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REVIEWPAPER

Analytical methods for microplastics in the environment: a review

Zike Huang[1] · Bo Hu[2] · Hui Wang[1]

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Abstract
Microplastic pollution is a recently discovered threat to ecosystems requiring the development of new analytical methods. Here, we review classical and advanced methods for microplastic analysis. Methods include visual analysis, laser diffraction particle, dynamic light scattering, scanning electron microscopy, Fourier-transform infrared spectroscopy, Raman spectroscopy, thermal analysis, mass spectrometry, aptamer and in vitro selection, and flow cytometry.

Keywords Microplastics analysis · Physical characterization · Chemical composition identification · Quantitative analysis

Introduction

Plastics have been widely used in numerous fields such as agriculture, industry, medicine, military, daily necessities and aerospace. However, with the wide use of plastic products, a large number of waste plastics have entered the ecological environment without any treatment (Geyer et al. 2017). And microplastics dominate these waste plastics (Van Cauwenberghe et al. 2013). Microplastics are plastic particles less than 5 mm in diameter (Thompson et al. 2004). In recent years, the problem of microplastic pollution has become increasingly serious and it is urgent to control the increasingly serious microplastic pollution.

The analysis of microplastics is of great significance for the traceability analysis of microplastics and the evaluation of the removal efficiency of microplastics in the environment (Zhang et al. 2018). Therefore, microplastic analysis is an important prerequisite and foundation for the treatment of microplastic pollution. Nowadays, many techniques (Table 1) for microplastic analysis have been developed. But the information on microplastics obtained through these detection methods is usually disorderly and inconsistent. In view of this, we divide microplastic analysis into physical characterization, chemical composition identification and quantitative analysis in this review. We will introduce some microplastic analysis techniques and their applications from these three aspects in this review. We hope that this review will contribute to the development of novel and efficient microplastic detection techniques and biosensors.

Classification and hazards of microplastics

According to the source of microplastics, microplastics are divided into primary microplastics and secondary microplastics. Primary microplastics are plastic particles discharged into the water environment through rivers and sewage treatment plants. Secondary microplastics are plastic particles formed by the fragmentation and volume reduction in large plastic waste through physical, chemical and biological processes (Guo and Wang, 2019). Microplastics come in a variety of shapes, mainly including fragments, granules, fibers, and films (Cózar et al. 2014; Guo et al. 2020; Huang et al. 2019).

Microplastics pose serious hazards to the environment and organisms. Firstly, microplastics are relatively stable in the environment and are not easy to be degraded, causing serious harm to the environment and organisms (Guo et al., 2020; Mu et al. 2022; Queiroz et al. 2020; Wang et al. 2019b). In addition, a series of changes may occur to microplastics in the environment, resulting in the release of some plastic additives with biotoxicity into the environment and the formation of secondary pollutants (Liu et al. 2020). Furthermore, microplastics are highly likely to be carriers of other pollutants in the environment due to the large specific

✉ Hui Wang
huiwang1968@163.com

[1] College of Chemistry and Chemical Engineering, Central South University, Changsha 410083, China

[2] School of Engineering, The University of Edinburgh, Edinburgh EH9 3JW, UK

Table 1 Typical methods for the analysis of microplastics in the environment

Methods	Advantages	Limitations
Visual analysis	A traditional method for the identification and quantification of microplastics (Hidalgo-Ruz et al. 2012). Visual analysis has the advantages of simplicity, low cost and low chemical hazard (von Moos et al. 2012)	Visual analysis method is time-consuming and laborious. Besides, when particle size of microplastics is too small or environmental samples contain impurities such as organic particles or inorganic particles, visual analysis method is no longer applicable (Hidalgo-Ruz et al. 2012; Shim et al. 2017; Song et al. 2015a). The accuracy and efficiency of visual analysis method is relatively low (Dekiff et al. 2014; Lavers et al. 2016). Visual analysis can't provide information about the chemical component of microplastics (Lavers et al. 2016). Visual analysis is usually only used as an auxiliary method for the analysis of microplastics
Scanning electron microscope-energy-dispersive X-ray	A promising technique that can be used to simultaneously analyze the surface morphology and elemental composition of microplastics (Eriksen et al., 2013; Fries et al. 2013; Van Cauwenberghe et al. 2013; Vianello et al. 2013)	The pretreatment process is complicated (Fu et al. 2020). The work efficiency is low and the cost is high. The estimation accuracy of the amount of microplastics is not very high. The color of microplastics can't be effectively distinguished (Wagner et al., 2017). This method is mostly used to detect specific microplastics
Fourier Transform infrared spectroscopy	A vibrational spectroscopy technology that can provide information on chemical bonds and functional groups in samples (Araujo et al. 2018; Lˆder and Gerdts, 2014). This method has been widely used in qualitative detection and component analysis of microplastics	It can only be used for the identification of microplastics above 20 μm (Araujo et al. 2018; Prata et al. 2019; Schymanski et al. 2018). Besides, this method is easily affected by various factors
Raman spectroscopy	Another vibration spectroscopy technique based on inelastic scattering of light (Araujo et al. 2018). Besides, Raman spectroscopy can be used to identify the microplastics below 20 μm (Prata et al. 2019). Additionally, samples don't need to be dried and dehydrated before detection (Araujo et al. 2018). Raman spectroscopy and Fourier transform infrared spectroscopy can complement each other in the detection of microplastics (Käppler et al. 2016; Prata et al. 2019; Wright et al. 2019). This method has been widely used in the qualitative detection and composition analysis of microplastics	The detection time of Raman spectroscopy is relatively long (Araujo et al., 2018). In addition, Raman spectroscopy needs to be further improved in the analysis of microplastics (Löder and Gerdts, 2015; Prata et al. 2019; Sullivan et al. 2020)
Thermal analysis	A method of analyzing materials by studying their properties as a function of temperature and time (Majewsky et al. 2016). This method can be used to applied in the analysis of chemical characterization analysis and the mass concentration of microplastics	The sample pretreatment process is cumbersome. And this method is destructive to environmental samples, which means that this method can't be applied to the analysis of physical properties of microplastics (Huppertsberg and Knepper, 2018; Majewsky et al. 2016; Rocha-Santos and Duarte, 2015; Shim et al. 2017; Silva et al. 2018)
Mass spectrometry	An important method for the detection of polymers in microplastics (Weidner and Trimpin, 2010). Mass spectra of polymers can provide some important information on the structure, molecular weight, degree of polymerization, main functional groups and end group structure of polymers (Weidner and Trimpin, 2010). This method can be used for chemical characterization analysis and quantification of microplastics in environmental samples	The domain of application of this method is narrow (Huppertsberg and Knepper, 2018; Kirstein et al., 2016; Weidner and Trimpin, 2010). And this method is still so far incapable of quantifying total microplastics in the environment (Li et al. 2021b; Peng et al. 2020; Wang et al. 2017; Zhang et al. 2021)

surface area of microplastics, which may cause more serious damage to ecosystems (Li et al. 2018; Naqash et al. 2020; Padervand et al. 2020).

Last but not least, microplastics have a strong ability to migrate in the environment due to the small particle size of microplastics. As early as 1972, Carpenter et al. (Carpenter and Smith, 1972) discovered the distribution of plastic particles with a particle size from 2.5 mm to 5 mm in the Atlantic Ocean. Nowadays, microplastics, a new type of persistent pollutants, have been widely distributed in the ecological environment (Barnes et al. 2009; Imhof et al. 2017; John et al. 2022; Lusher et al. 2015; Peeken et al. 2018; Zhang et al. 2020b) and have entered a variety of organisms through the food chain (De-la-Torre, 2020; Egbeocha et al. 2018; Mercogliano et al. 2020).

Treatment of microplastic pollution

Nowadays, some composite materials have been synthesized recently to catalyze the degradation of microplastics or to synthesize degradable and environmentally friendly polymers. For example, Zhou et al. used non-noble metal cobalt–nickel phosphide as a bifunctional electrocatalyst to convert waste polyethylene terephthalate into high value-added products including terephthalic acid, potassium diformate and H_2 (Zhou et al. 2021). Besides, Shi et al. used a Pd-modified nickel foam catalyst to upgrade waste polyethylene glycol terephthalate into high value-added chemicals such as terephthalate and carbonate (Shi et al. 2021).

Furthermore, Wang et al. developed some composites with related performance including tourmaline-modified $FeMnTiO_x$ (Wang et al. 2019a) and a novel clay supported cobalt-based catalyst through a coprecipitation-reduction method (Wang et al. 2021). Additionally, they identified Zr promotion effects in atomic scale for Co-based catalysts in Fischer–Tropsch synthesis through multiple technologies (Piao et al. 2020). What's more, they used a microwave hydrothermal method to synthesize a pangolin-like composites made of 3–4 atomic layers of MoS_2 nanosheets deposited on tourmaline. This composite material has broad application prospects in photocatalytic degradation of organic pollutants (Hao et al. 2021).

Additionally, electrocatalytic degradation of microplastics may have broad application prospects. Inspired by this, Yuvaraj et al. synthesized FeS_2/MoS_2 composites intertwined on reduced graphene oxide nanosheets. This material can be used as a high-performance anode material for sodium-ion battery (Yuvaraj et al. 2020). It is believed that these catalysts have great potential in the degradation of microplastics or the synthesis of new degradable polymers, which are of great benefit to the treatment of microplastic pollution.

Sampling of microplastics

It is worth noting that the analysis results of microplastics are easily affected by the sampling methods of microplastics (Razeghi et al. 2021a). Therefore, the sampling of microplastics is an important basis for the analysis of microplastics. Based on this, before introducing the analysis techniques of microplastics, we will briefly introduce some typical sampling methods of microplastics. At present, the methods commonly used to extract microplastics in the environment include visual inspection (manual sorting), density separation, flotation, sieving or filtration (size separation), digestion method, biological removal and ingestion, chemical treatments and so on (Fu et al. 2020; Mai et al. 2018; Padervand et al. 2020).

In spite of this, the extraction of microplastics in the actual environment needs to consider the environmental media in which the microplastics are located (Fu et al. 2020). For instance, manta trawls are the main sampling tool for microplastic separation from surface water, whereas shovel, trowel, spade, scoop and spatula are commonly used to extract microplastics from sediments. And Van Veen grab is common for deep sediment sampling (Razeghi et al. 2021b). In the density separation method, sodium chloride is the most prevalent salt used in extracting microplastics from freshwater. In the digestion method, hydrogen peroxide and Fenton's reagent are most frequently used in digestion of organic materials (Razeghi et al. 2021a).

Among numerous methods for extracting microplastics from the environment, flotation method (Fig. 1) will play an important role in extracting microplastics in the environment (Jiang et al. 2020). For instance, Grbic et al. modified the surface of iron nanoparticles with silane to make the surface of iron nanoparticles hydrophobic. Then, these surface-hydrophobic iron nanoparticles were used to magnetize microplastics. Finally, iron nanoparticles adsorbed with microplastics were adsorbed to the liquid surface through a magnet, achieving magnetic separation of microplastics with a particle size of 15 μm (Grbic et al. 2019).

Besides, some metal–organic framework-based materials (Chen et al. 2020a) and some artificial magnetite nanoparticle (Chen et al. 2022) also can be used for the sampling of microplastics. These methods of separating microplastics also provide technical support for the analysis and recycling of microplastics.

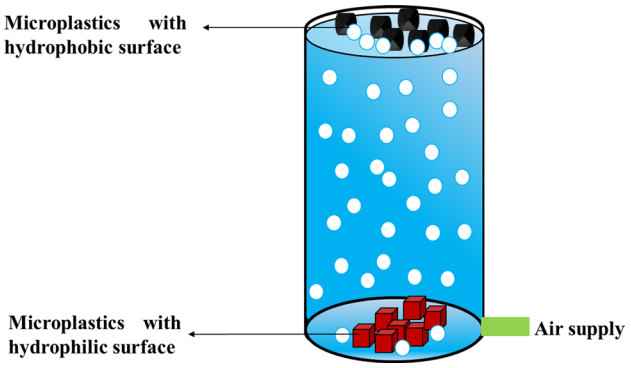

Fig. 1 Microplastic flotation. The flotation method allows separating microplastics based on the difference of wettability of microplastics. The main principle of the floatation method is that the hydrophilicity and hydrophobicity of microplastic surface can be regulated by various methods. In the flotation process, the microplastics with hydrophilic surface sink to the bottom of the flotation column while the microplastics with hydrophobic surface are taken out of the flotation column by bubbles, thereby realizing the flotation separation of different types of microplastics. Floatation method can be used as a separation method for microplastics with similar density and charging properties. Floatation method has the advantages of high separation efficiency, high separation purity, simple equipment structure, strong separation selectivity and low cost

Reviews on microplastic analysis

Currently, many review articles with the focus on the analytical techniques of microplastics have been published. For instance, Hanvey et al. systematically summarized and elaborated the sampling methods, microplastic separation methods and analytical techniques for measuring microplastics in sediment. They advocated for the development of strong quality assurance/quality control procedures to be adopted like other fields of analytical chemistry (Hanvey et al. 2017). Besides, Wirnkor et al. also elaborated some typical analytical techniques for detecting and quantifying microplastics (Wirnkor et al. 2019). Silva et al. also discussed numerous issues associated with the analysis of microplastics sampling, sample handling, the identification and quantification of microplastics and analytical quality control and quality assurance. They also presented the current challenges within this field of research and possible routes to overcome such limitations (Silva et al. 2018). These review articles provide references and ideas for people to develop new plasticity analysis techniques.

In this review, we summarize these reviews and summarize some classic microplastic analysis techniques according to the characteristics of the obtained microplastic information. Besides, the application, advantages and shortcomings of these methods are also elaborated in this review. Moreover, the futural prospects of the study on the analytical methods of microplastics are proposed.

Physical characterization

Physical characterization analysis of microplastics can preliminarily determine the particle size, color, shape, morphology, preliminary typing, corrosion degree and aging degree of microplastics (Hidalgo-Ruz et al., 2012). Here, we briefly introduce some main physical characteristics analysis techniques of microplastics including visual analysis (Karlsson et al. 2020), dynamic light scattering analysis (Sorasan et al. 2021) and laser diffraction particle size analysis.

Visual analysis

Visual analysis is one of the most widely used methods for the physical characterization analysis of microplastics (Karlsson et al. 2020). The main operation process of visual analysis method is to observe the pretreated samples with the naked eyes or microscopes, and then the microplastics can be roughly classified and counted according to the color, shape and size of the microplastics. Finally, the microplastics are picked out with tweezers (Cluzard et al. 2015; Dris et al., 2015).

Visual analysis method has the advantages of simple operation, low cost, and little chemical hazard during operation (von Moos et al., 2012). Nevertheless, visual analysis can't provide information on the chemical component of microplastics (Lavers et al. 2016). Besides, visual analysis method is time-consuming and laborious. Additionally, the accuracy and efficiency of visual analysis method are relatively low because the experimental results are easily affected by various factors such as environmental media, other impurities in samples, the color, shape, structure of microplastics, as well as individual subjective judgments (Dekiff et al. 2014; Lavers et al. 2016). For example, when the particle size of microplastics is too small or environmental samples contain other particle impurities, visual analysis method is no longer applicable (Hidalgo-Ruz et al. 2012; Shim et al. 2017; Song et al. 2015a). Accordingly, visual analysis method is usually only used as an auxiliary method for the analysis of microplastics, rather than an independent microplastic analysis method. Visual analysis can be divided into naked eye analysis and microscopic analysis.

Naked eye can only be used for the preliminary identification of microplastics with a particle size of 1–5 mm (Shim et al., 2017) while microscopic analysis can be used to identify microplastics with particle sizes of hundreds of microns and above (Cluzard et al. 2015; Dris et al. 2015). Microscopy generally includes optical microscopy and electron microscopy.

Optical microscopy is a convenient and economical analysis method (von Moos et al. 2012). Nevertheless, the

accuracy of optical microscopes for identifying microplastics is still relatively low. For example, the error rate for identifying microplastics is still over 20% under ordinary light microscopy (Hidalgo-Ruz et al., 2012) and the error rate exceeds 70% when microplastics are transparent (Song et al. 2015a). Moreover, it is difficult to analyze and identify microplastics with particle size less than 100 μm (Hidalgo-Ruz et al. 2012; Song et al. 2015a). Therefore, optical microscopy is often combined with electron microscopy to reduce the error rate of identifying microplastics.

Compared with optical microscopy, electron microscopy can distinguish microplastics from particulate impurities due to their higher magnification and clearer imaging (Shim et al., 2017; Wagner et al., 2017). For example, the resolution of scanning electron microscope, one of the most commonly used electron microscopes, can reach 0.1 μm (Wagner et al., 2017). Scanning electron microscopy can be used to identify the microplastics with the particle size as low as 1 nm (Shim et al., 2017). However, scanning electron microscopy images can't be used to analyze color and chemical composition of microplastics (Eriksen et al. 2013). Therefore, scanning electron microscopy is often combined with other techniques to get more information on microplastics. Furthermore, transmission electron microscopy can be used to observe fine structures smaller than 0.2 μm that cannot be observed under optical microscopy. For instance, Gigault et al. used dynamic light scattering and transmission electron microscopy to observe the presence of plastics at the nanoscale in water due to ultraviolet degradation (Gigault et al. 2016).

Last but not least, in order to improve the accuracy of identifying microplastics by visual analysis, fluorescence staining, as an important auxiliary technique for visual analysis of microplastics, has been widely applied (Maes et al., 2017). The main process of fluorescence staining is to use hydrophobic fluorescent dye to dye microplastics. And then these samples are irradiated with some specific light beams under a fluorescent microscope or confocal laser scanning microscope to make microplastics emit fluorescence. Finally, these fluorescent particles can be identified and counted through image analysis (Maes et al. 2017). For example, Anthony et al. used Nile red, a kind of lipophilic colorant, to help the identification of microplastics (Andrady, 2011).

However, the application of fluorescent microscopy and confocal laser scanning microscopy is limited because fluorescent dyes often need to be excited by specific wavelengths of excitation light to emit emission light. For example, when Nile red was dissolved in dimethyl sulfoxide, the excitation wavelength of the solution was 530 nm and the emission wavelength was 575 nm (Chen et al. 2009). Besides, fluorescence staining may produce false-positive results because some bioorganics in samples may also be stained with these hydrophobic fluorescent dyes. But so far, there is no effective method to completely remove these organics from environmental samples (Jee et al. 2009). Furthermore, some environmental samples may also have natural fluorescence properties (Shim et al. 2016). This may cause great interference to the analysis results. In short, the development of new fluorescent dyes that can recognize specific microplastics is likely to become important development directions for microplastics analysis in the future.

Laser diffraction particle size analysis

With the rapid development of material science, numerous advanced instruments have been developed. Laser diffraction particle size analysis a fast, reliable and automated method, can be used for the analysis of soil and sediment particle size distribution (Bittelli et al. 2022). The experimental results are detailed, highly resolved and high-precision. The technique is essentially non-destructive and critical samples can be recovered (Blott et al. 2004). This method can be used to analyze particles in the size range 0.04 μm–2000 μm (Blott et al. 2004). But some impurities in environmental samples may interfere with the experimental results. Besides, the premise of the application of this technology is to separate and extract the microplastics in the environment.

Although this method has not been widely used in microplastic particle size distribution, it will eventually play an important role in the detection of particle size distribution of microplastics with the improvement of technology.

Dynamic light scattering

Nanoplastics refer to plastic particles with a particle size of less than 1 μm (Li et al. 2021a). Dynamic Light Scattering analysis has great potential in the analysis of nanoplastics. For example, Sorasan et al. found through dynamic light scattering analysis that solar photochemical aging can make secondary microplastics produce nanoplastics (Sorasan et al. 2021). Nevertheless, similar to laser diffraction particle size analysis, some impurities in environmental samples may interfere with the experimental results.

Chemical characterization

Microplastics are usually mixtures of heterogeneous plastic particles, with a wide variety and complex compositions. The chemical composition identification of microplastics refers to the use of some methods to determine the functional groups, molecular weight, structure and degree of polymerization of polymers in microplastics. The identification of chemical composition of microplastics is of great significance for the determination of the treatment

methods of microplastics and the traceability analysis of microplastics (Song et al., 2015b). Nowadays, the techniques commonly used for the chemical characterization analysis of microplastics include scanning electron microscope-energy-dispersive X-ray (Wagner et al., 2017), Fourier transform infrared spectroscopy (Song et al. 2015b), Raman spectroscopy (Araujo et al. 2018), thermal analysis (Majewsky et al. 2016), mass spectrometry (Weidner and Trimpin, 2010), etc. These typical methods and some promising tools such as aptamer will be introduced in this section.

Scanning electron microscope-energy-dispersive X-ray

Scanning electron microscopy is one of the most important methods for the analysis of the morphology of microplastics (Wagner et al. 2017). In practical applications, scanning electron microscopy is usually combined with energy-dispersive X-ray technology. Energy-dispersive X-ray analysis is an important technique for analyzing the types and contents of constituent elements in micro-area of materials (Wagner et al. 2013; Zhao et al. 2017). Scanning electron microscope-energy-dispersive X-ray is a promising technique that can simultaneously analyze the surface morphology and elemental composition of microplastics (Eriksen et al. 2013; Fries et al. 2013; Van Cauwenberghe et al. 2013; Vianello et al. 2013).

However, there are still some shortcomings of scanning electron microscope-energy-dispersive X-ray. First of all, one of the important prerequisites for using scanning electron microscope-energy-dispersive X-ray to analyze samples is that the samples must be conductive. But most microplastics are non-conductive. Therefore, complex pretreatment procedures such as gold plating are required to analyze microplastics using scanning electron microscope-energy-dispersive X-ray (Fu et al., 2020). Besides, scanning electron microscope-energy-dispersive X-ray can't be used to analyze the color of microplastics (Wagner et al. 2017). Additionally, sometimes scanning electron microscope-energy-dispersive X-ray may be unable to identify microplastics due to technical limitations (Wagner et al. 2017). In short, the analysis of microplastics using scanning electron microscope-energy-dispersive X-ray is costly, time-consuming and inefficient (Wagner et al. 2017).

At present, scanning electron microscope-energy-dispersive X-ray is usually only used for the analysis of specific microplastics. This means that the application of scanning electron microscope-energy-dispersive X-ray in the analysis of microplastics in actual samples is still limited and needs further development.

Fourier transform infrared spectroscopy

Fourier transform infrared spectroscopy is a vibrational spectroscopy technique that can provide information of chemical bonds and functional groups of samples (Araujo et al. 2018; Lˆder and Gerdts, 2014). When using Fourier transform infrared spectroscopy to identify the chemical component of microplastics, the changes of material dipole moment produce infrared spectra (Prata et al. 2019). Then, these infrared spectra are compared with known polymer standard spectra in spectral libraries to determine the chemical composition of the microplastics (Lˆder and Gerdts, 2014; Song et al. 2015b). There are three main modes of Fourier transform infrared spectroscopy: specular reflection, transmission and attenuated total reflection (Tagg et al. 2015). The operation mode can be flexibly selected according to the characteristics of the samples.

The specular reflection mode is usually used to analyze materials with a certain thickness or opaque. This mode is suitable for the analysis of microplastics in real samples. However, this mode has some disadvantages such as weak signal, large noise interference, low matching degree with standard maps and low accuracy (Wenning et al. 2002).

The transmission mode can provide high-quality images and the imaging effect is usually better than that of the specular reflection mode. However, if the thickness of samples is less than 5 μm, the accuracy of the transmission mode analysis decreases. Therefore, the transmission mode has high requirements on sample pretreatment and is usually only suitable for the analysis of transparent, sufficiently light and not too thin materials (Prata et al. 2019; Qiu et al. 2015).

The attenuated total reflectance mode can provide high-quality imaging spectra with high accuracy. Besides, this mode is less susceptible to interference from impurities in samples. Thus, this mode has relatively low requirements for sample pretreatment. This mode is applicable to the analysis of irregular microplastics or microplastics with extremely small particle size. However, the cost of this mode is relatively expensive. Thus, this mode is not very suitable for large-scale analysis of microplastics (Prata et al. 2019; Renner et al. 2017).

Moreover, Fourier transform infrared spectroscopy has numerous advantages in the analysis of microplastics. Firstly, Fourier transform infrared spectroscopy, a non-invasive analysis method, is less destructive to environmental samples (Akhbarizadeh et al. 2020; Birch et al. 2020; Sana et al. 2020; Scopetani et al. 2020). Besides, the pretreatment procedure of Fourier transform infrared spectroscopy is relatively simple. Additionally, Fourier transform infrared spectroscopy is less susceptible to interference from autofluorescence from other substances in samples. Furthermore, Fourier transform infrared spectroscopy has the advantages

of high-throughput screening possibility and environmental friendliness (Araujo et al. 2018).

At present, Fourier transform infrared spectroscopy has been widely used in the quantitative detection and chemical component analysis of microplastics (Hahn et al. 2019; Jakubowicz et al. 2020; Primpke et al. 2020b; Sarijan et al. 2020; Shabaka et al. 2020; Zhang et al. 2020a). But samples must be dried thoroughly before Fourier transform infrared spectroscopy analysis because moisture in samples may interfere with the identification.

However, there are still some shortcomings in the analysis of microplastics by Fourier transform infrared spectroscopy. First of all, Fourier transform infrared spectroscopy can only identify microplastics with a particle size above 20 μm because the spatial resolution of Fourier transform infrared spectroscopy spectrum is 10–20 μm (Araujo et al. 2018; Prata et al. 2019; Schymanski et al. 2018). Besides, Fourier transform infrared spectroscopy is susceptible to various factors including heterogeneity of microplastics, aging degree of microplastics and other organic matter in the environment. For example, it is difficult to analyze opaque or black microplastics by Fourier transform infrared spectroscopy (Elert et al. 2017). Therefore, Jesús J. Ojeda et al. developed a method called focal plane array-Fourier transform infrared spectroscopy, which had great application potential for large-area and high-efficiency detection of microplastics (Tagg et al. 2015). In short, Fourier transform infrared spectroscopy still needs further improvement for better analysis of microplastics in real environmental samples.

Raman spectroscopy

When the excited light irradiates on samples, the molecules and atoms in samples vibrate. Then, different frequencies of scattered light appear due to the different structures of different molecules and atoms in samples, resulting in Raman shift (Löder and Gerdts, 2015). Raman spectra, a kind of fingerprint with the characteristic properties of the substances to be measured, are produced due to the change of the polarizability of molecular chemical bonds (Löder and Gerdts, 2015). Raman spectroscopy is another vibrational spectroscopy technique based on inelastic scattering of light (Araujo et al. 2018). Raman spectroscopy and Fourier transform infrared spectroscopy can complement each other in the detection of microplastics because infrared activity and Raman activity of some substances are mutually exclusive (Käppler et al. 2016; Prata et al. 2019; Wright et al. 2019).

Raman spectroscopy has many advantages including low damage to samples (Araujo et al. 2018), small sample amount needed (Collard et al. 2015; Van Cauwenberghe et al. 2013), high-throughput screening possibility (Araujo et al. 2018) and environmental friendliness (Araujo et al. 2018). Besides, the spatial resolution of Raman spectrum is as low as 1 μm. Furthermore, compared with Fourier transform infrared spectroscopy, Raman spectroscopy has the advantages of wider spectral coverage, lower signal-to-noise ratio and narrower spectral bands (Wright et al. 2019). Additionally, Raman spectroscopy can be used to identify microplastics with a particle size below 20 μm (Prata et al. 2019). Fischer et al. found that Raman spectroscopy can even identify particles down to 500 nm in size (Fischer et al. 2015). Last but not least, samples don't need to be dried and dehydrated before detection because compared with Fourier transform infrared spectroscopy, Raman spectroscopy is more responsive to non-polar functional groups (Araujo et al. 2018).

However, Raman spectroscopy also has some shortcomings in the detection of microplastics (Rocha-Santos and Duarte, 2015). Firstly, Raman spectroscopy can't be used to detect samples with fluorescence, which limits the application of Raman spectroscopy in the analysis of microplastics in real samples (Prata et al. 2019; Sullivan et al. 2020). Besides, Raman spectra generated by the additives in microplastics and contaminants adsorbed on the surface of microplastics may overlap with the Raman spectra of polymers, thereby interfering with the identification of microplastics (Oßmann et al. 2018; Van Cauwenberghe et al. 2013). This also limits the application of Raman spectroscopy in the analysis of microplastics in real environmental samples. In addition, monochromatic laser light sources in Raman spectrometers may cause photodegradation or thermal decomposition of polymers in microplastics, thereby affecting the analysis of microplastics (Löder and Gerdts, 2015; Prata et al. 2019; Sullivan et al. 2020). Finally, the detection time of Raman spectroscopy is relatively long because Raman spectroscopy includes manual spot selection and imaging (Araujo et al. 2018).

In short, the efficiency of using Raman spectroscopy to detect microplastics needs to be further improved. Very recently, a series of improvements to Raman spectroscopy have been made. For example, Catarina F. Araujo et al. combined the optimized software with Raman spectroscopy technology, realizing the automatic detection of microplastics with a particle size of 1 μm–500 μm, which significantly improved the effect of Raman spectroscopy to detect microplastics (Araujo et al. 2018). Raman spectroscopy will play an important role in the analysis of microplastics in real samples in the future.

Thermal analysis

The properties of materials vary with temperature and time. Thermal analysis is an important technique to analyze materials by studying the functional relationship of this change (Majewsky et al. 2016). When analyzing microplastics using thermal analysis, environment samples are first heated. With

the increase in temperature, the microplastics absorb a lot of heat, which makes the polymers in microplastics change from solid state to liquid or gas state gradually. Then, an endothermic peak appears at a specific temperature (Majewsky et al. 2016). The composition and type of microplastics and their additives can be analyzed according to the characteristic thermograms of polymers because different types of polymers have different thermal stability (Majewsky et al. 2016).

The classical thermogravimetric analysis methods currently used to analyze microplastics mainly include differential scanning calorimetry (Tsukame et al. 1997), thermogravimetric analysis-differential scanning calorimetry (Majewsky et al. 2016), thermogravimetric analysis-Fourier transformation infrared spectroscopy (Yu et al. 2019), pyrolysis gas chromatography-mass spectrometry (Fries et al. 2013; Hendrickson et al. 2018) and thermal extraction desorption gas chromatography-mass spectrometry (Duemichen et al. 2019), etc. Among these methods, pyrolysis gas chromatography–mass spectrometry and thermal extraction desorption gas chromatography–mass spectrometry will be introduced in the section of mass spectrometry. Differential scanning calorimetry, thermogravimetric analysis-differential scanning calorimetry and thermogravimetric analysis-Fourier transformation infrared spectroscopy will be introduced in this section.

Differential scanning calorimetry is an effective method for analyzing samples by studying the thermal properties of polymers (Tsukame et al. 1997). Nowadays, differential scanning calorimetry has been widely used to detect primary microplastics such as polyethylene in the environment (Castañeda et al. 2014). However, the scope of application of differential scanning calorimetry is relatively narrow. For this reason, differential scanning calorimetry is often used in conjunction with other techniques.

Thermogravimetric analysis-differential scanning calorimetry is an important method to analyze the purity of microplastics by studying the relationship between temperature difference and temperature during the solid–liquid phase transition of polymers (Huppertsberg and Knepper, 2018). Thermogravimetric analysis-differential scanning calorimetry is relatively simple to operate. And the amount of sample required is relatively small (1 to 20 mg). Besides, the analysis accuracy of this method is high (Huppertsberg and Knepper, 2018). Currently, this method has been used as a complementary or alternative method for the determination of polyethylene microplastics and polypropylene microplastics by Fourier transformation infrared spectroscopy (Majewsky et al. 2016).

On the basis of thermogravimetric analysis-differential scanning calorimetry and Fourier transformation infrared spectroscopy, thermogravimetric analysis-Fourier transformation infrared spectroscopy has been developed. The main process of this method is that samples are first pyrolyzed in thermogravimetric analysis to generate pyrolysis gases. And then these pyrolysis gases are analyzed by Fourier transformation infrared spectroscopy, ultimately realizing the identification of the chemical composition of microplastics (Yu et al. 2019). For example, after concentrating soil samples at low concentrations, Zhou et al. used thermogravimetric analysis-Fourier transformation infrared spectroscopy to identify and quantify polystyrene microplastics and polyvinyl chloride microplastics in soil samples (Yu et al. 2019).

In short, thermal analysis does not require complex pretreatment of samples and can be directly injected for analysis. But thermal analysis also has some shortcomings. Firstly, it is difficult to identify some copolymers by thermal analysis because the transition temperature of polymers tends to be influenced by polymer branching and other impurities in microplastics (Huppertsberg and Knepper, 2018; Majewsky et al. 2016; Rocha-Santos and Duarte, 2015; Shim et al. 2017; Silva et al. 2018). Besides, thermal analysis can't be used to characterize physical properties such as the appearance and morphology of microplastics because thermal analysis is destructive to environmental samples. Therefore, thermal analysis is generally used for the identification of chemical component of microplastics or the quantification of microplastics (Huppertsberg and Knepper, 2018; Majewsky et al. 2016; Rocha-Santos and Duarte, 2015; Shim et al. 2017; Silva et al. 2018). This may limit the application of thermal analysis.

Mass spectrometry

Mass spectrometry of polymers can provide important information about polymer structure, molecular weight, degree of polymerization, main functional groups and end group structure (Weidner and Trimpin, 2010). Mass spectrometry is usually combined with other methods to analyze the types of polymers in microplastics. At present, mass spectrometry techniques commonly used to analyze microplastics mainly include pyrolysis gas chromatography-mass spectrometry (Fries et al. 2013; Hendrickson et al. 2018), thermal extraction desorption-gas chromatography-mass spectrometry (Duemichen et al. 2019) and matrix assisted laser desorption ionization-time of flight-mass spectrometry (Kirstein et al. 2016; Weidner and Trimpin, 2010).

Pyrolysis gas chromatography–mass spectrometry and thermal extraction desorption-gas chromatography–mass spectrometry are two critical techniques for the identification of microplastics by reverse analysis of thermal degradation products of microplastics. The operation process of both two methods is to first place samples in an oxygen-free environment such as inert gas. Then, the polymers in microplastics are thermally degraded, producing a large amount of thermal degradation products. These products

are then captured and separated in a chromatographic column. Finally, these thermal degradation products are analyzed using mass spectrometry (Dekiff et al. 2014; Prata et al. 2019).

However, it is impossible to get information about physical characteristics of microplastics through these two methods because these two methods may damage samples. In addition, it is possible to misjudge the type of microplastics because different polymers may produce similar pyrolysis products (Huppertsberg and Knepper, 2018; Majewsky et al. 2016; Rocha-Santos and Duarte, 2015; Shim et al. 2017; Silva et al. 2018).

Although the principles, operations, advantages and disadvantages of these two methods are basically the same, the two technologies still have their own characteristics. Firstly, pyrolysis gas chromatography–mass spectrometry can be applied to the direct analysis of solid samples. Besides, this method can be used to identify main polymer types in microplastics and organic additives in microplastics simultaneously. Additionally, the amount of sample required is relatively small (5 µg–200 µg). Last but not least, there is no high requirement on the size of microplastics when using this method (Nuelle et al. 2014). But pyrolysis gas chromatography–mass spectrometry can generally only be used to identify the chemical composition of single form microplastics (Prata et al. 2019).

Compared with pyrolysis gas chromatography-mass spectrometry, the pretreatment time of thermal extraction desorption-gas chromatography–mass spectrometry is relatively short. Sometimes pretreatment of samples is not even required (Dümichen et al. 2017). However, the application scope of thermal extraction desorption-gas chromatography mass spectrometry is relatively narrow. This method is currently only used in the quantitative analysis of polyethylene microplastics.

Matrix assisted laser desorption ionization-time of flight-mass spectrometry is an analytical method based on the proportional relationship between the mass-to-charge ratio of ion fragments and the time-of-flight of the ion fragments (Kirstein et al. 2016; Weidner and Trimpin, 2010). This method can not only be used to identify the main polymers in microplastics, but also can be used to analyze physical characterization of microplastics through imaging technology (Huppertsberg and Knepper, 2018). However, this method generally lacks good generality because different ionization reagents are required for different kinds of microplastics. Therefore, although this method has been widely used in the determination of biological macromolecules, it is still rarely used in the detection of microplastics (Huppertsberg and Knepper, 2018; Kirstein et al. 2016; Weidner and Trimpin, 2010).

Other promising methods

In addition to these classical methods mentioned above, with the rapid development of analytical science, numerous tools for specific recognition of molecules have been developed in recent years. For instance, the development of some fluorescent dyes or probes with low toxicity and high specificity that can specifically recognize microplastics may be an important development direction in the future.

Additionally, as pioneered by Gold's and Szostak's labs, a technology called systematic evolution of ligands by exponential enrichment was developed in 1990, with which many functional nucleic acids, aptamers, have been screened (Ellington and Szostak, 1990; Kanwar et al. 2015; Shamah et al. 2008; Tuerk and Gold, 1990). Aptamers are short oligonucleotides screened from a very large nucleic acid library on the basis of their specific affinity with target cargos (Ku et al. 2015; Mok and Li, 2008; Neumann et al. 2009; Shamah et al. 2008). These target cargos can be highly diverse, ranging from small molecules, amino acids, peptides, proteins, cells, virus and even tissues (Baker et al. 2006; Cai et al. 2006; Ku et al. 2015; Le Floch et al. 2006; Radi et al. 2006; Shangguan et al. 2006).

By folding into specific secondary/tertiary conformation, aptamers can bind with their targets through non-covalent interaction, such as hydrogen bonding, hydrophobic effect and van der Waals force (Cai et al. 2018; Mallikaratchy, 2017). Such a molecular recognition process is similar to the antibody-antigen interaction. Thus, aptamers are regarded as "chemical antibodies" (Ku et al. 2015) and have been applied in numerous fields (Huang et al. 2021). For example, Tan et al. have developed numerous aptamer-based biosensors for monitoring living cells (Fang and Tan, 2010; Shangguan et al. 2006; Tan et al. 2013; Tang et al. 2007). Therefore, it is possible to screen out nucleic acid aptamers that can specifically recognize microplastics by in vitro selection technology (Fig. 2).

However, it is still a difficult challenge to successfully screen out aptamers or fluorescent dyes due to the complex composition of microplastics. If suitable aptamers or fluorescent dyes can be successfully screened, researchers can combine these tools with some advanced instruments such as flow cytometry to indirectly determine whether there are specific types of microplastics in environmental samples. But sometimes misjudgment may also occur due to the interference of impurities in environmental samples.

Quantitative analysis

The accurate quantitative analysis of microplastics is an important prerequisite to understand microplastics pollution in the environment. At present, two indicators,

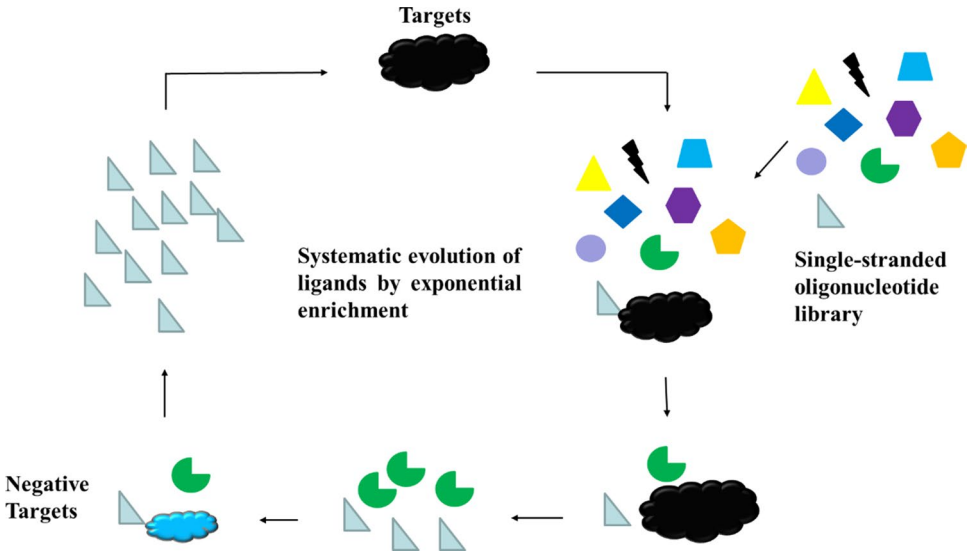

Fig. 2 Screening nucleic acid aptamers that can specifically recognize specific microplastics by systematic evolution of ligands by exponential enrichment. The basic idea of systematic evolution of ligands by exponential enrichment is to chemically synthesize a single-stranded oligonucleotide library in vitro. Then, this single-stranded oligonucleotide library is mixed with targets such as microplastics. After that, there is a complex between the target substance and nucleic acid in the mixture. Then, the nucleic acids that are not bound to the targets are washed away. Then, nucleic acid molecules combined with the targets are separated. Next, the nucleic acid molecules bound by targets are amplified by polymerase chain reaction using the nucleic acid molecule as a template, and the next round of screening process is performed. Through repeated screening and amplification, some nucleic acid molecules that can't bind to targets or have low or medium affinity with targets are washed away. Finally, the aptamer, the nucleic acid molecules with high affinity to the targets, is isolated from a very large random library. The purity of aptamer increases with the process of systematic evolution of ligands by exponential enrichment

quantitative concentration and mass concentration, are usually used to measure the amount of microplastics in the environment.

The quantitative concentration of microplastics refers to converting the specific number of microplastics got by manual counting into the concentration of microplastics in environmental samples. The methods for measuring quantitative concentration of microplastics mainly include visual analysis and spectroscopy. However, microplastics are very likely to be broken because of the brittleness of microplastics. This is highly likely to change the amount of microplastics in the sample, thus affecting the calculation of the quantitative concentration of microplastics (Andrady, 2011).

Compared with the number of particles, the mass of microplastics is not easily affected by various physical and chemical factors in the environment. And measuring the mass concentration of microplastics can be used to quantify the environmental load of microplastics and get some information about the source of microplastics (Rocha-Santos and Duarte, 2015). Therefore, mass concentration is more reliable than quantitative concentration in the quantitative analysis of microplastics (Simon et al. 2018). Thermal analysis is one of the most commonly used methods to measure the mass concentration of microplastics in environmental samples.

Last but not least, some indexes like chemical oxygen demand and total organic carbon can be adopted to evaluate the total amount of organic compounds in environmental water quality monitoring and risk assessment (Li et al. 2022). Besides, flow cytometry measurements and some aptamer-based biosensors also have great potential in the quantification of microplastics in the environment. But until now, there is no unified method for quantitative analysis of microplastics in the environment.

Visual analysis

The quantification of microplastics in environmental samples can be preliminarily estimated by manual counting. But the accuracy and efficiency of visual analysis method is relatively low. For instance, scanning electron microscope-energy-dispersive X-ray analysis is not very accurate in estimating the quantity of microplastics because sometimes scanning electron microscope-energy-dispersive X-ray analysis may be unable to identify microplastics in samples due to technical limitations (Wagner et al. 2017).

In view of this, fluorescence staining, as a simple and rapid method, has been currently widely applied to improve the accuracy of microplastics quantification (Costa et al. 2021; Maes et al. 2017). Nevertheless, some biological

organic matter in samples may also be stained with these hydrophobic fluorescent dyes. And there is no method to remove these organic matters from environmental samples completely (Jee et al. 2009). Furthermore, some environmental samples have natural fluorescence properties (Shim et al. 2016). Thus, fluorescence staining may produce false-positive results. Moreover, some fluorescence dyes may be hazardous to the environment, which further limit the application of fluorescent staining. Thus, developing some fluorescent dyes with low toxicity, high specificity and specific recognition of microplastics may be an important development direction of fluorescent dyeing in the future.

In short, nowadays visual analysis method can only be used as an auxiliary method for the quantitative analysis of microplastics.

Aptamer and in vitro selection

There may be interactions between nucleic acid molecules and microplastics. For instance, Peijnenburgac et al. found that microplastics interacted strong with the RNA fragment of severe acute respiratory syndrome coronavirus 2. And electrostatic and hydrophobic processes were the major mechanisms for the interactions (Zhang et al. 2022). Thus, using in vitro selection to screen out nucleic acid aptamers extends the application scope of traditional nucleic acids. Therefore, it is possible to screen out nucleic acid aptamers that can specifically recognize microplastics by in vitro selection.

Furthermore, aptamers can be coupled with fluorescent dyes or electroactive substances to quantify microplastics in samples. And microplastics can be quantitatively analyzed according to the intensity of fluorescent signal or the strength of electrical signal. However, misjudgment may also occur due to the interference of impurities. And it may be difficult to screen out aptamers that can recognize microplastics specifically.

Flow cytometry measurements

Flow cytometry has been widely applied in biological and medical fields (Adan et al. 2017). In flow cytometry, the laser light scattered from particles is recorded in forward or side scattering angles and can be applied to quantify substances in the particle size range of 0.5–40 μm (Primpke et al. 2020a). But this technology is rarely applied to the quantification of microplastics (Kaile et al. 2020). In view of this, Sorasan et al. used flow cytometry to track the formation of small (1–25 μm) microplastics by utilizing Mie's theory to derive the size of microplastic particles from scattering intensity readings (Sorasan et al. 2021).

Nevertheless, flow cytometry can only be used to detect microplastics with small particle size, and cannot analyze the types of microplastics. In addition, some impurities in environmental samples are highly likely to affect the accuracy of experimental results. Thus, flow cytometry needs to be further improved to detect microplastics with large particle size. It is believed that flow cytometry will play a greater role in the field of environmental analysis in the future.

Spectroscopy

Spectroscopy is a method for qualitatively classify and quantify microplastics without damaging samples. The commonly used spectral analysis methods mainly include Fourier transform infrared spectroscopy and Raman spectroscopy. Fourier transform infrared spectroscopy can be used to identify microplastics larger than 20 μm in size (Araujo et al. 2018; Prata et al. 2019; Schymanski et al. 2018) while Raman spectroscopy can be used to identify and quantify microplastics smaller than 20 μm in size (Prata et al. 2019). Accordingly, Fourier transform infrared spectroscopy and Raman spectroscopy are often used in conjunction with each other in the analysis of microplastics (Käppler et al. 2016; Prata et al. 2019; Wright et al. 2019).

At present, spectroscopy is often combined with other techniques to count microplastics. For example, Zhang et al. developed a method called μ-Fourier transform infrared spectroscopy by combining Fourier transform infrared spectroscopy with microscopy to improve the identification efficiency of microplastics. This new technique can not only be used to measure microplastics as small as size of 10 μm, but also can be applied to quantify microplastics in environmental samples (Chen et al. 2020b). Besides, based on the method of focal plane array-based reflectance micro-Fourier-transform imaging (Tagg et al. 2015), Loder et al. developed a novel method called focal plane array detector-based micro-Fourier-transform infrared imaging. This new technique can be used for the analysis of microplastics with a particle size of about 20 μm in marine plankton and sediment samples (Löder et al. 2015).

Moreover, Peter Fürsta et al. developed a non-contact and non-destructive analysis method called micro-Raman spectroscopy by combining Raman spectroscopy with microscopy. Micro-Raman spectroscopy can also be used to quantitatively analyze microplastics in samples. However, the maximum total number of micro-Raman spectroscopy particles is only 5, 000 because the ability of micro-Raman spectroscopy to identify particles of different sizes is different. Therefore, micro-Raman spectroscopy is highly likely to underestimate the abundance of microplastics in samples (Schymanski et al. 2018; Tsering et al. 2022).

In short, with the rapid growth of spectroscopy, spectroscopy will develop as a key technology for the simultaneous chemical characterization and quantification of microplastics in the future.

Thermal analysis

Thermal analysis is an analytical technique to measure microplastics based on the relationship between the physical properties of microplastics and temperature under programmed temperature conditions (Majewsky et al. 2016). Nowadays, thermal analysis has become a general method to measure the mass concentration of microplastics in environmental samples because thermal analysis is not affected by the shape, size and surface morphology of microplastics. For example, Majewsky et al. achieved quantitative analysis of polyethylene and polypropylene using thermogravimetric analysis-differential scanning calorimetry. But the analysis of other types of microplastics including polyvinyl chloride, polyamide, polyethersulfone, polyethylene terephthalate and polyurethane failed due to the overlapping of phase transitions (Majewsky et al. 2016). Besides, Zhou et al. used thermogravimetric analysis-Fourier transformation infrared spectroscopy to quantify polystyrene microplastics and polyvinyl chloride microplastics in soil samples (Yu et al. 2019).

In addition, both pyrolysis gas chromatography–mass spectrometry and thermal extraction desorption-gas chromatography–mass spectrometry can be used for the quantitative analysis of microplastics by comparing peak area with isotope labeled internal standard. Based on this, Erik Dümichen et al. combined differential scanning calorimetry with pyrolysis gas chromatography-mass spectrometry. They found that the change of sample mass in differential scanning calorimetry can be used to quantitatively analyze microplastics in environmental samples (Dümichen et al. 2017).

Moreover, thermal extraction desorption-gas chromatography–mass spectrometry can be used to quantify five polymers including polyethylene, polypropylene, polystyrene, polyethylene terephthalate and polyamide within 2–3 h. The mass of samples treated by thermal extraction desorption-gas chromatography–mass spectrometry can reach 100 mg. More importantly, thermal extraction desorption-gas chromatography–mass spectrometry can be used to analyze complex heterogeneous matrices without pre-screening microplastics in samples (Nuelle et al. 2014). In short, pyrolysis gas chromatography–mass spectrometry is suitable for the rapid qualitative and quantitative analysis of microplastics in complex environment such as complex soil matrix (Dümichen et al. 2017).

However, at present, thermal extraction desorption-gas chromatography–mass spectrometry is only applied in the quantitative analysis of polyethylene microplastics, which means that the scope of application of this method is still narrow. Thermal analysis is not as widely used as spectroscopy in quantifying microplastics. Moreover, thermal analysis cannot analyze physical characteristics of microplastics because thermal analysis is destructive to samples due to high temperature conditions (Huppertsberg and Knepper, 2018; Majewsky et al. 2016; Rocha-Santos and Duarte, 2015; Shim et al. 2017; Silva et al. 2018). This may bring difficulties to the traceability analysis of microplastics.

Mass spectroscopy

Both gas chromatography coupled with mass spectrometry and liquid chromatography coupled with mass spectrometry are techniques for analyzing microplastics by analyzing the characteristic products formed by the hydrolysis or pyrolysis of microplastics (Fabbri et al. 2000; Fischer Scholz-Böttcher 2017; Li et al. 2021b; Wang et al. 2017; Zhou et al. 2018). Due to their high sensitivity, these mass techniques show great potential in the identification and quantification of microplastics, especially nanoplastics.

Furthermore, with the development of isotope labeling technology, single particle inductively coupled plasma mass spectroscopy, a new mass spectrometry method for quantifying microplastics, has been developed in recent years. This new method is a powerful technique for quantitatively analyzing the number and size of nanoparticles (Laborda et al. 2019). Nowadays, this method has been widely applied for metal-based nanoparticles in environmental matrices (Cervantes-Avilés et al. 2019; Huang et al. 2020; Keller et al. 2018). For example, single particle inductively coupled plasma mass spectroscopy has been applied to quantify the size and number concentration of the model Au-coated microplastics (at submicrometer scale) with a relatively low detection limit (8.4×10^5 particles/L). But using this method required multiple steps of sample pretreatment because this method was based on indirect analysis of the Au coating (Jiménez-Lamana et al. 2020; Lai et al. 2021).

As the technique improves, it was found that single particle inductively coupled plasma mass spectroscopy has the capability to quantify model microplastics particle sizes and number concentrations by monitoring ^{13}C (Bolea-Fernandez et al. 2020; Laborda et al. 2021). Based on this, Liu et al. used single particle inductively coupled plasma mass spectroscopy to quantitatively analyze particle number concentration (down to 7.1×10^6 particles/L) with a wide particle size range (800 nm–5 μm) and environmentally relevant values generated during the photoaging of polystyrene microplastics (Liu et al. 2021). In short, single particle inductively coupled plasma mass spectroscopy has great potential in the studying of the dynamics of microplastics in the aging process.

However, the quantification of total microplastics in the environment is currently not available by mass spectrometry because microplastics often exist as mixtures of different polymer types, and most polymers do not have characteristic degradation products for mass spectrometry quantification (Li et al. 2021b; Peng et al. 2020; Wang et al. 2017; Zhang et al. 2021).

Index method

Although a few methods have been developed for the detection of microplastics, but the methods for the analysis of nanoplastics are still far from efficient (Ivleva et al. 2017; Sander et al. 2019; Wagner and Reemtsma, 2019). For instance, Fourier transform infrared spectroscopy can only identify microplastics with a particle size above 20 µm (Araujo et al. 2018; Prata et al. 2019; Schymanski et al. 2018) while Raman spectroscopy can be used to identify microplastics with a particle size below 20 µm (Prata et al. 2019). Besides, mass spectrometry is currently not suitable for large-scale analysis of nanoplastics (Li et al. 2021b; Peng et al. 2020; Wang et al. 2017; Zhang et al. 2021).

To improve the efficiency of monitoring total microplastics including nanoplastics in the environment, it is crucial to seek a universal index for all microplastics in an aggregate. Some researchers proposed that some indexes like chemical oxygen demand and total organic carbon can be adopted to evaluate the total amount of organic compounds in environmental water quality monitoring and risk assessment. This is because microplastics are mainly composed of six elements including C, H, O, N, S and Cl, which are similar to the characteristics of natural organic matter in the environment (Leenheer and Croué, 2003).

Inspired by this, Li et al. considered total organic carbon as an index for quantifying the pollution of total micro- and nano-plastics in environmental waters. They found that total organic carbon can be used to measure various micro- and nano-plastics of representative plastic types and sizes (0.5–100 µm) in tap, river, and sea water samples. This index method has advantages of low detection limits (~7 $\mu g \cdot C \cdot L^{-1}$) and high spiked recoveries (83.7–114%) (Li et al. 2022). Nevertheless, sometimes other organic matter in the environment besides microplastics may have some influence on the experimental results.

Conclusion

In conclusion, accurate analytical methods of microplastics are the key and foundation for the treatment of microplastics pollution. Based on this, numerous techniques for microplastic analysis have been developed in recent years. According to different microplastic information obtained, we divide microplastic analysis technology into physical characterization technology, chemical composition identification technology and quantitative analysis technology.

Physical characterization technology mainly includes visual analysis (Karlsson et al., 2020), dynamic light scattering analysis (Sorasan et al. 2021) and laser diffraction particle size analysis. And the techniques commonly used for the chemical characterization analysis of microplastics include scanning electron microscope-energy-dispersive X-ray (Wagner et al. 2017), Fourier transform infrared spectroscopy (Song et al. 2015b), Raman spectroscopy (Araujo et al. 2018), thermal analysis (Majewsky et al. 2016), mass spectrometry (Weidner and Trimpin, 2010), etc. And the methods for measuring quantitative concentration of microplastics mainly include visual analysis, flow cytometry measurements (Sorasan et al. 2021), spectroscopy, thermal analysis, mass spectroscopy and index method (Li et al. 2022).

Although many achievements have been made in microplastic analysis technology in recent years, many methods for analyzing microplastics have their own shortcomings in practical application. Moreover, using only one method may result in incomplete information on microplastics. And using one method is susceptible to interference from false positive or false negative signals, reducing the accuracy of analysis (Shim et al. 2017). In order to ensure the accuracy of the obtained information on microplastics, several analytical methods are often combined to analyze microplastics in the environment (Shim et al. 2017).

Furthermore, it is worth noting that the development of unified and efficient microplastic sampling techniques is of great significance for microplastic analysis. However, microplastics have characteristics of complex composition, small particle size, wide distribution and diverse shapes. In addition, microplastics are easily affected by external factors. Therefore, it is difficult to completely separate microplastics from the actual environment (Nguyen et al. 2019). Up to now, there is no unified and effective method to extract microplastics from complex environmental matrix. This not only affects the accuracy of microplastic analysis results, but also hinders the practical application of numerous microplastic analysis techniques.

Therefore, it is urgent to develop rapid, accurate, low-cost and practical analytical methods for microplastic sampling and analysis. Among various microplastic sampling techniques, flotation method has the potential to develop into a unique method for removing and recycling microplastics from the environment in the future.

Besides, many advanced instruments and some composites with related performance have been developed. For instance, Corrado et al. used a touch probe and some force sensitive resistors to measure high flexibility components in composite material (Corrado and Polini, 2019). More importantly, using in vitro selection to screen out some low-toxic tools that can specifically identify microplastics is highly likely to become an important field for the analysis of microplastics in the future. Last but not least, with the integration of biomedicine, material science, environmental medicine and environmental analysis, many novel techniques such as flow cytometry, dynamic light scattering analysis, laser diffraction particle size analysis and confocal laser scanning

microscopy may play an important role in the analysis of microplastics and even nanoplastics in the future.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Consent for publication All the authors have seen and approved the final version of the manuscript.

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