A review on the occurrence, distribution, characteristics, and analysis methods of microplastic pollution in ecosystems

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ABSTRACT
Although plastic materials play an essential role in life, the intensive production of plastic products and mismanagement of plastic waste worldwide have resulted in microplastic pollution. The two major characteristics of environmental microplastics are having small size and resistance to degradation, which make microplastics a persistent organic pollutant. As microplastic pollution has been observed in diverse environmental matrices, it has attracted great attention of scholars globally. Over the last decade, scholars have mainly documented the particle properties of microplastics, such as size, shape or color and their adverse effects on organisms. However, no research has updated on environmental microplastics from the perspective of multi-media. Our review first summarized the literature in the occurrence, distribution, and characteristics of microplastics in three kinds of environmental matrices (water, soil, and air) to the public. We then identify the methodological challenges in researches and discuss the advantages and limitations of popular methods to analyze environmental microplastics. Eventually, our paper highlights the current challenges and proposes suggestions for the future research on microplastic pollution.

1. Introduction
Plastics are made of multiple natural and synthetic polymers [1]. Because of the advantages in low cost, versatility, durability and strength, plastics are widely used in so various scenarios, such as automobiles, buildings, machinery, medicine, aerospace, packing and agriculture [2]. The total production amount of plastic out in 2018 reached 3.6×10^8 tons [3]. Mass production, long degradation time and improper disposal of plastics are leading to a visible accumulation of plastic pollution. While larger debris are easier to be collected, microplastics, defined as small plastic debris (<5 mm) [4], cannot be recycled and totally removed.

When imported into the environment, plastics are bound to experience progressive breakdown under the action of physical, chemical and biological factors [5]. Then, secondary microplastics gradually become the major pollution in ecosystems. Moreover, plastics are designed to be small in size, known as primary microplastics, which may be added as ingredients in cosmetic articles, personal care products and medicines. These are commonly from domestic and industrial sewerage discharge. For instance, body scrubs containing pellets microplastics are directly added to environment through sewerage [6].

Given the increasing output of microplastics, they are ubiquitous in different environmental matrices, including marine- and fresh-water [7,8], sea ice [9], sediments [10], soil [11], and the atmosphere [12].

Previous studies have shown that microplastic pollution is found in mountains, lakes [13], the remote Gobi Desert with rare human presence and karst groundwater [14]. Furthermore, because of their size, microplastics can be taken up by organisms, enter the food web, transfer along the chain, and accumulate at higher trophic levels [15]. Thus, microplastic pollution has become an ever-increasingly concerning environmental issue. Microplastics have the potential to absorb inorganic pollutants and persistent organic pollutants (POPs) from their nearby environment as they have an increased surface-to-volume ratio and minute size, causing detrimental effects on organisms upon exposure [16,17]. As microplastics are also prone to enter soil and water via wind, rainfall, surface run-off and atmospheric deposition, the impact of microplastics on the environment is enormous and extensive. The physicochemical properties (e.g., size, color, shape, density, component, and surface charges) of microplastics influence their environmental behaviors such as aggregation, migration and degradation [18,19].

To better understand the abundance of microplastics in ecosystems and their risk, numerous studies have focused on monitoring the quantification and identification of microplastics in various environmental matrices around the world [20–22]. However, there have been no standardized protocols for the analysis procedures, which creates a barrier of a spatial and temporal comparison among the published data.
Hence, it is urgent to establish standardized operational protocols.

Due to their high production amounts and application in the past decades, considerable research has focused on microplastic pollution in different environmental matrices. Based on the available literature, our review aims to provide a comprehensive overview of global microplastic pollution. Our review focuses on four topics: (1) Describe the potential sources, distribution, abundance and characteristics of microplastics in different matrices; (2) Delineate the migration and fate of microplastics in water, soil and atmosphere on a global scale; (3) Clarify the current knowledge on common methods for identification and quantification of microplastics in ecosystems as well as discuss advantages and limitations of these approaches in depth during the whole process; (4) Discuss knowledge gaps of microplastics and put forward some suggestions for further research. Finally, this review paper aims to identify knowledge gaps and propose future research directions and perspectives.

2. The occurrence and distribution of microplastics

The sources of microplastics in the aquatic environments are wide and can be roughly divided into land-based input and atmospheric deposition [23]. Table 1 provides examples of the average concentration of microplastics in environments. Due to improper management of plastic waste (e.g. towns, tourism, agriculture, and industry), ship transportation, fishery activities, and other processes, plastics are very likely to directly enter the water environment and cause a certain degree of plastic pollution [24–26]. The wastewater discharge containing synthetic textile and personal care products is the dominant source of fibers and pellets found in freshwater. The poor management of landfills also contribute to the export of microplastics in the aquatic environment [27–29]. The sludge in the sewage treatment plant is also a major source of microplastic pollution [30]. In particularly, the runoff after rainstorms or floods on landfill sites could deliver these microplastics into their nearby environment. Therefore, the amount of plastics transported increases with the degree of the erosion. Besides, rainfall could lead to resuspension of microplastics in surface water [31,32]. In addition, atmospheric deposition may play an important source of microplastic pollution in the aquatic environment [33]. Studies demonstrated that the amount of microplastics deposited in the atmosphere everyday reaches 29–280 particles/km². Through long-distance atmospheric migration and settlement, microplastics have accumulated in ice and snow, and then the microplastics in sea ice can be exported to seawater after sea ice melted. For instance, researchers found microplastic pollution with a maximum abundance of 1.54×10⁵ items/L in snow in the Arctic and high mountain regions of Europe [34].

Surface runoff, sewage irrigation, agricultural facilities (e.g. agricultural mulch), fertilizer use (e.g. sludge, organic fertilizer), plastic waste, and atmospheric deposition mostly attribute to microplastic pollution in soils [35,36]. At present, microplastics are found in soil ecosystems such as farmland, woodland, industrial land and construction land, including films, fibers, fragments, particles, and foams, as well as polystyrene, polyvinyl chloride, and polyethylene (Table 1) [37–40]. The abundance of microplastics varies from almost none to tens of thousands per kilogram across different sites. Sewage irrigation has important applications in many parts of the world, especially in arid and semiarid areas, and has largely alleviated the water crisis. However, at the same time, microplastics of high concentration in sewage directly enter the soil during the irrigation process [41]. It is estimated that the world’s farmland sewage irrigated area exceeds 2.0×10⁸ hm², accounting for approximately 10% of the total irrigated area [42]. Due to its significant economic benefits, mulch film is widely used in agricultural production around the world and has become one of the main sources of secondary microplastics in farmland [43]. In 2016, the global output of agricultural plastic film was 4×10⁸ tons [44]. Removing total mulch film from farmland is an arduous and time-consuming task. Improper disposal of agricultural plastic films may result in the accumulation of microplastics [45]. Spontaneously, the plastic fragments contained in the soil may be further fragmented under the actions of ultraviolet light and shearing forces in soils [46]. Sludge is commonly used as fertilizer and soil amendment. In Europe and North America, the farmland utilization rate of surplus sludge exceeds 50%, and 6.3×10⁶–4.3×10⁷ tons and 4.4×10⁶–3.0×10⁵ tons of microplastics are introduced, respectively [47,48]. With the development of the economy and improved living standards, the amount of domestic plastics waste has also increased rapidly. Similar to aquatic environments, microplastics can also come from plastic waste [49]. Poorly managed plastic garbage is usually scattered near roads, in the soil, or illegal dumping sites. According to statistics, 4.97 billion tons of waste is piled up in landfills. Particles and fibers generated from landfills can enter the soil ecosystem through atmospheric deposition [50].

In addition, there is a characteristic solid medium, that is, ground area dust or especially refers to the urban street dust. It mainly comes from the deposition of large suspended particles in the atmosphere or the accumulation of various surface particles closely related to human activities [51]. Since road dust can easily follow surface runoff directly into water bodies without any treatment, dust deposition is likely to be a potential pollution source of microplastic pollution.
**Table 1.** The abundance of microplastics and its properties in studies.

| Location                                      | Sample                        | Abundance | Size       | Shape                   | Color                      | Polymer type                  | Ref  |
|-----------------------------------------------|-------------------------------|-----------|------------|-------------------------|----------------------------|--------------------------------|------|
| Chong Ming island, China                      | Surface water                 | 0–259 items/m² | < 1 mm     | Fragment (9.2%)         | White                      | PE (37.3%) [91]               |      |
|                                              | Sediments                     | 10–60 items/kg | < 1 mm     | Fiber (66.7%)           | Transparent                | PP (28.6%)                    |      |
| Southern Mariana Trench                       | Bottom water                  | 2.06–13.51 items/1–3 mm L |           | Fiber                   | Blue, Red, green, white, purple | PET (19%), PA (14%), PVC (13%), PUR (12%), PS (11%), |      |
|                                              | Sediments                     | Polyester (11%), Rayon (9%) 200–2200 items/L | 0.1–0.5 mm | Fiber                   | Polyester (19%), PP (15%), PUR (14%), PA (12%), PVC (10%), PE (9%), Rayon (10%), | [24] |
| Spanish Mediterranean continental shelf       | Sediments                     | 113.2 ± 88.9 items/kg d.w | 0.5–1 mm (35%) | 1–2 mm (34%) | 2–5 mm (31%) | Fiber (82.9%) | Transparent | / | [141] |
| Taihu Lake, China                             | Surface water                 | 3.4–25.8 items/L | 100–333 μm | Fiber (48–81%)          | Transparent PET (29%)       | White (44%)               | [89] |
|                                              | Sediments                     | 11.0–234.6 items/kg d.w |           | Sheet, line, / fragment, and foam | PE, PP, PET [33] | PVC and PS | [37] |
| Tibet plateau, China                          | Sediments                     | 563 items/m² | 1–5 mm     | Granule, / fiber, fragment and foam | PA (32.5%), PP (28.8%), PS (16.9%), PE (4.2%), PVC (1.9%) | [33] |
| Wuhan city, China                             | Agricultural soils            | 320–12,560 items/kg d.w | < 0.2 mm (70%) | / | / | White (51%) | / | [38] |
| Baoding city, China                           | Farmland soil and industrial soil | / | 0–35 μm | / | / | PA (23.3%), PET (16.3%) | [39] |
| Yellow river delta, China                     | Wetland                       | 136–2060 items/kg | 13 μm-5 mm | Granule and/ fragment (30%), fiber (20%), film (11%) | PE, PC [39] | PET, PC [39] | [39] |
| Bohai Sea and the Yellow Sea, China           | Coastal soil                  | 1.3–14,712.5 items/kg d.w | < 1 mm (60%) | Flake (69%),/ foam (27.8%), fragment (11%), and fiber (10%) | PE, PP, PS, PEU | [40] |
| Hangzhou bay, China                           | Agricultural soils            | 571 pieces/kg | 1–3 mm     | Fragment and fiber | PP, PE, PA, | [11] |
| Polyester Illinois, USA                       | Karst groundwater             | 15.2 items/L | / | Fiber                   | Blue (65%), PE Red (15%), gray (13%) | [14] |
| Lake Ulansuhai, China                         | Freshwater                    | 1760 ± 710 to 10,120 ± 4090 items/L | < 2 mm | Fiber                   | Black PE (63.7%) | [115] | (Continued) |
Table 1. (Continued).

| Location                          | Sample                  | Abundance        | Size                       | Shape    | Color               | Polymer type      | Ref          |
|-----------------------------------|-------------------------|------------------|----------------------------|----------|---------------------|-------------------|--------------|
| Nordic Seas                       | Surface water           | EGC: 1.19 ± 0.28  | 0.1–2 mm (63.9%)           | Fiber    | Transparent (87.6%), blue (6.6%) | Polyester (35%), cellulose (9%), PE (9%), PP (8%), PS (2%), PVC (6%), PA (5%) | [142]        |
|                                  |                         | GSG: 2.43 ± 0.84  | 0.5–5 mm (41.9%)           | Fiber    | Transparent (76.2%), blue (16.7%) |                   |              |
|                                  |                         |                  |                            |          | Fragment (11.21%),   |                   |              |
|                                  |                         |                  |                            |          | Fiber (65%) /       |                   |              |
| Ciwalengke River, Indonesia       | Surface water           | 5.85 ± 3.28 items/50–100 μm L |                   |          |                     | PE, nylon         | [143]        |
| Lake Hovsgol, Mongolia.           | Freshwater              | 20,264 particles/ km² | 0.333–0.999 mm (41%)      | Fiber    | Fragment and film   |                   | [57]         |
|                                  |                         |                  |                            |          |                     |                   |              |
| The Laurentian Great Lakes, USA   | Surface water           | 43,000 particles/ km² | 0.355–0.999 mm (81%); 1,000–4,749 mm (17%); >4,75 mm (2%) | Fragment, film, pellet, line |                   | PE, nylon         | [143]        |
| Poyang Lake, China                | Surface water           | 5–34 items/L     | 0.1–0.5 mm (73.1%)        | Fiber    | Granule (65.9%)     | White, black, coloured, | [52]         |
| transparent                      | Air                     | 2.93–20.17 items/250–500 μm g |                   |          |                     | Black (29.9%); yellow (26.4%) |              |
| Tehran metropolis, Iran           | Air                     | PP (37%), PE (30%), PVC (8%), nylon (15%)[10] |                   |          |                     |                   |              |
| Dongguan city, China              | Atmospheric fallout      | 175–313 particles/m²/ day |                   | Film, foam, |                     |                   |              |
| transparent                      |                         | /                |                            |          |                     | PE, PP, PS [94] |              |
| YanTai city, China               | Air                     | 130–624 items/m²/day | < 0.5 mm (74%)            | Fiber (95%) |                     | Polyester (40%), PVC (10%) | [125]        |
| Asaluyeh County, Iran            | Street dust             | 200–900 particles/15 g | < 100 μm (79%)            | Spherule (74%); film (14%) |                     | White and yellow (26%) |              |
| transparent (66%)                | /                       | [51]             |                             |          |                     |                   |              |
| Paris city, France               | Indoor air              | 1–60 items/m²    | < 3250 μm (79%)           | Fiber    |                     | PP, PE, PA [54] |              |
|                                  | Outdoor air             | 0.3–1.5 items/m²/2 < 1650 μm |                   |          |                     | PE, PVA, PTFE |              |
| Hamburg, Germany                 | Atmospheric deposition  | 275 particles/m²/ day | < 63 μm                  | Fragment (95%); fiber (5%) |                     | PE, PA, PET | [56]         |
| French Pyrenees                  | Atmospheric deposition  | 365 particles/m²/ day | 50–2600 μm               | Fragment, film, fiber |                     | PS, PP, PE |              |

There are also studies on microplastic pollution in dust. For example, the abundance of granular and fibrous microplastics in urban dust detected by Iran is 2.93–20.17 items/g dry dust [52]. The sources of microplastics in the atmosphere are diverse and complex. Industrial dust emissions, clothing, living facilities, and other daily life processes, as well as microplastics generated during plastic waste stacking, landfilling, or burning, may all become sources of microplastics in the atmosphere [53]. Microplastics are naturally light in weight and can, therefore, be suspended and transported by air in the atmosphere. Dris et al. observed that the indoor fiber concentration was 1.0–60.0 fibers/m³, and the sedimentation rate was 1586–11,130 fibers/day/m² [54]. It is proposed that fibers are the main source of microplastic pollution in the atmosphere (Table 1). The more common types of microplastics in the atmosphere are fragments and films, mainly composed of natural fibers and synthetic fibers [55]. Atmospheric microplastics flow and settle in the process of long-distance transportation [56]. In areas far away from pollution sources, the wind current may be the major force to transport microplastic pollution [57]. Many microfibers found in the mountain snow further proves the possibility of long-distance transportation of microplastics with atmospheric activities [53].

The transport of microplastics controls their temporal and spatial allocation among the aquatic systems, soil and the atmosphere. Microplastics can migrate between
different environmental compartments, for instance, wind and surface runoff can transfer microplastics from inland to marine [58] (Figure 1). Microplastics in the soil can also be transported into nearby environmental matrices, such as air and water, through wind erosion, runoff and anthropogenic activities [41]. The microplastic on soil surfaces can be easily suspended in the air through airflow and wind. Within the soil, the transport of them is dependent on a variety of factors, such as soil texture, aggregation, cracking and biotic transport (soil biodiversity and soil community composition) [59]. Agricultural practices, soil cracks, soil pores and root growth enhance microplastics vertical movement, while organisms have also been found to be involved in the transport and redistribution of microplastics in soil [35]. In addition, microplastics in soil have the potential to enter groundwater [14]. Microplastics in the atmosphere could result in aquatic and terrestrial microplastic pollution [60]. The transport of microplastics and their fallout or deposition in the atmosphere is influenced by many factors, such as wind speed, wind direction, rain, and particle density [56]. Part of microplastics keep suspended in the atmosphere, while the other part settles via dry and wet deposition processes. Then, atmospheric microplastics may be resuspended in the air, which eventually settles in the terrestrial and aquatic systems through surface [50]. The presence of microplastics in remote areas such as Tibetan glaciers can also be attributed to the long-distance transportation of atmospheric microplastics by wind [57]. The aquatic environment is an active region that has strong and continuous hydrodynamic activities such as rainstorms, monsoons, waves, tides and ocean current. Microplastics can move between the water environment and the land under the action of tide and floods [59]. Furthermore, winds and the associated wave action may cause vertical mixing within the water column, which resuspends plastics from the bottom. The transportation of microplastics is also affected by their inherent properties including density, size, color, and shape [61]. The microplastics from the production and consumption of plastic wastes are transported by surface through watersheds into rivers. Rivers are one of the important ways for microplastics transportation, transporting 88%–95% of the global microplastic load to the vicinity of ocean estuaries. In the freshwater, the density of microplastics may play a major role in the vertical distribution of microplastics. Low-density microplastics often appear on the surface layer, while high-density microplastics settle down [62,63].

3. Characteristics of microplastics

3.1 The physical properties of microplastics

The physical properties of microplastics mainly include the size, density, color, shape, and crystallinity of microplastics, which are usually measured with the help of microscopes. These properties can significantly influence environmental behaviors of microplastics and determine their toxic effects on organisms [64]. The size of microplastics is one of the most fundamental indicators in the study of microplastics. The characteristics of the size distribution of microplastics in each study depend on the sampling methods and separation methods. Besides, this characteristic is affected by the pore size of the filter membrane [65]. Determining the size of microplastics is of great significance in research, as size is the most fundamental feature to distinguish the new type of microplastics from traditional pollutants [66]. Studies have shown that the size affects the accuracy of counting. The smaller the size is, the greater
the error, and the larger the size is, the smaller the error [67]. The density of microplastics varies depending on the type of polymers and the production process. For example, the density of PP, PE and PVC is 0.85–0.94 g/cm³, 0.92–0.97 g/cm³, and 1.38 g/cm³, respectively [68]. Microplastics with less density than water float on the surface or suspend in water and then they may be ingested by organisms living in the upper and middle level in water [69]. The color of microplastics can be used as a useful tool for determining the potential origin sources of microplastics. Microplastics are commonly found in many colors, such as pink, transparent, red, yellow, blue, green, black, brown, grey, purple and white. In environmental media, colorful samples are easier to pick out, while dull samples tend to be ignored. The color can also determine their residence time and degradation degree in the environment. Different degrees of fading represent the exposure time of the sample in the environment [70,71]. The possibility of oxidation and degree of weathering increase with the prolongation of exposure time [72]. Microplastics exist in a wide variety of shapes in the environment, including films, foams, fragments, sponges, beads, fibers, flakes, and pellets. The shape of microplastics is so important that it can provide information and a basis for traceability. Some studies have revealed that the influence of microplastics on adsorption, desorption and ecological effects are corresponded to different shapes. Samples with sharp edges indicate their recent intrusion into the environment, while smooth edges indicate long residence time because of various environmental forces may form relatively smooth edges. At present, pellets, thin-films, fragments, foams, and fibers are the most dominant types of microplastics in the environment [73]. Crystallinity is another important polymer property. It refers to the mass ratio or volume ratio of the crystalline region in polymers [74]. Crystallinity ranges from 30% to 85% and the mechanical properties of microplastics are dependent on the extent of crystalline regions on the polymers [75]. According to the degree of crystallinity, polymers can be divided into three types including crystallinity polymers, semicrystalline polymers, and amorphous polymers. It is worth noting that there are no polymers belonging to crystallinity polymers [76]. PE, PP and PA have been shown to be of high crystallinity, while PC, PS, PVC and PMMA are of amorphous polymers [77] (Table 2). Semicrystalline polymers are characterized by high strength and resistance, while amorphous polymers are soft and flexible [78]. The crystallinity of environmental microplastics changes gradually with aging owing to the preferential degradation of amorphous polymers or the polymer chain molecular rearrangement [79,80].

### 3.2 The chemical properties of microplastics

The chemical properties of microplastics mainly include to the chemical composition and surface groups. Microplastics consist of polymers, additives (antioxidants, plasticizers), dyes, and pollutants adsorbed on the surface of them. These chemicals are easily released into the environment during the production, usage, and weathering of plastics [81,82]. A portion of the influence of environmental microplastics comes from the leakage of them, such as PVC, which is considered the most harmful due to its high chlorine content and the release of dioxins [83]. The leaching rate of a chemical substance is connection with the physical properties of polymers, such as the porosity of the polymer, the molecular size, and the degree of degradation [84]. The surface aging can promote the leakage of additives. The effect is noticeable and it depends on the concentration and distribution coefficient of the chemicals in the parent plastic [85]. In addition, the diversity of surface groups is the key factor affecting the associations with other chemicals. In primary microplastics, different functional groups are artificially modified, and their surface oxidation capacity is also different [86]. On the other hand, environmental microplastics may continue to oxidize, which leads to a gradual increase in their surface group content during their aging and degradation [87]. For example, after weathering, the number of carbonyl groups in PP increased significantly [88].

### 4. Analysis methods of microplastics

To attain a better understanding of the environmental effects of microplastics, a wide variety of techniques are applied for monitoring work. A complete microplastics analysis includes three stages: collection of microplastics, recovery of microplastics, identification

| Polymer | Chemical formula | Density (g/cm³) | Crystallinity | Applications |
|---------|------------------|----------------|---------------|--------------|
| PE      | (C₂H₄)ₙ          | 0.89–0.98      | Semi-crystalline | Packaging bags; plastic film; agricultural mulch; toys; milk bottles; microbeads. |
| PP      | (C₃H₆)ₙ          | 0.85–0.92      | Semi-crystalline | Microwave containers; medicine bottles; dishware; microbeads. |
| PS      | (C₃H₆)ₙ          | 1.02–1.08      | Amorphous       | Plastic-film dinnerware; meat trays; building insulation; plates. |
| PVC     | (C₂H₃Cl)ₙ        | 1.38–1.58      | Amorphous       | Water pipes, wallboard, artificial leather, tablecloth, raincoat. |
| PET     | (C₂H₄O₂)n        | 1.38–1.41      | Semi-crystalline | Bottles for water, soft drinks, juices. |
| PA6     | (C₆H₇NO)n        | 1.13–1.50      | Semi-crystalline | Wear-resistant parts, transmission structure parts, chemical machinery parts. |
| POM     | (C₅H₈O₃)n        | 1.41–1.43      | Semi-crystalline | Machine parts, auto parts, gears. |
and quantification of microplastics [20,27,32]. These three stages also have various methods in water, soil, air and biological samples (Figure 2).

### 4.1 Collection of microplastics

#### 4.1.1 Water samples

Considering the density of daily types of microplastics, they usually float on the surface of water or suspend in water. Therefore, manta trawls and water column sampling are generally used equipment. Abundances of microplastics recovered from the water matrix are directly influenced by the mesh size of the sampling tools. The employment of sampling tools with different mesh size makes it difficult to compare the available monitoring data. The mesh size of the sampling tools varies from tens of microns to millimeters, with the most common aperture size being 300 μm to 333 μm. To ensure the maximum collection of microplastics at the surface, a half of the trawl was in water [89]. The collection efficiency was also related to trawling time and local wind speed. To reduce the influence of wind speed in the collection, researchers decided to evenly obtain samples periodically with different wind speeds. The direction of the sampled trawl is generally determined by the wind [90]. Moreover, if the trawling time was too long, trawls would be blocking resulting the measured abundance might be smaller than the real one. The main shape of the water-collector device was cylindrical, and the in-outlet was set at both ends. Recently, an improved water-collector which is made of metal materials was applied. The difference between this one and the old one is the capability of collecting volume. The new one can collect the volume of 100 L approximately per run, which makes sense of the abundance of microplastics in samples. A metal filter with a mesh size of 300 μm is installed in the middle between the inlet and the pump and then water samples are filtered directly under the pump’s working. Finally, it is also easy to collect the filter membrane. This equipment has the advantages of decreasing of the transportation cost and so on [91]. However, there are some shortcomings in this method. It was difficult to ensure that there was enough power to keep the pump running all the time. Then, the filter membrane was blocked frequently, requiring high-frequency replacement. The last sampling step was that 5% formaldehyde or ethanol was added and then samples should be stored at low temperature for testing.

Plankton net sampling is a commonly used equipment in conjunction with water collectors. The water samples in the water collector were filtered with plankton nets (333 μm). The residue on the net was collected in a glass bottle using deionized water. Formaldehyde (5%) is added and stored at 4°C for testing [89]. The superiority of this method is reducing the sample volume and gathering microplastics to a great extent. Because the sampling depth can be controlled by the water collector method, the combination of the water collector method and the plankton net method is more suitable for some investigations which are intended to collect water samples at different depth.

#### 4.1.2 Soil samples

Soil samples are so easily affected by human interaction that it is even more difficult to obtain representative samples. It is recommended to use composite sampling, that is, samples from multiple
discrete sites of the same sampling area are combined and homogenized into a single sample [92]. Small sampling units (1 m × 1 m, 15 cm × 15 cm and 20 cm × 20 cm) are the most commonly used techniques [33,35,91]. When the depth of pollution is to be understood, stratified samplings should be conducted [89]. The sampling tool of soil are stainless steel corer, shovels, metal grabs or box corers [40,43,50]. Soil samples are usually stored in bags made of non-plastic, such as aluminum foil bags or glass bottles. The soil samples were stored at 4°C and naturally air-dried before analysis.

4.1.3 Atmospheric samples

Dust [93], atmospheric fallout [94] and suspended atmospheric microplastics (SAMPs) [95] are the main types of air samples among studies. Passive atmospheric deposition and active samplers are used for sampling microplastics in the air. Dust and atmospheric fallout are always passive atmospheric deposition. Street dust samples were collected by gently sweeping the study area with a local anti-static wooden brush made from dry stems of plants and a metallic pan to avoid plastic contamination [93]. The fallout was collected through a sampling device equipped with a glass bottle and a fixed support [94]. A stainless-steel funnel was applied to collect fallout, that is, a 20 L glass bottle placed at the bottom of the funnel to collect the water. The funnel was rinsed with water to facilitate collecting particles adhering to the funnel. Passive atmospheric deposition is always suitable for an unobstructed sampling location, such as squares and the roofs of buildings. This method allows long-term continuous collection in remote areas without power support, while investigators regularly transfer and preserve samples carefully as well [96]. SAMPs tend to be collected by an active sampler system consisting of a pump and a device with filters. SAMPs were collected using a KB-120 F type intelligent middle flow total suspended particulate sampler with an intake flow rate of 100 ± 0.1 L/min in triplicate over 1 h. This device can filter approximately 6 m³ of per sample. To simulate the way of human inhalation, the filtering instrument was placed horizontally at a height of 1.2 m and 1.7 m above the ground [97]. Compared with the passive sampling method, this method can rapidly finish the collection and adjust the flow rate and time according to different requirements [98]. Notably, weather conditions should be recorded during the sampling process to better understand the influence of meteorological changes on the abundance of microplastics. In conclusion, sampling locations, height, period, weather and sampling methods need to be considered based on aims of the study.

4.2 Recovery of microplastics

Because samples tend to absorb large amounts of organic matter and the gravel, so it is essential to remove them for subsequent separation, identification and characterization. This stage is known as the recovery of microplastics, including suspension, elutriation, sieving, digestion and so on. In most cases, researchers make use of several kinds of methods meanwhile and repeat this process twice or three times.

4.2.1 Suspension

Sediment is a complex heterogeneous system containing many impurities, so suspension is an indispensable process in separation and extraction. The suspension method is the most common and accepted extraction method for microplastics and it is based on the density difference between microplastics and other unwanted material. NaCl solution (1.2 g/cm³) is the most frequently used salt solution in suspension [91,92,99,100] and Na⁺ has a positive influence on particle dispersion [35]. However, the density of NaCl solution is lower than the density of PVC and PET, leading to underestimation in qualification of microplastics. To address this problem, some higher-density salt solutions, such as NaBr, NaI, ZnBr₂, ZnCl₂, and CaCl₂, have been successfully employed in many studies and considerably increased the extraction efficiency for the high-density microplastics. The results of a recovery experiment showed that the highest recovery rate of ZnBr₂ solution (1.71 g/cm³) could achieve 95% with a single wash in the treatment of mixed samples [101]. Nevertheless, ZnBr₂ solution is expensive and environmentally hazardous, so this method is not the best selection. The density of ZnCl₂ (1.55 g/cm³) is similar to that of ZnBr₂. Although it is corrosive and harmful, recycling and washing could address this issue. The experimental recovery data show that the separation effect is better than that of NaCl solution obviously [54,93,102–104]. In addition, CaCl₂ solution (1.5 g/cm³) is used for separation tests based on its eco-friendliness, density, and low cost [105]. Nevertheless, due to the flocculation of calcium ions (Ca²⁺) on organic matter, organic matter remained. Compared with ZnBr₂ and ZnCl₂, NaI (1.6 g/cm³) solution is more economically dominant and has less impact on the environment [106]. It is worth noting that the visual impact of the reaction of NaI and starch should be avoided during this procedure. In addition to the above five common salt solutions, potassium formate (1.5 g/cm³) is applied in the separation of microplastics, and there is no toxicity [33]. Furthermore, the separation have something with the size and shape of microplastics. For example, NaBr solution of the same density displayed a higher efficiency on smaller microplastics. Alkox-Silyl Induced Agglomeration, a new decoupling technique
based on the Agglomeration reaction, has the obvious advantage of making the separation process, that is, independent of the physical properties of microplastics and external factors (pH, temperature and air pressure), and making the Agglomeration 666 times [107]. There are also new emerging technologies developed based on density separation theory, such as Pressurized fluid extraction (PFE) [35] and the Air-induced overflow (AOI) [100]. Some optimizations, such as adding olive oil to a suspension device to aggregate microplastics attached to the glass walls, are in development [108]. Ultrasonic treatment, stirring-agitation, or continuous flow are combined to isolate microplastics adhered as much as possible. Repeating the extraction process is another effective way to achieve higher extraction efficiency.

4.2.2 Elutriation
Elutriation is a process established on density separation. Particles are separated according to the difference in density by the running of the flow of water and gas in the column. The lighter float upper layer and the heavier part float in the column or sink to the bottom. During the operation, it is necessary to constantly adjust the rate of water and aeration to ensure that the separation is complete [106]. Some optimized separation devices, OC-T [153], are in development. ZnCl₂ solution is regarded as suspension. The extraction efficiencies of PP, PE, PET and PVC using a ZnCl₂ solution can achieve 95% [27].

4.2.3 Sieving
Sieving is designed to pick up visible microplastics (>1 mm) from atmospheric samples or sediment samples. After sieving, we can get particles with different size ranges [109]. The sieve is made of metal and the mesh size mainly depends on the desired size range of microplastics. Sieving assists in reducing the sample volume for subsequent extraction [99].

4.2.4 Digestion
Microplastics inevitably interact with the biotic and abiotic components in ecosystems. The surface of microplastics is almost attached to organic matter and inorganic substances, forming biofilms. Digestion of the environmental matrix is essential for a more accurate identification of microplastics [110]. At present, the digestion agents mainly consist of strong acids, strong alkalinity, oxidizers, and enzyme preparation (Table 3). Nitric acid (HNO₃) is accepted in the Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR) as a monitoring protocol. Even though it has the ability to react with microplastics, it cannot eliminate the most organic matter rapidly compared with other digestions [111]. In the test using 65% HNO₃ in digestion, the recovery of PE and PP is 66%–100%, while that of PVC was only 3.3%, indicating that there is a reaction occurred between HNO₃ and PVC [112]. In addition, a ratio of 1:4 (v/v) mixture of 65% nitric acid (HNO₃) and 68% perchloric acid (HClO₄) is suggested as an improvement to isolate microplastics. This method showed that the abundance of microplastics is 0.18 ± 0.14 g/w. w. higher than the result treated with the pure HNO₃ [113]. Therefore, it is worthwhile to study how to improve the digestion efficiency. We can investigate from the aspects of acid concentration regulation, operation temperature, duration and types of microplastics [114]. Meanwhile, to avoid the loss of microplastics such as ABS, PET and PA, NaClO solution has also been adopted as a digestion agent and it can be mixed with potassium hydroxide (KOH) at a ratio of 1:1 (v/v) [35, 105].

Fenton’s reagent (a mixture of H₂O₂ and ferrous ions, Fe⁺²) [27] and hydrogen peroxide (H₂O₂) [115] have been widely used in digestion. When 4 ml 30% H₂O₂ is added to the samples for 7 days, 50%–56% of biogenic organic particles are in dissolution, while the remaining parts had chromogenic reactions such as semitransparent or partial dissolution. Changes also occurred in some particles, that is, PA, PC and PP become significantly smaller, thinner and more transparent; PET and LDPE are fragmented. Ninety-two percent of biogenic organic particles dissolve completely when the concentration increase to 35% [100]. Moreover, iron dust can be added into H₂O₂ to improve digestion efficacy [57].

| Biota        | Location          | Extraction                                  | Polymer types         | Efficiency | Ref   |
|--------------|-------------------|---------------------------------------------|-----------------------|------------|-------|
| Fish (Salmo trutta) | Southern Tyrrhenian Sea | 500 μg/mL protease K with CaCl₂ + oxidative treatment with 30% H₂O₂ | PS, PE, PMMA.         | 97%        | [108] |
| Asian clams  | Taihu Lake, China | H₂O₂ digestion of soft tissue               | PET, PP, cellophane, terephthalic acid | /          | [89]  |
| The common dolphinfish | The western Mediterranean Sea | Freshwater insects (Chironomus sp., Sphlonurus sp. and Lestes viridis) | theGulf of Guinea (Ogun and Osun rivers) in Nigeria | KOH        | [145] |
| 98.0% ± 0.16 | (10 M) +H₂O₂ (34.5–36.5% v/v) | PP, ABS, CPE, PET | /                      | PE, PP, PS   |       |
| velvet crabs (Necora puber) | Bay of Brest, France | 10% KOH                                     | CA, PE, PA, PC, PET, PMMA, PP, PS, PUR, PVC, EPS | 99%        | [146] |
4.3 Identification and quantification of microplastics

Following the successful separation, target microplastics require further identification. Overall, identifications are made up of the morphological analysis and the chemical analysis. Commonly used approaches for identifications consists of visual observation, staining, spectroscopy and thermal-analytical techniques (Table 4).

4.3.1 Visual identification

Visual identification is the most widely used method, which initially directly selects particles (1–5 mm) and some suspected particles from the mixture samples. It has the advantages of processing a large number of samples quickly and obtaining the physical properties of microplastics including color, shape and size easily. However, owing to different standards from different discriminators and inadequate pretreatment, it leads to make bias of the abundance of microplastics, which is the biggest drawback of this method. To address the issue, several criteria are recommended to be strictly followed, and the difference of multiple counting results is controlled within 10% [90,99]. As microplastics decline in size, the possibility of misidentification increases considerably. Smaller items often further identified with the aid of microscopes such as optical microscopy, stereomicroscope, and scanning electron microscope (SEM). The imaging characteristics of microplastics can be recorded by the combination of optical microscope and stereomicroscope [118]. Compared with the former two microscopes, SEM can provide us the images of microplastics with higher resolution and magnification with a nanoscale threshold. The surface texture of microplastics, such as grooving, pits, fragmentation, and fractures, can also be observed directly to analyze the weathering progress of microplastics [94]. For instance, SEM has been successfully used to examine the degradation of PP in the ocean [95]. Moreover, SEM can connect with energy-dispersive X-ray (EDX), which allows fast morphology analysis, qualitative and quantitative analysis of microplastic composition elements. This technology can identify the type of additives in the polymer [93,119]. However, SEM requires considerable time and effort for sample pre-preparation.

4.3.2 Staining

To improve the accuracy of identification results, the lipophilic dye Nile red and the 1% Rose Bengal stain have been introduced to the area of analysis of microplastics, providing an alternative identification method for smaller microplastics.

The lipophilic dye Nile red is added to the samples and then observed under a fluorescence microscope or UV light photo-box [120,121]. This method is applied in the identification of PE, PP, PS, PC and PU, and PE in the mixture is identified entirely similar to the results using FTIR or infrared (IR) microscopy [121]. One of limitations is the containing of natural organic matter, which leads to overestimate the abundances of microplastics in environmental samples. Therefore, digestion is an indispensable procedure [122].

The average amount of potential microplastics with the 1% Rose Bengal stain decreased in all types of samples (fish, crab, water, soil, and the droppings of waterbird) compared with the samples without staining, and the most significant difference is in the fish samples, from 7.10 ± 3.34 items to 2.10 ± 1.73 items. Because of the color of dye is red, 5.57% of red microplastics are lost after dyeing. Thus, the method is unable to recognize microplastics in red [123,124]. Apart from this limitation, it is a reliable, simple, and economical method that can be used independently without digestion.

4.3.3 Spectroscopy

Spectroscopy is used to provide information about the structure and chemical composition of microplastics. Microplastics are excited in a specific wavelength range to generate specific spectra, and then the spectra obtained from particles are matched with reference library collection to directly identify the types of polymers. Fourier transform infrared (FTIR), Raman spectroscopy, quantitative ¹HNMR spectroscopy, near-infrared spectroscopy (Vis–NIR) and a comprehensive recommendation of atomic force microscopy-based infrared spectroscopy (AFM-IR) are all commonly used in the spectroscopy. Because of the consumption of and high cost, most scholars randomly selected suspected particles for analysis.
Table 4. Analytical techniques currently used for the identification and quantification of microplastics in studies.

| Methods          | Principle and particle size by different analytical methods                                      | Advantages                                                                 | Limitations                                                                 | Ref.       |
|------------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|------------|
| Visual Analysis  | Optical microscope/SEM Fluorescence microscopy                                                 | Samples are identified and counted directly.                              | The particles with size down to micro-meter; Easy to observe their physical features; Short time with low cost. Nile Red stain neutral lipids in biological samples and synthetic polymers in polymer chemistry. The minimum size is 0.63 mm. | [92, 147] |
|                  |                                                                                               |                                                                            | Large errors might be caused by subjectivity of examiner. Limitation of higher than 0.5 mm. Charge effects. Independence concerning the color of microplastics; Slight different compared with the FT-IR; Category the particles according to their surface polarity. Failure in PVC, PA and PE; Co-staining of natural organic material leads to overestimation of microplastics abundances; |           |
| Staining and     | Nile Red+UV light photobox                                                                     |                                                                            |                                                                            |            |
| Staining and     |                                                                                               |                                                                            |                                                                            |            |
| The 1% Rose      | The 1% Rose Bengal stain exclusively stains live and dead cytoplasm and is used to stain normal healthy cells, degenerated cells, dead cells and mucous strands. This method can analyze particles down to 100 μm. | Staining residual organic materials to leave out microplastics; Effective way of reducing the level of false detection of microplastics under the optical microscope without SEM, spectroscopy and thermal degradation. | Inability to distinguish red microplastics; Unknown about the chemical composition of the particle. | [123, 124] |
| Bengal stain     |                                                                                               |                                                                            |                                                                            |            |

(Continued)
| Methods                  | Principle and particle size by different analytical methods | Advantages                                                                 | Limitations                                                                 | Ref.          |
|-------------------------|-------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------|
| Spectroscopic FTIR      | Sample are subjected to infrared radiation with defined range and the exciting vibrations depend on the composition and molecular structure of a substance; Plastic polymers have highly specific IR spectra with distinct band patterns. Larger particles (>500 μm) can be analyzed by ATR-FTIR; Smaller particles (20 μm-500 μm) can be analyzed by micro-FTIR. | Non-destructive, fast and quite reliable; It can combine with many automated tracking systems which scan slices of sample surface to detect the presence of microplastics such as AFM-IR, FPA-FTIR and ATR-FTIR; | The samples below 20 μm might not yield not enough absorbance interpretable spectra; The color of particles and environmental matrix impact on analysis easily; The cost of instrument is high and it requires professional operators. | [4,92,11,126,128,130,147] |
| Raman Spectroscopy      | Raman spectroscopy is vibrational spectroscopy technique based on the inelastic scattering of light that provides information upon the molecular vibrations of a system in the form of a vibrational spectrum. Particles between 1 to 20 μm can be analyzed by Raman spectroscopy coupled microscopy. | Better spatial resolution (down to 1 μm); Wider spectral coverage; Non-destructive; Higher sensitivity to non-polar functional groups; Lower water interference and narrower spectral bands; Low sample amount requirement; Possibility for high throughput screening and environmental friendliness; | Spectra databases is not comprehensive enough; Sample heating due to the of a laser as light source leads to polymer degradation; Prone to fluorescence interference; Time-consuming with the decreasing size; Weak signal; | [69,128,129,149] |
| AFM-IR                  | A technique that couples an infrared laser source to an atomic force microscope; exciting molecular vibrations in the sample using a pulsed infrared laser. AFM-IR can analyze particles down to 50 to 100 nm scale. | AFM-IR increase significantly the sensitivity and the spatial resolution down to 50 to 100 nm scale; The efficiency is strong agreement with FT-IR which allows spectroscopists to directly apply analytical techniques and expertise developed over the last 50 years or more, including the use of extensive material databases for the analysis and identification of unknown components. | High cost and time-consuming; The requirements for sample pre-treatment are very high because we need to get particles with the enough small size so that we can make full use of its advantages. | [136,137] |
| Vis-NIR                 | Vis-NIR measures the amount of light that is reflected from a surface within the wavelength range of 350 to 2500 nm, giving a reflected percentage for peak wavelength. | Faster and scalable compared to other spectroscopy due to avoiding extraction steps; Directly quantifying the amount of microplastics in a sample on-site. | Spectral library is poor and the wavelength range is narrow. | [111,132,133] |
| Quantitative ¹H NMR spectroscopy | Quantitative determination by ¹H NMR is based on the proportional relationship of integrated signal area and number of resonant nuclei. No size limitation. | Fast (about 1 min per measurement) and non-destructive; There is no upper or lower limit to the size of the particles; It has a high quantitative accuracy more than 98% can be achieved. | A loss of size information of the analysis; The influence of detection medium is great; Complex pre-treatment particularly for biological matrix. | [138,139,150] |

(Continued)
| Methods     | Principle and particle size by different analytical methods | Advantages                                                                 | Limitations                                                                                           | Ref.                                                                 |
|-------------|-------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Thermal     | Degradation       Py-GC-MS                                   | The thermal degradation products are first cryo trapped, then separated using a chromatographic column and subsequently identified with mass spectrometry. This method is suitable for particle with size bigger than 500 μm. | Bulk sample without a pre-treatment; Some common polymers spectra data library is available; The polymer type and organic additives can be determined simultaneously and fast. Py-GC-MS combine with other method such as TGA and TDS-GC-MS to establish a new technology called TED-GC-MS; | [92,95,121,140,151,152] Only individual particle with certain weight can be assessed per run; Be destructive to samples; Morphological properties unable to know; The maintenance is very high; The result is related with the amount of the sample and the concentration of microplastics. |
| Other       | Hot Needle Test   | The needle makes plastics sticky and leaves a mark on their surface, while not-plastic particles are not changed by the contact with the hot needle. Particles with size down to microscale range can be identified. | The hot needle test is an alternative for identification of microplastics directly within a bulk sample or among residues of a pre-treatment with low cost. | [110,113,147] The method only is applied to the organism sample yet. |
FTIR has three modes, reflection [92], transmission [91], and attenuated total reflection (ATR) [13,101,103,104]. The reflection mode is unsuitable for detection of irregular particles owing to uneven surface reflection or their refraction; the transmission mode requires the sample to be collected on an infrared transparent filter, and the thickness of particles is an important factor of the spectrum; ATR mode can produce stable spectra of irregular particles larger than 500 μm in a short time of approximately 1 min. For smaller sizes of below 10 μm, micro-FTIR could be selected for identification [125]. Considering the effect of weathering, the matching degree of spectra with the database varies from 60% to 80%. In a study in Chongming Island, FTIR was used to identify different types of microplastics in freshwater with the threshold of 75%, and PE was the major category (37.3%) [91]. Because of excessive fiber quantity load, researchers have trouble in making use of ATR-FTIR for processing and identification. In addition, single continuous identification is very time-consuming (10 h per sample) and has a high degree of device loss [126]. Focal plane array FTIR spectroscopy (FPA-FTIR) relied on a new automated analysis approach that solves this problem, allowing detailed and accurate analysis of microplastics on the entire membrane filter for 13 hours. Thus, FPA-FTIR provides better information of all microplastics with high resolution at a faster rate [104]. However, during the detection process of micro-FTIR, particles of 5–10 μm were completely lost, and only 11% of particles of 40 μm are detected. Therefore, it has relatively few applications in the detection of small particles and nanoparticles [127].

Raman spectroscopy can also be used to differentiate plastics. It shows better spatial resolution for small particles, highly sensitive to non-polar functional groups and spectral bands are narrower due to water having less influence on the results [128]. Micro-Raman spectroscopy, the optimizing technology that combines Raman spectroscopy and microscopy, had been successfully applied to identify smaller microplastics, paint particles and attached pigment particles of 1–50 μm. This technique demonstrated the existence of paint particles in the freshwater system and revealed that there is a negative correlation between the number of pigments and the size of microplastics [129,130]. Raman spectroscopy not only covers a wider wavelength range but also has higher sensitivity to non-polar functional groups. However, one of the limitations of this method is that identification of microplastics is easily interfered with fluorescence from the organic matter or additives of microplastics. Then, the laser signal is so weak that prolongs the consumption time, leading to degradation of the samples [131]. Raman spectroscopy can also be combined with the automatic particle tracking technology of image analysis to realize automatic recognition, such as full point mapping. It gives the direction to the laser to small areas of the particle for regional collection and then a complete picture of microplastics distribution is obtained by merging [121,128].

Vis-NIR (visible and near-infrared) spectroscopy is used to identify and quantify the presence of plastics in soil and associated properties such as soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), and total potassium (TK). Notably, sample preparation is not required and bulk samples can easily be examined with this method [132]. A handheld spectrometer with detection accuracy and a detection limits of 10 g/kg and 15 g/kg, respectively, was able to recognize microplastics on site. The major barrier of this method has a limitation in that the establishment of a general spectral library is trouble [133]. Black particles are difficult to analyze, this can be overcome by using Hyperspectral imaging (HSI) [131]. Hyperspectral imaging (HSI) is a rapid, noninvasive, nondestructive, and reliable technology based on Vis-NIR spectroscopy that has been successfully applied to identify microplastics and obtain reliable information about sizes, shapes, and polymer types of particles of 0.5–5 mm. The tests showed recovery rates were 79%–100% and 86%–99% of particles of 1–5 mm and 0.5–1 mm, respectively. In addition, the image was corroded and expanded by image morphology pre-processing, enhancing the physical information of the image [134,135].

The atomic force based infrared spectroscopy (AFM-IR) is a powerful technique to analyze polymers [136]. Spectra of PS produced in FTIR and AFM-IR have a strong consistency in the peak positions, heights, and band shapes. This relationship allows researchers to directly apply these techniques and professional knowledge developed in the past 50 years or more, including using of a wide range of material database to analyze and identify unknown components. The Resonance-enhanced AFM-IR is a new technology that integrates a multichip quantum cascade laser (QCL) with AFM. The light source repetition frequency is adjusted to be the same as the contact resonance frequency of the AFM cantilever beam, thereby the adjustment can significantly increase the oscillation amplitude. In addition, combined with the probe, the detection signal is enhanced by an order of magnitude, achieving the goal of extremely high sensitivity and high spatial resolution. However, it is time-consuming to identify individual nanoparticles by AFM-IR [137].

Quantitative 1HNMR (nuclear magnetic resonance) spectroscopy is a well-known analysis technique that is considered to be one of the most suitable techniques for comprehensive qualitative and quantitative analysis of natural products, with an accuracy of 98% [138]. As quantitative NMR (qNMR) is widely used in the study of metabolites, drug toxicity, forensic medicine
and environmental toxicity, it is cited a tool for identification of microplastics. Quantitative determination by qNMR is based on the fact that signal intensities or the integral value of the signal are proportional to the proton numbers that give rise to a particular resonance and the concentration of microplastics is determined by the calibration [139]. Due to the need of dissolution of microplastics in solvent, physical properties of particles such as size, shape and color are lost. However, it also showed the advantage of being independent on size. It is necessary to remove organic matter as much as possible before dissolution. The standard curves had considerable linearity of higher than 0.994$^2$. It was concluded that the range of the limit of detection (LOD) and the limit of the quantification (LOQ) is 19–21 μg/mL and 74–85 mg/mL, respectively. This method provides a high-speed, economical and reliable detection technology for the environmental microplastics, taking one only one minute per run. At the same time, the results are influenced by many factors, such as pH, ionic strength, sample storage, the concentration of analytes and references, solubility and chemical interactions [138].

4.3.4 Pyrolysis

Pyrolysis is suggested as a supplement to other identification methods to obtain a more accurate result. In recent years, pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) has been widely used to identify polymers. Py-GC-MS can avoid the risk due to incomplete separation, because it can directly analyze samples without any pretreatment to provide detailed information on polymer types and additives simultaneously. The shape, size, and color of microplastics do not affect the results, because the thermal decomposition products of microplastics are the basis for analysis [90]. However, during the pyrolysis process, some products of larger molecular weight are produced and then transferred to the condensing capillary. Therefore, the equipment is easy to be blocked and damaged, leading to excessive maintenance costs. Second, all thermal decomposition approaches fail to provide detailed information about morphological properties of the analyzed microplastics because of this methods are destructive to samples.

This method require only a small amount of sample (100–500 μg) per one run and the time needed for one measurement ranges from 30 to 100 min, which restricts the analysis of large numbers of samples. To circumvent these problems, pyrolysis has also been continuously upgraded and optimized. Thermo-extraction and desorption coupled with gas chromatography-mass spectroscopy (TED-GS-MS) [140] is a combination of thermal extraction with thermogravimetric analysis (TGA) and thermal desorption-gas chromatography-mass spectroscopy (TDS-GC-MS), which has been successfully applied to the identification of PE, PP, PS, PET, and PA. However, the biggest problem of this method is how to obtain a representative sample with good homogeneity, indicating that some pretreatments such as screening and digestion are still needed. Some studies aim to upgrade and optimize Py-GC-MS [121]. The pyrolysis temperature and the injector temperature is increased to 700°C and 300°C. The cracking ratio is set to 5 as well. In this mode, the LOD of common polymers is less than 1 μg. Moreover, the results of this method and Raman spectroscopy were also compared, and a coincidence rate of 100% was obtained. Py-GC-MS is even better.

5. Future perspectives and recommendations

Microplastics, as emerging pollutants, have been proven to be widely distributed in the environment, including aquatic, terrestrial and air environments. Because of its risks to the environment, microplastic pollution has gained great attention from scholars. While the presence of microplastics in the environment has been well documented, there is no standard method for the analysis of microplastics, leading to difficulty in comparing results. Our review summarizes the current progress of the study of microplastic pollution, including occurrence, distribution, and characteristics of microplastics. We then provide cutting-edge techniques used in general processing procedures for microplastics (collection-recovery-identification and quantification). Hopefully, our review can help scholars select the most suitable method and find a unified standard. Some crucial and challenging future research perspectives are listed below.

1) There is lack of techniques for enhanced identification and characterization of microplastics and advanced standardized methodologies must be developed. Meanwhile, it is essential to get balance between the identification and the investment of time. More research attention should be paid to the signal enhancement of functional groups or chemical bonds. In addition, it is necessary to establish matching libraries for identification of microplastics from environmental samples. Scientifical assessment the pollution degree of microplastics is needed in order to realize comparisons of the abundance of microplastics in spatial and temporal.

2) The transport of microplastics in soil and atmosphere is very poorly understood. Its contribution to aquatic and terrestrial environments needs to be investigated further and deeply. While the presence of microplastics in different matrices has been well documented, the issue is the inability to precisely predict a specific source for particles due to their transportation in the
environment. Therefore, there is an urgent need to develop accurate transport mechanisms of microplastics sources, pathways and sinks.

3) Currently, detection methods are mostly limited by size, and few methods can be applied in nanoplastics. Nanoplastics pose greater risks to organisms due to their higher specific surface area than microplastics. They are easier to be eaten by animals and adsorbs various pollutants to produce compound toxicity. Therefore, it is particularly important to abandon the limit standard on size and make a breakthrough for the research in nanoplastics.

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References
[1] Padervand M, Lighthouse E, Robert D, et al. Removal of microplastics from the environment: a review. Environ Chem Lett. 2020;18(3):807–828.
[2] Hu YL, Gong MY, Wang JY, et al. Current research trends on microplastic pollution from wastewater systems: a critical review. Rev Environ Sci Biotechnol. 2019;18(2):207–230.
[3] Europe P, 2019. Plastics Europe, 2019. Plastics – the facts 2018: an analysis of European plastics production, demand and waste data.
[4] Li PH, Wang XD, Su M, et al. Characteristics of plastic pollution in the environment: a review. Bull Environ Contam Toxicol. 2020.
[5] Yue Y, Zhou DR, Li ZM, et al. Advancement and Challenges of microplastic pollution in the aquatic environment: a review. Water Air Soil Pollut. 2018;229(5):140.
[6] Kumar M, Chen HY, Sarasija S, et al. Current research trends on micro- and nano-plastics as an emerging threat to global environment: a review. J Hazard Mater. 2021;409:124967.
[7] Peng L, Fu D, Qi H, et al. Micro- and nano-plastics in marine environment: source, distribution and threats - A review. Sci Total Environ. 2020;698:134254.
[8] Eriksen M, Mason S, Wilson S, et al. Microplastic pollution in the surface waters of the Laurentian great lakes. Mar Pollut Bull. 2013;77(1):177–182.
[9] Obbard RW, Sadri S, Wong YQ, et al. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth’ Future. 2014;2(6):315–320.
[10] Yuan W, Liu X, Wang W, et al. Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China. Ecotoxicol Environ Saf. 2019;170:180–187.
[11] Zhou B, Wang J, Zhang H, et al. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, east China: multiple sources other than plastic mulching film. J Hazard Mater. 2019;388:121814.
[12] Gasperi J, Wright SL, Dris R, et al. Microplastics in air: are we breathing it in? Curr Opin Environ Sci Health. 2018;1:1–5.
[13] Sighicelli M, Pietrelli L, Lecce F, et al. Microplastic pollution in the surface waters of Italian Subalpine Lakes. Environ Pollut. 2018;236:645–651.
[14] Panno SV, Kelly WR, Scott J, et al. Microplastic contamination in Karst groundwater systems. Ground Water. 2019;57(2):189–196.
[15] Deng Y, Yan Z, Zhu Q, et al. Tissue accumulation of microplastics and toxic effects: widespread health risks of microplastics exposure. In: Microplastics in terrestrial environments[M]. 2020. p. 1–21.
[16] Jiang H, JN D, YJ H, et al. Combined effects of polystyrene microplastics and roxithromycin on the Green Algae (Scenedesmus obliquus) and waterflea (Daphnia magna). J Ecol Environ Sci. 2019;28(7):1457–1465.
[17] Lee H, Shim WJ, Kwon JH. Sorption capacity of plastic debris for hydrophobic organic chemicals. Sci Total Environ. 2014;470-471(2):1545–1552.
[18] Lambert S, Wagner M. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere. 2016;145:265–268.
[19] Napper IE, Bakir A, Rowland SJ, et al. Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. Mar Pollut Bull. 2015;99(1–2):178–185.
[20] Liu M, Song Y, Lu S, et al. A method for extracting soil microplastics through circulation of sodium bromide solutions. Sci Total Environ. 2019;691:341–347.
[21] Grbic J, Nguyen B, Guo E, et al. Magnetic extraction of microplastics from environmental samples. Environ Sci Technol Lett. 2019;6(2):68–72.
[22] Ossmann BE, Sarau G, Schmitt SW, et al. Development of an optimal filter substrate for the identification of small microplastic particles in food by micro-Raman spectroscopy. Anal Bioanal Chem. 2017;409(16):4099–4109.
[23] Ileva NP, Wiesheu AC, Niessner R. Microplastic in aquatic ecosystems. Angew Chem. 2017;56(7):1720–1739.
[24] Peng X, Chen M, Chen S, et al. Microplastics contaminate the deepest part of the world’s ocean. Geochem Percept Lett. 2018;9:1–5.
[25] Zhao S, Zhu L, Teng W, et al. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar Pollut Bull. 2014;81(1–2):562–568.
[26] Zheng Y, Li J, Cao W, et al. Distribution characteristics of microplastics in the seawater and sediment: a case study in Jiaozhou Bay, China. Sci Total Environ. 2019;674:27–35.
[27] Vermeiren P, Muñoz C, Ikekima K. Microplastic identification and quantification from organic rich sediments: a validated laboratory protocol. Environ Pollut. 2020;262:114298.
[28] Murphy F, Ewins C, Carbonnier F, et al. Wastewater treatment works (WWTW) as a source of microplastics
in the aquatic environment. Environ Sci Technol. 2016;50(11):5800–5808.

[29] Cesa FS, Turra A, Baruque-Ramos J. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. SciTotal Environ. 2017;598:1116–1129.

[30] Lares M, Ncibi MC, Sillanpää M, et al. Occurrence, Identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Res. 2018;133:236–246.

[31] Zhang K, Shi H, Peng J, et al. Microplastic pollution in China’s inland water systems: a review of findings, methods, characteristics, effects, and management. SciTotal Environ. 2018;630:1641–1653.

[32] Horton AA, Walton A, Spurgeon DJ, et al. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. SciTotal Environ. 2017;586:127–141.

[33] Zhang K, Su J, Xiong X, et al. Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. Environ Pollut. 2016;219:450–455.

[34] Bergmann M, Müttel S, Primpke S, et al. White and wonderful? Microplastics prevail in snow from the alps to the arctic. Sci Adv. 2019;5(8):eaax1157.

[35] Li J, Song Y, Cai YB. Focus topics on microplastics in soil: analytical methods, occurrence, transport, and ecological risks. Environ Pollut. 2020;257:113570.

[36] He DF, Luo YM, Lu SB, et al. Microplastics in soils: analytical methods, pollution characteristics and ecological risks[J]. Trends Analyst Chem. 2018;109:163–172.

[37] Chen Y, Leng Y, Liu X, et al. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China[J]. Environ Pollut. 2019;257:113449.

[38] Du C, Liang H, Li Z, et al. Pollution characteristics of microplastics in soils in southeastern suburbs of Baoding City, China. Int J Environ Res Public Health. 2020;17(3):845.

[39] Duan Z, Zhao S, Zhao L, et al. Microplastics in yellow river delta wetland: occurrence, characteristics, human influences, and marker. Environ Pollut. 2019;258:113232.

[40] Qian Z, Zhang H, Fu C, et al. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma. 2018;322:201–208.

[41] Zhang B, Yang X, Chen L, et al. Microplastics in soils: a review of possible sources, analytical methods and ecological impacts. J Chem Technol Biotechnol. 2020;95(8):2052–2068.

[42] Carter LJ, Cheffetz B, Abdeen Z, et al. Emerging investigator series: towards a framework for establishing the impacts of pharmaceuticals in wastewater irrigation systems on agro-ecosystems and human health. Environ Sci Processes Impacts. 2019;21(4):605–622.

[43] Steinmetz Z, Wollmann C, Schaef er M, et al. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci Total Environ. 2016;550:690–705.

[44] Yan CR, He W, Turner NC. Plastic-film mulch in Chinese agriculture: importance and problems. World Agric. 2014;4(2):32–36.

[45] Brodhagen M, Goldberger JR, Hayes DG, et al. Policy considerations for limiting unintended residual plastic in agricultural soils. Environ Sci Policy. 2017;69:81–84.

[46] Ramos L, Berenstein G, Hughes EA, et al. Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. SciTotal Environ. 2015;523:74–81.

[47] Ma YJ Environment risk assessment of sludge application in agriculture[D]. Beijing: University of Chinese Academy of Sciences, 2014: 4–9. [马瑜静. 沼液农用的环境风险评价[D]. 北京:中国科学院大学, 2014: 4–9].

[48] Piehl S, Leibner A, Mgi L, et al. Identification and quantification of macro- and microplastics on an agricultural farmland. Sci Rep. 2018;8(1):17950.

[49] Weber CJ, Weihrauch C, Opp C, et al. Investigating microplastic dynamics in soils: orientation for sampling strategies and sample pre-processing. In: Land degradation & development. 2021;32: 270–284.

[50] Rochman CM. Microplastics research: from sink to source[J]. Science. 2018;360(6384):28–29.

[51] Abbasi S, Keshavarzi B, Moore F, et al. Distribution and potential health impacts of microplastics and micro-rubbers in air and street dusts from Asaluyeh County, Iran. Environ Pollut. 2019;244:153–164.

[52] Dehghani S, Moore F, Ahkbarizadeh R. Microplastic pollution in deposited urban dust, Tehran metropolis, Iran. Environ Sci Pollut Res. 2017;24(8):1–12.

[53] Dris R, Gasperi J, Saad M, et al. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar Pollut Bull. 2016;104(1–2):290–293.

[54] Dris R, Gasperi J, Miranda C, et al. A first overview of textile fibers, including microplastics, in indoor and outdoor urban environments. Environ Pollut. 2017;221:453–458.

[55] Klein M, Fischer EK. Microplastic abundance in atmospheric deposition within the metropolitan area of Hamburg, Germany. SciTotal Environ. 2019;685:96–103.

[56] Allen S, Allen D, Phoenix VR, et al. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat Geosci. 2019;12(5):339–334. DOI:10.1038/s41561-019-0335-5.

[57] Free CM, Jensen OP, Mason SA, et al. High-levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull. 2014;2014(85):156–163.

[58] Alimi OS, Budzar JF, Hernandez LM, et al. Microplastics and nano-plastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ Sci Technol. 2018;52(4):1704–1724.

[59] Campanale C, Stock F, Massarelli C, et al. Microplastics and their possible sources: the example of Ofanto river in Southeast Italy. Environ Pollut. 2019;258:113284.

[60] Dris R, Gasperi J, Röcher V, et al. Microplastic contamination in an urban area: a case study in Greater Paris. Environ Chem. 2015;12(5):592–599.

[61] Eerkes-Medrano D, Thompson RC, Aldridge DC. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 2015;75:63–82.

[62] Mai L, You SN, He H, et al. Riverine microplastic pollution in the pearl river delta, China: are modeled estimates accurate? Environ Sci Technol. 2019;53 (20):11810–11817.
[63] Schmidt C, Krauth T, Wagner S. Export of plastic debris by rivers into the sea. Environ Sci Technol. 2017;51(21):12246–12253.

[64] Wright SL, Thompson RC, Galloway TS. The physical impacts of microplastics on marine organisms: a review. Environ Pollut. 2013;178:483–492.

[65] Cai H, Chen M, Chen Q, et al. Microplastic quantification affected by structure and pore size of filters. Chemosphere. 2020;257:127198.

[66] Ho YS, Ng JCY, Mckay G. Kinetics of pollutant sorption by biosorbents: review. J Sep Purif Methods. 2000;29(2):280–295.

[67] Lenz R, Enders K, Stedmon CA, et al. A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar Pollut Bull. 2015;100(1):82–91.

[68] Zhang WW, Zhang SF, Wang JY, et al. Microplastic pollution in the surface waters of the Bohai Sea, China[J]. Environ Pollut. 2017;231:541–548.

[69] Hidalgo-Ruz V, Gutow L, Thompson RC, et al. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 2012;46(6):3060–3075.

[70] Andraydi AL, Pegram JE, Song Y. Studies on enhanced degradable plastics. II. Weathering of enhanced photodegradable polyethylene under marine and freshwater floating exposure. J Environ Polym Degrad. 1993;2(1):117–126.

[71] Turner A, Holmes L. Occurrence, distribution and characteristics of beached plastic production pellets on the island of Malta (Central Mediterranean). Mar Pollut Bull. 2011;62(2):377–381.

[72] Frias JPSL, Sobral P, Ferreira AM. Organic pollutants in microplastics from two beaches of the Portuguese coast. Mar Pollut Bull. 2010;60(11):1988–1992.

[73] Müller A, Becker R, Dorgerloh U, et al. The effect of polymer aging on the uptake of fuel aromatics and ethers by microplastics. Environ Pollut. 2018;240:639–646.

[74] Mei WP, Chen G, Bao JQ, et al. Interactions between microplastics and organic compounds in aquatic environments: a mini review. SciTotal Environ. 2020;736:139472.

[75] Guo X, Wang X, Zhou X, et al. Sorption of four hydrophobic organic compounds by three chemically distinct polymers: role of chemical and physical composition. Environ Sci Technol. 2012;46(13):7252–7259.

[76] Fayolle B, Richaud E, Colin X, et al. Review: degradation-induced embrittlement in semi-crystalline polymers having their amorphous phase in rubbery state. Mater Sci. 2008;43(22):6999–7012.

[77] Liu XM, Xu J, Zhao YP, et al. Hydrophobic sorption behaviors of 17β-Estradiol on environmental microplastics. Chemosphere. 2019;226:726–735.

[78] Guo X, Wang J. The chemical behaviors of microplastics in marine environment: a review. Mar Pollut Bull. 2019;142:1–14.

[79] Stark NM, Matuana LM. Surface chemistry changes of weathered HDPE/wood-flour composites studied by XPS and FTIR spectroscopy. Polym Degrad Stab. 2004;86(1):1–9.

[80] Rouillon C, Bussiere PO, Desnoux E, et al. Is carbonyl index a quantitative probe to monitor polypropylene photodegradation? Polym Degrad Stab. 2016;128:200–208.

[81] Gandara ESP, Nobe CR, Resaffe P, et al. Leachate from microplastics impair larval development in brown mussels. Water Res. 2016;106:364–370.

[82] O’Connor IA, Golsteijn L, Hendriks AJ. Review of the partitioning of chemicals into different plastics: consequences for the risk assessment of marine plastic debris. Mar Pollut Bull. 2016;113(1):17–24.

[83] Paluselli A, Fauvelle V, Galgani F, et al. Phthalate release from plastic fragments and degradation in seawater. Environ Sci Technol. 2018;53(1):166–175.

[84] Hermabessiere L, Dehaut A, Paul-Pont I, et al. Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere. 2017;182:781–793.

[85] Hahladakis JN, Velis CA, Weber R, et al. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J Hazard Mater. 2018;344:179–199.

[86] Lambot S, Wagner M. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere. 2016;145:265–268.

[87] Song YK, Hong SH, Jang M, et al. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ Sci Technol. 2017;51(8):4368–4376.

[88] Veerasingam S, Saha M, Sunee V, et al. Characteristics, seasonal distribution and surface degradation features of microplastic pellets along the Goa coast, India. Chemosphere. 2016;159:496–505.

[89] Su L, Xue YG, Li LY, et al. Microplastics in Taihu Lake, China. Environ Pollut. 2016;216:711–719.

[90] Fischer EK, Pagialonga L, Czech E, et al. Microplastic pollution in lakes and lake shoreline sediments – a case study on Lake Bolsena and Lake Chiusi (central Italy). Environ Pollut. 2016;213:648–657.

[91] Li YB, Lu ZB, Zheng HY, et al. Microplastics in surface water and sediments of Chongming Island in the Yangtze Estuary, China. Environ Sci Eur. 2020;32(1):15.

[92] Fries E, Dekiff JH, Willmeyer J, et al. Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy. Environ sci Processes Impacts. 2013;15(10):1949–1956.

[93] Zhang Y, Kang S, Allen S, et al. Atmospheric microplastics: a review on current status and perspectives. Earth Sci Rev. 2020;203:103118.

[94] Cai L, Wang J, Peng J, et al. Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ Sci Pollut Res Int. 2017;24(32):24928–24935.

[95] Khoironi A, Hadiyanto H, Anggoro S, et al. Evaluation of polypropylene plastic degradation and microplastic identification in sediments at Tambak Lorok coastal area, Semarang, Indonesia. Mar Pollut Bull. 2020;151:110868.

[96] Huang Y, Qin X, Wang W, et al. Mini-review on current studies of airborne microplastics: analytical methods, occurrence, sources, fate and potential risk to human beings. Trends Analit Chem. 2020;125:115821.

[97] Liu K, Wang XH, Fang T, et al. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci Total Environ. 2019;675:462–471.

[98] Prata JC, Castro JL, Costa JP, et al. An easy method for processing and identification of natural and synthetic microfibers and microplastics in indoor and outdoor air. Methods X. 2020;7:100762.
[99] Irfan T, Khalid S, Taneez M, et al. Plastic driven pollution in Pakistan: the first evidence of environmental exposure to microplastic in sediments and water of Rawal Lake. Environ Sci Pollut Res Int. 2020;27(13):15083–15092.

[100] Nuellea MT, Dekiff JH, Remy D, et al. A new analytical approach for monitoring microplastics in marine sediments. Environ Pollut. 2014;184:161–169.

[101] Quinn B, Murphy F, Ewins C. Validation of density separation for the rapid recovery of microplastics from sediment. Anal Methods. 2016;9(9):1491–1498.

[102] Townsend KR, Lu HC, Sharley DJ, et al. Associations between microplastic pollution and land use in urban wetland sediments. Environ Sci Pollut Res. 2019;26(22):22551–22561.

[103] Yurtsolver M, Kaya AT, Bayraktar S. A research on microplastic presence in outdoor air[M]. Springer Water. Springer, Cham. 2018; pp89–97.

[104] Bergmann M, Wirzberger V, Krumpen T, et al. High quantities of microplastic in arctic deep-sea sediments from the HAUSGARTEN observatory. Environ Sci Technol. 2017;51(19):11000–11010.

[105] Scheurer M, Bigalke M. Microplastics in Swiss Floodplain Soils. Environ Sci Technol. 2018;52(6):3591–3598.

[106] Cauwenbergeh LV, Claessen M, Van-degehuchte MB, et al. Assessment of marine debris on the Belgian continental shelf. Mar Pollut Bull. 2013;73(1):161–169.

[107] Herbst A, Sturm MT, Fiedler S, et al. Alkoyx-silyl induced agglomeration: a new approach for the sustainable removal of microplastic from aquatic systems. J Polym Environ. 2018;26(11):4258–4270.

[108] Karlsson TM, Vethaak DA, Almroth BC, et al. Screening for microplastics in sediment, water, marine invertebrates and fish: method development and microplastic accumulation. Mar Pollut Bull. 2017;122(1–2):403–408.

[109] Zhang K, Su J, Xiong X, et al. Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. Environ Pollut. 2016;219:450–455.

[110] Devriese LI, Meulen MDVD, Maes T, et al. Microplastic contamination in brown shrimp (Crangon crangon, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. Mar Pollut Bull. 2015;98(1–2):179–187.

[111] Ruggiero F, Gori R, Lubello C. Methodologies for microplastics recovery and identification in heterogeneous solid matrices: a review. J Polym Environ. 2020;2020(28):739–748.

[112] Phuong NN, Poirier L, Lagarde F, et al. Microplastic abundance and characteristics in French Atlantic coastal sediments using a new extraction method. Environ Pollut. 2018;243:228–237.

[113] Vandermeersch G, Cauwenbergeh LV, Janssen C, et al. A critical view on microplastic quantification in aquatic organisms. Environ Res. 2015;143:46–55.

[114] Naidoo T, Goordyal K, Glassom D. Are nitric acid (HNO3) digestions efficient in isolating microplastics from juvenile fish? Water Air Soil Poll. 2017;228(12):470.

[115] Wang ZC, Qin YM, Li WP, et al. Microplastic contamination in freshwater: first observation in Lake Ulansuha, Yellow River Basin, China. Environ Chem Lett. 2019;2019(17):1821–1830.

[116] Ali K, Abolfazl G, Keong CC, et al. Salaminatia Babak A high-performance protocol for extraction of microplastics in fish. SciTotal Environ. 2017;578:485–494.

[117] Cole M, Webb H, Lindeque PK, et al. Isolation of microplastics in biota-rich seawater samples and marine organisms. Sci Rep. 2014;4(1):4528.

[118] Rani M, Shim WJ, Han GM, et al. Qualitative analysis of additives in plastic marine debris and its new products. Arch Environ Contam Toxicol. 2015;69(3):352–366.

[119] Gniadek M, Dąbrowska A. The marine nano- and microplastics characterisation by SEM-EDX: the potential of the method in comparison with various physical and chemical approaches. Mar Pollut Bull. 2019;148:210–216.

[120] Maes T, Jessop R, Wellner N, et al. A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Sci Rep. 2017;7(7):44501.

[121] Hermabessiere L, Himber C, Boricaud B, et al. Optimization, performance, and application of a pyrolysis-GC/MS method for the identification of microplastics. Anal Bioanal Chem. 2018;410(25):6663–6676.

[122] Shim WJ, Song YK, Hong SH, et al. Identification and quantification of microplastics using Nile Red staining. Mar Pollut Bull. 2016;113(1):469–476.

[123] Gbogbo F, Takyi JB, Billiah MK, et al. Analysis of microplastics in wetland samples from coastal Ghana using the Rose Bengal stain. Environ Monit Assess. 2020;192(4):208.

[124] Feenstra RP, Tseng SC. What is actually stained by rose bengal? Arch Ophthalmol. 1992;110(7):984–993.

[125] Zhou Q, Tian CG, Luo YM. Various forms and deposition fluxes of microplastics identified in the coastal urban atmosphere. Chinese Sci Bull. 2017;62(33):3902–3909.

[126] Mintenig SM, Int-Veen I, Mgl L, et al. Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Res. 2017;108:365–372.

[127] Li WF, Luo YM, Pan XL. Identification and characterization methods for microplastics basing on spatial imaging in Micro-/Nanoscales. In: He, D., Luo, Y. (Eds.), Microplastics in Terrestrial Environments. The Handbook of Environmental Chemistry, vol. 95. Springer, Cham. 2020:25-37.

[128] Araujo CF, Nolasco MM, Ribeiro AP, et al. Identification of microplastics using Raman spectroscopy: latest developments and future prospects. Water Res. 2018;142(1):426–440.

[129] Imhof HK, Lafforsch C, Wiesheu AC, et al. Pigments and plastic in limnetic ecosystems: a qualitative and quantitative study on microparticles of different size classes. Water Res. 2016;98:64–74.

[130] Li JY, Liu HH, Chen JP. Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. Water Research. 2018;137:362–374.

[131] Mgl L, Gerds G. Methodology used for the detection and identification of microplastics—A critical appraisal. In: Klages M, Gutow L, Bergmann M, editors. Marine anthropogenic litter. Cham: Springer; 2015. p. 201–227.

[132] Xu SX, Zhao YC, Wang MY, et al. Comparison of multivariate methods for estimating selected soil properties from intact soil cores of paddy fields by Vis–NIR spectroscopy. Geoderma. 2018;310:29–43.
[133] Corradinia F, Bartholomeus H, Lwanga EH, et al. Predicting soil microplastic concentration using vis-NIR spectroscopy. Sci Total Environ. 2019;650:922–932.

[134] Serrantia S, Palmieri R, Ronfani L, et al. Characterization of microplastic litter from oceans by an innovative approach based on hyperspectral imaging. Waste Manage. 2018;76:117–125.

[135] Shan JJ, Zhao JB, Liu LF, et al. A novel way to rapidly monitor microplastics in soil by hyperspectral imaging technology and chemometrics. Environ Pollut. 2018;238:121–129.

[136] Dazzi A, Saunier J, Kjoller A, et al. Resonance enhanced AFM-I-R: a new powerful way to characterize blooming on polymers used in medical devices. Int J Pharm. 2015;484(1–2):109–114.

[137] Dazzi A, Prater CB, Qichi HU, et al. AFM-I-R: combining atomic force microscopy and infrared spectroscopy for nanoscale chemical characterization. Appl Spectrosc. 2012;66(12):1365.

[138] Bharti SK. Quantitative RR 1HNMR spectroscopy. Trends Analyt Chem. 2012;35:5–26.

[139] Peez N, Janiska MC, Imhof W. The first application of quantitative 1HNMR spectroscopy as a simple and fast method of identification and quantification of microplastic particles (PE, PET, and PS). Anal Bioanal Chem. 2019;411(4):823–833.

[140] Dümichen E, Eisenbraut P, Bannick CG, et al. Fast identification of microplastics in complex environmental samples by a thermal degradation method. Chemosphere. 2017;174:572–584.

[141] Filgueiras AV, Gago J, Campillo JA, et al. Microplastic distribution in surface sediments along the Spanish Mediterranean continental shelf. Environ sci Poll Res. 2019;26(21):21264–21273.

[142] Jiang Y, Yang F, Zhao Y, et al. Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. SciTotal Environ. 2020;712:136484.

[143] Alan FC, Sembriring E, Muntalif BS, et al. Microplastic distribution in surface water and sediment river around slum and industrial area (case study: ciwalingke River, Majalaya district, Indonesia). 2019; 224: 637–645.

[144] Schirinzi GF, Pedà C, Battaglia P, et al. A new digestion approach for the extraction of microplastics from gastrointestinal tracts (GItS) of the common dolphinfish ( Coryphaena hippurus) from the western Mediterranean Sea. J Hazard Mater. 2020;397:122794.

[145] Akindele EO, Ehlers SM, Koop JE. Freshwater insects of different feeding guilds ingest microplastics in two Gulf of Guinea tributaries in Nigeria. Environ Sci Poll Res. 2020;2020(27):33373–33379.

[146] Dehaut A, Cassone AL, Frère L, et al. Microplastics in seafood: benchmark protocol for their extraction and characterization. Environ Pollut. 2016;216:223–233.

[147] Irfan M, Qadir A, Mumtaz M, et al. An unintended challenge of microplastic pollution in the urban surface water system of Lahore, Pakistan. Environ Sci Pollut Res. 2020;27(14):16718–16730.

[148] Hengstmann E, Fischer EK. Nile red staining in microplastic analysis—proposal for a reliable and fast identification approach for large microplastics. Environ Monit Assess. 2019;191(10):612.

[149] Zarfi C. Promising techniques and open challenges for microplastic identification and quantification in environmental matrices. Anal Bioanal Chem. 2019;411 (17):3743–3756.

[150] Pauli GF, Gödecke T, Jaki BU, et al. Quantitative 1HNMR. Development and potential of an analytical method: an update. J Nat Prod. 2012;75(4):834–851.

[151] Fischer M, Scholz-Böttcher BM. Simultaneous trace identification and quantification of common types of microplastics in environmental samples by pyrolysis-gas chromatography–mass spectrometry. Environ Sci Technol. 2017;51(9):5052–5060.

[152] Dümichen E, Barthel AK, Braun U, et al. Analysis of polyethylene microplastics in environmental samples, using a thermal decomposition method. Water Res. 2015;85:451–457.