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Review

A critical review of sampling, extraction and analysis methods for tyre and road wear particles☆

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ABSTRACT

Tyre and road wear particles (TRWPs) have become an increasing contamination concern because of their extensive distribution in the environment. A comprehensive overview of the methods for sampling, treatment and analysis of environmental samples for TRWPs (and their benefits and limitations) is lacking. We evaluate and critically assess the sampling, treatment and analysis methods previously reported for water, air, road dust and sediment/soil samples. We suggest research frameworks for studying TRWPs in these media. Microscopy and thermal analysis techniques such as scanning electron microscopy (with energy dispersive X-ray analysis), environmental scanning electron microscopy, 2-dimensional gas chromatography mass spectrometry and liquid chromatography with tandem mass spectrometry in the case of complex samples, are optimal methods for determination of the number and mass of TRWPs. Issues for further investigation and analysis recommendations are provided.

1. Introduction

Water, soil and air are vital components for maintaining the integrity of an ecosystem and ensuring human life on Earth (Mian et al., 2022). Harmful and undesirable substances are increasingly impacting all of these resources. This problem will intensify if effective planning and management strategies are not rapidly implemented. A variety of contaminants can be found in air, soil, and water, including metals/metalloids, agricultural/industrial wastes and microplastics and other emerging contaminants (e.g. pharmaceutical and personal care products, per- and poly-fluoroalkylated substances etc, Mian et al., 2022). TRWPs particles (TRWPs), generated by the rolling/sheer stress between tyre tread and a road surface, are a significant environmental concern (Tariq et al., 2024). There is a growing understanding that TRWPs should be categorized as microplastics. However, compared to commonly used plastics (also termed as conventional plastics) such as polystyrene, polypropylene and polyethylene terephthalate, data on the environmental concentrations of TRWPs is limited (Rødland et al., 2022a).

On average, a tyre loses ~ 11.5 % of its weight into the environment throughout its lifespan (Ren et al., 2024). Approximately 53.9 % of microplastics found in environmental settings originate from TRWPs (Li et al., 2024), surpassing the collective emissions of other environmental pollutants such as pharmaceuticals (Mayer et al., 2024).

There are two primary routes for the dispersion of TRWPs into the environment: atmospheric deposition or road runoff into waterways (Rausch et al., 2022). Theoretical estimates suggest that 66–76 % of TRWPs end up in roadside soil, 12–20 % in surface water and 5 % in air (Baensch-Baltruschat et al., 2021). Particles that disperse into the air are categorized as airborne particulate matter (PM). Epidemiological studies have identified strong correlations between PM and short-term health effects such as premature mortality (Sanhueza et al., 2009). Long-term health effects have been observed, including lung cancer, morbidity, cardiovascular, and cardiopulmonary diseases (Panko et al., 2013). This is because fine and ultrafine particles penetrate the respiratory tract and reach the alveoli, with ~50 % remaining in lung tissue (Hassan et al., 2021). After exposure to PM, alveolar macrophages ingest semi-soluble particles and induce oxidative stress and inflammation of the lung tissues (Risom et al., 2005). Oxidative stress refers to an imbalance between the production and accumulation of oxidants, such

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as free radicals and ions, collectively known as reactive oxygen species (Pizzino et al., 2017; Chatterjee, 2016; Das et al., 2015).

TRWPs enter nearby drainage systems during rainfall or snowfall events (Barber et al., 2024; Rasmussen et al., 2024). Drainage systems channel storm-water runoff, via storm drains, without treatment into nearby waterbodies (Barber et al., 2024; Rasmussen et al., 2024). The accumulation of microplastics in waterbodies poses a significant global challenge, with TRWPs emerging as a significant contributor towards freshwater pollution and posing harmful effects (Rigano et al., 2024). Greer et al. (2023) reported increased embryonic mortality (>80 %) in coho salmon (*Onchorychus kisutch*) after 24h acute exposure to leachate of TRWPs. Rigano et al. (2024) found that an extract of TRWPs caused a significant decline in the fertility (reduction of 7.5 eggs from 233 eggs per parent) of *Chironomus riparius (a common benthic macroinvertebrate). TRWPs, due to negative zeta potential (surface charge on particles in liquid medium), are likely to adsorb cations from the surrounding environment (*Rocha Vogel et al., 2024*). For example,* Fan et al. (2021) *reported the adsorption of cadmium* $\left(Cd^{2+}\right)$ *and lead* $\left(Pb^{2+}\right)$ *on TRWPs, increasing their potential harmful effects on organisms.*

Runoff from roads, without a drainage system, ends up in ditches. A ditch is a shallow passage used to transfer the runoff away from the road (Gehrke et al., 2023). Ditches are designed to slow down the velocity of runoff and retain particulates, remvoing 60–90 % of TRWPs (Gehrke et al., 2023). Since roadside ditches are not associated with the sewage system, trapped TRWPs may migrate to the soil or infiltrate to groundwater, due to continuous exchange of water (Gehrke et al., 2023; Li et al., 2023).

The accumulation of TRWPs in sediments/soil may cause deterioration of environmental quality and cause potentially harmful effects on soil/sediment fauna and flora (Rocha Vogel et al., 2024). TRWPs ($\leq 30\mu$ m) can clog soil pores (Liang et al., 2024). Since soil pores determine the water-holding property of a soil (Shafea et al., 2023; Wang et al., 2023), blockage of pores leads to retention of water (de Souza Machado et al., 2018). This may impact evapotranspiration; an important phenomena for local and global atmospheric conditions (de Souza Machado et al., 2018). Photo-aging of TRWPs may induce the formation of free radicals (Liu et al., 2021) and increase soil pH (Azeem et al., 2024). Free radicals, upon light irradiation, facilitate the transfer of electrons (Liu et al., 2021). Since TRWPs comprise of transition metals and organic compounds, transfer of electrons may stimulate the formation of persistent free radicals (Liu et al., 2021). Leaching of these additives leads to increased pH values ($pH > 5.7$) in soil (Li et al., 2024). The presence of free radicals and increased pH levels may generate harmful effects on soil biota. For example, Chen et al. (2024) exposed earthworms (*Eisenia fetida*) to photo-aged TRWPs and found 50 % increase in mortality. The decline in soil microbial population impacts nitrogen cycling (Kim et al., 2023; Liu et al., 2023), in which an atmospheric nitrogen molecule is converted into nitrate (Kim et al., 2023; Liu et al., 2023). Nitrate is an accessible form of nitrogen that plants utilise for their growth and development (Kim et al., 2023; Liu et al., 2023). Exposure to TRWPs reduces the yield of plants (Zi et al., 2024; Leifheit et al., 2022). Plants are vital for human health as they provide essential nutrients (Kim et al., 2023; Liu et al., 2023). Overall, the presence of TRWPs may adversely affect the structure and functioning of an ecosystem (Mayer et al., 2024). These factors combined make it necessary to determine the environmental concentrations of TRWPs to adequately assess environmental risk.

A range of researchers have focused on the identification and quantification of TRWPs in environmental media. Studies vary significantly in methods of sample collection and subsequent analysis, leading to incomparable results (Feiβel et al., 2024). The European tyre emission-monitoring network has emphasized that “there is an urgent need to establish a scientific approach for empirically examining TRWPs in the environment and reach consensus on its implementation” (Rauert et al., 2021). Therefore, the goal of this review is to critically examine the methods used for sampling, extraction, and analysis of TRWPs in environmental samples. We aim to identify the most appropriate method for each type of sampling matrix, enabling researchers to select the most suitable approach for their specific study and to facilitate comparability and reliability.

2. Methods

A PRISMA-guided review of the sampling, treatment, and analysis methods for TRWPs across various environmental matrices was undertaken (Way et al., 2022a). Web of Science was used as the primary search engine as it is comprehensive and provides detailed bibliographic information (Li et al., 2010; Falagas et al., 2008). Articles published from January 2000 to October 2024 were selected since TRWPs were first recognised as microplastics in early 2000 (Kreider et al., 2010; Gustafsson et al., 2008).

The selection criteria included articles containing the keyword “tyre and road wear particles”, with four distinct environmental compartments: road dust, sediments, water, and air. These were selected as they provide the main pathways through which TRWPs are distributed, transported and potentially affect the health of ecosystems. For a comprehensive search, additional relevant keywords were used, and these are detailed in the supplementary information.

3. Results

3.1. Sampling of environmental samples for TRWPs

Sampling is an essential step toward quantifying environmental TRWPs. The sampling technique is dependent on a study’s objectives and sampling location. Contamination of samples must be avoided; this is beyond the scope of this paper but an example of the detailed quality assurance and quality control procedures necessary when working with microplastics (applicable to TRWPs) may be found in Radford et al. (2023).

3.1.1. Road dust

The presence of TRWPs in road dust is related to traffic density and climate (mainly wind and precipitation) (O’Brien et al., 2021). TRWPs in road dust flow into a freshwater ecosystem via runoff (O’Brien et al., 2021). TRWPs accumulate on the road with extended drying periods (Kang et al., 2022). Therefore, a minimum of three dry days is suggested before sampling (Kang et al., 2022). If the objective of the study is to evaluate the overall concentration of TRWPs in road dust samples, we suggest dry sampling. Wet sampling may provide information about the distribution of TRWPs. For example, sampling of road dust after each rainfall may inform on the mean concentration of TRWPs that flows into water channels. It may also give information about seasonal fluctuations. However, whilst estimating the concentration and flow pattern, other factors should also be considered. Strong winds may disperse TRWPs to a widespread area, reducing their actual concentration at the place of sampling (although this process will be controlled by the size and composition of the TRWPs).

A variety of sampling tools have been used for collection of road dust samples. These include a vacuum cleaner, a wet dust sampler, a broom, and a spatula (Kang and Kim, 2023; Järlskog et al., 2022; Jung and Choi, 2022; Worek et al., 2022; Klockner et al., 2021). A vacuum cleaner offers convenience in collecting a dust sample. To enhance efficiency in the collection of fine particles (<50 μm), water spray is used (Klöckner et al., 2020). Water spray helps in minimizing the dispersion of dust and increases collection efficiency (Klöckner et al., 2020). Organic constituents of TRWPs may leach out in the water used to reduce the dissemination of particles. However, this depends on the contact time between TRWPs and the water. For example, Wik (2007) reported that additives may migrate from TRWPs to water within 72h. Therefore, the collected samples may be air dried to prevent potential leaching (Wik, 2007).

The use of a vacuum cleaner may lead to cross-contamination. To overcome this issue, Ren et al. (2024) and Youn et al. (2021) used disposable cartridges for every sample. The use of a vacuum cleaner on high-traffic roads poses safety risks to researchers due to potential accidents. Vacuum cleaners powered by batteries have limited battery life. Thus, alternative options should be considered. Rødland et al. (2022) used a wet dust sampler (WDS) (Fig. 1a) for the collection of road dust samples. In a WDS, high-pressure water is used for sample collection (Lundberg et al., 2019). High-pressure water may disperse the TRWPs, so the collected sample may not be representative (Lundberg et al., 2019). Jung and Choi (2022) used a broom for collection of road dust, while Rosso et al. (2023) used a brush made of natural fibres. A brush is easy to use and minimizes the dispersion of particles (Rosso et al., 2023). Particles however may stick to the bristles of a brush. Therefore, it should be properly cleaned after every use. Worek et al. (2022) used a stainless steel spatula/scoop (Fig. 1b) as a cheap, efficient, and convenient option. To avoid cross-contamination, the spatula must be washed with deionized/distilled water after the collection of each sample.

3.1.2. *Water sampling*

During rainy weather, TRWPs that have accumulated on the surface of roads over the preceding dry days are washed into gully pots (Memon and Butler, 2002). A gully pot is a settling chamber designed to collect road runoff before it enters into a sewer system (Deletic et al., 2000) (Fig. S1).

TRWPs in gully pots remain suspended in water or settle to sediments at the bottom. Suspended TRWPs are collected through grab sampling. In grab sampling, a container/glass jar is held beneath the water surface, and a predetermined quantity is collected (Facchi et al., 2007). If the water level in gully pots is too low to reach, a telescopic rod attached to a beaker may be used (Fig. 1c) (Truitt et al., 2018). Increased stormwater flow transports the suspended TRWPs from gully pots to water channels (Gaggini et al., 2024). The distribution of TRWPs in the water column depends on various factors, including size, shape, and density of wear particles, and environmental conditions such as wind, waves, and water density (Browne, 2007). The density of TRWPs is associated with its chemical makeup; however, it may change with time owing to processes like weathering, or the formation of biofilm (biofilm is a microbial community that sticks to material surfaces) (Skalska et al., 2020). Therefore, the sampling depth and location influence the quantity and characteristics of collected TRWPs (Browne, 2007).

The sampling depth of the water column depends on the study objective. For the evaluation of the exposure concentration of TRWPs to plankton present in the upper layer, a surface microlayer (SML) may be collected (Richon et al., 2024; Setälä et al., 2014). The SML is the upper, 1–1000 μm, layer of water surface (Anderson et al., 2018); and is home to organisms such as bacteria and algae (Anderson et al., 2018). Accumulation of TRWPs can impact these organisms and those that consume them, with potential for trophic transfer of TRWPs (Anderson et al., 2018). Sampling of the SML provides information about their exposure concentration (Anderson et al., 2018). The SML has been investigated for conventional microplastics so far. Stead et al. (2020) and Anderson et al. (2018) used a glass plate for the collection of SML. A glass plate is submerged vertically in the water and pulled out at a constant speed. Water from the glass plate is collected into a sample storage bottle. When collecting surface water samples for TRWPs, analysis of the SML is often overlooked, indicating a future need to incorporate sampling of the SML for the assessment of TRWPs.

Surface water, below the SML, is manually collected through grab sampling. Grab sampling is a widely employed method since it is simple and inexpensive. Two key aspects must be considered. First, fluctuations in the concentration of TRWPs may be noticeable through moving water (Valenzuela et al., 2020; Facchi et al., 2007). Second, the physical or chemical properties of TRWPs change owing to variations in the pH and temperature of water (Valenzuela et al., 2020). Frequent water sampling is recommended to estimate the actual concentration of TRWPs (Valenzuela et al., 2020). The validity of collected environmental samples relies on collecting replicate samples (Skalska et al., 2020). Acquiring duplicate samples (2–3 samples on average) is common (Skalska et al., 2020). Many studies do not mention the number of collected samples or consider collecting one sample per site e.g. Rauert

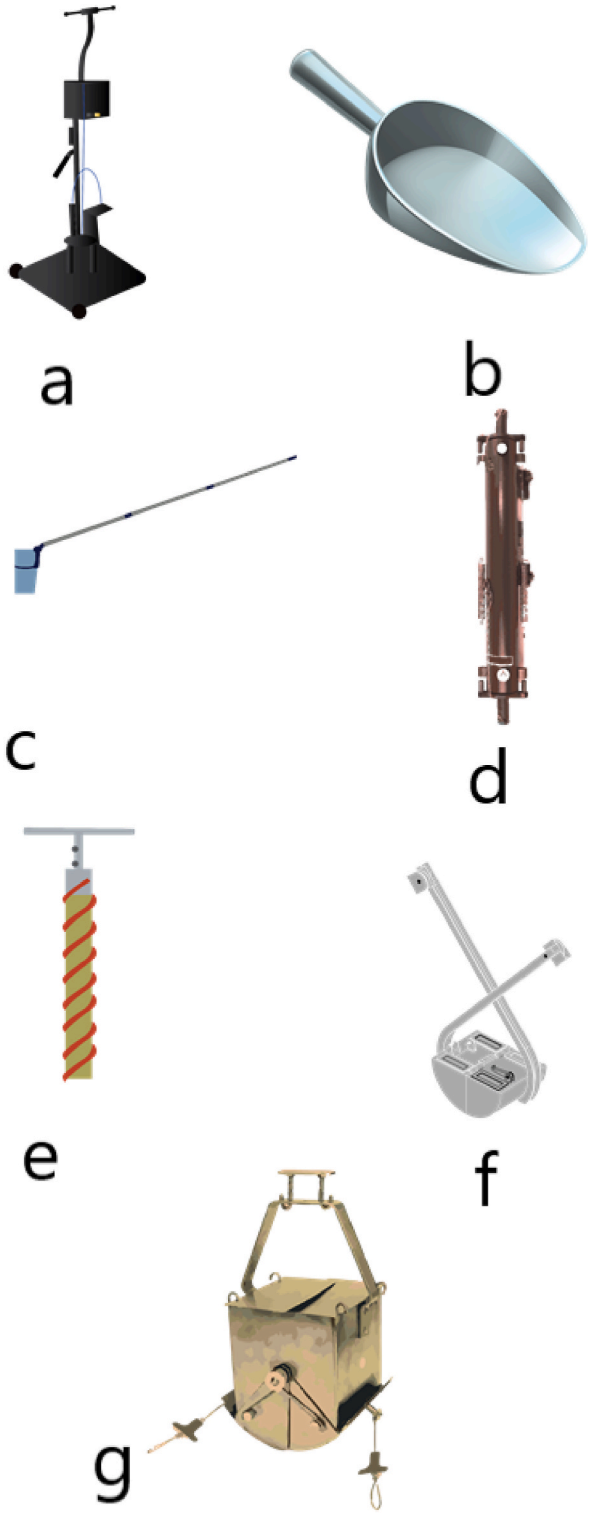

Fig. 1. Samplers for the collection of road dust (a) Wet dust sampler (b) Steel scoop, water samples (c) telescopic rod (d) Niskin bottle (e) snow corer and sediment samples (f) Van Veen grab sampler (g) Ekman dredge (adapted from Das, 2023; Müller et al., 2022; Rødland et al., 2022a; Worek et al., 2022; Lundberg et al., 2019; Batley and Simpson, 2016).

et al. (2022) collected surface water without mentioning the number of samples. Lack of transparency questions the reliability of sampling in a study.

With a density of 1.2–1.8 gcm^{-3}, TRWPs may sink to the bottom of a water column where they become available to benthic organisms (Issac and Kandasubramanian, 2021), suggesting a need to sample the whole water column, including the sediment-water interface (SWI). SWI is a biologically active zone between the aquatic column and sediments (Sun et al., 2022). Microorganisms are found in this zone that are involved in carbon and methane cycling (Sun et al., 2022). The presence of TRWPs in this zone may therefore have an impact on the ecological stability of the aquatic system (Sun et al., 2022).

Water samples from rivers, lakes, or oceans are collected using a range of sampling devices. The collection method depends on the sampling location. Water from the middle of lakes, rivers, or oceans is collected from a research vessel (Taylor et al., 2015). Sampling devices include the use of a submersible pump, where a pump is placed directly at the collection point of the water. Kovochich et al. (2023) used a submersible pump to collect water samples from a river site. Rødland et al. (2022) used a drain pump to collect tunnel wash water. As the pump is submerged, waterproofing is necessary (Garbus et al., 2008). Collection of water samples from the middle of water bodies may not always be feasible due to accessibility issues. Therefore, a discrete water sampler such as the Niskin bottle (Fig. 1d) has been used (Barber et al., 2024). A Niskin sampler is a tube made of an inert polymer. It has an opening at each end (Das, 2023). Both ends have a cap. The opening of the cap is controlled by a stretchable rope (Das, 2023). The sampler can approach the intended depth in oceans, rivers, or lakes. The weight of a “messenger” is used to activate the closing of both caps at a certain depth (Das, 2023). Consequently, deep water samples can be collected and brought back on board for subsequent analysis (Das, 2023). In remote areas, an autonomous underwater vehicle (AUV) may be used (Guo et al., 2024). A robotic fish named Gillbert has recently been used for the collection of conventional microplastics (Guo et al., 2024). Gillbert is fitted with a wireless control module and a filtering system. The gill structure of the robotic fish functions as a filter, capturing microplastics whilst allowing water to pass through it (Guo et al., 2024). The captured microplastics are retained in an internal storage compartment for further analysis (Guo et al., 2024).

The collection of snow samples also helps in understanding the concentration of TRWPs with changing weather conditions. As snow accumulates, it can capture TRWPs in real time (Rødland et al., 2022a). When snow melts, it releases the accumulated TRWPs (Rødland et al., 2022a). Rødland et al. (2022a) used a metal snow corer (Fig. 1e) for the collection of snow samples from the roadside and reported TRWPs in the range of 76-14,500 mg/L melt water.

3.1.3. Sediment sampling

Sampling sediments from gully pots, sediment basins, watersheds, and rivers provides information about the distribution and accumulation of TRWPs (Eisentraut et al., 2018). Sediment sampling can be categorized based on depth, such as surface sampling (up to 10 cm), deep sediment sampling (bottom of rivers, lakes, watershed), and stratified sediment sampling. Surface sampling is performed to evaluate the recent deposition of TRWPs (Järlskog et al., 2022). In surface sampling, grab sampling is usually performed to collect the sediments. Newly deposited TRWPs in gully pots may be collected using a steel scoop when dealing with dry sediments (Mengistu et al., 2021). Unice et al. (2013) used a steel scoop for the collection of surface sediments. In surface sampling, a 0–5 cm sediment layer should be collected to reduce the acquisition of organic matter (Thomas et al., 2022). Wet sediments, beneath the standing water in gully pots, may be collected using a bucket or a bottle. Järlskog et al. (2022) and Mengistu et al. (2021) used glass bottles to grab samples of the wet sediments. If the water level is high in gully pots, a telescopic rod attached to a beaker may be used. A container such as a bucket or a bottle with a known volume is submerged in water and a predetermined quantity of wet sediment is collected for subsequent analysis. Grab sampling may not be representative, thus replicate samples are recommended. Replicate samples are usually combined to ensure representative analysis (Mattsson et al., 2023). Van Veen grab samplers are used for the collection of sediments from gully pots (Fig. 1f) (Rødland et al., 2022; Müller et al., 2022). Accumulated sediments may represent different time periods based on how often the roads are flushed. These sediments might have built up over a few hours, several days, or even weeks. The use of a Van Veen sampler may disturb deep sediments, affecting the representativeness of the sample. The sampler may not be ideal for gully pots as they are typically smaller, making it challenging to handle the sampler.

The collection of sediments from water bodies depends on location. Surface or sub-surface sediments from a shore or riparian zone can be collected using a steel scoop. Sediments from the middle of shallow water bodies may be collected using telescopic rods. An Ekman sampler is suitable for collecting soft surface sediments (Batley and Simpson, 2016). Klöckner et al. (2019) used an Ekman dredge (Fig. 1g) for the collection of lake sediments. However, an Ekman sampler is not considered ideal for the collection of surface sediment samples during high waves (Batley and Simpson, 2016).

Sub-surface sediment samples are collected below 5 cm. For sub-surface sampling, an angular beaker attached to a telescopic rod has been used. A telescopic rod can disturb a sediment’s layers, affecting representativeness. To overcome this problem, a sediment corer should be used, as it provides a vertical profile and minimizes disturbance.

Over seasonal and annual timescales, TRWPs accumulate at the bottom of gully pots, lakes, rivers, and oceans, becoming trapped in deeper sediment layers. The pattern of distribution of TRWPs in sediment layers is influenced by the characteristics of TRWPs (morphology, density) and flow dynamics of water channels. It is not completely understood what determines the movement and fate of TRWPs. The settling pattern of conventional microplastics has been assessed by (Skalska et al., 2020). The diameter of particles was directly related to the settling velocity of conventional microplastics, and they increase in the order of fragments > fibres > pellets (Skalska et al., 2020). It may also differ across different chemical compositions of plastics (Skalska et al., 2020). For example, the settling velocity of polyamide was reported to be 0.39 cm/s compared to 31.40 cm/s for polystyrene pellets (Skalska et al., 2020). TRWPs are different to conventional microplastics in terms of shape and chemical makeup so they behave differently.

Sampling in deeper sediment layers provides information on the distribution pattern or temporal variation in the concentration of TRWPs in the sediment profile (Bigus et al., 2014). Stratified sediment sampling from gully pots is performed using a hand-driven corer (Cundy and Croudace, 2017). Sampling from deeper layers of rivers, lakes or oceans is conducted using specialized sediment corers. The most commonly used sediment corers are a gravity corer, a vibrocorer, and a piston corer. A gravity corer is simple and widely used. It has a weight attached to it to drive it into sediments. It is likely to disturb the upper layer of sediments during its downward movement owing to the shock wave it generates. This can displace soft sediments, leading to potential inaccuracy (Gallmetzer et al., 2016). A vibrocorer, also known as a vibratory corer, is used to propagate energy to the sediments to liquefy a 1–2 mm thick sediment layer inside and outside of the corer. During this process, high-frequency waves are generated that may disturb the sediment layers (Gallmetzer et al., 2016).

Piston sediment corers are used for sampling deep sediments (Fig. S2). A piston corer is a long column/tube with a piston inside. It is attached to a pulley and lowered from a ship down to the bottom of a river or the seafloor (Gallmetzer et al., 2016). A coring barrel/cylinder is then pushed into the sediment. As the coring cylinder goes into the sediment, the piston stays above. This process creates a low-pressure area (vacuum) above the sediments in the tube. The vacuum helps in removing the effects of hydrostatic pressure from outside the coring cylinder (Gallmetzer et al., 2016). The pressure difference encourages sediments to enter the core liner in an undisturbed manner. Freeze corers are also useful for collecting undisturbed sediment cores (McCarthy et al., 2023).

3.1.4. Air sampling

Airborne TRWPs are collected at varying distances from roads to understand the dispersion of particles (Järlskog et al., 2022). Sampling methods for airborne TRWPs are categorized as active sampling and passive sampling (Gao et al., 2022). In active sampling, power-driven filters are used to collect particles (Gao et al., 2022). In passive sampling, airborne TRWPs are naturally captured overtime on the sticky surface of a filter (Gao et al., 2022) (Fig. 2) or other devices/materials. Tree bark, owing to its deep furrowed structure, possesses a large surface area. Therefore, it may adsorb PM, and can be used for the passive collection of TRWPs. Before the collection of a sample, a predefined sampling site of the tree must be decontaminated. To avoid cross contamination, the area of the tree bark is typically cleaned with distilled water, using a toothbrush, until a transparent rinsed solution appears (Wang et al., 2024a; Catinon et al., 2009). Subsequently, the bark area is left undisturbed for a certain period. After the studied period, deposits on the bark area are scrubbed off, followed by analysis of the sample. Wang et al. (2024a) used the bark of *Cinnamomum camphora for the collection of particulate matter and reported* 1443.76 ± 95.28 μg cm^{-2} per unit bark area.

The adsorption potential of bark differs significantly based on its smooth/rough texture (Chrabąszcz and Mróz, 2017). The year-round availability of trees makes them suitable for sampling. When using tree bark for sampling, three things need to be considered. First, the bark should be sourced from tree species that are common in the sampling area, ensuring extensive sample collection (Chrabąszcz and Mróz, 2017). Second, samples should be collected from trees of the same age (age is calculated by estimating the height of the tree and diameter of the trunk) (Chrabąszcz and Mróz, 2017). Third, environmental conditions should be considered (Chrabąszcz and Mróz, 2017) e.g. wind speed/direction may affect the concentration of TRWPs collected.

Passive samplers are simple, relatively cheap, and can widely be used for long periods, without having to revisit (Fig. 2) (Gao et al., 2022). A disadvantage is that they cannot collect particles of <1 μm because fine particles have a low sedimentation rate. Järlskog et al. (2022) suggest that active samplers should be used for collection of particles <1 μm.

Airborne samples are typically collected at ground level, ~1.5–2 m above ground (Gao et al., 2022; Panko et al., 2013), to capture a sample that accurately represents airborne particles found within the typical breathing zone of human beings (Panko et al., 2013). During sampling, when particles strike the hard surface of a filter, they may rebound and be swept away by the air current (Wilson et al., 2002). Hence porous substrates/filters are recommended (Wilson et al., 2002). Choice of filter is dependent upon a study's purpose. Filters types include carbon, quartz, Teflon, and aluminium oxide (Gao et al., 2022; Järlskog et al., 2022a; Chiari et al., 2018). Filters must stabilize for 48h in controlled conditions (humidity and temperature) to ensure that any change in filter weight does not affect sampling accuracy (Panko et al., 2013).

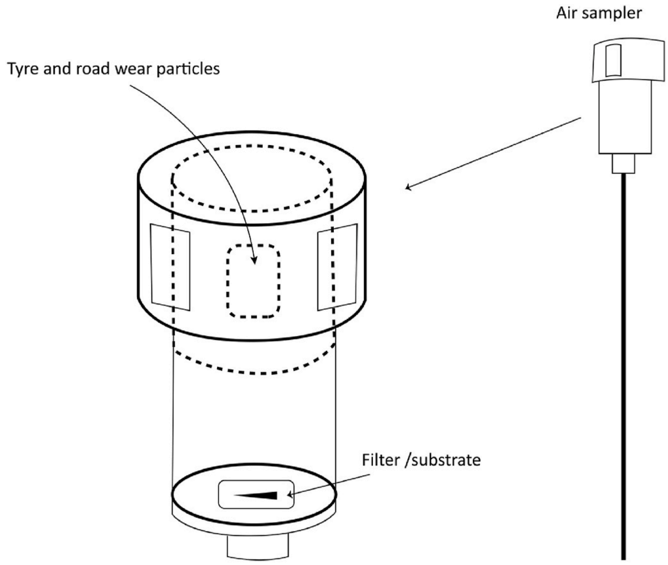

Fig. 2. Passive air sampler for the collection of airborne tyre and road wear particles (adapted from Olubusoye et al., 2023).

Carbon filters, also known as conventional filters, pose a challenge as quantifying carbon on a carbonaceous filter is difficult (Järlskog et al., 2022a). Thus, for the evaluation of elemental carbon (EC) or organic carbon (OC), quartz filters are recommended. This is because OC/EC is determined at high temperatures and quartz filters can sustain these temperatures. Particles may penetrate a quartz filter, leading to attenuation of X-rays during analysis (Chiari et al., 2018). This issue can be solved by using filters such as Teflon filters, as they are thin compared to quartz. Due to this, collected particles retain on the filter surface and do not penetrate the filter medium (Chiari et al., 2018).

Teflon substrates exhibit effectiveness for determining the mass of charged particles and elements (Sun et al., 2022) owing to their insensitivity towards relative humidity (Perrino et al., 2013; Brown et al., 2006). Teflon filters are used when elemental composition is required using X-ray fluorescence (Abu-Allaban et al., 2003) because they show high transmission properties, allowing the detection of trace elements even at low concentrations (Perrino et al., 2013).

Aluminium oxide filters are commonly employed to study the chemical composition of microplastics whilst using Fourier-transform infra-red spectroscopy (FTIR) (Gao et al., 2022). The substrate of a filter needs to be transparent to IR, meaning it should allow IR light to pass through it easily without absorbing the light itself (Gao et al., 2022). Löder et al. (2015) found that aluminium oxide filters provided better spectroscopic results and imaging in transmission mode than reflectance approaches. This shows that aluminium oxide filters can be employed for analysing TRWPs in the transmission mode of FTIR. Aluminium oxide filters are transparent in the near-infrared region in Fourier Transform near infrared spectroscopy (FT-NIR).

All collected samples (road dust, water, sediments, and air) should be stored in clean glass jars to prevent contamination. Before use, the glass containers should be decontaminated with distilled water. Kutralam-Muniasamy et al. (2023) reported the presence of fibre-shaped conventional microplastics in distilled water. The observed microplastics were <500 μm (Kutralam-Muniasamy et al., 2023). It is recommended that distilled water be screened for conventional microplastics. Distilled water should be filtered and analysed, employing the same analytical techniques as used for the sample, to avoid potential contamination (Kutralam-Muniasamy et al., 2023)

3.2. Extraction of TRWPs

Extraction of TRWPs from environmental samples is dependent upon sample type. For airborne TRWPs, filters are subject to analysis/quantification without pre-treatment (Panko et al., 2013). Water samples can be directly filtered by a vacuum filtration assembly. Suspended matter present in riverine or oceanic water may obstruct the analysis of TRWPs. Therefore, river and ocean water samples are sieved before analysis (Barber et al., 2024). Similarly, snow samples, due to low levels of impurities, often need no pre-treatment, requiring only melting at room temperature.

Complex environmental samples such as road dust/sediment samples need pre-processing. Methods used to isolate TRWPs from complex environmental samples include density separation, acid or alkaline digestion, sieving, enzymatic digestion, centrifugation, magnetic separation, and solvent separation, each with different costs and effectiveness (Mattonai et al., 2022; Jung and Choi, 2022; Järlskog et al., 2020;

Knight et al., 2020) (Table S1).

3.2.1. Density separation

Density separation is used to extract TRWPs from composite samples (Jung and Choi, 2022). In density separation, high density salt solutions are used to separate low-density particles. These particles float on the surface of the salt solution, enabling extraction from the complex composite (Jung and Choi, 2022).

The density of a pristine rubber particle is $\sim 1.2\ g\,cm^{-3}$ but encrustations of minerals and clay from a road surface can increase this to 1.8 $g\,cm^{-3}$ (Mattonai et al., 2022). Density-based separation media including sodium polytungstate (1.9 $g\,cm^{-3}$), sodium iodide (1.83 $g\,cm^{-3}$), sodium bromide (1.5 $g\,cm^{-3}$), sodium chloride (1.2 $g\,cm^{-3}$), canola oil and castor oil (Jung and Choi, 2022; Järlskog et al., 2020; Kovochich et al., 2021; Klöckner et al., 2019) have been used to separate TRWPs. High-density salt solutions have the advantage of extracting more particles compared to low density solutions. Mattonai et al. (2022) found that sodium polytungstate is efficient in extracting >85 % TRWPs from environmental samples. Järlskog et al. (2020) found that sodium iodide is nine times more efficient than sodium chloride. Canola oil and castor oil are effective in recovering 84–96 % of conventional microplastics (Radford et al., 2021) from the soil sample, owing to the oleophilic nature of the microplastics. Thomas et al. (2022) evaluated castor and canola oil for the separation of TRWPs from the soil matrix. Oil has not been found to be efficient in recovering TRWPs. This might be due to the different physical and chemical characteristics of TRWPs than conventional microplastics (Thomas et al., 2022). Further investigation is required.

Separation of TRWPs is achieved by mixing a sediment/soil sample with a saturated salt solution. A sample is thoroughly mixed to ensure that TRWPs are detached from the sample matrix. Mixing is via rigorous handshaking and the sample is allowed to settle (Thomas et al., 2020). In general, soil/sediments have a negatively charged surface (Dube et al., 2001). Positively charged metal ions such as iron (Fe^{2+}), zinc (Zn^{2+}), sodium (Na^{+}), calcium (Ca^{2+}), and copper (Cu^{2+}) are naturally bound to the soil surface (Uddin et al., 2024). At acidic pH (pH $<$ 7), the interaction between the solid phase of soil and the density solution may result in an exchange of metals/metalloids (Kicińska et al., 2022). At low pH, the concentration of hydrogen ions in the solution increases. This means that more hydrogen ions would compete for the binding sites on the soil. Consequently, it may result in the dissolution of the metals and metalloids from the soil (Caporale and Violante, 2016). Whereas, organic molecules present in soil consist of long-chain hydrocarbons (C-H). The electronegativity difference between hydrogen and carbon is insignificant. Therefore, there will be a small dipole moment (non-polar). Due to non-polarity, organic constituents of soil are likely not to react with changes in the pH (Mani et al., 2019). Since sodium polytungstate (pH 3.3 at density 3g cm^{-3}) (Plaza et al., 2019) and zinc chloride (pH = 4.2 and density = 1.9g cm^{-3}) have acidic pH, use of these solutions may solubilize the metals from the soil. Therefore, use of these density solution may overestimate the elemental constituents of TRWPs.

To enhance separation of TRWPs, density separation is coupled with centrifugation. Centrifugation works on the principle of sedimentation, in which suspended particles separate from fluids due to gravity (Hu and Zhang, 2019). In centrifugation, when a sample containing TRWPs is rotated at a certain speed, an outward force is generated (Grause et al., 2022). This force, centrifugal force, allows the mineral particles to settle whilst TRWPs remain suspended or move to the top. Upward movement of TRWPs is hampered due to settling mineral particles (Grause et al., 2022). This may decrease the recovery rate of TRWPs in the centrifugation process (Grause et al., 2022).

Filtration is typically undertaken before density separation to obtain the desired size of TRWPs. Järlskog et al. (2020) filtered a water sample through sieves of 20 µm. Some researchers have used a filtration step after centrifugation to obtain less dense particles in the supernatant. Rødland et al. (2022) filtered the supernatant using a 13 mm glass fibre filter. Filtration after centrifugation may lead to incomplete separation of particles due to disturbance of settled particles and consequently may clog the filter paper. Similarly, filtration before centrifugation may result in a biased particle size distribution.

Density-separating solutions are either expensive or potentially harmful (Mani et al., 2019), lowering their use in studies (Quinn et al., 2017). Sodium iodide is expensive (Way et al., 2022b) and known to cause skin and respiratory irritation (Thomas et al., 2022). Zinc chloride is high-priced (Radford et al., 2021) and corrosive and harmful to the environment; for example, it causes neurotoxic effects and abnormal development of bones in zebra fish (*Danio rerio*) (Thomas et al., 2022; Horie et al., 2020). Sodium polytungstate solution may interact with free calcium in the sample. This reaction leads to insoluble precipitates of calcium polytungstate. The precipitates may clog the filter paper, leading to contamination of the sample for the chemical analysis (Morgun and Makarov, 2011).

Density separation methods usually target the inorganic fraction of a sample (Radford et al., 2021). However, sometimes, to separate the lighter fraction of organic material, two step density separation is used. In two phase density based separation, the initial separation is performed using a high-density solution. The second step involves a lighter density solution. This method is used when the targeted chemical constituent is also present in non-tyre related sources. This would help is evaluating how much targeted constituent is coming from other sources. For example, Barber et al. (2025) used NaCl to separate <1.2g/ cm^{-3} fraction of the sample. Use of multiple steps may result in loss of sample.

Organic matter, which can have a density similar to that of TRWPs, may obstruct their identification and detection (Radford et al., 2021). Similarly, in organic rich samples, organic material may form aggregates with TRWPs. To clearly analyse TRWPs, the organic fraction of a sample must be digested.

3.2.2. Acid/Alkaline/Enzymatic digestion

Extraction of TRWPs from an organic-rich environmental matrix requires chemical or enzymatic digestion to dissolve organic matter (Way et al., 2022b) and to clearly observe the wear particles (Monteiro and da Costa, 2022). Commonly-used chemicals (acids and oxidizing agents) are hydrogen peroxide (H_2O_2) (More et al., 2023), nitric acid (HNO_3) (Parker-Jurd et al., 2021; Klöckner et al., 2019), hydrochloric acid (HCl) (Haynes et al., 2020), Fenton's reagent (H_2O_2 in the presence of iron catalyst) (More et al., 2023) and alkaline solutions, each with their advantages and disadvantages (Table S1). Rødland et al. (2023) employed H_2O_2 to digest the organic matter in soil samples. Ren et al. (2024) used HNO_3, HCl, and Fenton's reagent to assess the digestion efficiency of the organic matter. Fenton's reagent when combined with hydrogen peroxide generates hydroxyl radicals that can degrade organic matter (Goßmann et al., 2021). The reaction is exothermic and may affect the properties of TRWPs (Thomas et al., 2022). H_2O_2 (30 %), HNO_3 and HCl are reported to degrade 95 % of organic matter at 70 $^{\circ}C$ (Thomas et al., 2022) - yet they may also be detrimental for the TRWPs. An alkaline solution like potassium hydroxide (KOH) has not been found to be effective in removing organic matter from soil or sediments (Way et al., 2022a). Yet, LaPlaca et al. (2022), Way et al. (2022b) and Parker et al. (2020) reported that KOH dissolves fish tissues efficiently, suggesting that the choice of a chemical for digestion depends upon the targeted sample. Enzymatic digestion is efficient in removing 98 % of organic matter. But the use of an enzyme is target-specific. Yang et al. (2021) used protease and lipase to digest plankton-rich sea water samples. Loder et al. (2017) used chitinase and protease enzyme to dissolve biogenic matter. However, this is not effective in the case of soil since it contains a range of organic matter - for example, lipids from microbial communities (Ding et al., 2020), cellulose from plants (Lavanya et al., 2011; Wiesenberg et al., 2010) and proteins from decaying plants and remains of animals (Berg and Laskowski, 2005). Using enzymes is expensive owing to the purification required (Way et al., 2022b).

Enzymatic digestion, to the best of our knowledge, has not yet been applied to TRWPs in the published literature.

3.2.3. *Magnetic separation*

Magnetic separation may extract TRWPs from soil/sediment samples. The surface of TRWPs is magnetized by the binding of hydrophobic iron particles to their external surfaces (He et al., 2021). Subsequently, iron-bound TRWPs can be isolated from an environmental matrix by applying a magnetic field (Budhiraja et al., 2022; He et al., 2021). This method is environmentally-friendly and economically viable. Its efficiency depends on the size/surface characteristics of the particles. Budhiraja et al. (2022) reported 13 % less extraction of weathered TRWPs than pristine TRWPs, which might be due to the increased hydrophilicity of weathered particles. Environmental samples comprise a broad spectrum of particles, including minerals and debris. These contaminants may be susceptible to magnetic separation and lead to false positive results (i.e. resulting in the extraction of incorrect material) due to non-specific binding (Nabi & Zhang, 2022). Researchers are currently trying to develop methods that can extract real environmental concentrations of TRWPs (Thomas et al., 2022).

3.2.4. *Solvent extraction*

Solvent extraction is a selective method in which analytes are separated by using a suitable chemical. It tends to be performed when the evaluation of the mass of TRWPs based on the quantification of targeted constituents is required.

An organic solvent is used to extract a specific constituent of TRWPs from an environmental matrix (He et al., 2021). Pressurized solvent extraction, also known as pressurized liquid extraction (PLE) or accelerated solvent extraction, is considered to be an environmentally-friendly method to extract required constituents from environmental samples (Alvarez-Rivera et al., 2020). A significant advantage of using PLE is that it uses small volumes of solvents and enables faster extraction (Hu et al., 2011). Thus, pressurized solvent extraction is termed as a “green” extraction method. This “green” extraction approach aims to eliminate the use of hazardous solvents (Breil et al., 2017; Mustafa and Turner, 2011). One way is to minimize the use of aggressive and toxic solvents. Traditional extraction methods, which include Soxhlet extraction and solid-liquid extraction, require a longer extraction time as well as a large amount of organic solvent (Mustafa and Turner, 2011). Disposing of large amounts of solvent may have negative impacts on the environment and on human health (Mustafa and Turner, 2011), as well as being a waste of valuable resources.

3.2.5. *Digestion of tyre and road wear particles*

In the digestion of TRWPs, strong acids are used to dissolve the rubber matrix. This results in the release of soluble elemental constituents from the TRWPs. There is no standard method of dissolving TRWPs. Different research groups have used combinations of different acids for this. For example, Klöckner et al. (2019) used hydrogen peroxide (H_2O_2) and nitric acid (HNO_3) in a ratio of 1:3. O’Loughlin et al. (2023a) assessed 70 % HNO_3 and 30 % H_2O_2 for the digestion of particles. Wi et al. (2023) evaluated 65 % HNO_3 to digest road dust sample containing TRWPs. Perchloric acid (HCl O_4) and hydrofluoric acid (HF) have also been used (Bocca et al., 2009). However, the digestion of TRWPs may not always be complete (Braysher et al., 2024). Therefore, analytical techniques would not be able to detect all the elements present in TRWPs. This indicates an urgent need to standardize methods to allow comparison of experimental results between different research groups.

3.2.6. *Bespoke apparatus*

Bespoke apparatus such as an Erlenmeyer flask, filtration assembly and separating tower have been used for the separation of TRWPs from different environmental samples (Järlskog et al., 2020; Knight et al., 2020; Stolte et al., 2015). However, during the separation process, TRWPs may adhere to the surface of a separating tower. Similarly, during filtration, TRWPs may clog the pores of the filter paper, leading to partial separation (Table S1).

Overall, various methodologies have been tested to separate TRWPs from road dust/sediment samples. Accuracy in the identification of TRWPs depends heavily on the extraction method (Maw et al., 2022). Density solutions usually do not alter the morphology of TRWPs (Munno et al., 2018). They may obstruct analysis due to interference with the spectrum, hiding the signature peaks (Primpke et al., 2020). Digestion solutions, used to remove organic matter from environmental samples, may react with TRWPs. Different solutions may react differently with TRWPs. Oxidative reagents, such as H_2O_2, may chemically react with TRWPs. This would ultimately lead to change in the physical characteristics of the particles (Lee et al., 2022). For example, Lee et al. (2022) found that sulphuric acid (H_2SO_4) altered conventional microplastics (polyethylene terephthalate) into flower-shaped particles. Similarly, HNO_3 may bleach TRWPs (Prata et al., 2019). Mechanical processes such as mixing and sieving are effective to isolate TRWPs from an environmental sample. However, these steps are likely to increase the fragmentation of the particles and so overestimate the particle count (Lusher et al., 2020).

Quality data on the chemical composition, size, and shape of TRWPs is imperative for accurate estimation of the concentration of TRWPs in the environment (Maw et al., 2022). Therefore, it is necessary to optimise the key methodological factors for the extraction of TRWPs (Han et al., 2019). Extensively researched data on variations in chemical structures and the consequent changes in morphologies can be used as the basis for improved detection and analysis of TRWPs following pretreatment in the future (Han et al., 2019).

3.3. *Analysis*

Extraction of TRWPs is followed by analysis. Evaluation of TRWPs in environmental samples is a challenging task because of limitations in present analytical methods that have been designed/adapted for analysis of conventional microplastics. The identification and quantification of TRWPs at environmentally-realistic concentrations needs highly sensitive analytical methods and some methods are inaccessible due to cost or limited access to equipment (Way et al., 2022b). The selection/use of an analytical technique depends on the goal of a study. Data may be needed regarding the size, shape, elemental or organic composition, mass, and number of TRWPs. Assessing the physical and chemical characteristics of TRWPs is imperative since it determines the fate and impacts of the particles. For complete understanding of TRWPs, it is necessary to evaluate the nano (1 nm- 1 μm) to micro (1 μm-5mm) size range. No single analytical technique is capable of covering this size range. Therefore, a combination of various complementary approaches may be used for the analysis of size and quantification of mass-based concentration of TRWPs (Caputo et al., 2021). Microscopy, spectroscopy, vibrational spectroscopy, and thermo-analytical methods have been used for the analysis of TRWPs.

3.3.1. *Microscopy*

If the objective of a study is physical characterization/quantification of TRWPs then, depending on the number of particles, this can be performed using microscopy. Such methods involve the use of specialized instruments such as an optical microscope, stereomicroscope, scanning electron microscope (SEM) and transmission electron microscope (TEM). The detection limit of an analytical instrument determines an instrument’s efficacy. Detailed information regarding each analysis technique is given in the Supplementary Information.

3.3.2. *Vibrational spectroscopy*

Vibrational spectroscopy is used to analyse the molecular structure of a sample without degrading the sample (Song et al., 2021). It uses light of a specific wavelength to evaluate the molecular structure of a sample (Larkin, 2017). The molecules in a sample vibrate at a specific frequency, producing spectral fingerprints (Siesler et al., 2008). These fingerprints are compared with a library of known spectra, providing information about the make-up of a sample (Eisentraut et al., 2018; Siesler et al., 2008). Vibrational spectroscopy has long been used for the identification of polymers (Eisentraut et al., 2018). Raman analysis, FT-NIR and FTIR spectroscopy have evolved as common methods for the comprehensive identification (and understanding) of microplastics (Kovochich et al., 2021; Eisentraut et al., 2018). FTIR spectroscopy allows the absorption and emission of IR radiation, giving information about the surface characteristics. Detailed information regarding each spectroscopic method is given in the Supplementary Information.

3.3.3. *Thermo-analytical methods*

Thermo-analytical methods are efficient for the analysis of cross-linked polymer materials such as TRWPs (Dümichen et al., 2019). Thermoanalytical methods usually rely on the decomposition products of additives as distinguishing markers. Polymers, present in tyre tread, are decomposed and the resultant monomers are analysed. For example, dipentene and isoprene have been recommended as an analytical marker for the quantification of natural rubber (Miller et al., 2022). This is because natural rubber is formed by polymerization of dipentene and isoprene. Similarly, 4-vinylcyclohexene and 1,3 butadiene are markers for the identification of butadiene rubber in an environmental sample (Chae and Choi, 2022). The pyrolyzates are then separated and quantified. Deng et al. (2022) and Johannessen et al. (2022) discussed in detail the additives present in tyres and the use of potential constituent (s) as marker(s) for the identification of TRWPs in the environment. For the quantification of targeted constituent(s) in a sample, a calibration curve is used, established via an external or internal standard.

In external standardization, a series of known concentrations of a standard solution is prepared. A standard sample is injected into the instrument and the response of the instrument is recorded. A plot between the concentration of the standard sample and area (response) is made. The same volume of a sample, containing an unknown concentration of target constituent(s), is injected into the instrument (Dolan, 2009). The resultant peak area is compared with the peak of the standard solution. Regression equation is used to evaluate the concentration of the constituent(s) (Dolan, 2009). In internal standardization, the test solution is spiked with known concentration of stable isotopically labelled standard analyte (internal standard). The ratio of an analyte's signal response and that of an internal standard is plotted against the concentrations to derive a calibration curve (Unice et al., 2012). This calibration curve is then used to evaluate the concentration of a target analyte(s) in the sample (Tan et al., 2011).

Thermal analysis covers a range of techniques such as thermal extraction and desorption-gas chromatography/mass spectrometry (TED-GC/MS), pyrolysis-gas chromatography mass spectrometry (Py-GC/MS), liquid chromatography mass spectrometry (LC/MS), inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma optical emission spectroscopy (ICP-OES). Detailed information regarding each thermo-analytical method is provided in the Supplementary Information.

4. Synthesis and critical evaluation

A comprehensive literature review of sampling, extraction, and analysis methods for TRWPs shows benefits and limitations of present approaches. Whilst samplers such as a metal scoop, glass bottles, piston corer and other sampling devices have been used, there is no standard sampling protocol for TRWPs. Different environmental compartments possess unique physical and chemical characteristics. Therefore, the sampler that is suitable for road dust may not work well for airborne samples, making it difficult to establish a one-size-fits-all method. Once the samples have been collected, the extraction and analysis protocol should be selected based on the objective of the study and nature of the sample. For example, when the objective is to quantify TRWPs, based on particle count, a simple filtration step followed by microscopic analysis should be adopted when dealing with simple samples (water and air samples).

For complex samples such as road dust or sediment samples, processing is dependent on the nature (wet/dry) of the samples. If the objective is particle count from a dry sample, based on physical characteristics, a stereomicroscope should be used. Separated particles can be evaluated for elemental or targeted organic composition using SEM-EDX, XRF, ICP-MS/MS, 2D-GC/MS or LC/MS/MS.

Whilst dealing with wet organic-rich samples, a series of pre-processing steps like density separation, alkaline or acid digestion may result in loss of sample during handling. For this reason, wet sediment samples are compatible only for the evaluation of mass of TRWPs. In this scenario, solvent extraction followed by thermal analysis is suitable. Future studies should improve the understanding of distribution and transportation of TRWPs across different environmental matrices, so that the associated environmental risks may be evaluated.

5. Conclusions and recommendations

TRWPs are a global challenge owing to their widespread presence and potential harmful effects. Given the physiochemical behaviour of TRWPs in different environmental compartments, it is urgent to evaluate the actual environmental concentrations of TRWPs. The absence of a standardized methodological approach restricts the quality and reliability of studies. This study has reviewed the methods used, from sampling to analysis, to present a comprehensive evaluation of potential areas for standardization. Sampling methods may differ from water to air; but it is possible to obtain consistency. We recommend considering the characteristics of sampling media to collect representative samples. For example, air samples, irrespective of the sampling device, should be collected from the typical breathing zone. Similarly, when collecting samples from water channels, sampling depth, place of collection and dynamics of a water channel should be considered to ensure representativeness of the collected sample. Future studies should always include information on quality control (QC), and quality assurance (QA) approaches. QA/QC helps in minimizing contamination. For example, field blanks during sampling provide information about the extent of contamination. We recommend conducting multiple field blanks during sampling to avoid reporting false positive or false negative results. By following the sampling protocols for different environmental media, reliability can be ensured in future studies. If the key focus of a research question is the size, shape and particle count of TRWPs, microscopy and spectroscopic methods (SED-EDX, XRF, FT-NIR, μ-FTIR, ESEM) are preferred. For quantifying TRWPs in terms of mass, thermo-analytical methods (2D-GC/MS, ICP-MS/MS and LC/MS/MS) are favourable. Calibrations must be applied to ensure inter-study accuracy.

By following the analysis techniques recommended in this paper, these methods can be used as a standardized approach for future studies. Over time, it would help in building unified knowledge about the distribution and transportation of TRWPs in different environmental matrices.

We highlight gaps in the literature. Therefore, recommendations for future study are.

- TRWPs may transport to water channels and associate with the SML (surface microlayer), depending on water column characteristics, wind/weather and TRWP composition (Birkenhead et al., 2020). The SML is understudied for TRWPs, so we recommend future studies to assess the presence of TRWPs in SML and their associated risks.
- During deposition in sediments, TRWPs may be suspended at the SWI (sediment-water interface). Future studies should consider evaluating the SWI for comprehensive understanding of suspended TRWPs.

- TRWPs may be deposited in deep sediment layers over time. However, the rate of deposition and the factors determining the sedimentation rate are rarely investigated. Evaluation of the deposition rate of TRWPs is urgently required to better understand the function of rivers and streams in holding and transporting TRWPs across environmental compartments.
- Tree bark has recently been used for the collection of PM. Further investigation is required to evaluate its suitability for the sampling of TRWPs.
- Reference standards for TRWPs are required to validate results by providing known benchmarks for comparison (Khan et al., 2024). This ensures reliability and accuracy of the analytical instruments used for the identification and quantification of TRWPs in environmental samples.
- When reporting data, transparency is required about the procedures implemented. This includes characteristics of the sampling location, number of samples collected, volume of sample, number of replicates, and field blanks. Transparency will help in inter-study comparisons and standardizing of protocols. Standardizing the approach for the analysis of TRWPs will help in providing robust data about the fate, transport and the distribution of TRWPs in the environment. This will assist in making policies to manage TRWPs.

CRediT authorship contribution statement

Zainab Tariq: Writing – original draft, Data curation, Conceptualization. **Ian D. Williams:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Andrew B. Cundy:** Writing – review & editing, Supervision, Conceptualization. **Lina M. Zapata-Restrepo:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126440.

Data availability

I have attached the file.

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