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Micro- and nanoplastics in the air: sources, transport & analytical methods for their determination

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Contents

Abstract

Plastics have been instrumental in providing innovative solutions to society, owing to their versatility, durability, and adaptability. As a result, plastic manufacturing has seen an exponential increase, with global production reaching almost 390 million tons in 2021 (57 million tons in Europe).

This surge in plastic production has led to the proliferation of micro- and nanoplastics, which are small plastic particles generally less than 5 millimetres in size. These particles originate from various sources like cigarette filters, textile fibres, cleaning products, personal care items, and also from tyre wear and weathered plastic products. Unfortunately, their small size and persistence have resulted in their widespread presence in land, water, food, and air, posing significant environmental risks and potential threats to human health.

The European Commission (EC) has responded to this pollution and health challenge through key policy documents like the Green Deal and the European Strategy for Plastics.

Although there has been considerable research on the presence of microplastics in soil, water, and food, their occurrence in the air, both indoors and outdoors, has not been given sufficient attention so far. Limited data exists on the quantitative characterization of microplastics in urban and non-urban atmospheres, but this data is growing. However, the atmospheric emission rates from specific materials, actions, and environments are largely unknown at present. Furthermore, there is a scarcity of data regarding particles smaller than 3 µm, which are specifically those capable of reaching deep into the lungs.

The introduction of regulatory instruments must be rooted in scientific evidence, and effective monitoring tools are required to assess their implementation and impact. Currently, the absence of fit-for-purpose technologies and harmonised methods is hindering progress in this regard.

This report addresses some of these challenges, which are pivotal for a precise evaluation of the presence of micro- and nanoplastics and their potential impact on health and the environment. It aims to systematically review and evaluate the available published literature on methodologies used to measure primarily micro-plastic (to a lower extent also nanoplastic) in the air as well as their sources and transport.

Authors

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1 Introduction

Plastics have been instrumental in providing innovative solutions to society, owing to their versatility, durability, and adaptability. As a result, plastic manufacturing has seen an exponential increase, with global production reaching almost 390 million tons in 2021 (57 million tons in Europe) [1].

Micro- and nanoplastics, which are small plastic particles (including elastomers) generally less than 5 millimetres in size, originate from various sources like cigarette filters, textile fibres, cleaning products, personal care items, and even dust from tyres and weathered plastic products. Unfortunately, these tiny particles are persistent pollutants, leading to a rapid rise in their presence in land, water, food, and air, posing environmental risks and potential threats to human health.

Recognizing the urgency to address plastic pollution and marine litter, the European Union (EU) has taken action to promote a circular and resource-efficient plastics economy. Specific regulations and targets are in place for single-use plastics, plastic packaging, microplastics, and bio-based, biodegradable, and compostable plastics.

The European Commission (EC) has responded to this pollution challenge through key policy documents like the Green Deal and the European Strategy for Plastics [2], leading to restrictions under REACH and the adoption of a methodology required for monitoring purposes under the Drinking Water Directive (DWD) [3] and a newly proposed Regulation on preventing pellet losses (SWD(2023) 332 final). Additionally, regulatory measures are being considered for areas such as groundwater, wastewater, sludge, tyres, textiles, washing machines, and more.

While the presence of microplastics in soil, water, and food has been extensively studied, its occurrence in the air, both indoors and outdoors, has received less attention [4]. Existing research has primarily focused on deposition samples [5], providing limited information about the smallest size fractions, such as PM_{10} (thoracic particles) and $PM_{2.5}$ (alveolar particles), which may carry potential health risks. Accurate atmospheric concentration data is crucial for assessing human inhalation risk and understanding long-range transport [6].

However, the lack of standardised methodologies for sampling, treatment/extraction, and identification/quantification of micro- and nanoplastics in air has led to low comparability of results from different studies.

The introduction of regulatory instruments must be rooted in scientific evidence, and effective monitoring tools are required to assess their implementation and impact. Currently, the absence of fit-for-purpose technologies and harmonized methods is hindering progress.

The development of standardised analytical methods is urgently needed to address plastic pollution in the air and better understand its impact on health and the environment.

Thus, this report aims to systematically review and evaluate the available published literature (2010-2023) on the main sources of micro- and nanoplastics in the air and the analytical methods employed for their identification and quantification.

2 What are nano- and microplastics?

Plastics and elastomers have become indispensable in our lives, offering convenience, lighter weight, and cost-effectiveness compared to alternative materials. However, improper disposal and insufficient recycling practices lead to their presence in the environment (Figure 1), where they persist for centuries, breaking down into smaller fragments known as microplastics [7]. These microplastics are solid particles comprising various polymers or polymer-mixtures, functional additives, and possible residual impurities.

Definitions [8], [9]

Microplastics (MPs):
Plastic particles equal to or greater than 1 µm and less than 5 mm in (aerodynamic) diameter

Nanoplastics (NPs):
Plastic particles less than 1 µm in (aerodynamic) diameter

Plastics:
Material which contains as an essential ingredient a high polymer and which, at some stage in its processing into finished products, can be shaped by flow (ISO 24187:2023)

Elastomers:
Macromolecular material which returns rapidly to its initial dimensions and shape after substantial deformation by a weak stress and release of stress (ISO 24187:2023)

The introduction of microplastics into the environment stems from various sources, including ingredients in cigarette filters, textile fibres, cleaning products, personal care items, as well as particulates from vehicle tyres. Additionally, larger plastic items disintegrate over time due to exposure to the sun, wind, and ocean waves, releasing more microplastics. These particles find their way into rivers, and ultimately the oceans.

Microplastics can be categorized into two types: primary and secondary.

Primary microplastics encompass tiny particles intentionally designed for commercial purposes, found in products like cosmetics, as well as microfibres shed from clothing and other textiles, such as fishing nets.

On the other hand, secondary microplastics are particles resulting from the breakdown of larger plastic items like plastic bottles, packaging boxes and films. This degradation is primarily caused by exposure to environmental factors, particularly the sun's radiation, ocean waves and grinding by sand. Secondary microplastics can also originate from vehicle tyre undergoing wear and tear as they come into contact with the road surface as well as from paint during the application process or due to exposure to solar radiation, cooling, heating, drying, and rain.

An additional concern arises with the presence of nanoplastics, formed from the further degradation of microplastic particles. Nanoplastics pose a higher risk as they are more easily taken up by organisms and are likely to have greater ecological and health implications compared to microplastics [10].

Figure 1. Plastic waste accumulated at the ‘Murazzi’ on the island of Pellestrina (Italy)

Source: photo by Otmar Geiss

3 Sources of airborne micro- and (nano)plastics

The potential sources of atmospheric MP in indoor and outdoor environments are numerous, as plastic products are ubiquitous in everyday life. They can be determined based on the MP characteristics (*i.e.* chemical composition, morphology, size and colour) and on the human activities (*i.e.* location, population density, meteorological conditions). A study, carried out during a COVID lockdown and after the human activities went back to track, showed an increase of MP deposition rate highlighting the effect of human activity and the fact that MP sources are mainly local [11].

Microplastics in indoor and outdoor environments have distinct potential sources (described in the following sections). Sources mentioned in the literature primarily focus on microplastics, as the detection of nanoplastics remains challenging. Considering that nanoplastics are often generated through the degradation of microplastics, it can be inferred that the sources are likely to be the same.

Abundance of MPs in indoor environments is generally more important than in outdoor environments due to the confined spaces ([12]–[16]). Table 1 compares the indoor and outdoor concentrations of several selected studies. Outdoor and indoor concentrations may be comparable when the sampling is performed in urban areas [17].

Table 1. Indoor/outdoor concentrations comparison

Reference	Indoor concentration	Outdoor concentration
Dris, 2017 [12]	1.0 - 60.0 fibres m^{-3}	0.3 - 1.5 fibres m^{-3}
Liao, 2021 [16]	1583 ± 1180 MPs m^{-3}	189 ± 85 MPs m^{-3}
Chen, 2022 [13]	46 ± 55 MPs m^{-3}	28 ± 24 MPs m^{-3}
Perera, 2022 [14]	0.13 - 0.93 MPs m^{-3}	0.01 - 0.23 MPs m^{-3}
Perera, 2023 [15]	0.47 - 2.25 MPs m^{-3}	0.17 ± 0.06 MPs m^{-3}

Source: own production

3.1 Sizes and shapes of microplastics in the air

Microplastics can take the form of fragments, fibres, foams, spherules, or films, with fragments and fibres being the most prevalent. Fibre shape is characteristic of textiles, carpets and upholstery, and is the principal, if not the only, shape found in indoor environments. The fibrous particles in the air are not necessarily plastics, and the majority are natural or cellulosic fibres, although the proportion of synthetic microfibre in the atmosphere is increasing [18]. The predominance of fibre identification in the majority of size range studied is probably due to their low mass to surface area ratio, which facilitate their resuspension via transport or dispersion [19]. The smallest size ranges (< 50 µm) studied in the literature may increase the proportion of other MP shapes notably the fragments. For instance, Fan et al (2022) showed that the percentage of fragment was higher in the class size of 10-25 µm while for fibres the higher percentage was in the size class of 300-500 µm [20]. Liu et al. (2022) showed that, in the valley basin of Lanzhou city (China), the predominant shape depended on size range: MPs ≥1000 µm are primarily fibres (88 %) and MPs in the 50 - 100 µm size range are mainly fragments [11]. Similar outcomes were observed by Liao et al. (2021) where fragments were predominant in the 5-100 µm size range for both indoor and outdoor environments [16]. These results can explain why a majority of fibres are observed in the atmospheric MPs studies since in general the minimum size studied can be higher (> 25 - 50 µm). The probability of having more diverse shapes with higher density than fibre in the smallest size ranges is supported by O'Brien et al. 2023 [21].

3.2 Relevance of the polymer type for identifying microplastic sources

Identifying the polymer type is another approach to identify potential MP sources. Indeed, once the polymer type is determined, it can provide valuable clues in narrowing down the possible sources. To do so, specialized techniques are required to analyse the chemical composition of the microplastic particles, as detailed in section 5. Table 2 describes the main applications of several widely used polymers. Polymer applications are vast, ranging from automotive and packaging to clothing and household products, to name a few.

Table 2. Main applications of the different plastics [22], [23]

Polymer name	Acronym	Main applications
Polyethylene terephthalate and other polyesters	PET/PES	▪ Textile fibre: clothing, home furnishings (curtains, carpets, sheets, upholstery…) ▪ Packaging: containers for food, beverages, and non-food items (*e.g.* cleaning products) ▪ Paint
Polyamide (Nylon)	PA	▪ Textile fibre: clothing, carpets, fishing nets ▪ Automotive parts ▪ Electrical components
Polyethylene High density polyethylene Low density polyethylene	PE HDPE LDPE	▪ Packaging bottles (HDPE) and films (LDPE) ▪ Medical and healthcare (personal protective equipment, containers and bag headers…) ▪ Pipes, Hoses & Fittings ▪ Household products (kitchenware, housewares, ice boxes, buckets…) ▪ Agriculture (greenhouse, mulching…) ▪ Electrical: Wire and cable insulation and jacketing
Polystyrene Expanded polystyrene	PS EPS	PS: ▪ Takeout packaging, disposable cutlery and cups ▪ CD cases ▪ Laboratory equipment EPS: ▪ Building and Construction (insulation properties) ▪ Food packaging (thermal insulating properties) and food service containers ▪ Transport packaging ▪ Other products (sports helmets, infant car seats…)
Polypropylene	PP	*Rigid (bottles, pots…) or flexible (film)* ▪ Packaging (food, personal care, medical and labware, household chemicals) ▪ Consumer Goods: housewares, furniture, appliances, luggage, toys… ▪ Automotive parts ▪ Textile fibre: clothing, carpets, upholstery, ropes ▪ Medical and lab equipment (disposable syringes, vials, intravenous bottles, pill containers…)
Polyvinyl chloride	PVC	▪ Construction (window frames, pipes, roof lining, roofing membranes, house siding…) ▪ Household products (curtain rails, flooring, laminates, shower curtains, hosepipe, furniture…) ▪ Packaging (transparent packs, blisters, pharmaceutical tablets blisters, cling film) ▪ Sports equipment ▪ Waterproof clothing and shoes ▪ Electrical: wire and cable insulation, plugs, sockets…
Polyurethane	PUR or PU	*Flexible or rigid foam, coatings, adhesives* ▪ Textile fibre (Spandex, sports clothes…) ▪ Automotive: bumpers, interiors, car body, doors, windows… ▪ Household products (flooring, Furnishings, refrigerator and freezer thermal insulation systems, finishes…) ▪ Building and Construction (insulation properties…) ▪ Electronics ▪ Paint
Styrene-Butadiene rubber	▪ SBR	▪ Tyres
Polyacrylonitrile	PAN	▪ Textile fibre ▪ Production of carbon fibre

Source: own production

3.3 Occurrence and sources of indoor microplastics

On average people tend to spend approximately 90% of their time indoors (at home, at work, at school, in stores...) [24]. It is known that indoor environments have higher concentrations of some pollutants (including from plastics [25]) than outdoor environments impacting the human health [26]. These higher concentrations in enclosed spaces implies chronic exposure to MPs [27].

The MPs in indoor environments may come from wear and tear of textiles, flooring, packaging materials, building materials or furniture (Figure 2, Table 3). The MP occurrence is closely linked to the human activity and can be influenced by the occupancy, the cleaning habits and/or the air conditioning. Several of these parameters will be further discussed in the following subsections.

Figure 2. Principal sources of MPs in indoor environments

Source: own production

Table 3. Indoor sources with their main polymer types

Indoor source	Main polymers
3D printer	PLA, ABS, PETG
Textiles (clothing, curtains...)	PET, PES, PA
Packaging materials	PET, PP, PE, PS
Floor (rugs, carpet, flooring)	PA, PET, PES, PP, PVC
Paint and wall finishes	Acrylic polymers, PUR, PES
Household objects (furniture, kitchenware, toys...)	PP, PE
Air conditioning	PET, Rayon

Source: own production

3.3.1 Textiles

Textiles (e.g. clothing, furniture or carpet) are one of the main reported sources of airborne MPs due to the particle shapes (predominance of fibres) and composition (predominance of PES, PA and PP). The primary processes that contribute to the degradation and release of MPs from textiles are wear and tear and abrasion. Moreover, studies have demonstrated that drying process after laundry can involve the release of fibres into the air [28], [29]. Textile damage usually occurs during the washing process and may contribute more significantly to fabric deterioration compared to normal use of textile [30]. Therefore, during the drying process (line drying or tumble drying) release of fibres can be substantial.

3.3.2 Floor covering

The influence of the floor covering was also mentioned in several studies which highlighted the release of fibres from carpets [17], [24], [28], [29]. The amount of released MPs can be higher in homes with carpet on the floor. For instance, Dris et al. (2017) observed that between the two studied apartments, the one with more carpet on the floor had more MPs than the one without [12]. Soltani et al. (2021) observed a significant difference between the dust deposition concentration and the main floor covering in the 32 Australian homes studied with the average being 60 % higher in homes with carpet (2339 fibres/m^2/day) than in homes without (1484 fibres/m^2/day) [31]. However, others studies did not see significant difference in concentrations between carpeted and non-carpeted homes [27], [33]. Another (maybe more relevant) way of identifying the influence of floor covering on airborne MPs is by polymer type, which has shown to be dependent on the floor covering. Thus, PE, PES, PA, and acrylic polymers were characteristic of carpeted floors while polyvinyl were more characteristics of wooden floors (probably coming from the wooden finishing) and linoleum floors [31]. Soltani et al. (2022) compared the MPs in dust deposition in 108 homes from 29 countries. They observed a higher amount of PE in carpeted homes compared to other type of floor as well as a higher amount of polyvinyl in homes with wooden floor [27].

3.3.3 Occupancy

In the literature, there is no consensus on the influence of occupancy on the MP levels. Several studies found that there are no significant differences in MP concentration ([27], [31]–[33]) while others observed a significant effect ([13], [34], [35]). For example, Bahrina *et al*. (2020) observed MP concentrations in dust deposition twice as high in offices and schools (compared to homes) where the number of people and therefore the human activities are greater [34]. Chen et al. (2022) collected indoor air samples from nail salons and found higher MP concentrations in salons with higher number of occupants [13]. Another study carried out in schools from kindergarten to the university highlighted the influence of the number of people in the indoor spaces and the duration of human activity on MP abundance [35].

3.3.4 Cleaning habit

The cleaning habit has also been shown to influence the MP occurrence in indoor environments. Soltani *et al*. (2021) studied the effect of the vacuum cleaner use and frequency among 32 homes sampled in the Sydney area (Australia) [31]. The results show that MPs deposition rate is inversely proportional to the frequency of vacuum cleaner use, with a significantly higher concentration in households that use the vacuum cleaner once a month than in those that use it once a week. Soltani *et al.* (2022) confirmed those observations in a larger study assessing the influence of the vacuum cleaner use and frequency in 29 countries (108 locations categorized by income). They observed a significant decrease of the MP deposition rate while increasing the use of the vacuum cleaner from once a week to twice a month to once a month or less. It's worth noting that this trend was observed irrespective of the country income as long as the use of the vacuum cleaner was applied consistently [27]. These works show how cleaning habits, specifically vacuuming, can reduce the deposition of MP in indoor environments.

3.3.5 Air flow (air conditioning)

Air flow has the ability (as wind) to transport MPs in the air. In indoor environment the air flow can be induced by the air conditioning (A/C) but can also be generated by a fan, people movements (walking, dancing…) or shutting doors. The air flow is not an actual source of MPs, however, it can resuspend the settled particles and increase MP airborne concentration and the MP deposition rate [36]. A number of studies have reported an increase in the particle fallout concentration ([32], [36]) or suspended MP concentration [13] with the use of ventilation systems, and A/C in particular. The A/C type may also play a role in the abundance of MP in air. Indeed, Uddin et al. (2022) compared different types of air conditioner: central plant, split unit and packer unit [33], and measured MP occurrence in the respirable (PM10) and inhalable (PM2.5) fractions. The highest MP concentrations were found in locations using split unit and the lowest in locations using a central plant. The air circulation and filter use being different for each A/C type. In another study, Chen et al. (2022) suggest that air conditioners (split unit) and more precisely A/C filters can both trap and release MPs in the air. When an A/C is used for a long time (> 35 days), it accumulates MPs on the filter and releases them into indoor spaces at varying distances from the A/C [37]. Consequently, A/C is an important factor influencing the MP abundance in indoor environments due to its ability to resuspend deposited particles, to trap them and release them into the room.

3.4 Occurrence and sources of outdoor microplastics

The main possible sources of MPs in outdoor environments are local and determined by atmospheric MP deposition [38], [39]. Figure 3 presents the main sources of atmospheric MPs in the outdoor environment and Table 4 shows the main associated polymers. The transport sector is a major contributor to MPs in air due to tyre wear and road dust [40]. In addition, other human activities are important factors in MP pollution, like agriculture, construction, paint and industry as well as landfill erosion. Finally, re-emission from oceans should not be overlooked as source of MP emissions into the atmosphere. Several studies report that MPs in urban outdoor environments are higher than rural or suburban environments [14], [16], [41], [42]. Urban emissions are closely linked to human activity and population density [14], [41], [43]. The nature and sources of MPs change with the type of anthropogenic activities (residential, industrial, commercial…).

The ocean, tyre wear and road dust, as major contributors of MPs in air, are discussed in more detail in the following subsections.

Figure 3. Principal sources of MPs in outdoor environments

Source: own production

Table 4. Outdoor sources with their main polymer types

Outdoor sources	Main polymers
Tyre wear	SBR, PBR
Road dust	SBS, SIS, EVA, PA, PE
Construction work	PC, PVC, EPS
Paint(s)	PES, PUR, PVA
Agriculture	PE
Industry	Not specific (large variety of polymers)
Landfill	Not specific (large variety of polymers)
Ocean	Not specific (large variety of polymers)

Source: own production

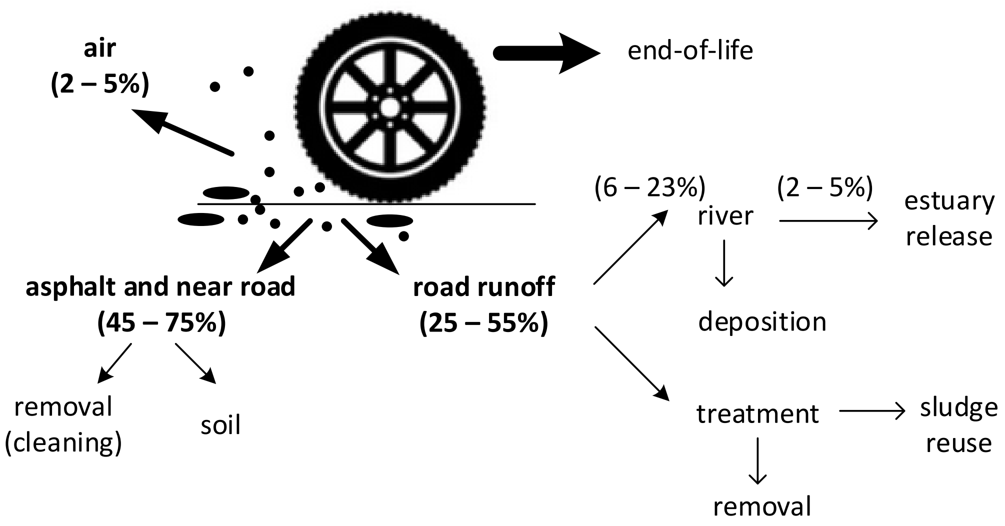
3.4.1 Road dust

Road surfaces are typically asphalt- or concrete-based. Asphalts are composed of minerals, sands, fillers and bitumen binder, while concretes are mixtures of sand, cement and coarse aggregates. The term road-wear is used to characterize material emitted from the road surface. Road re-suspension or road dust on the other hand consists of particles generated by various mechanical processes (abrasion, crushing, impact, degradation…) of natural materials (*e.g.* rock, soil, ore…) or anthropogenic materials (tyres, bitumen, road paint, construction, vehicle exhaust emission resuspension…) [44], [45], [46]. This dust can become airborne, primarily by the friction of tyres moving on roads. Road dust can be an important pathway for pollutants to environmental compartments via wind or water runoff. MPs in road dust can come directly from the road surface components (e.g. asphalt and road marking) and vehicles (mainly tyres) but also from atmospheric deposition particularly in urban and industrial areas. The main polymers originating from wear of car tyres, road pavement (where polymer modified bitumen are used) and road marking paints are: styrene-butadiene rubber (SBR) and polybutadiene rubber (PBR) from tyres; styrene butadiene styrene (SBS) from bitumen and styrene-isoprene-styrene (SIS), ethylene vinyl acetate (EVA), polyamide (PA) and polyacrylate from road marker paint [47]. Since the range of secondary sources of microplastics in road dust is wider, the range of polymer types is also wider. In the literature the most frequently mentioned polymers are PES and PA from textile, PP, PS, PET and PE from packaging and PVC from construction [48], [49].

3.4.2 Tyre wear

Tyre wear is considered as a main contributor to microplastics emissions into the environment. Globally, tread wear from road tyres results in approximately 6 million tonnes (t) of tyre particles being emitted annually [50]. The estimated mass of tyre wear generated in 2014 was 1,120,000 t for the United States and 1,327,000 t for the EU [51]; however, more conservative estimates assume half of this figure [52]. The major part of tyre wear ends up in the soil, another part enters wastewater treatment plants, and another one ends up in surface water (6-23%). The estimated amount entering in the airborne phase is between 2 and 5% [53], [54] (Figure 4). A typical tyre tread consists of approximately 40–60% rubber polymers, 20–45% reinforcing/filler agents, 5–15% chemical additives. The exact composition depends on the tyre and its application (for trucks, passenger cars or other vehicles). Rubber polymers typically reported are butadiene rubber and/or styrene-butadiene rubber, and natural rubber [55], [56]. The size distribution of particles derived from tyres spans over a wide range [57], [58]. Typically, based on road samples, the mass distribution peaks at 20–100 μm [54], [59]–[61] . A peak in the 2–5 μm range is also found in some studies [57], [58], [62]–[64].

Figure 4. Fate of tyre wear particles in the environment based on [65], [66] with data from [50], [51], [67], [68]



Source: own production

Tyres Contribution to Ambient Particulate Matter (PM)

In general, road transport is responsible for 10-15% of Particulate Matter below 10 μm (PM10) [69]. This percentage can be much higher in cities and near roads [70], [71]. Tyres contribute 5–31% to road transport PM10 (based on the overview table in [70]), which would translate to 0.3% to 4.5% tyres contribution to total PM10. In general, this estimate is in good agreement with field measurements. For example, measurements of airborne concentrations of tyre and road wear particles in urban and rural areas of France, Japan, and the United States found 0.6-22% contribution to PM10 [72]. The annual average mass fraction of tyres in PM10 was 1.8% at an urban background site in Switzerland, but 10.5% at an urban kerbside site [73].

Based on source apportionment studies tyres contribute 5–6% to PM10 in traffic sites and 0.1–0.4% to PM2.5 [74]. An EEA report mentioned 4% contribution to PM10 an 2% contribution to PM2.5 [69]. A review found tyre contribution <10% to total PM10 in most studies [75]. However, the data are sparse, in many cases 20 years old, and most estimates are indirectly calculated with only a few observational studies.

Emissions Factors of Tyre Wear and PM

The tyres wear (abrasion) rate is determined by the difference in the tyre mass before and after driving a specific distance (usually 5,000 – 15,000 km). Recent studies with actual on-road testing reported abrasion rates for passenger cars (expressed per vehicle): 56-86 mg/km for four vehicles, with a fifth one 193 mg/km probably due to wheels misalignment [56], 95-136 mg/km for 100 tyres (scatter 58-171 mg/km) [76], 67 (±20) mg/km for 18 tyres [77]. Another study found normalised factors of 35-126 mg/km/t for 50 tyres [78]. Emission inventories give a value of 57.3 mg/km/t [80]. These values are in agreement with the rough approximation that a 10-15 kg tyre loses 10% of its mass after 50,000 km use, which results in 80-120 mg/km. Emission factors of studies conducted before the year 2000 are summarized elsewhere [56]. Recent emission factors for buses, light commercial vehicles and motorcycles are almost non-existent.

In general, PM10 is assumed to be 2-5% of total tyre wear. PM2.5 is assumed to be 70% of PM10 [74]. The emission factor used in inventories is 5.8-8.7 mg/km for PM10 for motorway and urban driving [81]. One of the latest reviews in 2021 [82] cited similar studies with older reviews in 2014 [57]; the most recent studies cited were published in 2013 for tyre wear. The last review in 2023 [83] included a more recent study of 2020 [62], which reported PM10 2 mg/km, and another recent one [63] ten times lower. Roadside measurements estimated tyre fleet PM10 emissions (from passing vehicles 5% were heavy-duty vehicles) to be 10-11 mg/km [84].

In particular, for electric vehicles, there are no studies on the impact of electrification on tyre emissions. Most studies assume an increase due to the higher weight. This is based on findings that a positive relationship between vehicle weight and non-exhaust emissions exists, especially for PM deriving from dust resuspension [85], [86].

Particle number emission factors are even scarcer. One of the first studies reported values in a range 3.7 to 31×10^{11} particles/km [87]. An on-road study could hardly distinguish them from the background levels and only at 120 km/h a value of to 1×10^{11} particles/km was determined [88]. A recent study found on average emission levels of to 1×10^{10} particles/km [89]. Other researchers reported values between to 1×10^{11} particles/km (for >23 nm) to 15×10^{11} particles/km (for >6 nm) [90]. It should be mentioned that the reported values include road wear and resuspension particles, which can be a significant portion. Furthermore, the reported numbers include both solid and volatile particles. For example, particle number emissions from one tyre, measured in the chassis dynamometer, were 3.3×10^9 particles/km/tyre and $\sim0.6\times10^9$ particles/km/tyre with hot sampling illustrating a strong emission of volatile particles [91]. Higher emissions were observed on the road, due to the influence of background particles.

3.4.3 Oceans

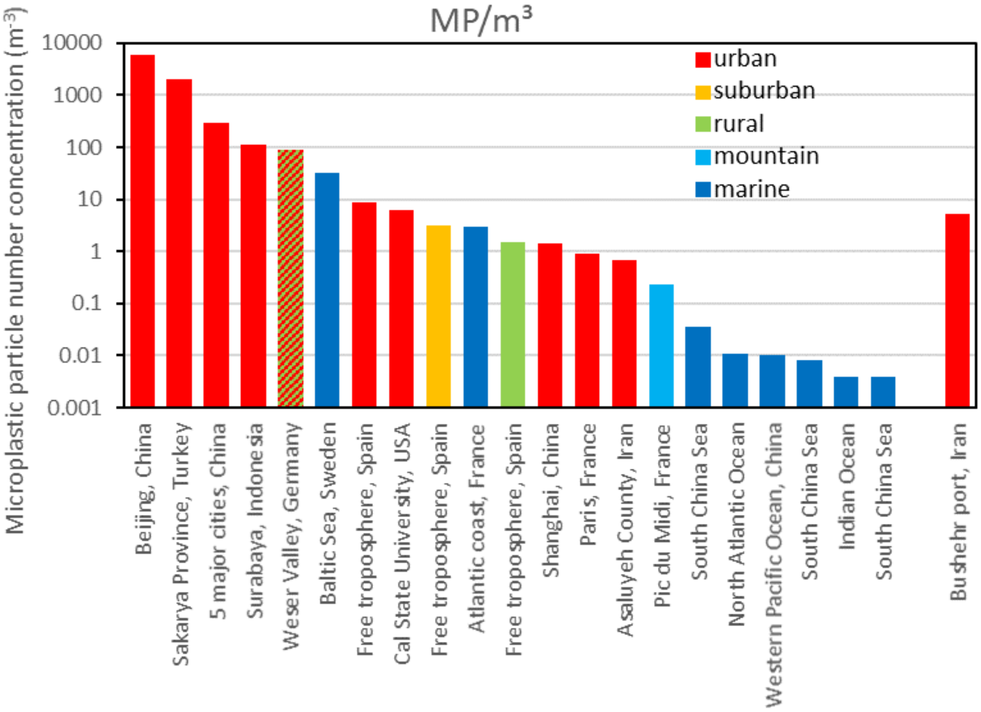
Oceans are known to be a major reservoir/sink of plastic debris with an estimated quantity of 117 to 320 Mt [92]. The greatest proportion of marine plastic waste originates from continental sources and is transported to the beaches and the oceans by rivers, wind or human activities (inland and offshore activities). Given this large plastic reservoir, oceans can be a substantial source of MPs. Depending on size and density of the particles, MP can be carried from the water into the atmosphere. Brahney et al. (2021) estimated that atmospheric MPs in the western United States came mainly from secondary re-emission sources with oceans accounting for 11 % behind the roads (84%) [40]. Evangeliou *et al.* (2022) modelling suggested a prevalence of the ocean MP emissions on the basis of several assumptions [93]. MP emission from ocean can occur through sea spray aerosols via wave action and bubble burst ejection [94], [95]. Allen et al. (2020) determined potential ocean MP emission on the French Atlantic coast by sea spray. The main plastics found were as follows: PE (>50%), PET, PS, PVC, PP corresponding to the most produced plastics [95]. Another study from Caracci et al (2023), assessed the aerosol composition (PM10) in an Atlantic north-south axis (from Vigo (Spain) to Punta Arenas (Chile)) [94]. They support the importance of the sea spray aerosol as a source of airborne MPs and nanoplastics (NPs). The most frequently identified polymers were PE and polyisoprene (PI) [94]. Bubble burst generation under controlled laboratory conditions demonstrated that MP and NPs are aerosolized during wave action via sea spray aerosols [96], [97]. The particle concentration is highly size dependent with a number of particle aerosolized much larger in the smallest size range. Particles with sizes above 10 µm exhibit much less aerosolization [96], [97]. Also, less dense plastics as PE showed a lower aerosolization compared to PS [96].

4 Long-range transport of airborne micro- and nanoplastics

Quantitative measurements of micro- and nanoplastic (MNP)-concentrations in the atmosphere are still limited. However, MNP deposition has been observed and quantified at many remote locations including the Pyrenees [5], the Alps [98]–[101], US conservation areas [102], the Andes [103], the Iranian Plateau [104], the Tibetan Plateau [105], the Arctic [106], [107] and the Antarctic [108]. This suggests that atmospheric transportation (or a combination of atmospheric and marine transportation) of MNP particles is effective, potentially spaying remote sites located up to thousands of km from sources. While seawater could be a significant source of atmospheric MNP particles in coastal areas (via sea spray and bubble burst ejection (section 3.4.3)), MNP deposition at remote continental locations can be attributed to atmospheric transport only. The magnitude of this process indicates that the atmospheric boundary layer contains significant amounts of MNP particles. Factors influencing the motion and concentration of MPs in the atmosphere comprise transport (wind flow and direction), deposition (precipitation, scavenging, and sedimentation) and dispersion (local turbulence) [109]. Modelling shows that MNP transport is very sensitive to the particle size.

In many of these studies, the number of atmospheric MNP particles collected is very limited (a few tens), making the statistics on particle shape and nature less significant. Furthermore, due to differences in sampling and analytical methods applied, the comparability of results is limited. Figure 5 relates the average microplastic particle concentrations to the locations where measurements have been performed. Many atmospheric MNP studies either focus on tyre and brake wear or ignore these particle types and quantify non-elastomer plastic particulates only. This segregation can create a biased perception on the atmospheric concentration and transport of MNP particles.

Figure 5. Number-concentrations of microplastic (MP) particles observed in various environments across the world. Owing to differences in particle collection and analyses, these data are not rigorously comparable. Only the data from Bushehr port possibly include NP particles (< 1 µm)



Source: own production

4.1 Atmospheric concentrations of micro/nanoplastics and their contribution to PM10

In urban areas, MNP number concentrations ranging from 0.7 to 5700 m^{-3} (Figure 5) have been observed (they refer to number concentrations of MP particles with dimensions in the range 2.5 – 500 µm). Microplastic number concentrations are extremely low compared to the total number of particles[1] in the urban atmosphere, which is typically around 10000 cm^{-3} (i.e. 10 billion per cubic meter) [110]. The contribution of MP particles to the total number of particles larger than 500 µm (typically from several tens of thousands to several tens of millions per cubic meter in urban atmosphere) is also most probably very small. However, there is a deep lack of knowledge regarding NP particles (size < 1 µm) since they are currently not efficiently collected and/or detected. Microplastic particles measured in Beijing, China, were mostly in the range 5 – 20 µm [111]. Assuming all these particles sized 10 µm, 5700 MP particles per cubic meter would yield 3 µg m^{-3} PM10 (assuming spherical particles with a density of 1 g cm^{-3}). Assuming a more probable lognormal size distribution as usually observed at polluted locations, these 5700 MP m^{-3} would account for about 0.05 µg m^{-3} PM10 only. As a comparison, the concentration of tyre wear particles in PM10 at an urban background site in Leipzig (DE) was estimated (from Zn measurements) to 0.2 – 0.4 µg m^{-3} [112]. In short, it can be expected that MP particles currently contribute a marginal to insignificant fraction to PM10 mass concentrations in polluted urban air.

There is very little information regarding the air concentration of MNP particles at remote locations where they could end up through atmospheric long-range transport only. One study reports about MP particle measurements performed at 2900 m a.s.l in the Pyrenees (Allen et al., 2021). They measured on average 0.23±0.15 MP m^{-3} in the size range 3.5 µm (limit of quantification in this study) - 20 µm (aerodynamic diameters). This is once more negligible compared to the median number concentration of particles between 3.4 µm and 10 µm measured at this site during the same period (15000 m^{-3}). However, the occurrence of MP in the free troposphere demonstrates the possible atmospheric long-range, trans-continental and trans-oceanic MP transport. Particles observed in the free troposphere were classified as fragments (70%) and fibres (30%). They consisted of PE (44%), PS (18%), PVC (15%), PET (14%) and PP (10%) [5].

4.2 Deposition fluxes

Atmospheric deposition of MNP in inhabited areas is very probably negligible as compared to local production.

At a marine site in the Canadian Arctic, the mean atmospheric deposition flux (rate at which particulate matter is deposited onto a given surface area over a certain period of time) of microparticles was evaluated to be 2400±1200 m^{-2} day^{-1} [113]. Fibres (80%) and fragments (20%) were observed, of which 50% had a "length" less than 800 µm (no particles smaller than 100 µm were detected). Only a quarter of these microparticles could be identified as MP particles, consisting mainly of PET and PP. Owing to the huge size of the MP particles observed, their deposition flux in the Arctic could be similar to or greater than that of black carbon measured at Point Barrow, Utqiaġvik, USA [114] (about 1 mg C m^{-2} day^{-1}), at least at marine locations.

Regarding continental pristine environments, Allen et al. (2019) reported about MP particle deposition measurements performed in the Pyrenees at 1425 m a.s.l. They observed a daily particle deposition of 365 ± 69 $m^{-2}day^{-1}$ from November 2017 to March 2018. Particles were classified as fragments (67%), films (20%) and fibres (12%). 85% of the fragments were smaller than 50 µm, while fibre length was mostly below 900 µm (35% between 200 and 300 µm). Film particle size ranged mainly (>70%) between 50 and 150 µm. Predominant plastics were PS (41%) -as fragments-, PE (32%), PP (18%), PVC (7%) and PET (2%). Fibres were primarily PP and PET. Considering the particle number size distribution determined by Allen et al (2019), and typical film thickness (25 µm) and fibre diameter (12 µm) values, a MP deposition flux of about 150 µg m^{-2} day^{-1} was estimated. For comparison, the deposition flux of soot on the other side of the Pyrenees during the same period at a similar altitude (1200 m a.s.l.) was about 550 µg m^{-2} day^{-1} [115].

In the same area, a temporal archive established by Allen et al. (2021) from the analysis of a peat core sampled in an ombrotrophic peatland (fed solely by atmospheric deposition of nutrients and precipitation) revealed an increase of the MP deposition rate over the last century (from almost zero in the 40's to nearly 200 MPs m^{-2} day^{-1}), in a trend similar to that of the European plastic production and waste management [116].

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[1] As measured with condensation particle counters, which detect all particles bigger than 10 nm.

4.3 Modelling viewpoint

Modelling studies specifically dealing with airborne MNP are still very few, probably because little is known about MNP sources (emission processes, emission rates, particle number size distribution, size-segregated chemical composition...).

MNP emissions would be expected to mainly occur in densely populated areas. However, by analysing the deposition of plastic particles in protected areas of the United States, Brahney et al. [102] state that while urban centres indeed contribute to emissions, also resuspension from soils or water are major sources for wet-deposited MP. In contrast, dry-deposited (and smaller) MP particles could come from longer-range or global transport.

Combining their observations with an atmospheric transport model, Branhey et al. [40] calculated that atmospheric MP in the western USA come primarily from secondary re-emission sources including roads (84%), the ocean (11%), and agricultural soils (dust). This suggests that MNP particles are nowadays ubiquitous in various compartments of the Earth system, and may travel long distances, not only via purely atmospheric transport, but also following deposition / re-mobilisation cycles (the so-called grasshopper effect).

Long-range transport of tyre-wear particles (TWPs) and brake-wear particles (BWPs) was specifically studied by Evangeliou et al [117]. They addressed the PM10 and PM2.5 size fractions, neglecting the MP/NP usual distinction. Direct TWP emissions (no remobilisation) were estimated to range between <0.1 mg m^{-2} yr^{-1} (Arctic, Sahara, Amazonia, Antarctic) and > 100 mg m^{-2} yr^{-1} (eastern USA, Western Europe, China, Japan), while BWP emissions were about 20 times less. Running their model for various particle number size distributions in emissions and assuming that TWPs and BWPs are hydrophobic, they estimated atmospheric global mean concentrations up to 50 ng m^{-3} for both TWP and BWP (in PM10), and maxima (in 0.5° x 0.5° grid cells) of 1.8 and 1.4 µg m^{-3} (in PM10) for TWP and BWP, respectively. TWP was calculated to deposit on lands (65%) and oceans (35%), 10% being deposited on snow and ice. The spatial distribution of BWP deposition was similar (72:28 on lands vs oceans, 14% of the global emissions on snow and ice).

Making use of the measurements by Brahney et al. in the USA, Evangeliou et al. [93] computed source-specific emissions of MPs (5-2500 µm) in western USA and calculated global emissions by extrapolating regional emissions. They estimated that continental emissions of plastic micro-fragments ranged between < 1 mg m^{-2} yr^{-1} (remote areas) to > 20 mg m^{-2} yr^{-1} (e.g. in eastern USA, Europe, India, China), while emissions of micro-fibres range between < 1 mg m^{-2} yr^{-1} (remote areas) to > 100 mg m^{-2} yr^{-1} (e.g. in central Europe, India, China). The most striking feature of their global emission map is the major contribution of oceans to the atmospheric emissions of plastic micro-fragments (up to 50 to 130 mg m^{-2} yr^{-1} from mid latitude oceans in both hemispheres), due to the accumulation of insoluble plastic debris at the sea surface, where they can be re-emitted as sea spray aerosols. These emissions result in global mean surface concentrations of about 3 ng m^{-3} for both plastic micro-fragments and fibres, corresponding to approximately a few items per cubic meter. Deposition was computed to mostly occur near sources due to the limited transport of the large fragments and fibre-sizes considered in this work. Deposition rates up to ca 30 mg m^{-2} yr^{-1} in north-eastern USA, central Europe and north-eastern China, and up to > 100 mg m^{-2} yr^{-1} in mid-latitude oceans (fast sea spray deposition) were estimated for plastic micro-fragments, while values ranging from < 1 mg m^{-2} yr^{-1} on the oceans up to 200 mg m^{-2} yr^{-1} in central Europe, India, and eastern China were estimated for micro-fibres. The comparison of the model outputs with observation data indicates that the model generally underestimated concentrations (mean bias = -57%) and overestimated deposition rates (+39%). This is probably due to the fact that NP particles were not considered, while e.g., Ter Halle [118] detected plastic particles mostly in the 150 – 500 nm range in the colloidal fraction of surface seawater collected in the Atlantic Ocean.

Confronting the results of these various modelling studies shows that MP emission rates, atmospheric concentrations, transport and deposition are very sensitive to the size distribution and shape of MP particles emitted. NP can undoubtedly be transported over much larger distances in the atmosphere. However, NP are generally not detected in field studies, making it quite impossible to check models performance levels regarding this size fraction.

5 Practices for sampling and analysing microplastics in air

In order to get an overview about the knowledge base regarding currently used approaches for sampling, sample preparation, detection and quantification of microplastics in air, a systematic examination of the scientific literature was conducted. Besides air, including ambient (outdoor) and indoor air, also deposition, and dust matrices were considered.

The methodology used for the literature search and its outcome are described in the following section (5.1) while the findings on analytical approaches are summarised in sections 5.2 - 5.6.

5.1 Literature review methodology

Conventional search tools such as Scopus, Science Direct, PubMed, and Google Scholar (section 5.1.1) were employed, as well as the "Tool for Innovation Monitoring (TIM Analytics)" developed by JRC (section 5.1.2).

Throughout the screening process, the primary focus was placed on evaluating the methodologies employed in each study for sampling, sample preparation, and detection of microplastics. By adopting this approach, the goal was to gather reliable and relevant information from the selected publications.

5.1.1 Analysis of the existing literature following the PRISMA methodology

The systematic literature review was conducted based on a simplified version of the 'Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)' methodology [119].

A systematic review is a review of a clearly formulated question that uses systematic review and explicit methods to identify, select and critically appraise relevant research and to collect and analyse data from the studies that are included in the review.

Systematic reviews are essential tools for summarising evidence accurately and reliably [120]. Systematic reviews should be reported fully and transparently to allow readers to assess the strengths and weaknesses of the investigation [121].

5.1.1.1 Definition of the parameters upon which the systematic review was based

Table 5 includes the parameters that have been used for the systematic literature search.

Table 5. Definition of the parameters upon which the systematic review was based

Parameter	Value
Research question	The objective of this systematic review is to identify and analyse published scientific information pertaining to the measurement and detection of plastic particles, both in nano- and microscale, present in the air. This review will specifically focus on sources that provide comprehensive details regarding the sampling methodology employed, the analysis techniques utilized, and the quantification of plastic concentrations in the air.
Searched databases	Scopus, Science Direct, PubMed and Google Scholar
Source type	Journals, books, conference proceedings
Location of keywords (search terms)	Article title, abstracts, and keywords
Languages	Limited to English
Search period	2010 – May 2023

Source: own production

5.1.1.2 Search terms and hits

A summary of the search results obtained with the approach described in Table 5, applying two to ten different search terms depending on the database, is provided in Table 6. It presents the total number of hits generated, along with the number of hits that were subsequently selected for further analysis.

Table 6. Number of hits for each database and search term

figr	Scopus			
Search Term	“Plastic particles” AND “air”	“Microplastics” AND “air”	“Nanoplastic” AND “air”	“plastic” AND “inhalation”
Total Hits/Selected for further analysis	92/14	532/80	85/13	273/35
Search Term	“nanoplastic” AND “inhalation”	“microplastic” AND “inhalation”	“plastic” AND “indoor air”	“plastic” AND “outdoor air”
Total Hits/Selected for further analysis	37/5	130/27	361/10	67/15
Search Term	“plastic analysis” AND “air”	“plastic measurements” AND “air”		
Total Hits/Selected for further analysis	23/0	25/0		
	Science Direct			
Search Term	“Microplastic” AND “air”	“Nanoplastic” AND “air”		
Total Hits/Selected for further analysis	290/78	56/14		
	PubMed			
Search Term	“Microplastic” AND “air”	“Nanoplastic” AND “air”	“Airborne” AND “plastic”	
Total Hits/Selected for further analysis	358/86	67/15	153/19	
	Google Scholar			
Search Term	“Microplastic” AND “air”	“Nanoplastic” AND “air”		
Total Hits/Selected for further analysis	Selection not possible due to too many hits (> 5000)	Selection not possible due to too many hits (> 5000)		

Source: own production

5.1.1.3 General comments

Scopus and Science Direct databases have very powerful filtering engines and provided similar hits.

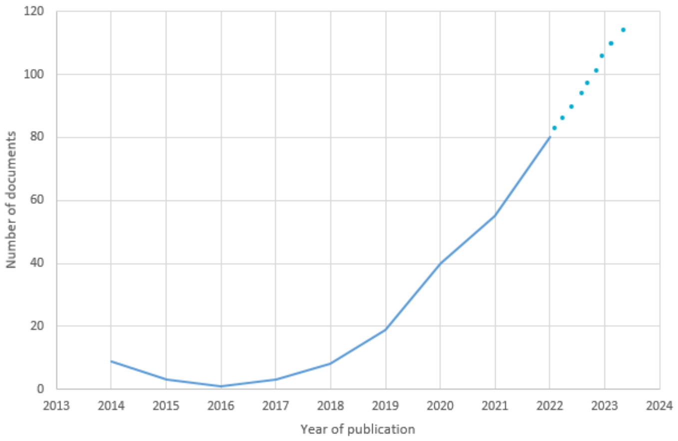
PubMed and Google Scholar listed a few papers that were not detected by Scopus and Science Direct. Due to the very high number of hits obtained with Google Scholar, no detailed analyses was possible.

A total of 251 potentially relevant documents were detected in total. The complete list can be found in annex 1.

Basic statistics on the identified and selected documents

From Figure 6 it clearly appears that the research on plastic particles in air has started becoming of higher interest to the scientific community from 2019 onwards and can therefore be considered as a relatively new field of research.

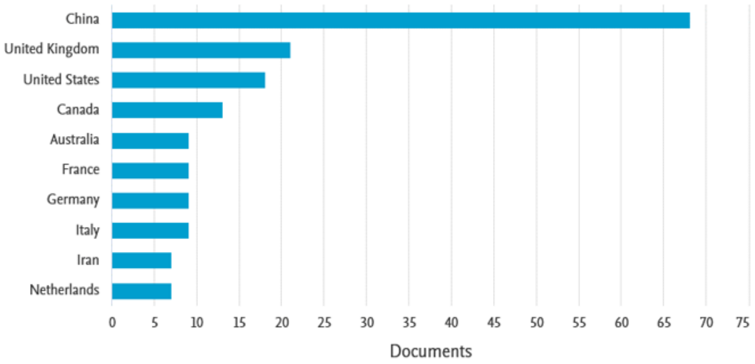
Figure 6. Number of documents (journals, books, conference proceedings) by year.



Source: own production

Figure 7 illustrates the geographic distribution of institutions responsible (authors and co-authors) for publishing the identified studies. Notably, China emerges as the leading country with the highest number of contributions in this scientific field, followed by several Anglophone nations (UK, USA, Canada, and Australia) and a selection of EU countries.

Figure 7. Number of documents by geographical origin



Source: own production

5.1.2 Identification and analysis of the existing literature using TIM Analytics

The Tool for Innovation Monitoring (TIM Analytics, http://www.timanalytics.eu/) is a series of analytics tools developed by the Joint Research Centre to interpret vast and intricate datasets with policy relevance. It can be tailored to support different stages of EU policy-making across various domains, such as impact evaluation, detecting emerging technological trends, or gaining insights into regional innovation. This is achieved by linking datasets of semi-structured data together to build domains of information relevant for policy. Once linked, TIM processes the data using text mining techniques to build an index for each data item containing all the fields and their values, enriched with additional data generated by TIM using semantic extraction techniques or clustering algorithms, for example. Users can query this index to build subsets of data that are then visualised through various types of graphs.

The TIM suite includes three tools that extract information from news, patents, scientific publications, and EU-funded R&D projects and relies on data from the following databases: Scopus, European Patent Office, and CORDIS.

A query with the following string was conducted:

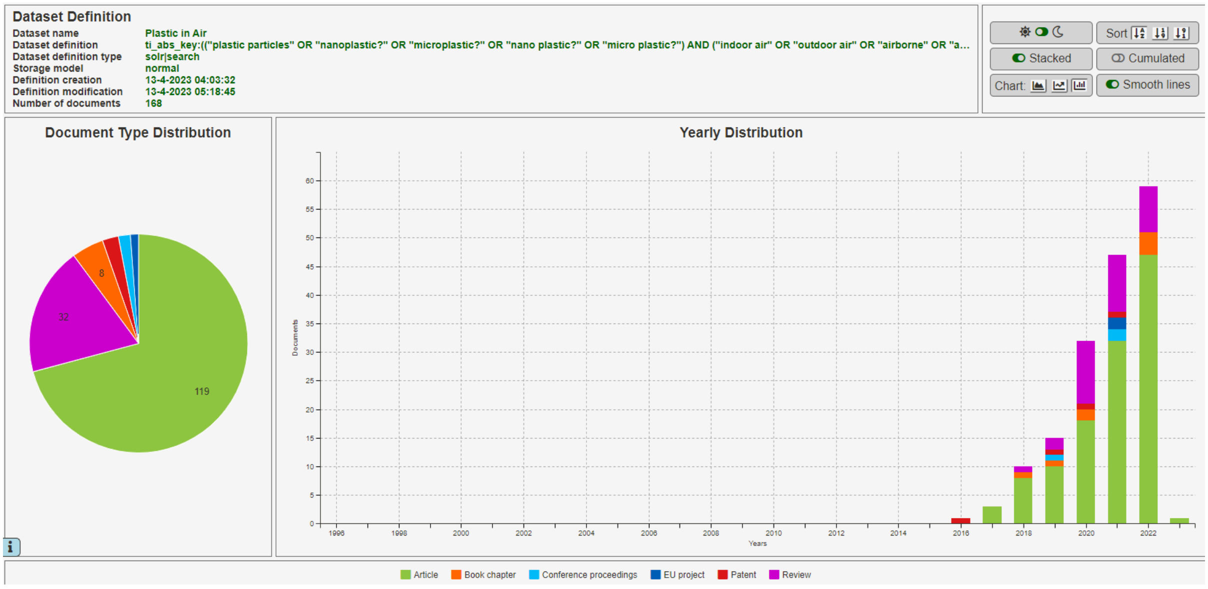
```
Query :
 ti_abs_key:(("plastic particles" OR "nanoplastic?" OR "microplastic?" OR
"nano plastic?" OR "micro plastic?") AND ("indoor air" OR "outdoor air" OR
"airborne" OR "atmospher?")) AND emm_year:[2013 TO 2023]
```

Explanation of the fields included in the query:
Ti_abs_key: Documents containing the searched terms in the title or in the abstract or in the author keywords are retrieved
emm_year: Time frame in which documents are retrieved [year TO year]

Using this specific query string, 168 relevant documents were identified.

Figure 8 illustrates the number and quota of relevant articles, book chapters, conference proceedings, patents, EU projects, and reviews published since 1996 (status May 2023). According to this analysis, the majority of research on micro- and nanoparticles in air was conducted from 2018 onwards, which aligns with the findings of the structured literature research described above (see Figure 6). The pink part of each bar represents the number of published review studies. These review studies make up a significant portion of the total documents and possibly indicate the interest of numerous research groups in the topic.

Figure 8. Relevant articles (green), book chapters (orange), conference proceedings (light blue), patents (red), EU projects (dark blue) and reviews (pink) published since 1996 detected with TIM Analytics



Dataset Definition

Dataset name	Plastic in Air
Dataset definition	ti_abs_key:(("plastic particles" OR "nanoplastic?" OR "microplastic?" OR "nano plastic?" OR "micro plastic?") AND ("indoor air" OR "outdoor air" OR "airborne" OR "a...
Dataset definition type	solr|search
Storage model	normal
Definition creation	13-4-2023 04:03:32
Definition modification	13-4-2023 05:18:45
Number of documents	168

Source: own production

TIM Analytics provides versatile ways to analyse selected documents, including:

Networks of collaboration

a) Organisations

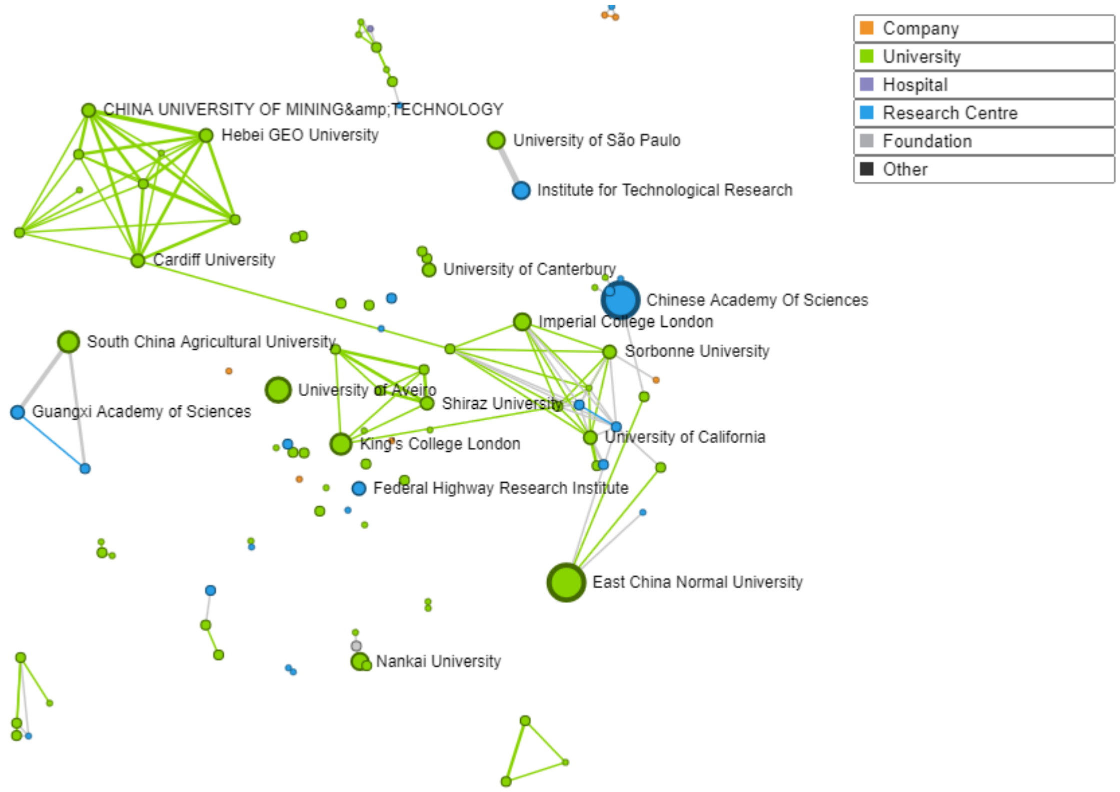
Organisations refer to institutions or companies affiliated with authors of scientific publications, applicants of patents, or beneficiaries of EU Framework program grants.

These graphs (Figure 9), also known as sociograms, depict the "social network" of organisations. Each node represents an organisation, and the links between nodes signify collaboration between two organisations. These collaborations could involve co-publishing, co-patenting, or co-granting of EU projects. The thickness of the node indicates the intensity of collaboration, measured by the number of common documents.

Groups of organisations sharing the same colour tend to collaborate more among themselves than with others, forming distinct communities of nodes.

These graphs allow the study of collaboration patterns among organisations engaged in publishing, patenting, or EU-funded projects.

Figure 9. Collaboration between organisations in the field of nano- microplastics in air



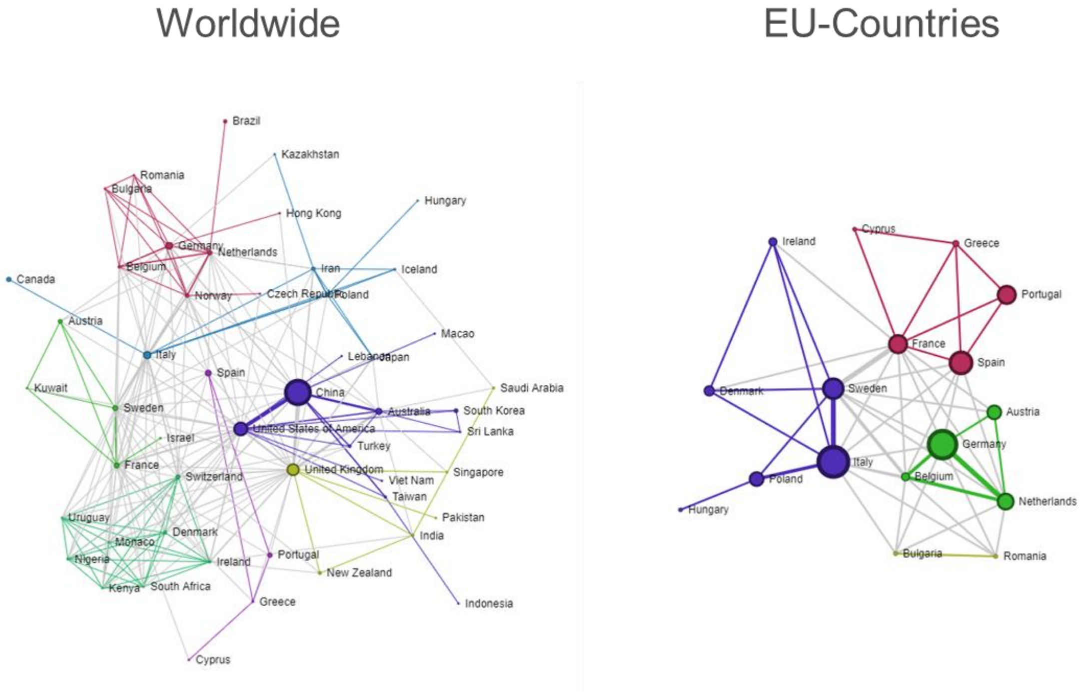
Source: own production

The sociogram highlights that a significant number of studies focusing on microplastics in air are being conducted by Chinese institutions, notably The East China Normal University and the Chinese Academy of Sciences. In Europe, active institutions in this area include Sorbonne University in France, Imperial College and King's College in London, Cardiff University, and the University of Aveiro. Notably, the University of California in the USA demonstrates collaboration with both Chinese and European institutions.

b) Countries

In this type of graph, each node represents a country, and the links between nodes signify collaboration between two organisations located in different countries. Similar to organisation graphs, these links correspond to co-publishing, co-patenting, or co-granting of EU projects across different geographical locations (Figure 10). The thickness of the node indicates the intensity of collaboration, measured by the number of common documents. Groups of countries sharing the same colour suggest a higher tendency to collaborate among themselves than with others.

Figure 10. Collaboration between two organisations located in different countries (left: Worldwide, right: EU-countries) in the field of nano- microplastics in air



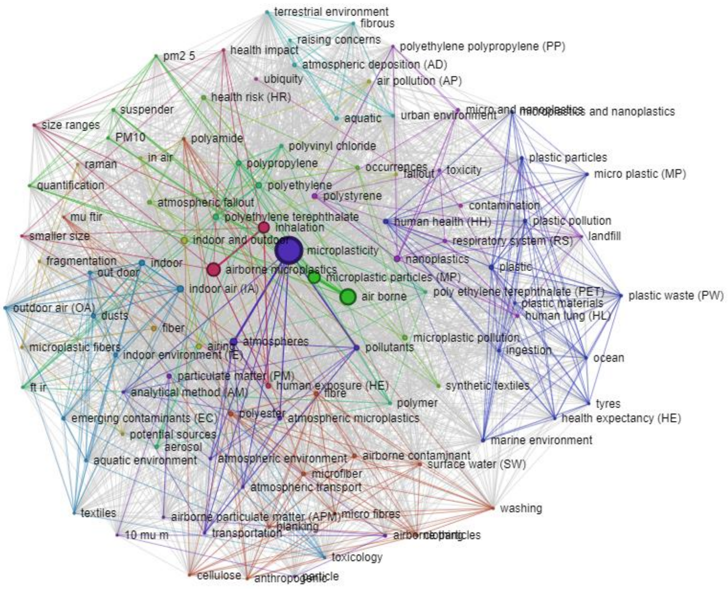
Source: own production

c) Keywords

“Keywordgrams” provide visualisations of the keywords attributed to the documents (Figure 11). These keywords can be sourced directly from the documents or calculated by TIM using text processing algorithms. In a keyword graph, each node represents a keyword.

The link between two keywords indicates that at least one document contains both keywords. The thickness of the node reflects the number of documents containing that specific keyword.

Figure 11. Keywords attributed to the documents identified as being relevant for nano- and microplastic analysis in air



Source: own production

5.1.3 Relevant Standards/Guidances

Microplastics analysis, in particular in air, is a relatively new field compared to other areas of environmental analysis and although the number of scientific publications has increased in the last years, the lack of consistent methods, protocols, and criteria for the detection, measurement, and analysis of microplastic particles present in the air, hinders the comparability of results. Standardisation helps to ensure that measurements are accurate and comparable across different studies.

Standardisation in this field involves several aspects, including sample collection, sample processing, identification, and quantification of microplastics. The following are some key elements of standardisation in microplastic air analysis:

1. Sampling: Standardisation involves developing guidelines for selecting appropriate sampling locations, the duration of sampling, and the volume of air to be collected. It may also include recommendations on sampling equipment and the use of blank samples for quality control.

2. Sample processing: Standardised protocols specify how air samples should be processed to extract/concentrate particulate matter, e.g. by filtration, and to separate from these microplastic particles. This latter may involve, for example, digestion or separation techniques.

3. Identification: Standardisation includes the use of consistent methods for identifying microplastics. This may involve visual identification using microscopy, spectroscopic analysis, or the use of specialized techniques like Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy or thermo-analytical techniques such as pyrolysis GC-MS.

4. Quantification: Standardised procedures are also needed for quantifying the total abundance or concentration of microplastics in air samples. This may involve counting the number of particles, measuring their size, or estimating their mass.

5. Quality control: Standardisation involves implementing quality control measures to ensure the reliability and accuracy of data. This may include the analysis of replicates, the use of reference materials, blank samples, and participation at inter-laboratory comparisons to validate analytical methods and assess measurement uncertainties.

European and International Standardisation Organisations, such as CEN at European level and ISO at worldwide level, play a crucial role in establishing standards that enhance the comparability of measurement results and reduce technical barriers to trade, thereby facilitating the smooth functioning of the Single European Market. Through the Vienna Agreement, ISO and CEN optimise the utilization of resources in standardisation efforts by exchanging information, promoting transparency of CEN's activities to ISO members, and avoiding duplication of standardisation work.

The Organisation for Economic Co-operation and Development (OECD) develops and publishes a set of guidelines known as OECD test guidelines. These internationally recognized and standardised methods are designed for testing the safety and environmental impact of chemicals, products, and substances. Covering diverse areas such as toxicology, ecotoxicology, environmental fate and behaviour, and physical-chemical properties, these guidelines offer detailed instructions on conducting experiments or studies to evaluate potential hazards and risks associated with various substances. Regulatory authorities, industry players, and research institutions rely on these guidelines to generate data concerning the safety and environmental properties of chemicals and products. The application of these guidelines facilitates the assessment of chemical substances for regulatory purposes, including registration, classification, and risk assessment.

While both OECD and ISO are international organisations, the OECD concentrates on policy analysis and recommendations to promote economic growth and wellbeing, while ISO is primarily involved in the development and publication of international standards to ensure consistency and quality in different areas.

To ensure access to the latest information regarding relevant standards and guidelines pertaining to microplastics in air, thorough examination has been conducted on the websites of the aforementioned organisations (Table 7):

Table 7. Standardisation bodies and their corresponding websites

Standardisation Body	Website(s)
European Committee for Standardization (CEN/CENELEC)	https://www.cencenelec.eu/about-cen/
International Organization for Standardization (ISO)	https://www.iso.org/standards.html https://www.iso.org/standards-catalogue/browse-by-tc.html
Organisation for Economic Co-operation and Development (OECD)	https://www.oecd.org/chemicalsafety/, and in particular the test guideline program https://www.oecd.org/chemicalsafety/testing/oecd-guidelines-testing-chemicals-related-documents.htm and its section 1 related to the physical and chemical characterization https://www.oecd-ilibrary.org/environment/oecd-guidelines-for-the-testing-of-chemicals-section-1-physical-chemical-properties_20745753

Source: own production

To broaden the scope of the review and explore related aspects that may be relevant to the study of microplastics in air, additional search terms and areas were considered. This involved examining technical committees within ISO and CEN, as well as the OECD test guidelines. The following specific areas were deemed of interest: plastics, air (both indoor and outdoor), rubber and rubber products, reference materials, and construction products (particularly emissions of dangerous substances). Although many of the standards retrieved primarily focus on the measurement and analysis of particulate matter (PM) in the air rather than specifically targeting microplastic particles, these standards provide essential guidance and methodologies for sampling particles in air, which can be adapted for the sampling and analysis of microplastics in the future.

A summary of the relevant information gathered is provided below in a tabulated format (Table 8).

Table 8. ISO/CEN documents and an OECD test guidelines directly or indirectly relevant for micro/nano plastic analysis

Domain	Document	Abstract
CEN Standards		
Ambient Air	CEN EN 12341:2023 Ambient air - Standard gravimetric measurement method for the determination of the PM10 or PM2,5 mass concentration of suspended particulate matter	This European Standard describes a standard method for determining the PM10 or PM2,5 mass concentrations of suspended particulate matter in ambient air by sampling the particulate matter on filters and weighing them by means of a balance.
Ambient Air	CEN EN 14907:2005 - Ambient Air Quality - Standard Gravimetric Measurement Method for the Determination of the PM2.5 Mass Fraction of Suspended Particulate Matter	This European Standard describes a standard method for determining the PM2,5 mass concentration of suspended particulate matter in ambient air by sampling the particulate matter on filters and weighing them by means of a balance.
ISO Standards		
Microplastic from textiles	ISO 4484-2:2023: Microplastics from textiles sources. Part 2: Qualitative and Quantitative analysis of microplastics	This standard deals with the qualitative and quantitative analysis of microplastics (from the textile sector) to define the morphology, polymer type, particle number, dimensional distribution , and express the results in terms of estimated surface area and mass of microplastics per unit of sample. It applies to the analysis of microplastics in different samples

Domain	Document	Abstract
		(including air samples) related to the production, processing, treatment and use of textiles.
Microplastics	ISO 24187:2023: Principles for the analysis of microplastics present in the environment.	This standard that specifies minimum requirements as basis for future specific norms. It includes unique particle-size classification of plastics, use of certain apparatus for sampling, sample preparation and determination of representative sample quantities. It does not include requirements for monitoring actions.
Indoor air	ISO 16000-27:2014 Indoor air - Part 27: Determination of settled fibrous dust on surfaces by SEM (scanning electron microscopy) (direct method)	ISO 16000-27:2014 specifies a method giving an index for the numerical concentration of fibrous structures with fibres equal or greater than 0,2 µm in diameter in settled dust on surfaces and their classification into specific substance groups (e.g. chrysotile, amphibole asbestos, other inorganic fibres). It is primarily applicable to indoor areas, but it is also suitable for certain outdoor situations. A sampling technique for collection of settled dust using adhesive tape is described. The method incorporates an analytical method for evaluation of the collected samples by scanning electron microscopy. The result can be specified in asbestos structures per unit area and/or classified into four different loading classes. The analytical sensitivity depends on the area examined and can be as low as 10 structures/cm2.
Indoor air	ISO 16000-34:2018 Indoor Air - Part 34: Strategies for the measurement of airborne particles	This document specifies the general strategies for determining the concentration of airborne particles indoors and covers the size range from approximately 1 nm to 100 µm. In addition, this document describes methods for identifying typical indoor particle sources and gives general recommendations for obtaining a representative sample. The main sources of indoor particulate matter are described in this document, together with indoor particle dynamics. Various measurement methods are described, along with their advantages, disadvantages and areas of application, as well as some general sampling recommendations. Measurement strategies for determining airborne particles indoors are discussed, including reference case studies with more specific sampling recommendations.
Indoor air	ISO 16000-37:2019 Indoor Air - Part 37: Measurement of PM2,5 mass concentration	This document specifies the measurement methods and strategies for determining the PM2,5 mass concentrations of suspended particulate matter (PM) in indoor air. It can also be used for determining PM10 mass concentration. The reference method principle consists of collecting PM2,5 on a filter after separation of the particles by an impaction head and weighing them by means of a balance. Measurement procedure and main requirements are similar to the conditions specified in EN 12341.
Plastics	ISO/TR 21960:2020: Plastics — Environmental aspects — State of knowledge and methodologies	This document summarizes current scientific literature on the occurrence of macroplastics and microplastics, in the environment and biota. It gives an overview of testing methods, including sampling from various environmental matrix, sample preparation and analysis. Further, chemical and physical testing methods for the identification and quantification of plastics are described. This document gives recommendations for three steps necessary for the standardisation of methods towards harmonized procedures for sampling, sample preparation and analysis.
Rubber and rubber products	ISO/TS 21396:2017 Rubber - Determination of mass concentration of tire and road wear particles (TRWP) in soil and sediments Pyrolysis-GC/MS method	This document specifies a method for the determination of the soil or sediment mass concentration (µg/g) of tyre and road wear particles (TRWP) in environmental samples. It establishes principles for soil or sediment sample collection, the generation of pyrolysis fragments from the sample, and the quantification of the generated polymer fragments. The quantified polymer mass is used to calculate the concentration of TRWP in soil or sediment. These quantities are expressed on a TRWP basis, which includes the mass of tyre tread and mass of road wear encrustations, and can also be expressed on a tyre rubber polymer or tyre tread basis.
Rubber and rubber products	ISO 7270-1:2020 Rubber - Analysis by pyrolytic gas-chromatographic methods Part 1: Identification of polymers (single polymers and polymer blends)	This document specifies a method for the identification of polymers, or blends of polymers, in raw rubbers and in vulcanized or unvulcanised compounds from pyrograms (pyrolysis-gas chromatographic patterns) obtained under the same conditions. This document is not intended for quantitative analysis. The method applies first and foremost to single polymers. When the pyrogram indicates a characteristic hydrocarbon, the method is also

Domain	Document	Abstract
		applicable to blends. The method can be also applicable to other types of polymer when verified by the analyst in each particular case.
Rubber and rubber products	ISO/DIS 22638 (DRAFT) Generation and collection of tyre and road wear particles (TRWP) Road simulator laboratory method	This document specifies a method for the generation of tyre and road wear particles (TRWP) in a road simulator laboratory that is representative of actual driving conditions. Guidance is provided for the road simulator system, test pavement and tyres, vacuum collection system, monitoring, and reporting. This method is applicable for the collection of TRWP from a known pavement and tyre type under realistic driving conditions without the inference of road surface contaminants (i.e. brake dust, exhaust, grease, etc.).
Air Quality	ISO 7708:1995 Air quality Particle size fraction definitions for health-related sampling	Defines sampling conventions for particle size fractions for use in assessing possible health effects of airborne particles in the workplace and ambient environment. Defines conventions for the inhalable, thoracic and respirable fractions; extrathoracic and tracheobronchial conventions may be calculated from the defined conventions. The conventions should not be used in association with limit values defined in other terms, for example for limit values of fibres defined in terms of their length and diameter.
Plastics	ISO/DIS 6775 (DRAFT) Plastics — Plastics identification using Raman spectrometric methods	This document is applicable to the qualitative analysis of plastic materials in their original form by Raman spectroscopy. It describes procedures to determine the composition of unknown general plastics and multi-layer film plastics.
Reference materials	ISO Guide 33:2015 Reference materials - Good practice in using reference materials	ISO Guide 33:2015 describes good practice in using reference materials (RMs), and certified reference materials (CRMs) in particular, in measurement processes. These uses include the assessment of precision and trueness of measurement methods, quality control, assigning values to materials, calibration, and the establishment of conventional scales.
Reference Materials	ISO Guide 80:2014 Reference materials - Guidance for the in-house preparation of quality control materials (QCMs)	ISO Guide 80 outlines the essential characteristics of reference materials for quality control (QC) purposes, and describes the processes by which they can be prepared by competent staff within the facility in which they will be used (i.e. where instability due to transportation conditions is avoided). The content of this Guide also applies to inherently stable materials, which can be transported to other locations without risk of any significant change in the property values of interest.
OECD Test Guidelines		
Size and size distribution of nanomaterials	Test No. 125: Nanomaterial Particle Size and Size Distribution of Nanomaterials	This Test Guideline, covering nanomaterials spanning from 1 nm to 1000 nm, is intended for particle size and particle size distribution measurements of nanomaterials. The TG includes the following methods: Atomic Force Microscopy (AFM), Centrifugal Liquid Sedimentation (CLS)/Analytical Ultracentrifugation (AUC), Dynamic Light Scattering (DLS), Differential Mobility Analysis System (DMAS), (Nano)Particle Tracking Analysis (PTA/NTA), Small Angle X-Ray Scattering (SAXS), Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM).

Source: own production

5.2 Outcome of structured literature review

The systematic literature review in section 5.1 yielded approximately 250 articles, which were subsequently screened for their specific relevance to the objectives of this study. The screening process involved reviewing the abstracts, the methodological, and the results sections of each article. Table 9 presents the studies that, based on our judgment, were deemed most relevant. As one of the primary aims of this study was to review existing analytical methods for determining suspended micro- and nanoplastics, the majority of papers listed in the table pertain to methods based on active sampling.

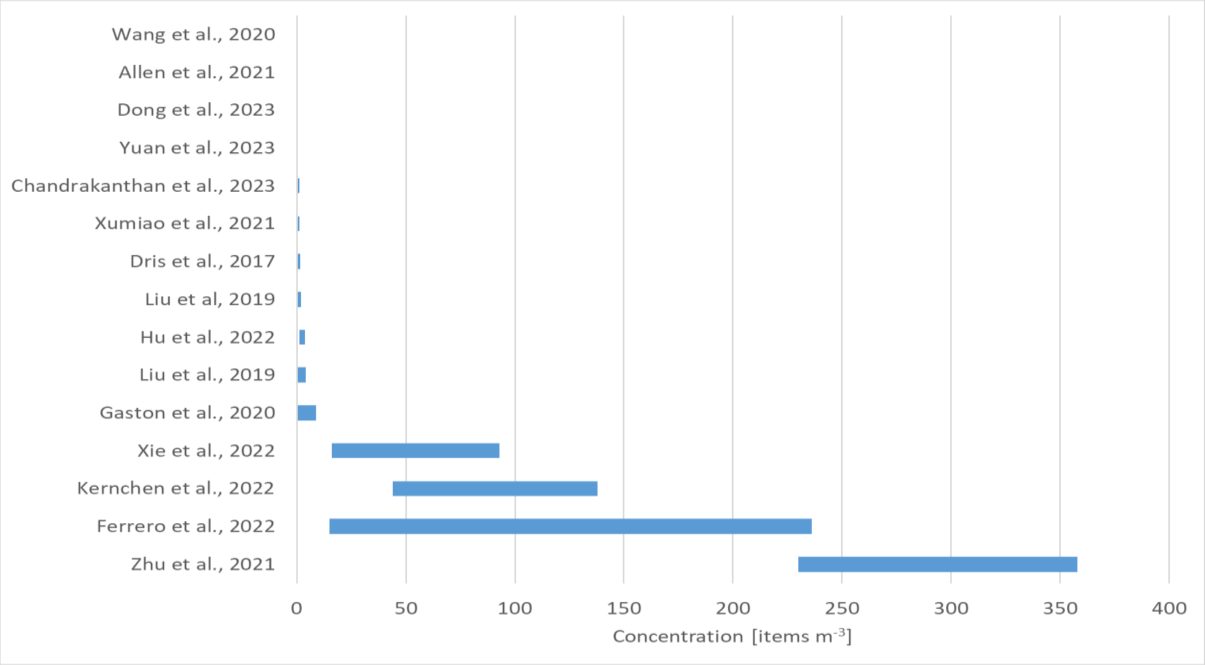
A key observation across all studies is their successful detection and measurement of plastic particles in the air. The concentration, size, composition, and shape of these particles varied depending on the study area, microenvironment of sample collection, and methodological approach (sampling, sample preparation, and analysis).

A notable finding concerns the shape of detected particles. While some studies mainly reported fibres, others primarily detected fragments. In Table 9, studies focusing on fibres were commonly associated with deposition samples or indoor locations, possibly due to typical indoor sources such as textiles and the relatively larger size of fibres, resulting in faster deposition rates. Conversely, studies focusing on fragment-shaped particles were more prevalent in large cities.

In terms of polymer types, not all studies in Table 9 distinguished between fibre and fragment shapes. However, those that did, revealed dominant polymer types for fibres, including natural cellulose (NC), polyamide (PA), polyethylene terephthalate (PET), Rayon, polyethylene, polyacrylonitrile (PAN), and polysulfone (PES). For sampled fragments, the dominant polymer types were polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), polysulfone (PES), polyvinylchloride (PVC), polyamide (PA), polycarbonate, and polyacrylonitrile (PAN). These patterns roughly correlate with their respective global production tonnages.

Figures 12-14 display the concentration ranges reported in the studies listed in Table 9 for outdoor air, indoor air, and deposition samples. Figure 12 reveals that in most studies, outdoor concentration ranges were below 10 items per cubic meter (items/m³). However, a few studies detected substantially higher concentrations above 100 items/m³. Notably, two of these studies conducted sampling in large Chinese cities.

Figure 12. Concentration ranges of plastic particles - outdoors[2]



Source: own production

Figure 13 illustrates the reported particle concentrations in indoor environments. In contrast to the wider concentration ranges seen in ambient air samples, indoor air samples exhibit shorter concentration spans. However, the limited number of studies hinders a robust statistical evaluation.

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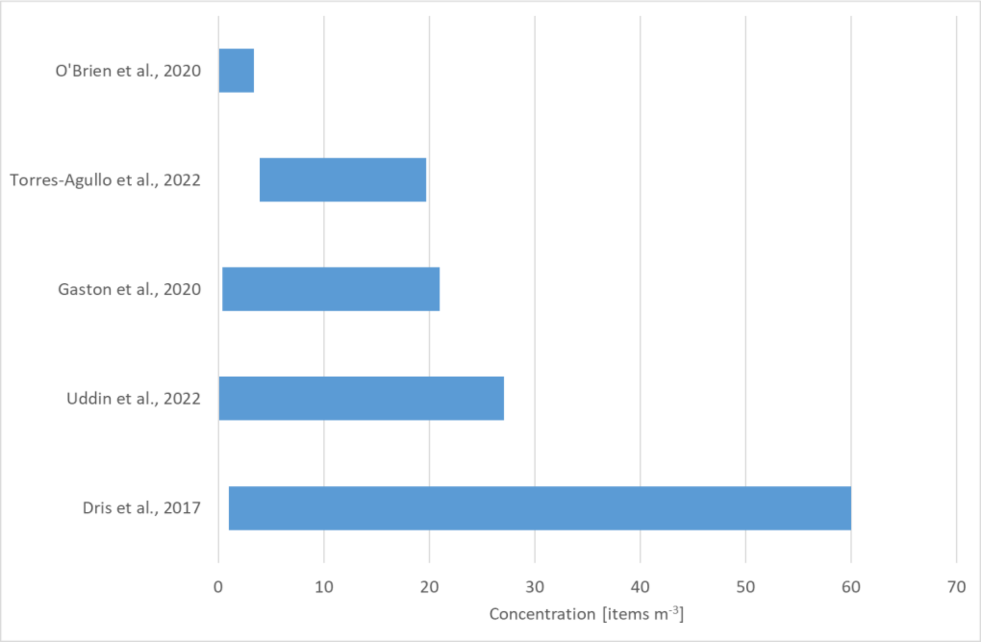
[2] Please note that the differences in the range of concentrations shown in Figure 12 and Figure 5 are due to the utilisation of different data sources for data analysis.

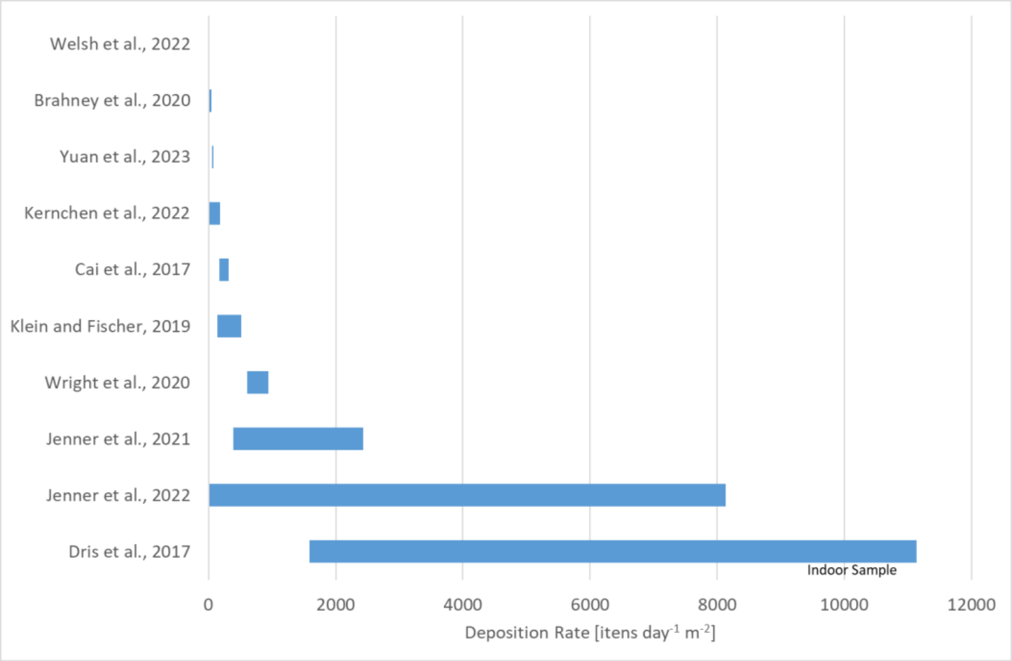
Figure 13. Concentration ranges of plastic particles - indoors



Source: own production

Figure 14 presents the deposition ranges reported in the studies listed in Table 9. Please note that all reported ranges pertain to ambient samples, except for the range reported in the study by Dris et al. [12], which refers to indoor samples.

Figure 14. Concentration ranges of plastic particles – deposition samples



Source: own production

The subsequent sections delve into the discussion of sampling methods, sample preparation techniques, and analytical approaches employed for measuring plastic particles.

Table 9. Collection of the principal identified studies

Study title and reference	Study area and microenvironment(s)	Matrix **[Dust, TPM, …]**	Sampling Method Sampled volume/Sampling duration	Analysis Method Identification process	Dominant shapes	Size-Range [µm]	Dominant polymer type	Concentration
A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Dris et al, 2017 [4]	France, Paris Three different indoor sites: two private apartments and one office. In parallel, outdoor air was sampled in one site. The deposition rate of the fibres and their concentration in settled dust collected from vacuum cleaner bags were also estimated.	TSP, deposition, settled dust from vacuum cleaner bag	Pump, 8 L/min of indoor air on quartz fiber GF/A Whatman filters (1.6 µm, 47 mm), V= 2-5 m^3 Passive sampling of dust fall to estimate the deposition rate of fibres. Quartz fibre GF/A Whatman filters (1.6 µm, 47 mm) were exposed once per season at each of the locations. Passive sampling at 1.2 m height. Duration varied between 4 and 15 days.	Counted with stereomicroscope and identified by µFTIR	Looked only at fibres	50-2500 Most frequent 50-450	Natural (cellulose): 67% Petrochemical derived: 33% (PP predominant)	Indoors: 1-60 fibres/m^3 Outdoors: 0.3-1.5 fibres/m^3 Deposition rate indoors 1586 - 11,130 fibres/day/m^2
A Flow-through Passive Sampler for Microplastics in Air, Dong et al., 2023 [6]	Oudoors on Lhasa campus of the Institute of Tibetan Plateau Research	TSP	Sampling with novel passive sampler and comparison with active sampling Active sampling: 100 L/min, V=5-594 m^3	Focal plane microscope for morphology, size and colour Polymer type identification with micro-FTIR	Fibres 44-54 % Film 22-25 % Fragments 18-33 % Foam 1-3 %	10-100: 24-40% 100-300: 23-31% 300-1000: 27-33% 1000-2000: 7-10%	Cellophane 49-58 % PES 10-16 % PA 13-17 % PE 3-5 % PP 4-6 %	Average: 0.15-0.25 items/m^3
Plastic rain in protected areas of the United States, Brahney et al., 2020 [102]	Conservation areas of the United States	Deposition	Both wet atmospheric deposition, collected at week-long intervals while precipitation occurred, and dry atmospheric deposition, collected at monthly or bimonthly intervals	FTIR spectroscopy particle mapping in reflection mode	Microfibres: 70% (cotton, polyester, nylon) Particles: 30%	Paticles: 4-188 µm Fibres: 20-3000 (width 18)	Particles: PE, PP, polyvinylacetate	Deposition rates: Around 50 plastics/m^2/day
Evidence of free tropospheric and long-range transport of microplastic at Pic du Midi Observatory, Allen et al., 2021 [5]	France, Alps, Pic du Midi (high altitude long-term monitoring station)	PM$_{10}$	PM10 sampler, quartz fibre filter membrane. Samples were collected over an average of 8 days, V=7880 m^3 per sample	µRaman (each filter was analysed for total plastic presence). Filters were analysed using the cross-section analysis method.	Fragments: 51% Fibres: 49%	Particles: <20 Fibres: < 30	HDPE 44% PS 18% PVC 15% PET 14% PP10% Mix in both fibres and fragments	Average 0.23 MP/m^3
Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source, Wang et al., 2020 [122]	China, South Sea Suspended atmospheric particles collected during a cruise in 2019	TSP	Flow rate: 100 L/min; V= 53-259 m^3 of air	Stereomicroscope for shape and colour The sizes of particles were measured by the ImageJ software Identification: Micro Fourier Transform Infrared Spectrometer in transmission mode	Fibres: 80% Fragments: 20%	58-1800	PET, PP, PA, PEP, PAN-AA, PR, PEVA	0-7.7 items/100m^3 air
A novel application of thermogravimetry mass spectrometry for polystyrene quantification in the PM10 and PM2.5 fractions of airborne microplastics, Costa-Gomez, 2023 [123]	Spain, Agricultural area (Cartagena)	PM$_{10}$, PM$_{2.5}$	PS-MP samplings were performed with 150 mm diameter fiberglass filters PM10 and PM2.5 inlets Sampling time: 24h, flow-rate: 30m^3/h, V=720 m^3	Thermogravimetric analysis coupled with mass spectrometry	ND	ND	Study limited to analysis of PS	Mean concentrations of polystyrene found in the PM10 and PM2.5 fractions were 2.09 and 1.81 ng m^{-3}
A Preliminary Assessment of Size-Fractionated Microplastics in Indoor Aerosol—Kuwait's Baseline, Uddin et al., 2022 [33]	Kuwait, indoor environments	TSP and < 0.65 µm 0.65-1.1 µm 1.1-2.1 µm 2.1-3.3 µm 3.3-4.7 µm	A six-stage ambient viable cascade impactor Flow: 30 L min^{-1} for 360 min. V=10m^3 The samples were collected directly onto the impactor plates without using any substrate	Optical microscopy for identification and quantification. Verification using hot needle and micro-Raman spectroscopy (Raman data not evaluated thoroughly)	Fibres 91% Fragments 9%	0.45 – 2800 µm	ND	MP concentration in the indoor air in Kuwait varied between 3.2 and 27.1 particles m^{-3} (TSP)

Study title and reference	Study area and microenvironment(s)	Matrix **[Dust, TPM, …]**	Sampling Method Sampled volume/Sampling duration	Analysis Method Identification process	Dominant shapes	Size-Range [µm]	Dominant polymer type	Concentration
		4.7-7.0 µm > 7.0 µm						
Origin of Synthetic Particles in Honeys, Pol. J.Food Nutr. Sci., Liebezeit et al., 2015 [124]	Germany	Natural Samplers 47 honeys and 22 flowering plants were analysed for their load of synthetic fibres and fragments.		Optical dissecting microscope	No attempts were made to determine fibre lengths or polymer type.	No attempts were made to determine fibre lengths or polymer type.	No attempts were made to determine fibre lengths or polymer type.	Fibres and fragments ranged from 10 to 336 kg^{-1} and 2 to 82 kg^{-1} honey, respectively
Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. Liu et al., 2019 [125]	China, Megacities	TSP	GF/A glass microfiber filters (Whatman, UK), each with a 1.6 µm pore size and a 90 mm diameter	Stereomicroscopy FTIR equipped with a mercury cadmium telluride (MCT) detector was chosen to verify these isolated microplastics	Fibres: 43% Fragments: 48% Microbeads: 9%	12.35 to 2191.32 µm	PET, Epoxy resin, PE, alkyd resin, rayon, PP, PA, PS Fibres: PET (87%) PE Rayon	0-2 n m^{-3}, with a mean value of 0.41 n m^{-3}
Airborne and marine microplastics from an oceanographic survey at the Baltic Sea: An emerging role of air-sea interaction? Ferrero et al., 2022 [126]	Baltic Sea, Research Cruise	TSP Deposition	Specifically designed “Deposition Box”	µ-Raman (for the airborne ones) and FTIR (for marine ones)	Fibres 98% Fragments 2%		PES 39.5% PC 35.5% PE 11.8% PU 5.3% PA 2.6% PET 5.3%	Gdansk harbour (161 ± 75 m^{-3}) Open Baltic Sea (24 ± 9 m^{-3}) Gotland island (45 ± 20 m^{-3}).
A Novel Strategy to Directly Quantify Polyethylene Microplastics in PM2.5 Based on Pyrolysis-Gas Chromatography–Tandem Mass Spectrometry. Luo et al., 2023 [127]	China, Cities	PM2,5	Quartz fiber filters (90 mm diameter Flow rate: 0.1 m^3 min–1, Sampling time: 23.5 h, V= 141 m^3	pyGCMS-MS 1/32 of the collected filter was used for each detection (very time expensive)		ND	ND	Corresponding values varied in the range of 0.8–13.7 pg m^{-3} (mean of 5 pg m–3 and median of 3.5 pg m^{-3}) in Zhengzhou, 4.2–16.3 pg m^{-3} (mean of 10.2 pg m^{-3} and median of 10.5 pg m^{-3}) in Taiyuan 0.3–8 pg m^{-3} (mean of 5.2 pg m–3 and median of 6.5 pg m^{-3}) in Guangzhou
Airborne emissions of microplastic fibres from domestic laundry dryers. O’Brien. 2020 [29]	Emissions of microplastic fibres from residential dryers into air investigated	TSP	Sampling volume of 55 m3/h Samples were collected onto a Whatman GF/A glass filter (1.6 µm)	Optical microscope for total particle count and characterisation (colour, morphology, size) FTIR and pyGCMS only for confirmation of PET (material of blanket)	ND	ND	ND	Fibres: 1.6 ± 1.8 fibres/m^3
Airborne microplastic concentrations and deposition across the Weser River catchment; Kernchen et al., 2022 [128]	Germany, Weser River Catchment in Northwest and Central Germany	TSP Cascade impactor PM10 Deposition samples	Flow: 3.4 L/min, t=3h, V= 0.6 m^3	µFTIR µ-Raman	Irregular shape: 79% Spherical: 21% no fibres in air but in deposition samples	Air: 4-33 µm Deposition: 10-600 µm	In air PE 78% Deposition (most common): PP, PE, PET, PS, PVC,	Air: 91 ± 47 particles per m^3 Deposition: 99 ± 85 particles per m^2 per day (>11 µm)

Study title and reference	Study area and microenvironment(s)	Matrix **[Dust, TPM, …]**	Sampling Method Sampled volume/Sampling duration	Analysis Method Identification process	Dominant shapes	Size-Range [µm]	Dominant polymer type	Concentration
Airborne Microplastic Concentrations in Five Megacities of Northern and Southeast China; Zhu et al., 2021 [129]	China, Megacities	TSP	Flow rate: 100 L/min, V=1 m^3 Airborne particles were collected on glass microfiber filters (Whatman GF/F, 0.7 µm pore size, 90 mm diameter).	Identification and enumerattion by a combination of Nile Red (NR) staining/fluorescence detection and micro-Fourier transform spectroscopy (µ-FTIR)	Fragments: 88.2%	<100µm: 94,7%	PE, PP, PS, PET, PA, PVC	230 - 358 items/m^3
Airborne microplastic particle concentrations and characterization in indoor urban microenvironments; Torres-Agullo et al., 2022 [130]	Spain, Barcelona Buses, subways, houses	TSP	Flow: 10 L/min, sampling duration: 1.5-3h, V=0.9-1.8 m^3 Nylon net filters (20 µm pore size, hydrophilic membrane, 25 mm diameter	Optical microscopy for visual inspection and characterisation (colour, length or area). Polymer dentification was performed through µFTIR analysis. Particles were removed from filter after visual inspection and analysed with FTIR.	ND	Fibres: <100µm: 64% Fragments: <100µm: 78%	Polyamide, PA (51%), polyester PES (48%) and PP (1%)	Buses: (17.3 ± 2.4 MPs/m^3) Subways: 5.8 ± 1.9 MPs/m^3 Houses: 4.8 ± 1.6 MPs/m^3
Airborne microplastics and fibers in indoor residential environments in Aveiro, Portugal; Xumiao et al., 2021 [131]	Portugal, Aveiro. Airborne microplastics and fibres in indoor and outdoor air	TSP	Flow rate of 5 L min^{-1} for 24 h, V=7,2 m^3 Quartz fibre filters (pore size of 2.2 µm,	Optical microscope with Nile Red.	ND	ND	ND	1.1 synthetic particles m^{-3} (fibre and non-fibre microplastics).
Airborne microplastics in a suburban location in the desert southwest: Occurrence and identification challenges; Chandrakanthan et al., 2023 [132]	USA, Arizona	TSP	Flow rate of 1.13 m^3 min^{-1} for 24 h, V=1600 m^3 Quartz fibre filters	Optical microscopy µ-Raman spectroscopy was used to identify the chemical composition of microplastics.	Fibres: > 82%	(5–5000) µm	PVC (19%) PES, and PS were the main polymers identified.	0.02 to 1.1 microplastics/m^3
Atmospheric deposition of anthropogenic particles and microplastics in south-central Ontario, Canada, Welsh et al., 2022 [133]	Canada, Ontario	Deposition	Bulk precipitation collectors	Stereomicroscope Of the anthropogenic particles that were identified, 20% were randomly selected and tested using a hot needle to determine the proportion that were plastic (i.e., polymers with a petrochemical base).	Fibres: 85% Fragments: 15%	Fragments: 20-3500 µm (most < 200µm)	PA: 24% PET: 19%	4–9 mp/m^2/day
Atmospheric microplastic deposition in an urban environment and an evaluation of transport; Wright et al., 2020 [134]	UK, London	Deposition		Optical Microscopy for counting + FTIR for identification	Mostly fibres	Fibres: <100µm Fragments: 75-100 µm	Fibres: PAN 67 % PES 18.8% PA 9.4% Fragments: PP, PVC, PE, PET, PS	771 ± 167 particles/m^2/d
Atmospheric microplastics at a southern China metropolis: Occurrence, deposition flux, exposure risk and washout effect of rainfall; Yuan et al., 2023 [135]	China, Guangzhou	TSP, total atmospheric deposition and rainfall		Screening with Stereoscopic microscope µFTIR for compositional verification of suspected particles		12.96 to 333.62 µm	PET 53% Rayon 53% PE PP	0.01–0.44 items/m^3 65.94 ± 7.53 items/m^2/d (Annual deposition flux)
Emission of airborne microplastics from municipal solid waste transfer stations in downtown; Hu et al.; 2022 [136]	China, Shangai	TSP	Flow: 100 L min^{-1}, t=1h, V=6m^3 Quartz fiber filters (Whatman GF/A, pore size 1.6 µm, diameter 90 mm	Stereomicroscope Suspected MPs were identified by µ-FTIR in transmission mode		50 – 1000 µm	Rayon (most abundant)	2.5 ± 1.3 n/m^3
Household indoor microplastics within the Humber region (United Kingdom): Quantification and chemical characterisation of particles present. Jenner at al., 2021 [32]	UK, Humber Region	Deposition	Deposition	Microscopy and FTIR	Fibre>Fragments> Film>Sphere> Foam	250-5000 µm	PET (63%) PA PP PE PAN	1414 MP m^{-2} day^{-1} ± 1022

Study title and reference	Study area and microenvironment(s)	Matrix **[Dust, TPM, …]**	Sampling Method Sampled volume/Sampling duration	Analysis Method Identification process	Dominant shapes	Size-Range [µm]	Dominant polymer type	Concentration
							PE	
Inhalable microplastics prevails in air: Exploring the size detection limit; Xie et al., 2022 [137]	China, Shangai	TSP Indoor and outdoor samples	Flow rate of 2.5 m3 h^{-1} for 4 h. V=10 m^3	Raman microscopy	Dominant shape: fragment (85%)	2.40–2181.48 µm	PE (74%) PES (9%) PVC (3%) Cotton (1.4%) PP(0.6%) Rubber (0.18%)	15.56 to 93.32 N/m^3
Microplastic occurrence in settled indoor dust in schools. Nematollahi et al., 2022 [28]	Iran, Schools	Dust		Optical microscopy and TEM/EDX for selected particles		500 µm to 1000 µm	PET 50% PP 35% PS10 %	195 MPs·g^{-1} of dust
Microplastics Differ Between Indoor and Outdoor Air Masses: Insights from Multiple Microscopy Methodologies; Gaston et al., 2020 [138]	USA, California	TSP	Flow: 11.7 L min^{-1}, t=8h, V=5,6 m^3 glass microfiber filter (GF/A or GF filter; nominal pore size of 1.6 µm; 47 mm diameter	Microscope (fluorescence following staining with Nile Red) + FTIR + Raman	Fibres+fragments		PS 46% PET 36% PE 9%	indoor (3.3 ± 2.9 fibres and 12.6 ± 8.0 fragments m^{-3} outdoor air (0.6 ± 0.6 fibres and 5.6 ± 3.2 fragments m^{-3}
Microplastics in dust from different indoor environments. Zhu et al., 2022 [139]	China Indoor environments	Dust	Dust samples	Stereomicroscope and FTIR	Fibre predominant (80-90% depending on indoor environment)	50 - 1000	PE PP PES PC PS PA	62 - 3861 MPs/g
Outdoor Atmospheric Microplastics within the Humber Region (United Kingdom): Quantification and Chemical Characterisation of Deposited Particles Present; Jenner et al., 2022 [140]	UK Outdoors	Deposition		FTIR	Film-shaped (67%) Fibre (9%) Fragment (24%)	10 - 500	PE (31%) Nylon (28%) PET (6%) PS (3%) PP (3%)	3055 ± 5072 MP m^{-2} day^{-1} (1164 median).
Plastic in the air?! - Spider webs as spatial and temporal mirror for microplastics including tire wear particles in urban air; Grossmann et al., 2022 [141]	Germany, mid-sized city	Natural samplers, spider nets		pyGC-MS			dominant polymer was C-PET (Ø 36.0% of total MP PVC Tyre-tread	11.4 µg/mg to 108 µg/mg spider web sample.
Direct analysis of airborne microplastics collected on quartz filters by pyrolysis-gas chromatography/mass spectrometry; Mizuguchi et al., 2023 [142]	Japan, Tokushima	TSP, PM_{10}, $PM_{2.5}$	Flow: 20 L min^{-1}, t=2 weeks, V=403 m^3 A multi-nozzle cascade impact (MCI) sampler to collect airborne particulates with classification PM10 and PM2,5	pyGC-MS				TSP PS 0.09-0.25 ng/m^3 SBR 2.3-6.3 ng/m^3 PM2.5-10 PP 0.36-0.83 ng/m^3 PS 0.44-0.109 ng/m^3 PM2,5 PP 3.5 ng/m^3 PS 0.7 ng/m^3

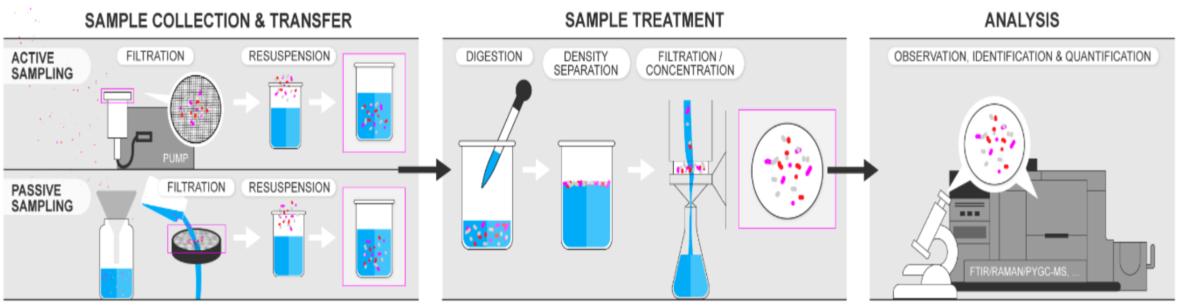
Study title and reference	Study area and microenvironment(s)	Matrix **[Dust, TPM, …]**	Sampling Method Sampled volume/Sampling duration	Analysis Method Identification process	Dominant shapes	Size-Range [µm]	Dominant polymer type	Concentration
Source and potential risk assessment of suspended atmospheric microplastics in Shanghai; Liu et al., 2019 [143]	China, Shangai	TSP	Flow: 100 L min^{-1}, time: 1h, V=6 m^3 Whatman GF/A glass microfiber filters (1.6 µm pore size, 90 mm diameter)	Enumerated by stereomicroscope and identified by µFTIR	Microfibres comprised 67% of all SAMPs, followed by fragments and granules comprising 30% and 3% of SAMPs, respectively.		PET, PE, PES, PAN, PAA, Rayon,	0 to 4.18 n/m^3
Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence; Cai et al., 2017 [144]	China, Dongguan	Deposition		digital microscope Samples were initially identified by visual observation based on the common criteria suspected samples, µ-FTIR analysis	Fibre, foam, film, fragment	< 200–4200	RY, PE, PP, PS	175 to 313 particles/m^2/day
Microplastic abundance in atmospheric deposition within the Metropolitan area of Hamburg, Germany; Klein and Fischer, 2019 [145]	Germany, Hamburg	Deposition		Particles and fibres were counted under UV light within a photo box and under a fluorescence microscope µRaman for identification of single particles	fragments were significantly dominating compared to fibres		polyethylenes/ethylvinyl acetate copolymers are dominating significantly (48.8 and 22.0%, respectively)	136.5 and 512.0 microplastic particles per m^2/day

Source: own production

A method for the analysis of micro- and nanoplastics comprises three main parts (Figure 15):

a) Sampling and collection
b) Sample preparation
c) Sample Analysis

Figure 15. Methodological parts of method for the analysis of microplastics



Source: own production

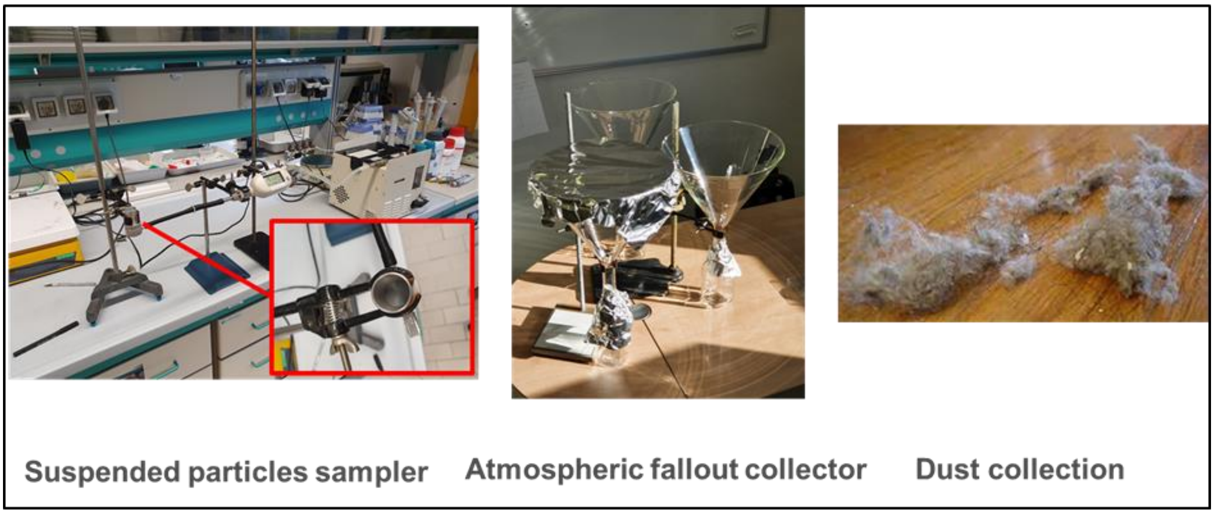
Each of these parts are discussed in the following sections.

5.3 Sampling and collection methods

Due to the nature of atmospheric plastic particles as a complex and emerging contamination class, standardised sampling protocols are not yet established. Consequently, various sampling collection methods are employed across published studies. This sometimes makes comparison of the obtained results difficult.

Broadly, sample collection methodologies fall into three categories (see Figure 16): active sampling for collecting particles suspended in air, passive sampling for atmospheric fallout collection (deposition), and (active) dust collection.

Figure 16. Sample collection methodologies



Source: own production

Each of these sample collection methods comes with its own set of advantages and disadvantages, which are summarised in Table 10.

Table 10. Advantages and disadvantages of active and passive sampling

	Active sampling (Suspended particles)	Passive Sampling (Dust fallout)
Advantages	Generally shorter sampling times Sampling of all suspended particles (unselective)	Longer sampling times In most cases no electricity required
Disadvantages	High volume pump required Electricity required	Selective for larger and denser particles, depositing particles

Source: own production

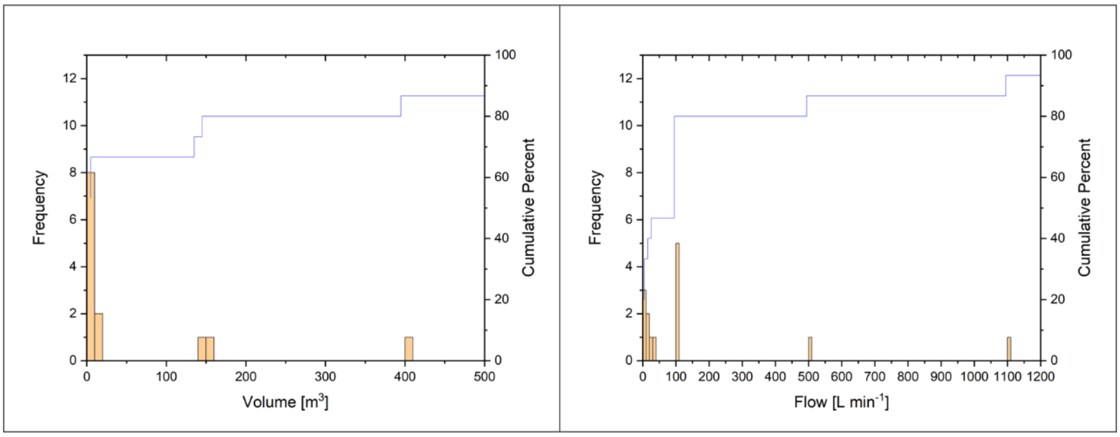
5.3.1 Active pumped samplers

Active air sampling methodology is a widely accepted and traditional approach for monitoring atmospheric pollutants. It has been used since a long time to concentrate various types of airborne pollutants, such as PM10, PM2.5, or microbes, onto filters for subsequent identification and quantification. This method involves using a pump to collect particulates or aerosols by passing air through a membrane housed in a membrane-holder, cassette, or size-selective sampler. Compared to passive sampling methods, active sampling is faster but requires electricity.

The selection of the filter material largely depends on the analytical technique used for sample analysis. Commonly used membranes include mixed cellulose, polycarbonate, PTFE, PVC, aluminium oxide, silver, and glass-fibre. For pyrolysis gas chromatography mass spectrometry (pyGC-MS), the filter material should not contain organic materials (e.g., mixed cellulose or PVC), while for microscopic and spectroscopic methods, the smoothness of the filter material plays a crucial role. Table 9 shows that the majority of studies use glass-fibre filters with a 'pore size' ranging from 0.7 to 20 µm for sample collection. Glass-fibre filters have been presumably favoured due to their extensive use in traditional high-volume particulate sampling for decades. The most commonly used 'pore size' is 1.6 µm, which strikes a good balance between collection efficiency and achievable flow rate. It is important to note that glass-fibre filters do not contain pores by nature; the equivalent pore size is determined through filtration measurements of particles with known sizes. Moreover, air samples have much higher retention efficiency compared to liquid samples. Glass-fibre filters with a declared pore size of 1.6 µm can retain particles down to approximately 0.3 µm in diameter.

Another important parameter is the total amount of sampled air, which should be chosen appropriately based on the analytical technique used for detection and analysis of plastics. In the studies mentioned in Table 9, the flow rates (Figure 17, right) range from 5 to 2500 L min^{-1} (50th percentile = 50 L min^{-1}), and the collected volume (Figure 17, left) ranges from 0.6 to 1600 m^3 (50th percentile: 10 m^3). The concentration of micro- and nanoplastics suspended in the air varies depending on the sampling point and the associated level of pollution. However, for initial exploratory sampling, a flow rate of 50 L min^{-1} over a 3-hour period resulting in a sampling volume of around 10 m^3 could be considered.

Figure 17. Cumulative distributions of the flow-rate (right) and the sampled volume (left) in the studies included in Table 9. Statistical robustness is limited by the relative low number of available studies



Source: own production

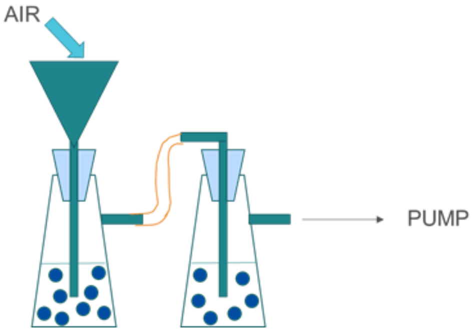
Size selective sampling

Without the use of size-selective inlets, the so-called total suspended particulate (TSP) is collected on the filter membrane, as done in most studies listed in Table 9. However, it may be necessary to selectively preselect particles within a defined hydrodynamic diameter range. Particles smaller than 10 µm are of particular concern as they can enter the human respiratory system and penetrate deeply into the lungs, causing adverse health effects. Preselection by size can be achieved using cyclonic flow inlets, cascade impactor inlets, or virtual impactors. Size preselection becomes especially relevant when samples are analysed using thermo-analytical techniques that determine polymer mass but do not provide information on particle size.

5.3.1.1 *Alternative active sampling techniques*

Alternative to concentrating particulates on filter membranes, particles can be trapped using sampling (wash) bottles or impingers, as demonstrated in a study by Xie and co-workers [137]. In this method, filter flasks are connected by a rubber tube, and a long-neck funnel is used to suction air. The total suspended particulates are then trapped in the sampling bottle filled with ultrapure water (Figure 18). Approximately 10 m^3 of air was collected for analysis. The collected samples were initially treated with hydrochloric acid to remove carbonates and then filtered using glass-fibre filters before analysis.

Figure 18. Impinger sampling device



Source: own production

5.3.2 Passive atmospheric deposition

To date, the majority of published research on atmospheric microplastics has been conducted using passive collectors (total deposition). Table 9 includes only a small selection.

The principle of passive sampling relies on the fact that large solid (and liquid) particles, typically larger than 10 µm in hydrodynamic diameter, are collected via gravitational settling. Particulate matter in the atmosphere naturally settles to the ground due to gravity or external forces such as precipitation and wind [43]. The duration of passive sampling varies depending on the precipitation rate of plastic particles and can range from days to months. Passive sampling devices, or fallout collectors of known area, can be as simple as a glass funnel, a glass bucket [146], [147], or a petri-dish, glass beakers [148], or commercially available options. To avoid particle loss during transfer from, for example, a petri-dish to the filter, glass-fibre filters can also be directly exposed for a defined period of time [149].

At the end of the sampling period, the surfaces of the collection devices are rinsed, and the collected fallout is typically transferred and concentrated onto a filter for further analysis [27].

Depending on the meteorological conditions, the deposition can be wet or dry. Wet deposition results in more particles [150], [151]. Jia *et al.* (2022) found that the MP sizes were larger after dry deposition than after wet deposition [151]. Potential interferences of atmospheric deposition may include bird droppings, insects, algae (in case of wet deposition sampling), and larger plant materials. Commercial sampling devices often incorporate bird rings to prevent bird droppings, and sieving can remove particles larger than 1 µm. Particle blowout by wind can be minimized by adding a small amount of water to the collection device [152].

A standardised metallic/glass system developed by the Norwegian Institute of Air Research (NILU) has been widely used for passive sampling of atmospheric deposition. This user-friendly plastic-free equipment provides an effective option[3].

Since only particles with a hydrodynamic diameter greater than 10 µm tend to gravitationally settle, smaller particles are not collected with this methodology. As a result, direct comparison with pumped atmospheric samples is not possible.

Results obtained from passive atmospheric deposition samples are expressed in mass (polymer) x (sampling area)$^{-1}$ x time^{-1}.

5.3.3 Deposited dust

Deposited dust (dustfall) refers to air particles that settle out over a given area and time under the influence of gravity. As described in section 5.3.2, this deposition can be collected on a defined surface area and over a specific period. Alternatively, already settled dust can be collected and analysed.

In the latter case, samples can be collected from horizontal and flat surfaces in specific micro-environments. Surfaces of wall shelves, cabinets, and floors are particularly suitable for this type of sampling. A brush made of horsetail strands or a steel dustpan can be used for sampling, and the collected particles are subsequently extracted (washed) with ultrapure water for particle removal [28]. In studies by Zhu et al. [139] and Dris et al. [12], samples were collected from vacuum cleaner bags.

Results of particles detected in deposited dust are expressed as the mass of polymer per mass of dust.

Before analysis, most of these samples require sample preparation to remove interfering matrix components. Sample clean-up procedures are described in section 5.4.

5.3.4 Biomonitoring as sampling method

Simple and cost-effective complementary tools to active and passive sampling are the biomonitoring techniques [153]. Airborne pollutants, including microplastic particles, are adsorbed by a variety of biological materials that are sampled in the area of interest. Typical matrices include mosses [154], lichen [42], plant leaves [155], honey [124] and flowering plants and spider nets [141]. Biomonitoring methods offer advantages in terms of not requiring power supply and maintenance, leading to lower sampling costs.

For example, Großmann et al. [141] used spider webs as a collection medium for microplastics in a mid-sized German city. The spider webs were then treated with Fenton's reagent and measured using pyrolysis-gas chromatography-mass spectrometry to detect specific polymer-related indicator compounds. The study detected tyre wear particles and other microplastics in all samples.

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[3] https://innovation.nilu.no/wp-content/uploads/sites/14/2020/04/innovation_nilu_Atmospheric_Microplastic_Collector_2020.pdf

Roblin and co-authors [154] collected Hylocomium splendens from three lake catchments remote from anthropogenic disturbances and emission sources. They successfully detected anthropogenic microfibres in all moss samples.

In the INSIGNA-EU[4] project, funded by the European Union, microplastics were monitored in bees, air filters, and the newly developed in-hive passive sampler called APITrap. Microplastics were detected in samples collected using all three sampling methods.

Biomonitoring techniques are interesting and can be used as a complementary approach to conventional air sampling methods [156].

5.4 Sample Preparation

There is currently no standardised method for the preparation of airborne microplastic samples. In the sampling methods described in section 5.3, plastic particles are not selectively sampled. Environmental matrices containing microplastics usually coexist with organic materials. The amount of other substances suspended in the air collected during sampling varies depending on the location and duration of sampling. Some of these substances or particulates may interfere with the analytical technique used for sample analysis, necessitating their removal before accurate characterisation and quantification of microplastics (MPs). The pre-treatment aims to separate microplastics from impurities, eliminate pollutants attached to microplastics, concentrate the microplastics, and prepare them for identification and quantification.

Table 11 outlines the general steps involved in a sample preparation protocol [157], with further details provided in sections 5.4.1 to 5.4.4.

Table 11. General sample pre-treatment procedure

Step	Purpose
Sieving with stainless steel mesh	Removal of very large undesired matrix components
Digestion	Reduction of organic matter, interfering with most analytical techniques
Density separation	Separation of plastic particles from other interfering materials
Filtration concentration step of plastic particles	Concentration/enrichment of plastic particles in defined surface area

Source: own production

Samples collected through active sampling and atmospheric fallout may require slightly different sample preparation procedures. Not all studies listed in Table 9 have undergone all of these pre-treatment steps, with some conducting only partial or no pre-treatment at all [4]. However, it appears that the detection rate of synthetic polymers significantly improved in most studies after the digestion and flotation process. This indicates that the presence of organic matter hinders the identification of plastic particles, especially in studies where analysis was performed using a combination of optical microscopy and FTIR [49]. Specific sample preparation protocols for suspended aerosols, dry and wet depositions, and dust are proposed in section 5.4.5.

Each sample preparation steps is discussed in the following subsections.

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[4] INSIGNIA-EU is funded by the European Union under grant N° 09.200200/2021/864096/SER/ ENV.D.2.

5.4.1 Sieving with stainless steel mesh

This step helps reducing large-sized environmental impurities, such as leaves, stones, hair, and paper. Researchers often use stainless steel sieves with a pore size of 5 mm, and occasionally stainless steel sieves with pore sizes of <5 mm (e.g., 2.5 mm, 2 mm, and 150 µm) [32].

5.4.2 Density separation (flotation)

In this process, the sample is mixed with a solution of defined density and continuously stirred for a specified period, after which it is allowed to settle. This separates low-density microplastic particles from higher-density impurities, such as mineral matter [51], [52]. A solution with a density range of 1.6–1.8 g mL^{-1} appears optimal for density separations of plastic particles.

Zinc chloride (with a density of 1.6 mg mL^{-1}) is commonly used for preparing airborne MPs samples due to its low cost and low toxicity to humans [149], [158]. Other salt solutions suitable for this purpose are summarised in Table 12, and the densities of the most common polymers are provided in Table 13.

Table 12. Salt solution and their densities used for density separation of micro-plastics

Salt Solutions	Density [g mL^{-1}]	Remarks
NaCl	1.2	+: Cheap -: PVC and PET – multiple washing for recovery necessary
$ZnCl_2$ (most frequently used)	1.5 - 1.7 → Concentration = 700 g L^{-1}	+: Recovery up to 95%, cheap -: Hazardous
NaI	1.6	+: Greater density than NaCl -: Costly, blackens cellulose
NaBr	1.37 - 1.6	+: Recovery rates 87-100 %
$ZnBr_2$	1.7	+: Recovery rates 99%, -: Expensive, environ. hazardous

Source: own production

Detailed procedure for density separation with $ZnCl_2$ (from Rodrigues et al. [159]):

- Assembly of the density separator (if available)
- Add 50 mL of $ZnCl_2$ solution (concentration = 700 g/L) to the dried sample.

  Note: Stir the $ZnCl_2$ solution during at least 24 h before adding to the sample.
- Add the sample to the density separator (or beaker)
- Rinse the glass bottle with $ZnCl_2$ solution to transfer all remaining solids to the density separator
- Cover loosely with aluminium foil
- Allow solids to settle 1 h at room temperature
- Collect floating MPs into a flask with forceps and a glass Pasteur pipette
- Remove the Mohr’s pinch clamp. Drain settled solids (if present) and $ZnCl_2$ solution into a flask

- Rinse the density separator several times with a squirt bottle filled with distilled water to transfer all solids to the flask containing recovered MPs
- Stir the flask with MPs and the flask with $ZnCl_2$ for 10/15 min
- Vacuum filtration

Filter the $ZnCl_2$ solution and settled solids (if present) through a 0.45 μm clean membrane filter.

- Store the reused solution in a glass bottle at 4 °C
- Rinse the filtration setup with a squirt bottle filled with distilled water several times to ensure that no MPs are lost
- Once filtration is complete, carefully remove the membrane and put it in a Petri dish
- Place the Petri dish in 40 °C drying oven for 3–5 days
- Visual inspection

Table 13. Densities of most common polymers

	Polymer	Density [g cm^{-3}]
Light Density Polymers	PS	0.96-1.06
	EPS	0.01 – 0.05
	PP	0.85-0.92
	LDPE	0.89-0.93
	HDPE	0.94-0.98
	PA, PA6,6	1.12-1.22
	PU	1.20–1.26
High Density Polymers	PET	1.38-1.41
	PVC	1.38-1.41
	PTFE	2.10-2.30

Source: own production

5.4.3 Digestion

After density separation, a post-treatment process is carried out to remove unwanted materials from the MPs using chemical solutions such as acids, alkalis, enzymes, and oxidizers (e.g., hydrogen peroxide) [53]. The application of acids and alkalis in treatments has the potential to induce hydrolysis in polyesters and polyamides. Oxidative digestion with hydrogen peroxide at a controlled temperature and digestion time (depending on the amount of organic residues) has proven to be effective in many cases. In fact, digestion with 30% H_2O_2 is the only method reported for the sample preparation of airborne MPs [160]. Temperature significantly affects the duration of digestion, with 30% H_2O_2 taking 7–8 days to degrade impurities at 20–25 °C, while this duration shortens to less than 1 day at 60–70 °C. Temperatures exceeding 70 °C may damage the microplastic surface [161]. Additionally, the addition of $FeSO_4$ to H_2O_2 (Fenton's reagent) can further eliminate persistent organic pollutants [162]. Enzymatic digestion using sodium dodecyl sulfate in combination with enzymes has also been reported in several studies.

5.4.4 Filtration concentration step of plastic particles

This step concentrates microplastics onto a substrate [163][164]. The choice of substrate depends on the analytical technique used for sample analysis. For instance, glass microfiber filters are suitable for pyGC-MS analysis, while flat Anodisc filters may be preferable for microscopic and spectroscopic methods [135].

After filtration, the filters may be wet and need to be dried before analysis. In order to accomplish this, the filters are transferred to a glass petri dish and covered with the corresponding glass lid. The petri dishes are then placed in an oven at 40 °C for approximately 4 hours to facilitate drying. Once dried, the filters can be stored at room temperature in the dark.

5.4.5 Proposed sample preparation protocols for suspended aerosols, dry/wet depositions and dust

5.4.5.1 *Suspended aerosols*

a) Extraction step

- Collected (on filter) MPs and NPs are dispersed in ultrapure water in a sonicating bath [160]

< or in alternative >

- Collected (on filter) MPs and NPs are washed to glass beaker with deionized water and/or ethanol

In some of the studies included in Table 9, the extraction step is combined with the digestion/treatment step. This reduces the probability of particle losses:

- Samples on quartz fiber filters are directly transferred to a 15% H_2O_2 solution and left to react for eight days at room temperature (20˚C) to remove natural organic matter without damaging microplastics [131] [6]

The extraction step can also be done directly with hydrogen peroxide:

- The airborne particles collected on the filters were washed into a glass beaker using ~30 mL of 30% H_2O_2 and then heated to 70 °C for 1 h to digest natural organic materials [129]

b) Digestion/treatment

- The extracted sample material is treated with 30% H_2O_2 for 8 days

< or in alternative >

- 10 mL aqueous 0.05 M Fe (II) solution prepared from $FeSO_4$ x7H2O and 10 mL of 30% hydrogen peroxide are added separately to the aqueous extracts to eliminate natural organic matter. The mixtures were left to stand for 5 min on a lab bench at room temperature and thereafter heated to 60 °C on a hot plate [132].

c) Density separation

- With $ZnCl_2$ solution (1.5-1.7 g/mL)

d) Filtration

- The solutions are vacuum filtered through a filter suitable for the selected analysis technique. The filters are then oven-dried at 70- 80 °C until complete dryness.

5.4.5.2 *Dry/wet depositions (Fallout-samples)*

Wet deposition [145]

- The bulk volume of each sample is determined using a glass measuring cylinder
- 200 mL of each sample are then transferred into a glass beaker and covered with a watch glass. If there is <200 ml deposition in the bulk sampler, the whole sample is transferred into the jar.

a) Digestion/treatment

- To eliminate the organic matter, each sample was treated with sodium hypochlorite solution

b) Density separation

c) Filtration

- Samples are filtered on suitable filter using a glass vacuum filtration device
- The glass beakers and the glass vacuum filtration device are thoroughly rinsed with ultrapure water to remove possible adhering microplastic particles.
- The filters are transferred to glass petri dishes, additionally covered with aluminum foil and left to dry for 24 h at room temperature under a fume hood

Dry deposition [32]

a) Sieving

- If necessary, samples can be sieved through stainless steel sieves (mesh: 2 mm, 2.5 mm or 5 mm) to remove large debris

b) Digestion/treatment

- Each beaker was washed three times with 200 ml of 30% hydrogen peroxide solution (H_2O_2)

  Each sample was placed in a shaking incubator at 55 °C to ensure no destruction of polymers with a low degradation temperature (Allen et al., 2019), and rotated at 65 rpm for 3 days.

c) Density separation

- After sieving, MPs are density separated from the dust using $ZnCl_2$ solution (1.6 g/mL or 1.78 g/mL)

d) Filtration

- Suspension is filtered on a filter, suitable for the analytical technique chosen for analysis.

  Allowed to dry at room temperature in the dark for a minimum of 24 h.

5.4.5.3 Dust [160] [139] [165] [12]

a) Sieving

- Dust samples were usually sieved through stainless steel sieves (mesh: 2 mm, 2.5 mm or 5 mm) to remove large debris

d) Sample transfer

- Transfer defined mass of dust samples to 100 mL glass Erlenmeyer flasks

e) Digestion/treatment

- To remove organic matter in dust, street dust samples were treated with 200-300 mL 30% H_2O_2 for 8 days before separation (or until bubble formation ceased).

b) Density separation

- After sieving, MPs were density separated from the dust using ZnCl2 solution (1.6 g/mL or 1.78 g/mL)

  (Sonication 1h, shaking 2h, settling 1h)

c) Filtration

5.5 Analytical Methods

A wide array of analytical techniques are available for the detection, identification, and quantification of plastic particles, each capable of providing different types of information, such as particle number concentration, shape, polymer mass concentration, polymer identity, and particle size. Table 14 presents a summary of the key characteristics of these main techniques employed in the analysis of microplastics.

Table 14. Main characteristics, strengths and weaknesses of some of the main analytical techniques used for the analysis of microplastics

Analytical Technique	Advantages	Disadvantages	Detection Limit	Information that can be obtained
Fluorescence Microscopy	Easy Fast Relatively unexpensive Provides information on size, number and shape	No chemical identification High probability of false positives Difficult for detection of transparent particles	5-10 µm	Number-Concentration Shape Size
µ-Raman Spectroscopy	Chemical identification Analysis non-destructive	Expensive Time-consuming Interferences by pigments	> 5 µm (size)	Number-Concentration Shape Size Chemical identity
µ-FTIR Spectroscopy	Chemical identification Analysis non-destructive	Expensive Time-consuming	> 10-20 µm (size)	Number-Concentration Shape Size Chemical identity
Thermoanalytical Analysis	Less expensive compared to Raman and FTIR Sample workup (preparation) has less impact on result Chemical identification and (semi)-quantification of airborne MPs and NPs without further sample preparation steps may be possible	Destructive Limited linear range Complex data evaluation Challenging calibration procedure Limit amount of sample can be transferred in sample holder Large sample amount lead to system overload/saturation and/or contamination	Detection limit in mass Depends on polymer and split-ratio set on injector	Mass Chemical identity

Source: own production

In many studies listed in Table 9, a combination of analytical techniques was applied to identify and quantify sampled micro/nano-plastics present on the filter. For instance, techniques like µFTIR or µRaman were frequently utilized to determine the type of microplastic polymer, preceded by optical analysis of the microplastic particles on the filter membrane [157]. Initially, particles on the filters were sorted under an optical microscope, and then suspected plastic particles were further confirmed and identified as microplastics [136].

In the following sections, the analytical principles and advantages/disadvantages of the most common techniques are detailed.

5.5.1 Microscopic Methods

Microscopes play a crucial role in counting plastic particles and characterising their physical morphology. They are commonly used to identify suspected MPs and classify them based on their physical characteristics, such as size, colour, and shape. However, it is important to be cautious, as anthropogenic particles other than plastics (like fly ash, road paint particles, and natural fibres) can be mistakenly identified as MPs.

The error rate associated with using only microscopes has been reported to be relevant; for example, fibres are easier to identify than other shapes, and bright colours are easier to distinguish than white and transparent colours [41].

Considering these limitations, relying solely on optical microscopy may introduce deviations in the final quantitative results of MPs, and it is advisable to combine this technique with a method that allows for chemical confirmation. Nevertheless, optical microscopy remains a significant method for the qualitative and quantitative separation of MPs from other particles [166].

To save time, researchers sometimes analyse defined parts or sections of the filter, extrapolating the obtained results to represent the entire sample. This approach assumes that particles are evenly distributed on the filter surface during the sampling process [32].

5.5.1.1 Optical Microscopy

Optical detection is one of the most common and straightforward methods widely employed to describe the structural characteristics of MPs based on their physical properties, such as colour, shape, and size [167]. The identification criteria for microplastics include:

- Plastics should lack of biogenic (cellular) structure
- Fibres are expected to have a relatively even or consistent thickness along their length and exhibit three dimensional bending
- Fragments and films are expected to have relatively uniform colouring and demonstrate varying levels of transparency and/or clarity
- Aged plastic, as typically found in environmental samples, often display embrittled and weathered surfaces, with irregular shapes and broken and sharp edges
- Colour serves as an essential identifier for plastics, ranging from transparent and various shades of white to bright orange, blues, greens, purples, and black

5.5.1.2 Stereomicroscopy

Stereomicroscopy differs from classical optical microscopy in that its illumination comes from above, providing a three-dimensional examination of the studied sample. It observes the sample from two slightly different angles, allowing for the collection of two images needed for stereoscopic vision.

In the majority of examined studies, the magnification of the used microscopes ranged between ×6 and ×100. The detection limit of this technique depends on the technical details of the microscope, particularly the magnification. The most common limit for the morphological description of suspected MPs is up to a size of 50 µm. Stereoscopic microscopy is a popular and useful tool for MPs analysis due to its simplicity, speed, and cost-effectiveness in categorizing them.

However, despite the straightforward nature of this microscopic approach, its accuracy in identifying polymers is often limited without the use of complementary techniques. The precision of the results strongly depends on the subjectivity and experience of the researcher, which may lead to potential over- or underestimation of plastic particle abundance [167].

5.5.1.3 Fluorescence Microscopy

Fluorescence microscopy is utilized in certain studies to enhance visual identification. Samples are treated with a dye that selectively renders hydrophobic surfaces, like plastics, fluorescent. In fluorescence, MPs primarily absorb UV light at 300–400 nm and emit blue (450–480 nm) or purple (400–450 nm) fluorescence [60].

Nile red, a lipid-soluble fluorescent dye, is commonly used to stain hydrophobic materials such as polymers. Nile Red staining techniques can help distinguish synthetic from natural particles. However, the selectivity of Nile Red is not perfect, as some plant materials can also be stained by Nile Red. Furthermore, certain polymers, like rubber, do not exhibit fluorescence and cannot be identified using this technique.

Polymers that can be stained with Nile Red include polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyethylene (PE), nylon (PA), polyester, and elastane (polyurethane). However, not all plastic polymers are stained to the same extent. For example, polypropylene (PP) and unaltered polyethylene (PE) are strongly stained, while polyethylene terephthalate (PET) or weathered PE show less fluorescence after staining [168].

On the other hand, polymers as for example cellulose, polyacrylonitrile or natural cotton fibres cannot be identified under a fluorescence microscope [167].

5.5.1.4 Scanning electron microscopy

Scanning Electron Microscopy (SEM) is renowned for its exceptional resolution, making it a valuable tool for discerning intricate details of microplastic surfaces [169]. When combined with Energy Dispersive X-ray Spectroscopy (EDS), SEM becomes capable of detecting elements present on the microplastic surface, including attached heavy metals. Despite these advantages, SEM suffers from certain drawbacks, such as high costs and reduced flexibility when analysing a large number of samples [144].

One significant limitation of this technique is its inability to reveal the chemical composition of the investigated particles. This restricts its capacity to fully characterise the nature of the microplastics under examination.

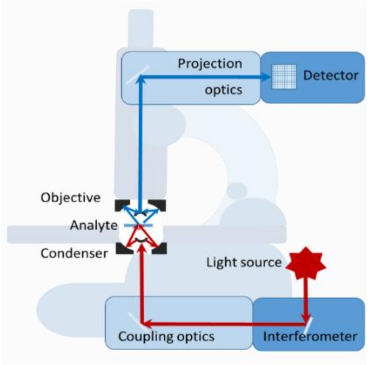
5.5.2 Spectroscopic Methods

Fourier transform infrared (FTIR/µFTIR) spectroscopy and Raman/µ-Raman spectroscopy are widely employed analytical techniques for the identification and quantification of microplastic particles. FTIR is effective in identifying plastic polymer types with particle sizes greater than 20 µm, while Raman spectroscopy can discern particles as small as 5 µm [170].

5.5.2.1 Fourier-transform infrared spectroscopy (FTIR / µFTIR)

FTIR has been used extensively as a tool for characterization and mapping for particle counting and size distribution. It determines the composition (molecular structure) of particles by examining the sample within the infrared wavelength range of 400–4000 cm^{-1} [171]. During analysis, certain wavelengths are absorbed by the particle being studied. By studying the absorbed wavelengths and applying the Fourier Transform function, a spectrum describing the particle's composition is generated. This spectrum is then compared with reference libraries and/or analysed for its individual chemical structure to define the particle's composition. FTIR offers an advantage over classical microscopic methods by enabling the detection and characterization of the particles and the possibility of automating particle spectral analysis using polymer spectral libraries [63].

Figure 19. Schematic drawing of FT-IR spectromicroscope (in transmission mode)



Source: JRC Technical report JRC125383

FT-IR microscopes (µFTIR) used to create FT-IR images combine traditional microscopy with FT-IR spectroscopy (Figure 19). To create a chemical image, the initial step involves obtaining a digital image of the sample using the microscope, followed by selecting a region of interest for analysis. In the subsequent step, IR data is collected across the entire selected region, producing an IR spectrum for each point on the sample. With every point in the region of interest corresponding to an FT-IR spectrum, all spectra can be analysed to identify the particle of interest. This analysis can be performed manually or automatically using computer software or even artificial intelligence algorithms. After analysis, each compound is assigned a unique colour, and the pixels on the image are coloured based on the compound present at each point, creating the chemical image.

To detect IR light after interacting with the sample and create the spectrum, FT-IR microscopes employ various detector options. One such option is the single-element detector, which obtains an IR spectrum at one point on the sample. However, analysing an entire region this way can be time-consuming.

Alternatively, special imaging detectors can be used, including line array or focal plane array (FPA) detectors. Line array detectors are a cost-effective pseudo-imaging solution, comprising multiple single-element detectors arranged in a line to capture several spectra simultaneously. The sample is then scanned line-by-line, and the lines of spectra are stitched together to create the chemical image. FPA detectors represent the state-of-the-art technology for FT-IR imaging, consisting of an array of IR detectors arranged in a square (e.g., 64 x 64 detectors). With this configuration, thousands of spectra can be captured in a single shot, akin to a digital camera.

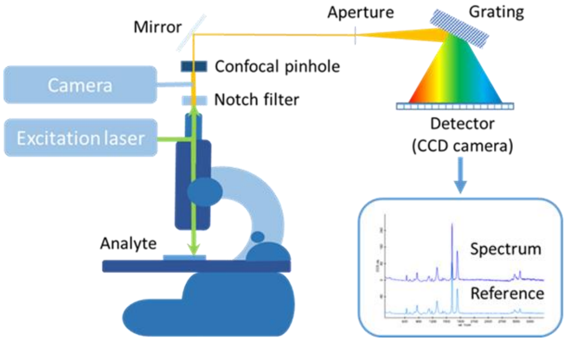
FTIR equipped with a confocal microscope (μFTIR) and focal Plane Array (FPA) with Mercury Cadmium Telluride (MCT) liquid nitrogen-cooled detectors has reduced the practically detectable particle size towards the diffraction limit. In theory, for infrared (IR), this limit is 10 μm (particle diameter) as the entire wavelength must pass through the material. However, due to the normally weathered surface of environmental microplastic samples, reliable signals below ~20 μm are challenging to obtain. MCT detectors necessitate cooling with liquid nitrogen to minimize noise created by dark energy passing through the detector, requiring refilling of the liquid nitrogen dewar at least every 8 hours for most machines.

Some early studies employed Attenuated Total Reflectance (ATR) to obtain spectra from a particle. This method involves placing individual particles (large enough to be manipulated using tweezers) between two points before running the analysis. However, the minimum size that can be physically manipulated for ATR limits its practical use for atmospheric microplastics to around 50 μm [172].

5.5.2.2 Raman / μRaman

Raman spectromicroscopy combines the optical microscopy's visualizing capabilities (down to 1 μm) with the analytical power of Raman spectroscopy. In this technique, a sample (e.g., particles captured on a filter) is placed on the motorized stage of the microscope. After imaging the filter, Raman spectra are collected either at single particle positions or by mapping a selected area of interest (Figure 20).

Figure 20. Schematic drawing of Raman spectromicroscope

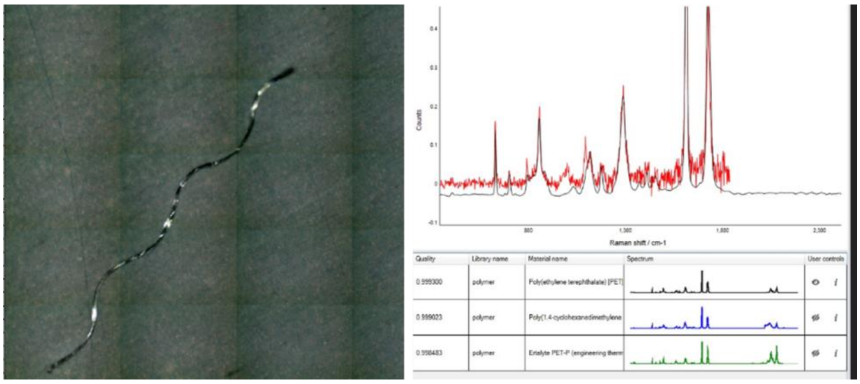


Source: JRC Technical report JRC125383

Raman spectroscopy identifies polymer types primarily based on the backscattered light of different frequencies generated by molecular vibrations [173] [174]. While both Raman and FTIR are classified as vibrational spectroscopy methods, Raman differs from FTIR in its use of a higher frequency laser (typically 532 nm) to excite the material's surface until it emits photons. These photons are usually emitted in line with the laser (Rayleigh scatter), but approximately 1 in 10^{-7} photons are emitted at right angles, known as Raman scattering. The advancements of μFTIR and μRaman spectroscopy (FTIR and Raman adapted for microparticle analysis rather than meso or macro particle analysis) enable the direct analysis of small microplastics on filters without the need for visual pre-sorting, opening up possibilities for automation.

Raman spectroscopy is relatively new to microplastics research and lacks the extensive history in industrial polymer research, resulting in less well-developed libraries for identification. However, as μRaman usage increases, it is expected that similar library resources will evolve, providing identification and comparison functionalities equivalent to the current detailed and available µFTIR libraries. Figures 21 and 22 display two examples of polymers identified on sample filters.

Figure 21. Raman spectrum of polyester fibre

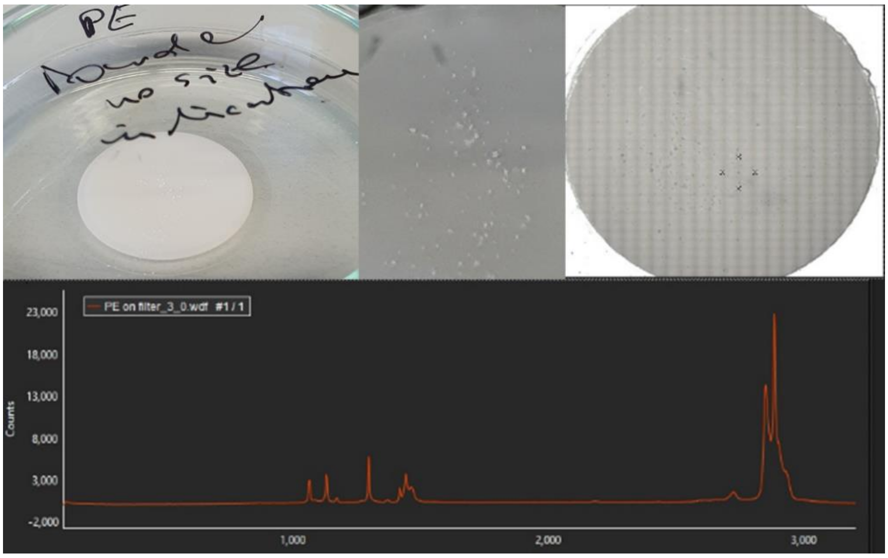


Quality	Library name	Material name	Spectrum	User controls
0.999300	polymer	Poly(ethylene terephthalate) [PET]		
0.999023	polymer	Poly(1.4-cyclohexanedimethylene		
0.998483	polymer	Ertalyte PET-P (engineering therm		

Source: own production

The initial purchase costs of µRaman are higher than its µFTIR counterpart, mainly due to Raman's use of Thermo Electrically Cooled (TEC) detectors, which eliminate the need for liquid nitrogen cooling. This simplifies operation, reduces costs, and enables overnight operation without supervision, increasing the runtime per day.

Figure 22. Raman spectrum of filter spiked with polyethylene particles



Source: own production

Nonetheless, there are certain factors that can affect the measurement accuracy. The main issue with short wavelength Raman lasers is fluorescence. The wavelengths commonly used for Raman spectroscopy are very close to many maximum excitation wavelengths, causing the particles to fluoresce. This fluorescence can obscure the signal and hinder the analysis of chemical bonds. Fluorescence can be caused by inorganic substances, such as clay minerals or dust particles, as well as organic matter, such as humic substances, pigments, and microbiological specimens, acting as impurities in the samples [65].

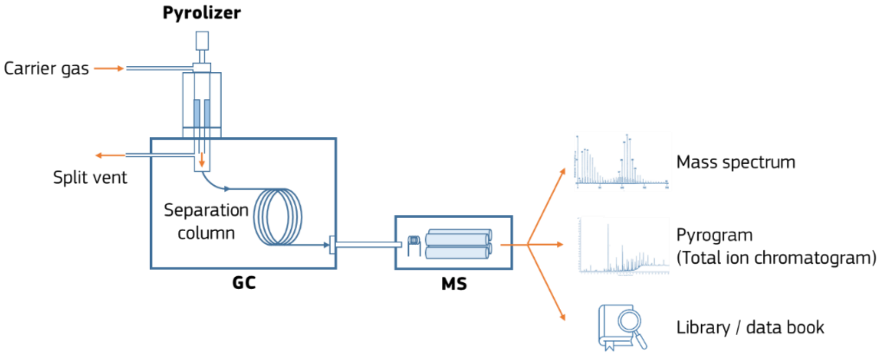
5.5.3 Thermoanalytical Methods

Thermoanalytical methods coupled with mass spectrometry started playing a role in the analysis of microplastics, such as pyrolysis-gas chromatography-mass spectrometry (pyGC-MS) and Thermal Extraction - Desorption Gas Chromatography Mass Spectrometry (TED-GC-MS). These techniques allow for the identification and mass-based quantification of microplastics, but they do not directly provide information on particle size, morphology, and number.

5.5.3.1 Pyrolysis-gas chromatography-mass spectrometry (pyGC-MS)

Pyrolysis gas chromatography with mass spectrometry (pyGC–MS) is the most widely used technique among the thermoanalytical methods. PyGC-MS involves the thermal decomposition (cracking) of MPs samples in an inert gas medium. The specific polymer breakdown markers and their indicator ions can be used for the identification and (semi)-quantification of the polymers (Figure 23).

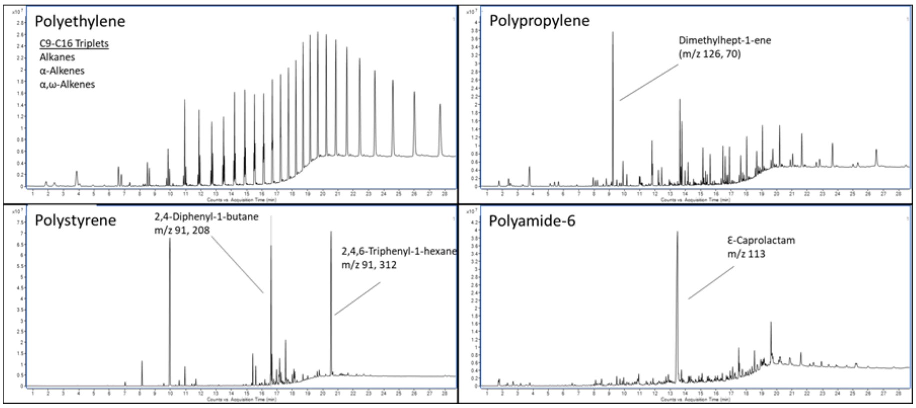
Figure 23. Configuration of a typical pyrolysis-GC/MS system



Source: own production

Each polymer produces unique decomposition products (Figure 24), which serve as fingerprints for identification. Polymer identity is confirmed by the presence of specific indicator compounds. The intensity of these indicator ions is proportional to the amount of pyrolysed product and is used for quantification against external calibration curves.

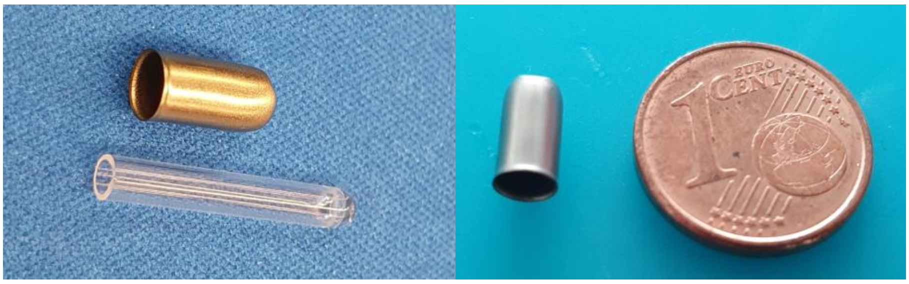
Figure 24. Characteristic fingerprints and specific indicator ions of polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyamide-6



Source: own production

For each identified polymer, a separate calibration curve is necessary. These calibration curves are generated by weighing known amounts of polymer into sample holders, with an ultra-microbalance allowing precise weighing within about 5 µg. For smaller absolute masses, accurate amounts of polymers are dissolved in solvents, and aliquots of these solutions are transferred to the sample holder. After solvent evaporation, the polymer residues are pyrolysed. However, it should be noted that each polymer may require a different solvent, and dissolution is often achieved only under harsh conditions. Alternatively, lower absolute masses on the calibration curve can be achieved by "diluting" the polymer standard with an inert matrix, if the standard material is sufficiently homogeneous and consists of small particles. Commercial diluted standards have recently become available [175].

Figure 25. Examples of sample holders used in two different types of pyrolysers



Source: own production

PyGC-MS has an advantage over FTIR and Raman for the analysis of airborne samples, requiring less pre-treatment and allowing simultaneous analysis of organic additives present in MPs.

However, one disadvantage of thermoanalytical techniques, including pyGC-MS, is the inability to define the number of particles or their shapes using this method. Additionally, the transfer of the filter into the very small sample holders (vials or cups) presents technical challenges. Small 13 mm glass fibre filters can be entirely transferred into certain sample cups, depending on the cup size (Figure 25).

If this technique can be demonstrated as robust, it holds the potential to offer higher throughput, resulting in reduced analysis time compared to numerous other techniques. However, it is important to note that this technique is still in the developmental stage, and there are presently no established routine methods, standards, or standard operating procedures available for the analysis of microplastics. Recently, two papers have been published that explore the direct analysis of airborne microplastics collected on quartz filters using pyGC-MS, without the need for sample preparation [142], [176]. By eliminating the sample preparation stage, pyGC-MS could become a significantly faster analytical technique when compared to spectroscopic methods. Nevertheless, the presence of other inorganic and organic materials may interfere with the targeted polymers during the pyGC-MS analysis.

5.5.3.2 Thermal Extraction - Desorption Gas Chromatography Mass Spectrometry (TED-GC-MS)

TED-GC-MS relies on a thermal extraction/pyrolysis of the sample on the TGA balance inside the TGA furnace, combined with solid-phase extraction of complex volatile hydrocarbons released at high temperatures. In the second step, the solid-phase adsorber is transferred to the TD-GC/MS analysis system. There, the polymer breakdown markers are thermally desorbed in the introduction system and analysed by the GC-MS system for polymer identification and (semi)-quantification.

TED-GC-MS shows promise for analysing air filtration fractions without additional sample preparation steps, as it eliminates most of the environmental matrix. An additional advantage is that it enables the analysis of significantly larger sample quantities (up to 100 mg) without the risk of system overload or contamination, allowing analysis of more representative samples.

The main drawbacks of using TED-GC-MS are similar to those of pyGC-MS, with an emphasis on complex data interpretation, extensive and time-consuming method development, and the inability for particle-by-particle analysis [170]. The high purchasing cost of this complex system may also limit its wider diffusion.

5.5.4 Other Methods

5.5.4.1 Liquid chromatography coupled to UV detector and/or mass-spectrometers

LC-based methods utilising alkali-assisted thermal depolymerisation are employed for the identification and quantification of ester-based polymers like PET and PC. PET, a high-molecular-weight polymer, is obtained through the esterification of terephthalic acid (TPA) and ethylene glycol. On the other hand, PC is a high-molecular-weight polymer formed by bisphenol A (BPA) linked by carbonate groups. In LC-based techniques, the concentrations of TPA and BPA are measured after the sample undergoes depolymerisation, allowing for the calculation of PET and PC concentrations.

However, some interferences may arise during the analysis. TPA can be produced not only from the depolymerisation of PET but also from the depolymerisation of polybutylene terephthalate (PBT) and polytrimethylene terephthalate (PTT). However, as the concentrations of PBT and PTT are very low, and their properties and applications are very similar to those of PET, PET concentrations can be used as a proxy to estimate the total concentrations of PBT, PTT, and PET.

LC-based techniques allow for direct treatment and identification of the sample without the need for sieving, digestion, density separation, and filtration, thereby avoiding possible contamination caused by the pretreatment procedure [177], [178].

5.5.5 Final considerations concerning the analysis of nanoplastics

Detecting nanoplastics in environmental samples remains a nascent field. While analytical techniques discussed earlier may be effective for the detection of microplastics, they struggle to identify particles smaller than 5 micrometers. Further research is crucial to develop reliable methods for characterizing plastic particles and fibres in the low micrometer and nanometer range.

5.6 Quality control and quality assurance practices in micro- and nanoplastic analysis

Micro- and nanoplastics are found everywhere, making it crucial to implement stringent measures to prevent sample contamination during the sampling, pre-treatment, and analysis processes. Below are some recommended best practices to achieve this.

5.6.1 Workstation

If possible and if available, procedures should be conducted inside a clean room under the laminar flow hood.

The laminar flow hood (or any other available fume hood) should be maintained by cleaning with ethanol and paper towels, ideally followed by cleaning with a duster which attracts and retains dust particles.

Benches should be cleaned with ethanol.

5.6.2 Clothing

The usage of synthetic textiles should be avoided as much as possible [179].

(Coloured) cotton laboratory coats - with the sleeves pulled up whenever possible [23] - and single-use nitrile gloves [180] should be worn during all procedures [71].

Clothes should ideally be cleaned with a lint roller to remove any loose fibres [132].

A fibre could be taken from the lab coat during each day of laboratory analysis and analysed under the optical microscope to check for fibres with similar appearance in samples [132].

5.6.3 Reagents and materials

All solutions used should be previously filtered.

Only glass and metal materials should be used [23].

Prior to use, all glassware should be washed once with filtered 70% ethanol and three times with filtered (0.45 µm) ultrapure water [26] before being immediately wrapped in foil [29].

All samples and equipment should be covered with glass petri dishes or aluminium foil after cleaning [16].

If using glass bottles, all plastic components should be removed. The bottles should then be filled with ultrapure water and placed in a sonicating bath for 5 min to remove any potential particles from the inside surface.

All openings, including bottles, filtration unit and beakers, should be covered with aluminium foil to prevent airborne contamination [134].

5.6.4 Preparation of filters

Glass fibre filters are carefully wrapped with aluminium foil and heated at 450 °C for 4 h prior to use [16].

Once conditioned, filters should only be manipulated inside the laminar flow hood, including transfer to Petri dishes, mounting in the sample inlet, and transfer to Petri dishes after aerosol collection [131].

5.6.5 Sampling step

Suspended particulate samplers and passive samplers should be rinsed with filtered pure water (Whatman GF/A, 1.6 μm) and/or with ethanol before use [135].

During sampling, personnel should move away from the sampler to prevent contamination [136], possibly downwind.

After collection, the collected samples should be preserved in a dust-free glass petri dish, wrapped in aluminium foil and transported back to the laboratory horizontally [136].

5.6.6 Sample preparation step

During all sample preparation steps such as digestion and/or flotation separation, samples should be covered with a watch glass or aluminium foil.

5.6.7 Sample analysis step

The entire process of sample identification and measurement should ideally be done in a dust-free room [136].

5.6.8 Blanks

Running blanks is important to account for background contamination during sampling, laboratory procedures, quantification and characterization of nano- and microplastics.

A procedural (i.e., field) blank filter should be acquired for each sampling date by exposing a filter through the entire field sampling protocol, but without drawing air through the filter. The filter is subjected to the same laboratory digestion and identification processes as the actual samples [16].

6 Conclusions

Micro- and nanoplastics are widespread in the environment, even infiltrating the atmosphere. However, quantifying their presence in the air presents numerous challenges. The absence of standardised sampling and analysis methods complicates cross-study comparisons. Furthermore, each analytical technique available has varying size or mass detection limits and selectivity, resulting in different studies focusing on distinct particle size ranges, leaving gaps in coverage. In the context of airborne particles, discrepancies in size detection limits hinder the assessment of human exposure to microplastics through inhalation, a crucial factor in understanding their potential health and environmental repercussions. To obtain accurate results, it is also imperative to prevent contamination during both the sampling process and sample analysis, thereby minimizing the risk of false data.

This report addresses some of these challenges, which are pivotal for a precise evaluation of the presence of microplastics and their potential impact on health and the environment. Most previous studies have primarily relied on optical microscopy and spectroscopic methods like Raman or FTIR. These techniques enable the identification of particles down to approximately 5-10 µm in size. However, particles that penetrate deep into the lungs typically measure less than 3 µm (Bronchus: 2-3 µm; Bronchiole: 1-2 µm; Alveoli: 0.1-1 µm), and optical or spectroscopic methods currently cannot detect particles of this size. A possible strategy to encompass these smaller particles could involve combining the sampling of PM2.5 and PM1 and utilizing pyrolysis GC-MS or other thermoanalytical methods for analysis. The primary challenge here is to collect a sufficient mass on the filter to reach the mass detection limit.

Further research is necessary to tackle these challenges and to establish standardised protocols that facilitate comparisons across different studies.

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List of abbreviations

Abbreviations	Definitions
ABS	Acrylonitrile butadiene styrene
a.s.l.	Above sea level
ATR	Attenuated total reflectance
DWD	Drinking Water Directive
EC	European Commission
EDS	Energy dispersive spectroscopy
EPS	Expanded polystyrene
EU	European Union
EVA	Ethylene-vinyl acetate rubber
FPA	Focal pane array
FTIR	Fourier-transform infrared spectroscopy
GC-MS	Gas chromatography coupled to mass-spectrometry
MPs	Microplastics
MNPs	Micro- and nanoplastics
NPs	Nanoplastics
PA	Polyamide
PAN	Polyacrylnitrile
PBR	Poly butadiene rubber
PE	Polyethylene
PES	Polyethersulfone
PET	Polyethylene terephthalate
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
PM2.5	Particulate matter, which represents fine inhalable particles with a diameter of 2.5 micrometers or smaller.
PM10	Particulate matter, which represents inhalable particles with a diameter of 10 micrometers or smaller
PP	Polypropylene

Abbreviations	Definitions
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PS	Polystyrene
PSU	Polysulfone
PTFE	Polytetrafluoroethylene
PU/PUR	Polyurethane
PVA	Polyvinyl alcohol
PVC	Polyvinylchloride
pyGC-MS	Pyrolysis gas chromatography-mass spectrometry
R&D	Research and Development
SBR	Styrene-butadiene rubber (random copolymer)
SBS	Styrene-butadiene styrene (block copolymer)
SEM	Scanning electron microscopy
SIS	Styrene isoprene rubber
SOP	Standard operating procedure
TED-GC-MS	Thermal extraction desorption-gas chromatography-mass spectrometry
TGA	Thermogravimetric Analysis
TIM	Tool for innovative monitoring
TSP	Total suspended particulates

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Annexes

Annex 1. Complete list of potentially relevant documents for further analysis

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