W1 and 4651 mg L^{-1} for RTgutGC.

Terrestrial toxicity studies of particulate tire wear emission have also been conducted and include a limited number of acute mortality studies on soil invertebrates (*E. crypticus*, *F. candida*, *E. andrei*). However, there are 10 studies of terrestrial invertebrates for chronic endpoints of mortality (*E. fetida*, *P. scaber*, *F. candida*, *E. andrei*, *E. crypticus*), and reproduction (*F. Candida*, *E. andrei*, *E. crypticus*). Only one study of a plant species (*V. radiata*) was reported in the literature and no effect was observed at the highest test concentrations.[131] All datasets have hazard values (*e.g.* LC50, EC50, NOEC) exceeding 1000 mg kg^{-1}, except for one of the studies for *E. crypticus*.[132]

The toxicity to particulate tire wear emission among marine aquatic and sediment dwelling species has been studied the least, compared to freshwater and terrestrial environments. For marine water organisms, mortality was evaluated across five species, however, no mortality was observed at the highest test concentrations greater than 1 mg L^{-1} for four of the organisms (*F. heteroclitus*, *M. beryllina*, *A. bahia*, *C. virginica*). Only one acute study of the marine copepod, *T. japonicus*, reported a definitive LC50 for mortality.[133] There is only one study on the chronic toxicity to particulate tire wear emissions for marine

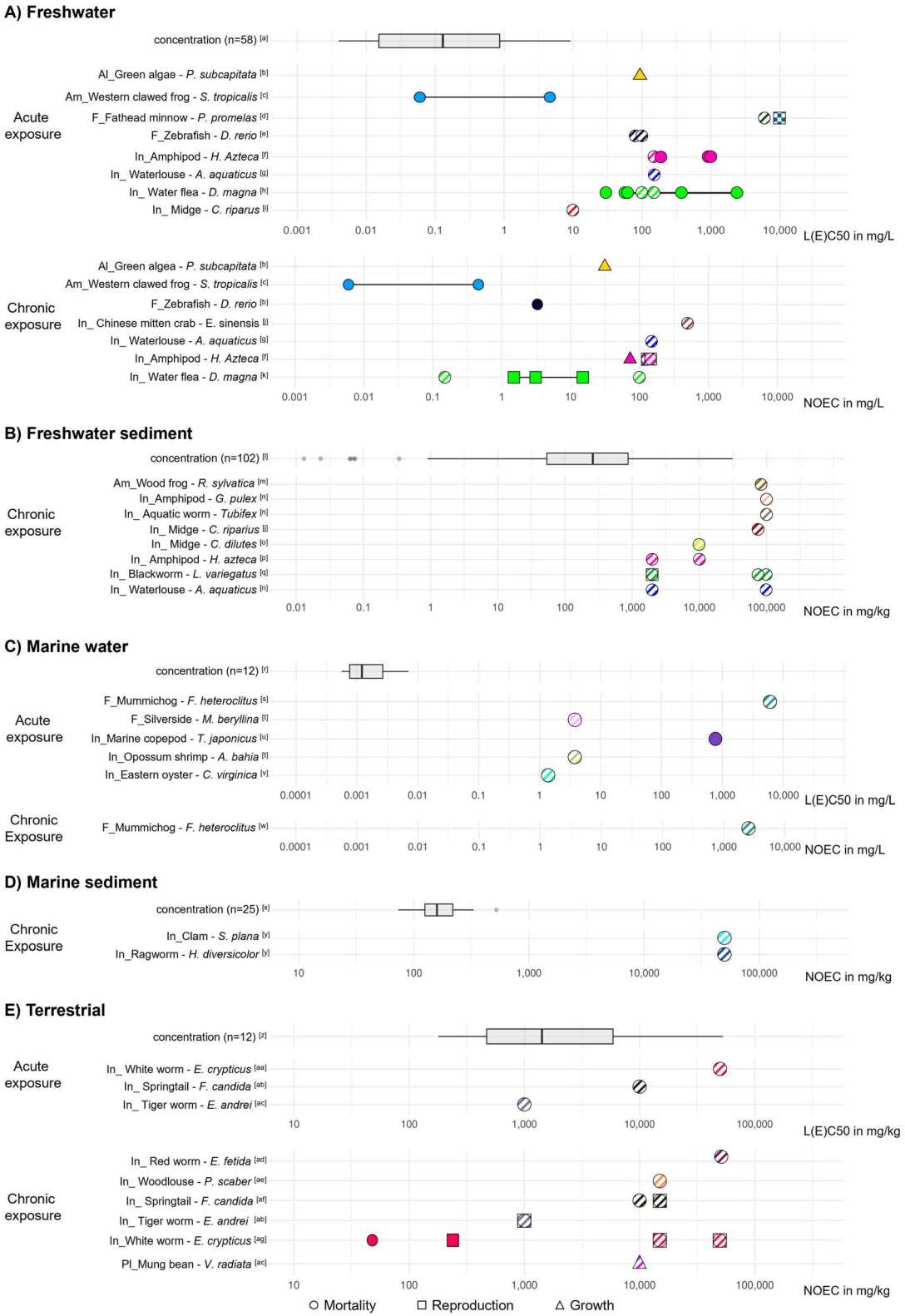

Fig. 1 Environmental concentrations, L(E)C50 and NOEC of direct particulate tire wear exposure: Acute L(E)C50 and chronic NOEC values by species for the compartments (A) freshwater, (B) freshwater sediment, (C) marine water, (D) marine sediment and (E) terrestrial for the endpoint's mortality, reproduction, and growth. Figure contains point estimates, minima, maxima, and ranges. Multiple ranges and estimates are provided per species track and open patterned shapes indicate nondefinitive values (dashed pattern: the actual value is greater than reported value; dotted pattern: the actual value is lower than reported value). Peak shapes refer to the investigated endpoints. *X* axis is log transformed. Each species is represented by a different color. Taxonomic groups are abbreviated: Al – algae, Am – amphibian, F – fish, In – invertebrate, Pl – plant. For references see Table S2.†

aquatic organisms.[134] In this study, no effect to mortality was observed after chronic exposure to the highest test concentration.

Similarly, acute exposure to particulate tire wear emission in marine sediment did not result in mortality at the highest test concentrations for two species studied (*S. plana* and *H. diversicolor*). However, sub-lethal endpoints were examined in the sediment organisms in a chronic test where the endpoints included behavioral (feeding and burial rates), physiological (condition index) and biochemical (energy reserves and oxidative stress) markers; although differences between controls and exposed groups were only observed at the highest test concentration of 50 000 mg kg^{-1}.[135] Additional studies of marine sediment organisms are necessary to support hazard assessment for the marine sediment compartment.

Many research studies have investigated the toxicity of tire particle leachates to aquatic organisms (Table S3†). Thirty studies have investigated mortality, reproduction, growth, and other endpoints across the main trophic levels of fish, invertebrate, amphibian, algae/plant, and various microbes. In all, 46 species have been evaluated. Given the lack of a standardized leachate testing framework, however, it is extremely difficult to compare across the studies to characterize the potential adverse effect levels. The studies varied significantly in the leachate preparation with respect to the solid to liquid ratio which ranged from 0.1 to >100 g L^{-1}, percent concentration of leachate for the dose groups, duration of the leaching, and temperature of the solution. Additionally, the test material was quite different from study to study. Nevertheless, findings from these studies show effects may occur in some species after exposure to leachate with preparation concentrations equal to or greater than 0.1 g tire particle per L.

In addition to the *in vivo* toxicity tests described above for tire particulate emissions, Bergmann *et al.*[136] applied three high-performance thin-layer chromatography (HPTLC) bioassays to evaluate the estrogenicity, genotoxicity, and bacterial luminescence inhibition of leachable chemicals from CMTT. Aqueous leachates of CMTT were prepared at 100 g L^{-1} under different conditions (*e.g.*, with or without sediment). The authors reported that estrogenic and luminescence-inhibiting chemicals leached from CMTT into aqueous media. No genotoxicity was detected in CMTT leachates. None of the other leachables studies directly evaluated the potential for endocrine disruption. However, several studies identified chemicals in the leachate solutions that have been identified as endocrine disrupters including bis-phenol A,[137,138] and DiBP, DBP, BBP and DEHP.[37] Recent guidance from the European Chemicals Agency (ECHA) regarding the classification of endocrine disrupting properties states that the classification criteria require evidence on three elements, including adverse effect(s), endocrine activity, and a biologically plausible link between the endocrine activity and the adverse effect(s).[139] Overall, the acute toxicity of tire emissions as particle or leachate to aquatic species has been well studied, however, it may be helpful to have tire particle toxicity data on other fish species. Additionally, there are numerous chronic studies for freshwater aquatic and sediment organisms as well as terrestrial organisms, however chronic data for the marine sediment species are lacking. Lastly, the potential for endocrine disruption from the tire emission leachables has not been well studied, and as such additional characterization *via* bioassays using environmentally relevant leachate solutions are necessary to accurately characterize this hazard endpoint. Thus, additional studies of species across the trophic levels and expansion of hazard data for the marine environment and to characterize the potential for endocrine disruption are necessary for a risk assessment.

3.3.3 Trophic transfer of tire chemicals from leachate is more relevant as for tire particles. Several of the tire particle emission studies showed that laboratory organisms can ingest tire particle emissions when present in their habitat, however, once removed from the exposure scenario the particles were egested.[140–143] The uptake of chemical constituents from the tire particles was demonstrated in three laboratory studies to investigate the potential for bioaccumulation. Hägg *et al.*[143] found no significant difference in metal concentrations between the controls and the exposed fish, but for targeted organic chemicals there were significant differences, demonstrating the bioaccessibility of phenylenediamine substances. Bioaccumulation of tire-related chemicals was also demonstrated in earthworms *E. andrei*.[144] In an *in vitro* study, Masset *et al.*[145] demonstrated the low to moderate bioaccessibility of various tire related chemicals including, their transformation products and PAHs. One study was identified that investigated a natural estuary for the presence of various tire additive chemicals and their transformation products.[95] The authors evaluated biota samples in the food web of the estuary (snails, shrimp, sea cucumbers and fish) and reported bioaccumulation for two phenylenediamine substances and through Monte Carlo analysis predicted biomagnification trends. Overall, studies related to trophic transfer of tire related chemicals are limited and warrant further research.

3.4 Step 3: Risk characterization of tire wear emissions in the environment

Environmental risk characterization of tire wear emissions utilizes exposure concentration and hazard data. For a risk characterization of tire wear emissions, both particulate tire emissions such as TRWP and dissolved tire leachables are of interest. In risk characterization the exposure concentrations are compared to the effect concentrations. In this work we derived relevant exposure pathways,[22] assessed the exposure concentrations and hazard data based on the structure literature review. Although the available exposure concentration data lacks comparability, as does the hazard data because of differences in the applied methodologies, it offers the opportunity to at least develop an idea on potentially sensitive species and affected environmental compartments. As a screening level risk prioritization, we identify environmental compartments and species of interest and comparing the exposure data with the hazard data for different environmental compartments and test organisms (Fig. 1).

3.4.1 Data reveals low risk prioritization of particulate tire wear emissions. The concentrations of tire wear particulates are

shown in the first row of Fig. 1 for each of the environmental compartments. For freshwater organisms, there are only 4 datasets available to which we can compare the hazard values. Nevertheless, all species have acute hazard values that are orders of magnitude above the median and 75th percentile measured concentrations, except for the *S. tropicalis*,[128] where the hazard values are within the range of the measured concentrations. A comparison of the chronic hazard values is similar to that of the acute, where most are an order of magnitude higher than the median measured water concentration, except for *S. tropicalis*.[128] Nevertheless, there is an appreciable lack of environmental measurements in the freshwater compartment and the available concentrations span 4 orders of magnitude (Table 4) suggesting highly location specific influences, such as traffic levels, extent of impervious surfaces, stormwater discharge, and sampling conditions (*i.e.*, wet or dry). As such, additional freshwater measurement data is crucial to drawing a firm conclusion regarding risk prioritization.

For freshwater sediment, there are eight datasets available to which we can compare the hazard values. All of the tested species have hazard values that are well above the median and 75th percentile measured concentrations, some by more than 2 orders of magnitude. This screening level comparison indicates a low prioritization of risk, although similar to the water measurements, the concentrations span many orders of magnitude and are likely influenced by the same factors.

The marine environment including water and sediment are not well characterized, with only one measured dataset for each compartment. Although quite limited in terms of species, where hazard values are available, they are many orders of magnitude higher than the measured sediment concentrations. Nevertheless, the sparse environmental concentration data for the marine environment, coupled with the limited hazard dataset do not allow for confidence in conclusions regarding prioritization for risk to marine organisms.

For terrestrial organisms, there are three soil concentration data sets available to which we can compare the hazard values. Although quite limited in terms of terrestrial species, the acute hazard values indicated no effects at concentrations within the range of the reported soil concentrations. More species hazard data is available for the chronic exposures, but similar to the acute hazard values, no effects were reported at concentrations within the range of the measured soil concentrations, except for *E. crypticus*.[132] For this species, three studies were identified and one of the three showed adverse effects at concentrations lower than the range of soil measurements and 2–3 orders of magnitude lower than the other studies of this organism. Overall, the screening level comparison indicates a low potential for risk to terrestrial organisms, however, additional investigation of *E. crypticus* may be helpful to understand the marked difference in hazard values for the same endpoints in this species.

3.4.2 Risk prioritization of leachables from tire emissions is not yet possible due to inconsistent hazard data sets. The available hazard data of leachate from particulate tire wear allows for an understanding of the risk prioritization from tire emissions that are not related to direct exposure to the particles. These data are most relevant for risk assessment in the road run-off exposure scenario where precipitation initiates leaching of deposited particulate tire emissions allowing chemical components of the particle to migrate into the water phase and subsequently transported to the aquatic and terrestrial environment *via* direct discharge to surface waters, wastewater treatment plants or roadside soil. The study of coho salmon urban runoff mortality syndrome is a case where observations of acute mortality in freshwater streams were associated with rainfall events and chemical analysis of the stormwater lead to implications for chemicals associated with tires.[79] A toxic identification evaluation study from tire particle leachate revealed that the mortality may be associated with 6PPD-Q, rather than the overall mixture of the leachate. Subsequent laboratory studies showed similarity of effects when 6PPD-Q was specifically studied and additional studies demonstrated coho salmon as a highly sensitive species.[79,146,147] Given that the effects seen in the tire emission leachate studies are likely associated with the chemicals in the leachate, the chemical composition resulting from the leachate preparation is important to characterize; recognizing of course that the chemicals may include parent chemicals present in the tread rubber, as well as transformation products resulting from interactions with the ambient environmental conditions and weathering over time.

4 Risk characterization for tire wear emissions is not only challenged by exposure and hazard data

4.1 From laboratory to reality: the key gaps for tire wear risk assessment

Risk assessment requires a thorough definition of the problem addressing its scope and purpose. The problem formulation usually reflects potential harms, the pathways to those harms, and the information needed to assess the risk. The necessary particulate tire wear emission and non-tire microplastic hazard and exposure studies have not been completed to fully inform the problem formulation.[7,11,22,39,79,148–150] The tire wear specific data gap identified consistently in the three stages (problem, hazard & exposure and risk) is the assessment of the unknown and variable composition components (UVCC) and weathering products of tread additives which may either be related to particulate contaminants or leachables. Tread additives must already comply with international regulatory environmental safety requirements, often including chemical-specific toxicity testing inclusive of unknown or variable composition of the chemical as formulated.[151] These assessments include quantitative measures of risk, such as the risk quotient derived from predicted environmental concentrations and predicted no-effect concentrations. These data must be comparable and uncertainties quantifiable. It is therefore necessary to establish and apply harmonized analytical methods (sampling, identification, and quantification) for tire wear emissions for the relevant environmental compartments and hazard tests. While

there is already a number of data points for the aquatic environment available, the review revealed that exposure data of particulate tire wear emissions in terrestrial environments and for leachables and UVCC substances for various environmental compartments *e.g.* groundwater is required for more comprehensive risk characterization.

Risk assessment also relates to representative and harmonized test materials for tire wear emissions bridging the gap between laboratory and reality. Hazard testing is often challenged by the complexity of the real conditions making the identification of effect drivers hardly possible. Therefore, it is proposed to implement a tiered approach for hazard assessment starting with effect testing of tire tread leachates and particulate tire wear making use of suitable and harmonized test systems and test materials. In a second tier, if positive findings occur, further tests under more realistic conditions *e.g.* presence of matrices should be conducted. In a third tier, depending whether local or global assessments are performed, data on *e.g.* site specific environmental concentrations of tire wear particles and tire leachable concentrations including transformation products; reliable emission data, global distribution data incl. uncertainties and most affected environments for particles and leachables, fate data (transformation, breakdown, half-life), information on sensitive species, are needed. Such a stepwise approach combined with harmonized and robust methods for sampling and sample analysis as well as hazard testing would reduce the uncertainty of the data and thus enhance its interpretability.

4.2 Building on progress: globally harmonized risk assessment of tire wear emissions

The implementation of an extended risk assessment framework requires interdisciplinary action from various stakeholders including tire and automotive industry, road management, and regulation. There are already existing frameworks which may help the development of such an extension *e.g.* the safe and sustainable-by-design framework.[152] Tire wear emissions do not conform to the International Organization for Standardization definition of plastic as shaped by flow.[153–155] Thus, appreciable physiochemical and morphological differences exist between particulate tire wear emissions such as TRWP, which contain tread elastomer as well as road materials and thermoset plastics or thermoplastics-derived microplastics. As such, it is useful to examine the essential components of the PDF as described by Koelmans *et al.* (2023)[11] and assess the suitability or adaptation of each element for the study of TRWP (Table S4†). Overall, the PDF framework for MPs is suitable for the risk assessment and communication of environmental tire wear emission risks. Much of the information and tools necessary to perform the screening and first tiers of an environmental risk assessment for tire wear emissions have already been generated as it was demonstrated in Sections 2 and 3. However, there are still knowledge and data gaps with respect to higher tiers. Therefore, research on tire wear emission would benefit from a clear harmonization guideline how exposure and hazard studies should be designed. Such guidelines should be developed between all relevant stakeholder covering the entire product life cycle.

5 The way forward: suggestions for future tire wear emission research

While progress has been made in exposure and hazard assessment of tire wear emissions in the environment, the complexity of tire wear emissions creates challenges which are not yet overcome. The following challenges, needs and data gaps for environmental risk assessment of tire wear emissions were derived:

- While there is existing aquatic exposure data, the review highlights the necessity for additional data on tire wear emissions in terrestrial environments and for leachables and substances of unknown or variable composition, including transformation products in environmental media, such as groundwater, freshwater and marine environments.
- A key data gap identified across all stages of assessment (problem, hazard, and exposure) is the evaluation of unknown and variable composition components and weathering products from tread additives, which are related to both particulate contaminants and leachables.
- There is a recommendation for further research into the trophic transfer of tire-related chemicals, including studies on bioaccumulation in various biota and the potential for biomagnification in food webs.
- For a risk assessment, insufficient consistent exposure and hazard data are available. Quantitative risk measures, like risk quotients derived from predicted environmental and no-effect concentrations, must be comparable and have quantifiable uncertainties. Consequently, there is a need to establish harmonized analytical methods for the sampling, identification, and quantification of tire wear emissions across relevant environmental media and hazard tests. These guidelines should be collaboratively established by all relevant stakeholders involved throughout the product life cycle and aligned with existing regulatory practices.

Data availability

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

Conflicts of interest

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