

# The Development and Prospect of Microplastic Detection and Analysis Technology

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**Abstract.** During recent years, nano-detection technology and machine learning-assisted identification methods have developed rapidly, providing new ideas for the precision, standardization and high-throughput quantification of microplastic detection. This article systematically reviews from early detection methods such as sieving and optical microscopy, to mainstream chemical identification techniques such as Fourier Transform infrared spectroscopy (FTIR), Raman spectroscopy, pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), and then to atomic force microscopy-infrared (AFM-IR), tip enhanced Raman spectroscopy (TERS), and machine learning. The evolution process and technical advantages and disadvantages of cutting-edge methods such as deep learning-assisted automatic recognition are analyzed, with a focus on core challenges such as matrix interference in complex environments, bottlenecks in nanoplastic detection, and the lack of method standardization. Research shows that a single technology is difficult to meet the comprehensive demands of high-throughput, nanoscale, and on-site rapid detection, while the integration of multimodal technologies and artificial intelligence-driven intelligent analysis will become the breakthrough direction. It is necessary to accelerate the establishment of a globally shared spectral database, unified operation norms, and the research and development of low-cost portable devices, in order to achieve efficient, accurate and comparable monitoring of microplastics in environmental samples, and provide solid technical support for the prevention.

## 1 Introduction

With the large-scale production and application of plastics worldwide, their accumulation and degradation in the environment have drawn widespread attention to the pollution problem of microplastics (MPs). MPs are typically defined as plastic fragments with a diameter of less than 5 millimeters and have been detected to be widely present in the ocean, fresh water, soil, atmosphere, and within living organisms (such as aquatic organisms and soil organisms), posing a potential threat to ecosystem functions and biological health [1]. Against this background, the ability to accurately, rapidly and automatically detect and quantify

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microplastics has been a significant issue in some fields like environmental science and analytical chemistry.

The traditional detection methods for microplastics mainly rely on physical separation and microscopic observation, including sieving technique, density separation and microscopy, etc. This kind of method is simple and the cost is low. However, its drawback is that it lacks specificity in identifying the composition of polymers and has limited detection capabilities for particles with a diameter of less than 100  $\mu\text{m}$ . Nowadays, analytical methods based on spectral and thermal analysis have become mainstream. Among them, Fourier Transform Infrared spectroscopy (FTIR) and Raman spectroscopy can determine the composition of polymers and are also the most widely used detection methods [2]. In addition, the application of detection methods such as micro-FTIR, Raman imaging, and pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) has enhanced the precision and automation of microplastic detection. However, some problems such as the long time required for the detection process of the above-mentioned methods, the complex sample processing procedures, and the expensive detection equipment still exist. In recent years, the development of related detection technologies has advanced towards high-speed and high-throughput quantification, automated analysis, and nanoscale detection technologies. The machine learning method is utilized to automatically identify polymer types and conduct high-speed analysis of complex samples by using FTIR as the identification means [3]. Meanwhile, high-resolution imaging techniques such as  $\mu$ -FTIR, atomic force microscopy - infrared (AFM-IR), and tip-enhanced Raman spectroscopy (TERS) can further expand the detection range to above the nanometer level.

Despite the continuous innovation of detection technologies, their application in real-world environmental samples still faces severe challenges. The recent research indicates that, apart from the interference of complex matrices, the lack of standardization in detection methods and the insufficient application of intelligent analysis means are the key bottlenecks restricting the comparability of microplastic monitoring data [4]. Firstly, the comparability of identification results among different technologies, instruments and laboratories is poor, and there is a lack of unified standards and spectral databases. Then, the interference of complex matrices such as organic matter, mineral particles, and residual dyes on the detection method is difficult to be completely eliminated. At the same time, there is still considerable room for improvement in the detection sensitivity of small-sized, low-concentration or nanoplastic particles. On-site rapid detection and portable equipment are still not mature, making it difficult to meet the actual monitoring requirements. This article aims to review the evolution of microplastic detection technology, covering the current application status from traditional physical sieving and microscopic observation to mainstream spectroscopy and thermal analysis techniques. This article will focus on analyzing the challenges faced by various methods in complex matrix interference, characterization and standardization of nanoscale particles, and explore the breakthrough progress of cutting-edge technologies such as AFM-IR and machine learning-assisted identification.

## **2 Traditional detection methods**

### **2.1 Sieving method and density separation**

Sieving is a fundamental physical separation technique that classifies particles in environmental samples by size through the use of sieves with different pore sizes. It is often used for initial extraction of microplastic particles [5]. This method is simple to operate, low in cost, and suitable for batch processing of complex matrices such as soil, water bodies and sediments. However, it is unable to effectively distinguish microplastics from other organic

or inorganic particles of similar size, leading to potential false positive results. Furthermore, this method completely fails for nanoplastics smaller than the sieve pore size.

The density separation is based on the density characteristics of microplastics. It uses saturated salt solutions such as sodium chloride or zinc chloride to make the microplastics float while heavy deposits sink. The density separation principle is based on the density characteristics of microplastics. It uses saturated saline solutions such as NaCl or ZnCl<sub>2</sub> to make the microplastics float while heavy deposits sink. This method improves the separation efficiency and is widely applied in Marine sediment samples, but it has limitations: particles of similar density may be mixed in, and high-concentration salt solutions may cause sample contamination or environmental impacts [6]. In addition, repeating the separation steps may result in the loss of small-sized particles and increase the operation time. Although these conventional methods are economical and practical, their overall accuracy and resolution are relatively low, and they cannot provide information on chemical composition. Therefore, they need to be combined with advanced analytical techniques to enhance reliability.

## **2.2 Optical microscopy and image observation**

Optical microscopes observe the morphological characteristics of microplastics, such as shape, color and surface texture, at magnification, meanwhile, combined with digital image analysis software, semi-automated counting and size measurement are achieved. This method is visual and widely equipped, and is suitable for the preliminary sieving of microplastics in environmental samples in laboratories, especially effective in water bodies and biological tissues. However, its resolution is limited, making it difficult to identify transparent or colorless particles, and it is highly dependent on the subjective judgment of the operator, which may lead to classification errors as high as 20-30%.

Image observation technology has further expanded its application by capturing particle images with high-resolution cameras and using algorithms for edge detection and morphological quantification. However, background interference can reduce accuracy [7]. Furthermore, in complex samples, this method is unable to distinguish microplastics from natural particles such as algae or mineral fragments, and lacks chemical identification capabilities, which limits its role in qualitative analysis. Despite this, by combining with fluorescent labeling, optical microscopes can enhance detection sensitivity, but overall, spectroscopic methods are still needed to confirm the results.

## **2.3 Staining method**

The staining method mainly uses fluorescent dyes such as Nile red, which selectively adsorbs onto the hydrophobic surface of microplastics and emits fluorescence signals under ultraviolet light excitation, facilitating the distinction of microplastics from other substances through a fluorescence microscope. This method is rapid and highly sensitive, and is suitable for the preliminary screening of soil, sediment and water samples, especially performing well in a high organic matter background [8].

However, the selectivity of dyes is not perfect. Some natural organic substances may also be stained, resulting in a relatively high false positive rate. In addition, the differences in affinity for Nile red among various polymer types may lead to missed detections, and environmental factors such as pH or salinity can interfere with fluorescence intensity. The optimization strategy includes pretreating the sample to remove organic interference and combining it with image analysis software to quantify the fluorescence signal. Although it is low-cost and easy to operate, this method still needs to be verified in combination with spectroscopy to avoid misjudgment and is used for large-scale monitoring but not for precise chemical identification.

## **3 The application of spectroscopy and thermal analysis in microplastic detection**

### **3.1 FTIR and micro-Fourier-transform infrared spectroscopy( $\mu$ -FTIR)**

FTIR identifies the characteristic peaks of microplastics by measuring the infrared light absorption spectrum of the sample, thereby determining the type of polymer such as polyethylene or polypropylene.

$\mu$ -FTIR further enhances the spatial resolution to 10-20  $\mu\text{m}$ , enabling the analysis of individual small particles and the generation of chemical imaging images. This method is non-destructive and provides highly specific chemical fingerprint information, making it suitable for the precise identification of environmental samples such as sediments and biological tissues [9]. However, sample preparation is complex, and interference from moisture or organic matter can weaken the signal, and the analysis time is long. In reflection mode,  $\mu$ -FTIR can directly scan the particles on the filter membrane, but an uneven surface may cause spectral distortion [10]. Overall, this technology plays a key role in standardizing microplastic monitoring, but it is necessary to optimize the algorithm to reduce false negatives and combine it with an automated system to increase throughput.

### **3.2 Raman spectroscopy and Raman imaging technology**

Raman spectroscopy uses lasers to excite molecular vibrations and generate scattering spectra, which are used to identify the chemical composition of microplastics. Raman imaging technology can generate high-resolution ( $<1\ \mu\text{m}$ ) spatial distribution maps, which are suitable for the analysis of nanoscale particles and are not disturbed by moisture. This method performs well in complex components, such as biological tissues or sewage samples, but the fluorescence background may drown out the signal, leading to an increase in the detection limit.

In addition, the analysis speed is slow, and it is sensitive to colored or fluorescent particles. It is necessary to optimize the laser wavelength to reduce interference. The sensitivity can be enhanced through surface-enhanced Raman scattering (SERS) variants, but the instrument cost is high [11]. This technology provides complementary information to FTIR, especially showing obvious advantages in the identification of small particles, but it requires algorithmic assistance for automated spectrum matching. In recent years, Raman spectroscopy has been extended to high-throughput systems, combined with automated platforms for scanning hundreds of particles, significantly enhancing the detection efficiency of Marine sediment samples and reducing fluorescence interference through wavelength tuning. In biological samples, Raman imaging can map the distribution of microplastics and automatically identify polymer types in combination with machine learning algorithms. However, it is sensitive to sample thickness and requires thin section preparation to optimize signal quality.

### **3.3 Py-GC/MS**

Py-GC/MS generates characteristic fragments by high-temperature pyrolysis of microplastics, which are separated by GC and identified by MS to achieve quantitative analysis of polymer types and additives. This method has high sensitivity, can detect nanoscale particles and provide mass concentration information, and is suitable for trace microplastics in soil or biological samples [12]. However, it is a destructive technology that cannot preserve the particle form, and the sample needs to be highly purified to avoid interference. The pyrolysis

products are complex and may lead to overlapping peaks, requiring selective index compounds. Also, it is crucial in environmental risk assessment, but it takes a long time to analyze and has a high cost for instrument maintenance. By optimizing the cracking conditions and database matching, accuracy can be improved, but it is not suitable for on-site applications. The latest research has developed a standardized protocol of Py-GC/MS for quantification in biological matrices, solving the problem of peak overlap and supporting more polymer types through the expansion of the mass library. In atmospheric samples, Py-GC/MS combined with the pre-concentration step can detect airborne microplastics, but thermal degradation by-products need to be treated to improve quantitative accuracy.

## **4 Emerging and cutting-edge detection technologies**

### **4.1 Nanoscale characterization method**

AFM-IR and TERS combined with nanoscale imaging (resolution <10 nm) and spectral analysis achieve fine characterization of the surface structure, chemical composition and mechanical properties of microplastics. AFM-IR uses the photothermal effect to capture IR absorption, while TERS enhances Raman signals through nano-tips. This method demonstrates unique chemical characterization capabilities at nanoscale spatial resolution and is particularly suitable for the analysis of trace environmental samples. For instance, recent research has successfully utilized AFM-IR combined with optical photothermal infrared spectroscopy (O-PTIR technology to achieve precise qualitative and quantitative detection of nanoplastics in snow samples from ski resorts [13].

These technologies fill the nanoscale gap of traditional methods, but they are costly and require professional training [13]. By integrating with machine learning, data interpretation can be automated, promoting research on the toxicity of nanoplastics. The combination of AFM-IR and O-PTIR achieves sub-micron resolution for the analysis of nanoplastics in the environmental water matrix, providing dual information on chemistry and morphology. However, the light source needs to be optimized to reduce thermal damage. TERS has shown advantages in surface degradation studies, capable of mapping molecular changes in nanoplastics. However, emerging pollutants pose a challenge, and an inert environment is required to enhance repeatability.

### **4.2 Image recognition methods based on machine learning and deep learning**

Image recognition based on machine learning and deep learning automatically classifies the morphology, size and type of microplastics using training datasets, with an accuracy rate of up to 98%. For instance, the YOLO algorithm can process fluorescence or hyperspectral images in real time and adapt to complex backgrounds such as sewage samples. This method is efficient and reduces subjective bias, but it requires a large amount of labeled data, and the generalization ability of the model needs to be verified across datasets [14]. Deep learning can integrate spectroscopic data and enhance polymer recognition, but it requires high computing resources. These methods revolutionize microplastic monitoring, but they need to address the overfitting issue and integrate with traditional technologies to achieve end-to-end automation [15].

Although cutting-edge detection technologies have made significant breakthroughs in resolution and automation, they are still limited by the high cost of instruments and complex sample pretreatment processes in their promotion and application. Moreover, there is a lack of unified standardized operation norms among different laboratories, making it difficult to conduct horizontal comparisons of data. The future development urgently needs to break

through technological barriers. On the one hand, efforts should be made to develop low-cost and portable on-site rapid detection equipment to meet the real-time monitoring requirements. On the other hand, by building a globally shared spectral database and deeply integrating multimodal detection technology with artificial intelligence algorithms, it will be the key path to achieving high-throughput, fully automatic and precise analysis of micro-nano plastics in complex environmental samples.

## 5 Conclusion

Microplastic detection technology, which has evolved from traditional microscopic and spectral analysis to automated and nanoscale characterization, is moving towards the direction of intelligence, automation and nanoscale. Although methods such as FTIR, Raman and Py-GC/MS have been relatively mature under laboratory conditions, their application in samples in complex environments is still limited by aspects such as sensitivity, throughput and normalization. Future research should integrate multimodal detection and machine learning algorithms, focusing on the development of high-throughput automation platforms to achieve rapid identification and quantitative analysis of polymer types. At the same time, to enhance the comparability of results and the practicality of environmental monitoring, it is indispensable to establish a unified spectral database and standardized operation procedures. To promote the improvement of the research and regulatory system for microplastics, nanoscale detection, portable on-site analysis, and AI-driven spectrum interpretation will be important development directions.

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