Supplementary Information

Tire Crumb in the Environment: A Review on Occurrence, Fate and Recent Advances in Detection and Analysis

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Table S1: Tire-wear particle concentrations found in different environmental matrices/ compartments across different locations around the globe

Environmental Matrix/ Compartment	Location	Country	Detected TWP Concentration/ Chemical additive marker concentrations	Analytical Method	Reference
Road Dust	Hong Kong and Berlin	China and Germany	Mean 8840 µg TWPs/g 6750 µg TWPs/g	UPLC-MS/MS and pyrolysis-GC/MS with different marker chemicals	[1]
Surface water and sediment samples	Osaka Bay	Japan	231 µg/g on a dry weight basis and 1.53 µg/L expressed on a volume of water basis in water 312 µg/g and 460 µg/g in sediment (grab) and sediment (trap) samples, respectively	Vinylcyclohexane and Phenylcyclohexane as markers for StyreneButadiene Rubber Pyrolysis-gas chromatography/Mass Spectrometry (Py-GC/MS) and the particulate zinc (Zn) method	[2]
Road Dust Samples	London	UK	Average from all five sampling sites 4.068 mg TWPs/g	Different SBR markers detected using TGA-GC/MS	[3]
Road Dust **Water** **Sediment** **Snow Bank**	Beijing	China	0.46×10^4–3.55×10^4 µg TWPs/g (road dust), 0.65–46.18 mg TWPs/L (water), 0.28×10^4–1.79×10^4 µg TWPs/g (sediment), and 9.46–19.12 mg TWPs/L (snowbank)	SEM-EDS ICPMS using bonded Sulphur as a marker	[4]
Road Dust	Seol	South Korea	9581 ± 4086 mg/kg	Py GC/MS	[5]
Air borne particulate matter	Oxford, Mississippi	United States	1789-2048 particles/cm^2/day	Stereo microscopy/SEM-EDX/Micro-Ftir	[6]
Urban Air	Pearl River Delta	China	Phenylenediamines, 2-OH-BTZ Concentrations (3130–317,000 pg/m^3)	UPLC-ESI-sMS/MS	[7]
Road dust and Soil	Krakow	Poland	372 ± 50/kg dry weight	Microscope/FTIR Spectroscopy	[8]
Sediments	Seine River Chesapeake Yodo-Lake	France United	4500 µg/g dry weight	Pyrolysis-GC/MS	[9]

	Biwa	States Japan	910 µg/g dry weight 770 µg/g dry weight		
Urban water system	Pearl River Delta region	South China	1,3-DPG (58780 ng/L) BTZ (480-42160 ng/L) 6PPD-Q (1562 ng/L) 6PPD (7.52 ng/L)	UPLC-ESI-MS/MS	[10]
Air borne Respirable Particulate matter (PM10)	Seine Chesapeake Yodo	France United States Japan	0.27 µg/m^3 0.14 µg/m^3 0.10 µg/m^3	Pyrolysis-GC/MS	[11]
Particulate samples from road run off	Berlin Halensee	Germany	Zn applied as marker 0.38-150 mg/g	ICP-MS/OES, TED-GC-MS	[12]
Road Dust	Sejong University	Republic of Korea	1.4-4.7 wt.% of total samples	Py-GC/MS GC/MS GC-FID	[13]
Road side soils	Trøndelag county	Norway	TWPs (2000 to 26,400 mg/kg)	Py-GC/MS	[14]
Road dust samples	Seoul	South Korea	TWPs (6400 µg/g to 39,738 µg/g)	TG EGA-MS Py-GC/MS	[15]
Air borne particulate matter	Stockholm	Sweden	BTZ (199 pg/m^3) 2-MBTZ (599 pg/m^3)	HPLC-MS/MS LC/MS/MS	[16]
Air borne particulate matter	Kolkata	India	8 % TWPs by mass	FID-GC, Carbon analyser	[17]
Ambient Roadside and rooftop air	Hachioji City	Japan	0.68 and 0.83 % mass	Hydrogenated Resin acids as marker GC-MS	[18]
Roadside Air	Chennai	India	4.1 % TWPs by mass	ICP-OES	[19]
Ambient Air	London	United Kingdom	10.7 % TWPs by mass	ICP-MS Zn as Marker	[20]
Roadside Air	Granada Norte	Spain	8 % TWPs by mass	ICP-MS ICP-AES	[21]
Ambient air, traffic junction sites, street canyon, urban background	Leipzig	Germany	1.7-2.9 % TWP by mass 0.3–0.5 µg/m^3 (at the roads) 0.2–0.4 µg/m^3 (at the urban background station)	Total reflection x-ray fluorescence spectroscopy (TXRF), marker: inorganic Zn	[22]
Ambient Air	London, Los	UK,	0.45–2.48 % TWPs	Pyrolysis GC–MS;	[23]

	Angeles and Tokyo	USA and Japan	by mass	markers: 4-vinylcyclohexene (SBR, BR) and dipentene (NR)	
Roadside soils	721 samples from eight federal states	Germany	0.4–158 mg/g dw	Zn Marker ICP-OES	[24]
Road dust 7 sites - close to busy roads - in residential areas - in tunnels	Hachioji City	Japan	Contribution to PM10: 0.14% TWPs by mass 0.07% TWPs by mass 2.0% TWPs by mass	GC–MS Markers: hydrogenated resin acids	[18]
Road dust (4 sites)	London	UK	Content of tyre wear in fine particle fraction (≤3 μm): 4% referring to particle number	ATOFMS	[25]
Sediment and Surface water	Charleston Harbor estuary	US	17.1 % TWPs of total microplastic number	Stereomicroscopy and ATR-FTIR	[26]
Sweep Sand **Storm Water** **Wash Water**	Gothenburg,	Sweden	2170 TWPs/kg DW 5900 TWPs/L 4500 particles/L	Melting tests using an alcohol burner, Light Microscopy	[27]
Road Dust	Curzon street, North Melbourne and Bulban road, Melbourne	Australia	NA	FTIR SEM	[28]
Highway Storm Water	Highway, namely Passante of Mestre on the mainland near Venice	Italy	NA	Micro-Ftir	[29]
Natural environment (Liquid Sediment, Drain Water, Soil, River Water etc)	Plymouth	UK	0.6 ± 0.33 to 65 ± 7.36 in 5 mL of material	GC-MS using N-cyclohexyl-2-benzothiazolamine (NCBA) as a marker	[30]
Street Runoff	Treatment	Germany	3.4%–8.2% TWPs	TED-GC-MS	[31]

	system for highway street runoff (Berlin-Halensee)		by mass of Total filtered particulate matter		
Road Dust **Sediment** **Marine Salt**	Oldenburg	Germany	0.5 g TWPS/Kg Road dust 0.24 mg TWPs/Kg Sediment 0.126 mg TWPs/Kg Marine Salt	Py-GC/MS	[32]
NA	NA	NA	NA	quantitative NMR spectroscopy different markers used for different polymers	[33]
Storm Water Sediments	Ostersund Stockholm Vaxjo	Denamrk	Average 69,300 µg TWPs/kg sediment	µFTIR Py-GC/MS	[34]
Pond Water and Sediment Samples	Mariager Hedensted Lemvig Odense	Denmark	2.2×10^1 µg TWPs/L 3.2×10^2 µg TWPs/L 1.8×10^1 µg TWPs/L 2.0×10^1 µg TWPs/L	FPA-FTIR Py-GC–MS	[35]
Surface Water	21 Urban sites in Queensland and Brisbane	Australia	Additives 2.9–1440 ng/L TWPs 690 and 1990 µg/L	LC-MS/MS Py-GC-MS	[36]

Table S2: Summary of the currently existing analytical techniques for TWP analysis, along with their advantages and disadvantages.

Technique Category	Analytical Method	Purpose / Key Information Obtained	Advantages	Limitations	Representative Studies / References
Physical & Morphological Techniques	Optical Microscopy	Observation of TWP morphology, size, color, and texture	Simple, non-destructive, quick screening; useful for particles >20 µm	Lacks chemical specificity; poor nanoscale resolution	[9, 37, 38]
	Scanning Electron Microscopy (SEM)	Surface morphology, roughness, embedded materials; elemental analysis with EDX	High-resolution imaging; identifies unique surface textures; combined with EDX for Zn, S, Si	Requires conductive coating; limited for nanoscale; sample prep required	[39-44]
	Transmission Electron Microscopy (TEM)	Internal structure, nanoscale morphology, carbon black distribution	High magnification and resolution; suitable for <500 nm TWPs	Laborious sample prep (ultrathin sections); small area	[38, 42, 45]
	Atomic Force Microscopy (AFM)	3D surface morphology, roughness, adhesion at nanoscale	Sub-nm resolution; works in air/liquid/vacuum; detailed surface analysis	Low throughput; requires smooth samples	[46-50]
Spectroscopic Techniques	Fourier Transform Infrared Spectroscopy (FTIR)	Identifies polar functional groups (C=O, –OH) in rubber compounds	Widely used; non-destructive; chemical fingerprinting	IR absorption by carbon black reduces signal; poor for nanoscale	[8, 51-57]
	Raman Spectroscopy	Identifies non-polar functional groups	Detects particles <10 µm; complementar	Fluorescence interference; thermal	[8, 49, 58-60]

		(aromatic, aliphatic); chemical structure	y to FTIR	degradation possible	
	µ-FTIR / µ-Raman Spectroscopy	Microscopic-level vibrational analysis (10–1 µm range)	Combines spatial resolution & chemistry; effective for heterogeneous samples	Signal attenuation due to carbon black; sample prep sensitive	[8, 29, 55, 61, 62]
	ATR-FTIR	Surface-level IR characterization of larger TWPs (>0.5 mm)	Fast, minimal prep; ideal for bulk samples	Ineffective for <0.5 mm particles; requires contact with ATR crystal	[55, 63, 64]
	Raman Tweezers	Optical trapping and Raman analysis of individual TWPs in liquids	In-situ chemical detection in aqueous media	Limited to small particles (500 nm–few µm); high cost	[49, 57]
Thermal Analytical Methods	Pyrolysis–GC/MS (Py-GC/MS)	Polymer-specific identification (SBR, NR, carbon black) via pyrolysis products	High sensitivity; unaffected by particle colour	Complex mixtures may cause overlapping peaks	[57, 65-68]
Chromatographic Techniques	Liquid Chromatography (HPLC / UHPLC / LC-MS/MS / HRMS)	Detection of leached additives, antioxidants, PPDs, benzothiazoles, etc.	Excellent for polar, non-volatile, thermolabile compounds	Ion suppression; needs tandem MS for accuracy	[69-78]
Thermal & Mass-Based Methods	Thermogravimetric Analysis (TGA)	Thermal decomposition, organic/inorganic fractions	Simple quantification; compositional profiling	Destructive; no morphological info	[3, 79, 80]
	TGA-GC/MS (PyroTGA-GC/MS)	Combines TGA and GC/MS for thermal profiling and	Enhanced quantification of TWP in road dust	Complex instrumentation	[3]

		compound ID			
	Thermal Extraction Desorption GC/MS (TED-GC/MS)	Detects thermally labile compounds in TWPs	Effective for low-MW species; minimal sample prep	Narrow capillary; clogging risk >300 °C; small sample mass (0.1–0.5 mg)	[3, 81-83]
	ICP-MS / ICP-OES	Elemental composition (Zn, Fe, Pb, Mg, S, Al)	High sensitivity; Zn tracer potential	Isobaric overlaps; matrix effects; destructive	[84-95]
Emerging Techniques	High-Resolution Mass Spectrometry (HRMS)	Non-target and target detection of TWP-derived chemicals	Ultra-high mass accuracy; detects additives, oxidants, leachates	Expensive; complex data processing	[69, 96-98]
	Nanopore Sensors & Microfluidics	Real-time, single-particle detection of micro/nano-TWPs	Portable, fast, label-free; adaptable to aqueous samples	Still in developmen t for TWPs	[99-104]
	Machine Learning-Aided Analysis	Automated identification & classification of TWPs (e.g., SEM-EDX data, image recognition)	Reduces manual effort; large-scale data analysis; predictive modelling	Requires large training datasets; interpretabil ity challenges	[105-110]

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