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Recent advances and future technologies in nano-microplastics detection

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Abstract

The degradation of mismanaged plastic waste in the environment results in the formation of microplastics (MPs) and nanoplastics (NPs), which pose significant risks to ecosystems and human health. These particles are pervasive, detected even in remote regions, and can enter the food chain, accumulating in organisms and causing harm depending on factors such as particle load, exposure dose, and the presence of co-contaminants. Detecting and analyzing NMPs present unique challenges, particularly as particle size decreases, making them increasingly difficult to identify. Moreover, the absence of standardized protocols for their detection and analysis further hinders comprehensive assessments of their environmental and biological impacts. This review provides a detailed overview of the latest advancements in technologies for sampling, separation, measurement, and quantification of NMPs. It highlights promising approaches, supported by practical examples from recent studies, while critically addressing persistent challenges in sampling, characterization, and analysis. This work examines cutting-edge developments in nanotechnology-based detection, integrated spectro-microscopic techniques, and AI-driven classification algorithms, offering solutions to bridge gaps in NMP research. By exploring state-of-the-art methodologies and presenting future perspectives, this review provides valuable insights for improving detection capabilities at the micro- and nanoscale, enabling more effective analysis across diverse environmental contexts.

Keywords Nano microplastics (NMPs), Detection, Sample preparation, Pretreatment, Measurements, Improvements, Challenges

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Introduction

Plastic is a versatile material with indispensable applications in daily human life; however, it is increasingly becoming a significant environmental problem due to mismanagement and non-degradability [1–3]. Critical issues arise when plastics break down into NMPs. Particularly, MPs are defined as particles in the range between 1 µm and 5×10^3 µm, while NPs refer to particles with nanometric dimensions (< 1 µm) [4]. Once these particles are dispersed in the ecosystems, they can be ingested by animals and accumulated in tissues, and ultimately enter the food chain [5]. Primary NMPs are intentionally manufactured for various applications, including nano/microbeads, pellets, industrial cleaners and personal care products [6]. In contrast, secondary NMPs are formed by the fragmentation of plastic items during their usage and especially after their disposal due to UV radiation, mechanical degradation and biodegradation [7].

Environmental degradation of MPs can be initiated by biotic processes (involving enzymes, other biomaterials, bacteria, fungi, etc.), abiotic processes (such as thermal oxidation, photo-oxidation, mechanical degradation and atmospheric oxidation), or a combination of both [8]. Photodegradation, particularly through UV light, can cause fragmentation and breakage of polymers chains, resulting in reactive byproducts [9]. NMPs pollution is ubiquitous, extending beyond urban areas to remote regions [10–12].

Therefore, quantifying and characterizing NMPs using cost-effective and straightforward methods is essential. The dispersion of NMPs in the environment can be driven by climatic factors such as wind and rainfall, leading to both wet and dry deposition in remote areas [13, 14]. The presence of NMPs in surface waters and groundwater is primarily determined by hydrogeological conditions and proximity to major pollution sources [15]. Despite ongoing research, many aspects of the global circulation of plastics and NMPs in the environment remain unclear [13]. NMPs can enter the body and interact with cells, potentially leading to toxic effects influenced by factors such as plastic size, dose, and exposure duration. At the nanoscale, polymers with a density of less than 1 g cm^{-3} can float on water, while diffusion and aggregation significantly influence their behavior. Organisms can colonize larger pieces of plastic, while NMPs can be coated with biomolecules from the environment commonly defined as 'bio-corona'. Smaller NMPs can also undergo heteroaggregation, becoming coated and adsorbed on other large particles or bacteria [16]. Additionally, they can adsorb and retain other compounds, acting as carriers that increase complexity and reactivity with living organisms [8, 17]. Detecting NMPs is particularly important for investigating their interactions with biological organisms, as smaller particle sizes increase the likelihood of penetrating biological membranes [18].

Despite numerous reports on the presence of NMPs, a standardized protocol for sampling, pretreatment, quantification and classification remains absent [19, 20]. Sample pretreatment is a critical step to minimize the presence of non-plastic particles and focus on NMPs detection. Current challenges include: (a) separating NMPs from organic contaminants and inorganic sediment; (b) avoiding false-positive and false-negative during quantification and classification; (c) establishing universally accepted protocols and guidelines. While existing techniques may be effective at the micrometer scale, their efficiency diminishes for smaller contaminations or at the nanoscale, often becoming more expensive and less reliable [21, 22]. Furthermore, the heterogeneity of environmental samples complicates characterization and detection of NMPs, frequently leading to systematic errors [22, 23].

Recent reports address generalized aspects of sampling and separation of NMPs [26–28]; however, they often lack critical discussions on advancements, challenges and innovative solutions, alongside practical research examples. Many literature reviews mainly focus on analytical tools, such as microscopy and spectroscopy, for NMPs detection. However, they often fail to provide insights into how these techniques can be improved. Discussions on significant research outcomes addressing these limitations are also limited [27–29]. This work aims to fill these gaps by providing a comprehensive and critical overview of the current state-of-art technologies for sampling, pretreatment, and analytical detection of NMPs. It highlights recent advancements, particularly nanotechnology-based approaches and combined spectro-microscopic techniques, where nanomaterials are effectively employed in separations methods. Finally, this review explores the role of artificial intelligence (AI)-based classification algorithms, which remain underexplored in the existing literature, despite their potential to enhance accuracy and efficiency in NMPs detection.

Sample preparation

Sediments, sewage sludge, air, water and biological samples collected from the environment often contain organic and inorganic substances that must be removed to enhance accuracy in detecting, quantifying and classifying NMPs. This challenge is compounded by the absence of global regulations defining environmental limits for these emerging pollutants, making standardized measurements and assessments particularly difficult [30].

Sampling methods advancements

Common methods for sampling surface water include the use of nets, filters, or sieves. These approaches are effective in highly contaminated environments where large quantities of MPs or mesoplastics are present. However, they may not provide a complete representation of the overall water quality [31]. Alternatively, raw water samples can be collected in glass bottles or jars and later filtered in the laboratory, particularly when the focus is on detecting smaller MPs or NPs. A sequential filtration process is often employed, progressively removing larger fragments to facilitate the final isolation of smaller particles.

Sampling groundwater samples is more complex than surface water due to the limited availability of accessible sampling points, such as springs, water wells or monitoring wells. Spring water can be directly collected at the spring's mouth without perturbing the aquifer's natural dynamics. In contrast, collecting groundwater from monitoring wells typically requires pumps or volumetric samplers, which can increase the risk of cross-contamination [32]. Another critical challenge in groundwater sampling is determining the minimum volume required to achieve statistically reliable results [33]. For aquifers with very low contamination levels, low-flow pumping systems connected to in situ filtration are particularly useful, as they allow for collection of hundreds of liters of groundwater. Conversely, in more contaminated sites, a few liters of groundwater can be collected using volumetric samplers [34]. While general methods for sampling soil can be adapted, there is a pressing need for standardized techniques specifically designed for the quantification of nanoplastics and microplastics in groundwater and other environmental matrices [35].

Airborne NMPs can settle due to gravity and be collected using containers, which can be connected to a funnel at top as a passive sample collector device [36]. Collecting indoor dust by brush deals with NMPs as well as other dust components mixture and hence other impurities must be separated from NMPs. While active sampling devices can be effective, they are not suitable for difficult-to-access areas, such as remote mountains. These types of devices are complex and expensive [37].

Separation and pretreatment advancements

After collection, samples must undergo pretreatment to prepare them for analysis. This process depends on the type of analysis to be performed and generally involves the separation, concentration and purification of the specimens. Pretreatment methods vary depending on the sample type but typically aim to isolate NMPs from other components in complex environmental matrices, such as soil particles, dissolved ions and molecules, and organic residues. Common strategies for pretreatment include size selection (via sieving), digestion (using oxidation, enzymatic digestion, or acid-alkaline digestion), density separation (with salt solutions), and filtration.

Separation is primarily achieved through density separation and filtration. Density separation often relies on flotation, but this approach is less effective for NPs because, at the nanoscale, buoyant forces are minimal, and particle density can be altered by surface fouling. Froth flotation, another separation technique, is generally unsuitable for plastics due to significant particle loss caused by bubble interactions [38]. The effectiveness of density separation also depends on the density of the floating solution. For example, raw water can only separate low-density plastics such as polystyrene (PS), polyethylene (PE), and polypropylene (PP) [39].

Solutions containing salts like NaCl, $CaCl_2$, $KHCO_2$ can reach densities between 1.2 and 1.3 g cm-^{3}, enabling the separation of mid-density plastics such as some types of polyvinyl chloride (PVC), PS, and acrylic polymers [40, 41]. Higher density salts such as NaI [42], $ZnCl_2$ [43], $Na_6(H_2W_{12}O_{40})$ [44] can produce solutions with densities ranging from 1.6 to 1.8 g cm-^{3}, sufficient to suspend a broader range of plastics, including all types of PVC and polyethylene terephthalate (PET).

Preliminary sieving is typically used to remove larger materials from the sample, but is insufficient for complex sediments, as it can lead to artifacts related to particle polydispersity. The subsequent step usually involves the digestion of organic matter, often performed using the wet peroxidase method or Fenton's reagent, which effectively removes organic residues to improve the accuracy of NMP analysis. Additional care is requested in case of use of Fenton's reagent because the intense oxidative reaction can alter or destroy NMPs [45]. Although the wet peroxidase method does not affect the NMPs, some studies have shown that this method may alter or digest nylon (polyamide, PA) and low-density polyethylene (LDPE) [46]. Another approach in the organic matter digestion is based on enzymatic digestion. This method is cheaper but time-consuming; and enzymes may interact with other impurities present in sample limiting their efficacy [41].

Despite the challenges and drawbacks of existing approaches for sample pretreatment and separation, recent studies highlight promising developments, particularly for NPs, which are significantly affected by the aforementioned methods. This section discusses significant results achieved in separation processes, including filtration and centrifugation, as well as nanotechnology-based methods that incorporate novel nanomaterials. To understand the development in NMPs detection in

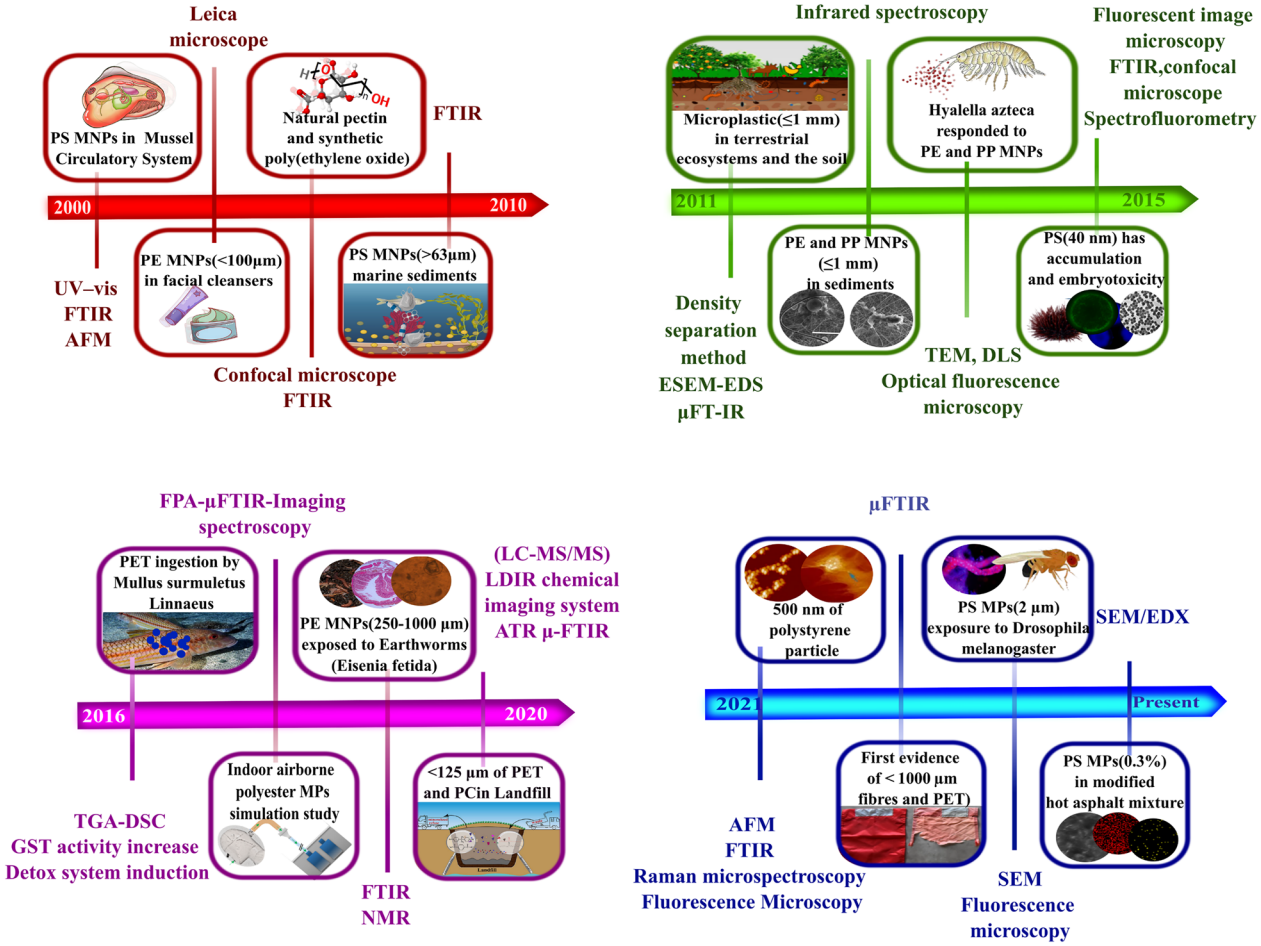

Fig. 1 Timeline of improvements in NMP detection

a timely manner, Fig. 1 summarizes the technical evolution from 2000 to the present, illustrating the methods used to study NMPs and their effects on the environment and living organisms. It also highlights various analytical and detection tools for NMPs in different environments and organisms, illustrating the growing understanding and detection capabilities regarding the distribution and impacts of NMPs over time.

Filtration and centrifugation advancements

Centrifugation is one of the most feasible and cost-effective techniques for density separation of NMPs that is performed prior to filtration or other separation techniques to reduce sample mass and minerals or can be employed independently for the purpose of separation. Ideally filtration and centrifugation are most widely used techniques, demonstrating high removal efficiencies of 74% and 98%, respectively [47]. In this section, we will discuss recent advancements in these two techniques.

Advancements in filtration process through engineering filtration membranes enables a more feasible way for NMPs removal. However, filtration technologies are still unable to show great potential to reach a commercial level from lab scale studies. These challenges can be overcome through using improved pre-treatments, modifications in membrane or filter media, integration with other technologies such as coagulation, photocatalysis, advanced oxidation process, etc. Owing to these issues, Ali et al. [51] highlighted wide range of filtration technologies explaining various types of filters, advantages, limitations and their overall capabilities towards NMPs separation. Yang et al. [48] reported a separation and detection method by using membrane filtration (Fig. 2a) for standard PS NMPs at different sizes and concentrations (50 nm to 10^3 nm and 0.1 g L^{-1} to 10^{-7} g L^{-1}). In this approach, silver nanowires were prepared by polyol method and self-assembled on a commercial quantitative filter paper (15–20 µm). During membrane filtration, it can be observed that 1 µm PS MPs are retained

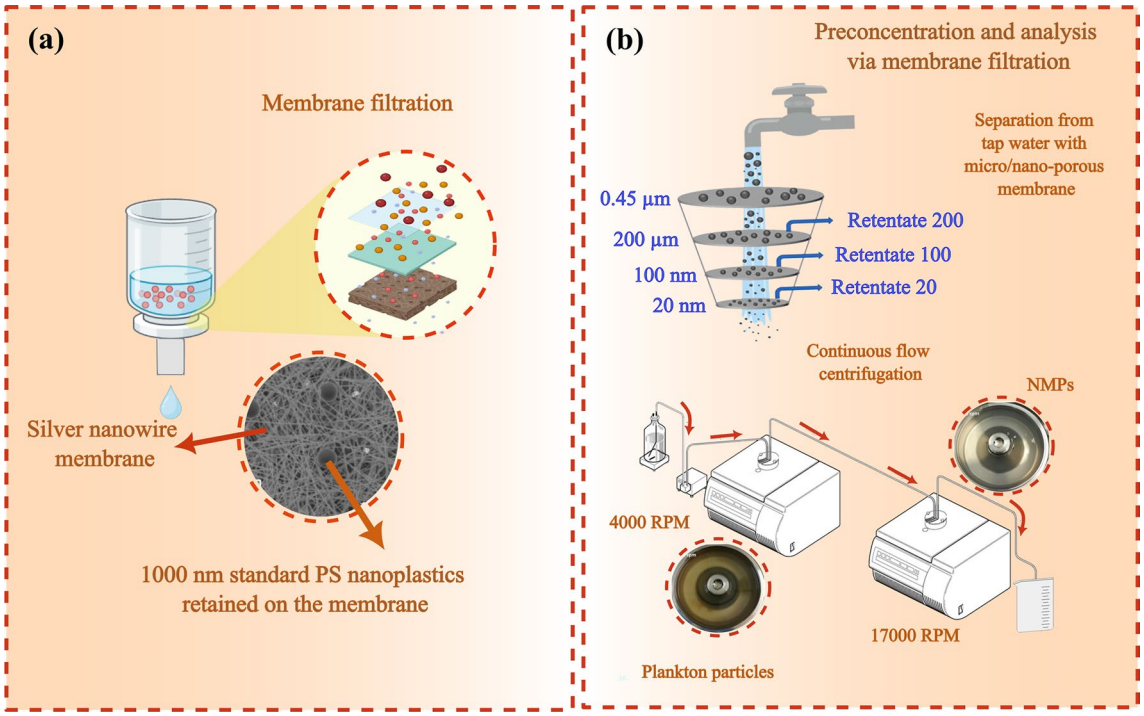

Fig. 2 Recent advances in filtration and centrifugation: **a** membrane made up of silver nanowire for NMPs filtration [48]; **b** NMPs separation from tap water [49]; **c** continuous flow centrifugation for NMPs [50]

on the silver membrane. This method addresses the issue of separation and loss during sample transfer process by providing methodological support for low concentration NMPs detection. While the technique offers simple operation and high sensitivity, detecting trace amounts of NMPs remains a challenge. In another attempt, Juraji et al. [52] fabricated polyurethane-based (PU) electro spun composite membrane the separation of NMPs via filtration. However, since the pore size of composite membrane is 624 nm, it is difficult to separate NPs with small size. In parallel direction, Lepointe et al. [53] reported iron grafted cellulose fibers for removal of contaminants from wastewater. Figure 2b represents a schematic about separation of NMPs (size: 58 – 255 nm; concentration: 1.67–2.08 µg L^{-1}) from tap water using micro/nano-porous membrane. In the first step, 0.45 µm glass fiber filter (borosilicate) is employed to separate large particles and bacteria, the filtration proceeds with Whatman Anopore (Al_2O_3) with pore size of 200 nm, 100 nm and 20 nm. Following the filtration process, NPs fractions are retained on the membrane due to electrostatic charge. Cleaning filters to remove NMPs by suitable chemical method without affecting membrane should be further optimized.

Hildebrandt et al. [50] reported two continuous-flow centrifuges (scheme in Fig. 2c) combined with two titanium rotors having 300 mL sedimentation capacity for NPs (about 160 nm) separation. Upon recirculating water sample twice or thrice, retention efficiency of > 90% was obtained. Pd doped NMPs were used in this study to estimate efficiency of this approach. Applying two continuous flow centrifugations in a sequence of different speeds can allow density/size selective separation of NMPs in terms of colloidal fractions. Separation efficiency of NMPs was tested in presence of interfering agents such as plankton; and it was found that lower speed retains planktons while NMPs were retained in secondary speed actuation. Grause et al. [54] attempted to develop a protocol for MPs separation from agricultural soil using centrifugation. In this study, Fenton oxidation was employed to oxidize biological matter, and NMPs were efficiently separated from heat-altered soil by centrifugation, achieving a recovery rate of 94% wt. However, the method was found to be unsuitable for high-density polymers due to their reduced buoyancy.

Nanotechnology-based advancements

Nanotechnology can play a central role in water treatment as well as in detecting pollutants in the air. NMPs at the micrometer scale are relatively easy to separate, but their removal at the nanoscale presents greater challenges. Nanotechnology offers potential new strategies to enhance separation processes.

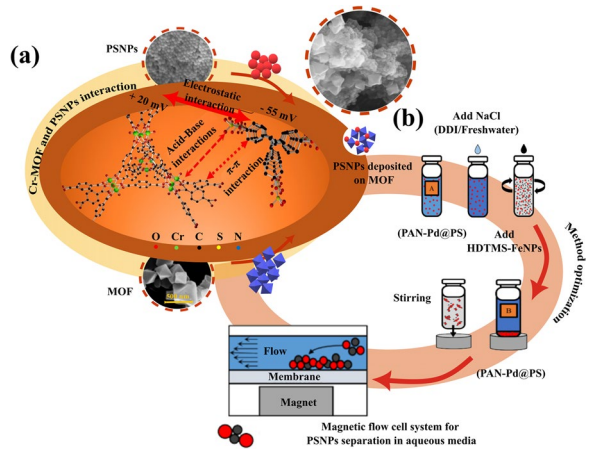

Fig. 3 Unique strategies for NMPs separation using nanomaterials: **a** PS NMPs removal using MOF (metal–organic framework) from water [55]; **b** functionalized magnetic nanoparticles-based separation of PS NMPs with respect to optimization and magnetic flow cell method [56]

Modak et al. [55] reported chromium-based metal organic framework (Cr-MOF) for removal of PS NPs (size < 1 μm), where 96% removal efficiency, 800 mg g^{-1} were achieved as shown in Fig. 3a. Electrostatic interaction between PS NMPs and Cr-MOF is the significant mechanism for adsorption of NMPs on the surface of Cr-MOF. In the present study, the adsorption behavior of PS NMPs on Cr-MOF, synthesized by hydrothermal method, investigated across varying pH levels. The adsorption mechanism was elucidated based on experimental observations. Further regeneration and reusability were tested. The results indicated that the adsorption increased in acidic conditions, particularly between pH 2–5, but decreased between pH 5–10. At lower pH levels, enhanced electrostatic interaction is attributed to the negatively charged PS NMPs and positively charged Cr-MOF surface. In contrast, at higher pH levels, zeta potential of Cr-MOF approaches its isoelectric point, leading to particle aggregation, which reduces the number of available active sites and consequently decreases adsorption efficiency. In another related study as shown in Fig. 3b, functionalized magnetic nanoparticles were used to separate PS NMPs via a magnetic flow cell method [56]. Furthermore, Liang et al. [57] detected PS NMPs by using a contactless conductivity detector (C^4D) made up of a glass microfluidic chip with controlled geometric parameters with a detection limit and a quantization limit of 0.25 μg mL^{-1} and 0.8 μg mL^{-1}, respectively. An experimental emission parametrization was also developed through well order experimentation and aerosolization for understanding NMPs size, density and concentration impact in water.

Recently, Liu et al. [58] demonstrated that mixing nanolayered double hydroxides (LDHs) with PDMS and epoxy resins and coating on PU sponges can maintain superhydrophobicity, electrostatic attraction property, capillary action and chemical bonding. Such properties demonstrated that this material can serve as efficient adsorbent for the removal of NPs in oil, offering both mechanical durability and excellent reusability. In a literature study, Wang et al. [59] critically discusses potential strategies for implementing bio-electrochemical systems (BES), i.e., bio-electrochemical systems to mitigate the inhibitory effects of NMPs during wastewater treatment procedures. This approach presents possibilities in electrochemical degradation of NMPs as well as attenuation via increased microbial metabolism in NMPs degrading bacteria. However, extensive research is still required, as this field remains in its infancy regarding the potential of BES for treating NMP-contaminated water.

Advances in current measurement methods

Microscopic methods advancements

Optical microscopy

Optical microscope uses a lens system to magnify small objects. The objective lens, with a short focal length of a few millimeters, creates an image of the object in an intermediate image plane, which is then captured by a detector [60]. Optical microscopy, despite its simplicity, offers several advantageous for detecting NMPs. Its ease of operation, accessibility, cost-effectiveness, non-destructive nature, and ability to provide real-time observations make it a highly effective tool for this purpose. It can efficiently scan large areas and detect large MP fragments. However, its main limitation is the resolution, around 200 nm, making it difficult to detect NPs smaller than that limit [61]. Optical microscopy cannot determine the chemical composition of particles, making it challenging to distinguish or conclusively identify different types of plastics [62].

Without fluorescence or labeling, differentiating NMPs from similarly sized particles like organic debris or minerals can be challenging, leading to misidentification. Staining with agents like Nile Red (NR), a lipophilic dye, helps distinguish NMPs by binding to hydrophobic substances and activating fluorescence under specific wavelengths. This preferential staining of plastic particles reduces the risk of mistaking them for non-plastic materials and aids in identifying smaller particles below the diffraction limit [63]. Nile red, for instance, was applied to detect NMPs in complex matrices and tissues from living organisms [64]. Unfortunately, Nile red can suffer from false-positive artifacts, as it can bind to other hydrophobic materials such as lipids, therefore requiring additional confirmation steps.

Further research will focus on improving the efficiency and selectivity of NMPS detection. Advanced staining techniques, including solvatochromic dyes that change color based on their environment, are being developed for NMPs. ATTO dyes (a class of highly fluorescent dyes from ATTO-TEC GmbH, Germany), such as ATTO 647N, have been used in fluorescence microscopy to label and track NMPs [65]. These dyes offer strong fluorescence signals, which help in the detection of small particles. A novel low-cost twisted intramolecular charge transfer-based staining agent has been developed for fluorescent labeling MPs [66]. This method provides a simple, cost-effective way to fluorescently label MPs. Co-staining with dyes like DAPI (4',6-diamidino-2-phenylindole is a fluorescent dye used for nucleic acids staining) and propidium iodide can further improve specificity by differentiating particle types based on fluorescence properties [67].

Despite labeling and fluorescence, chemical identification of different polymers remains challenging since staining agents are not polymer-specific. Optical microscopy often requires manual counting, which is time-consuming and prone to error, especially without automated analysis tools. Its limited depth of field also complicates focusing on 3D structures in thick samples. However, optical microscopy is easily integrated with other techniques to enhance accuracy of detection.

Electron microscopy

Electron microscopy uses an electron beam for high-resolution imaging. Scanning electron microscopy (SEM) reveals surface texture and morphology of MPs, while transmission electron microscopy (TEM) provides ultra-high-resolution images of internal structures at the nanometer scale. Both techniques are crucial for investigating the physical properties of MPs and frequently serve as complementary methods to spectroscopy for chemical identification [68].

SEM offers high magnifications and resolutions, allowing observation of fine surface details like texture, defects, and contamination in MPs. When combined with energy-dispersive X-ray spectroscopy (EDS/EDX), SEM can provide elemental composition data, identifying additives or contaminants. However, EDS mapping cannot distinguish between different polymer/additives types in complex materials [68]. By changing the electron beam generation process, FE-SEM (field emission-scanning electron microscope) provides a very high-resolution imaging compared to regular SEM. It guarantees high brightness, crisp images and stable beam current. Figure 4a presents a 350X FE-SEM image identifying cellulose and polymer fibers. Fluorescent 100 nm PS NPs localized inside C. Robusta are visible in the bright-field optical image in Fig. 4b, detected in gonads, demonstrating NPs detection in complex media.

NPs can get attached with commercially available dyes and super-resolution imaging can be achieved by using STED (STimulated Emission Depletion microscopy). STED microscopy is a far-field fluorescence imaging technique that overcomes the diffraction limit by switching the states of dye molecules between bright and dark, reaching 20 nm resolution. This technique was utilized recently for high-resolution imaging of stained proteins inside living cells [69].

Enhancing MPs analysis can be achieved by using advanced techniques like high-angle annular dark-field (HAADF) in TEM and backscattered electron (BSE) imaging in SEM. HAADF provides high-contrast images based on atomic number (Z-contrast), making it useful for distinguishing polymer additives and fillers, as materials with higher atomic numbers appear brighter. Coupled with EDX for elemental mapping, these techniques allow precise quantification and localization of additives or contaminants. Tire wear particles in airborne dust were analyzed using BSE and EDX, with machine learning algorithms for automation. SEM images (Fig. 4d) of tire wear particles from urban areas showed 1–10 µm particles embedded in dust. EDX identified larger particles as minerals (quartz, orthoclase, plagioclase, ferromagnesian silicates, calcite, barite, gypsum) and metals (Fe, Fe-alloy, Cu). This approach has also been effectively used to characterize micro- and nano-particles in Antarctic snow, focusing on anthropogenic pollutants as shown in Fig. 4e [73]. Interestingly, Yang et al. examines the release of nanoscale particles from polyester textiles, utilizing HAADF and EDX techniques to analyze the composition of these particles [74].

BSE imaging on SEM detects electrons scattered back from the sample surface. The intensity of these electrons, and thus the image brightness, depends on the atomic number; heavier elements scatter more electrons, creating a brighter image. For example, Sommer et al. used BSE and EDX in SEM to analyze single MPs fragments [72], providing insights into the environmental impact of tire abrasion. Bhat used the same technique to identify MPs from indoor environment [75].

In summary, advanced imaging modes such as HAADF in TEM and BSE in SEM are crucial for detailed compositional analysis of MPs. They provide valuable insights into the material properties, additives, contaminants, and structural characteristics of MPs, which are essential for comprehending their environmental behavior, toxicity, and long-term impacts.

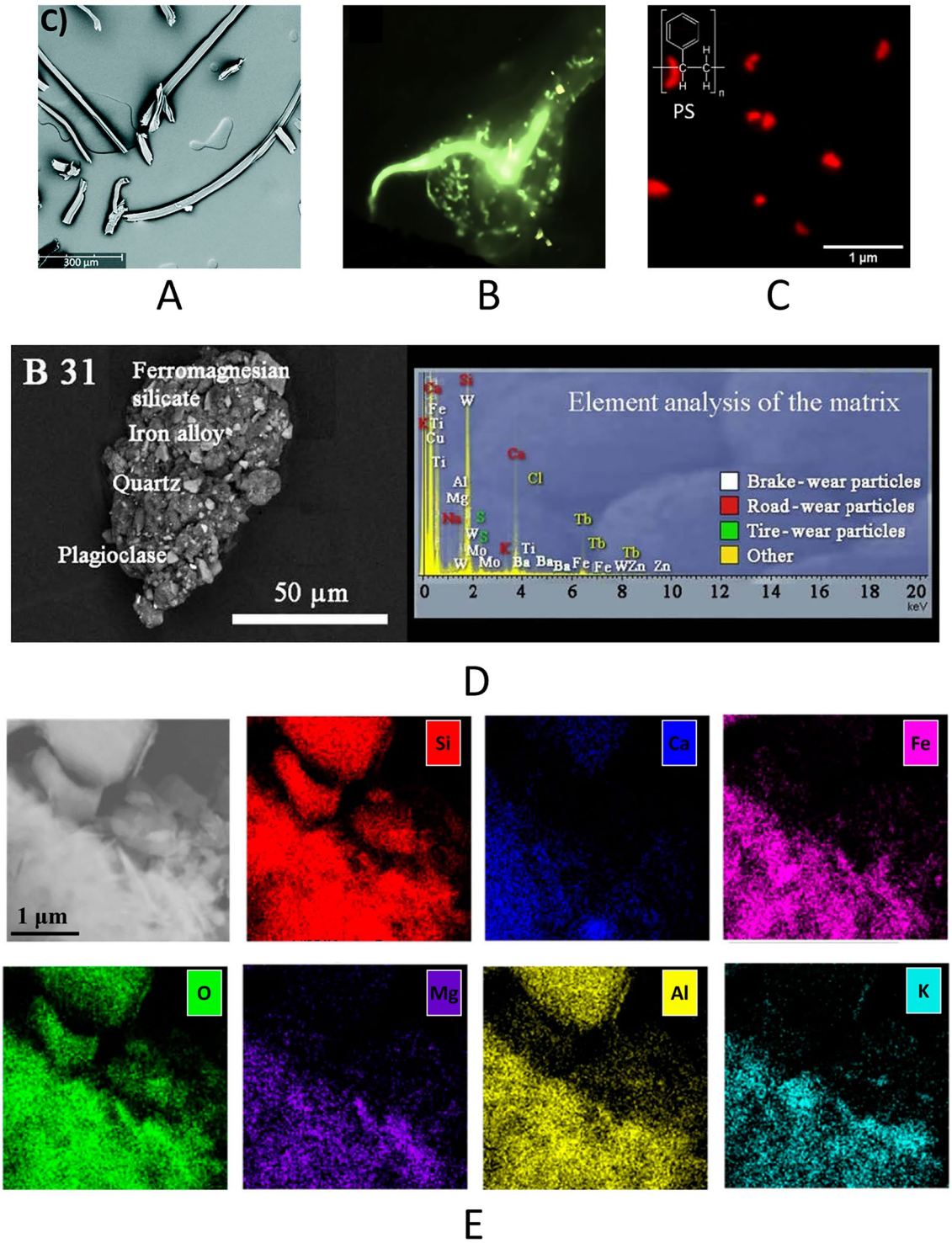

Fig. 4 SEM analysis of nano-fibers (350 × magnification) **a** [70]; bright-field photograph for wall of visceral cavity showing fluorescent PS particles in the gonads **b** [71]; STED image of sanding debris from PS **c** [65]; SEM image of a representative tire-wear particle with an entrustment > 50% vol, typical for the federal highwayB31. The EDX diagram on the right displays the superposition of 25 spectra from the imaged tire-wear particle with subsequent particle classification **d** [72]; HAADF-STEM image and the corresponding EDX maps of a mineral dust particle detected in sample **e** [73]

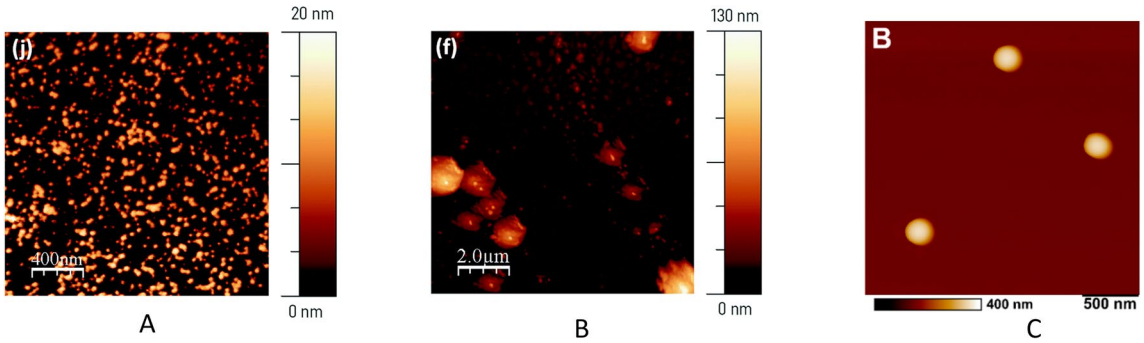

Fig. 5 AFM-based NMPs characterization; atomic force microscopy (AFM) topography images of T2LNPs adsorbed on mica, with a scan size of 2 µm **a** and 10 µm **b** [82]; AFM image of 200 nm PS NPs **c** [83]

Atomic force microscopy

Atomic force microscopy (AFM) is a high-resolution imaging technique that provides three-dimensional topographical data at the nanoscale. It operates by scanning a sharp tip across the surface of a sample, measuring forces between the tip and the sample to create detailed images. AFM is especially relevant in the investigation of NMPs due to its ability to precisely characterize surface morphology, mechanical properties, and interactions at the nanoscale [76, 77]. For NMPs research, AFM offers precise insights into surface roughness, degradation patterns, and the interaction of these particles with biological or environmental interfaces, making it an indispensable tool for understanding the environmental behavior and impact of these pollutants. Nguyen et al. [78] emphasized that AFM offers more in-depth characterizations compared to SEM, particularly in terms of evaluating mechanical stiffness [79] and hydrophobicity [76]. Recently, the method has been used to explore how MPs degrade in marine environments when adhering bacteria are present on the surface using AFM [80, 81]. Despite very high-resolution AFM operates by scanning a sample point-by-point, which makes it inherently slow compared to other imaging techniques. The time-intensive nature of AFM limits its practicality for analyzing large areas or large numbers of particles, making it challenging to obtain statistically significant data on heterogeneous MPs samples. AFM requires a clean, smooth, and accessible surface for effective imaging. However, NMPs found in environmental samples are often embedded with contaminants or biofilms, which can obscure surface features and interfere with AFM measurements.

In a different study, [84] manufactured a nano-TiO_2-coated PP MPs effectively and investigated their nanoscale infrared, thermal, and mechanical properties before and after photoaging using AFM and analytical technique. Figure 5a,b shows AFM images of "true-to-life" NPs (T2LNPs) at 2 µm and 10 µm scan rates. These T2LNPs nanoparticles were composed of spheroidal PS nanoparticles with respect to broad range of size distribution ranging from different nanoscale size ranges; and incubated with human plasma to allow interaction with diverse proteins, forming a protein corona around them. The primary objective of this approach was to develop a closer model to real life, i.e., "true-to-life" to understand interaction of NPs with biological environment at nanoscale in a more realistic manner. T2LNPs consist of spheroidal monomodal PS nanoparticles, with an average size of 165 nm. Figure 5c displays 200 nm spherical PS nanoparticles. AFM analysis reveals a mixture of tiny particles alongside larger particles and aggregates.

AFM primarily provides topographical and mechanical data, with limited ability to determine the chemical composition of samples. Unlike other techniques, AFM cannot distinguish between different types of plastics based solely on their surface features. This can be achieved via integrating AFM with complementary techniques for chemical identification leading to a powerful investigation solution [85].

Spectro-microscopic based advancements

Combining spectroscopic methods with microscopy allows visualization and improve characterization of NMPs. Table 1 summarizes various microscopic and spectroscopic techniques for detecting NMPs, highlighting their sensitivity, advantages, and challenges.

Infrared-based advancements

Fourier transform infrared (FTIR) spectroscopy is a widely used technique for material characterization, particularly for analyzing chemical bonds and molecular structures. The technique works by absorbing infrared photons, which cause molecules to transition from their ground state to an excited vibrational state [97]. FTIR devices come in various configurations, including transmission, specular reflection, diffuse reflection, and

Table 1 Comparison of recent selected detection methods for NMPs, highlighting sensitivity, challenges and advantages

Type	Method	Range	Challenges	Advantages	Refs.
Spectroscopy	DLS	1 nm to 3 mm	Large particles, polydispersity affects results	Fast, cheap, non-invasive	[86]
Spectroscopy	Multiangle laser scattering (MALS)	10 nm to 1000 nm	Require clean sample and only spherical models	Online coupling, large size ranges, easy, fast	[87]
Spectroscopy	Laser diffraction (LD)	10 nm to 10 mm	Only spherical model	Easy, fast and automated	[88, 89]
Spectroscopy	Nanoparticle tracking analysis (NTA)	10 nm to 2 µm	Complex in operation	Size and number concentration	[90]
Spectroscopy	Electrophoretic light scattering (ELS)	1 µm to 3 µm	Electro-osmotic effect	Rapid, cheap, non-invasive	[91, 92]
Spectroscopy	Raman spectroscopy	up to 1 µm	difficulty with data interpretation for complex structures,	Nondestructive, fast, reliable	[93, 94]
Microscopic	Stereo microscopy	≥ 100 µm	Identifying plastic nature, composition	Easy and rapid, shape, size, color identification	[61]
Microscopic	TEM	0.1 nm to 100 µm	Not effective to identify MPs/NPs	Chemical information and images	[93]
Spectro-microscopic	SEM–EDS	5 nm to 5 mm	Expensive technique	Information about the morphological surface	[72]
Microscopic	AFM	Up to 0.1 nm	Expensive, limited scan area (100 µm)	Surface morphology, mechanics	[83]
Spectro-microscopic	AFM-IR	Down to 20 nm	Expensive	Particle morphology, chemical identification	[95]
Spectro-microscopic	AFM-Raman	Single molecule detection capability	Expensive, under-development for rapid nanoscale chemical analysis	Particle morphology and chemical fingerprint	[96]

attenuated total reflection (ATR), each tailored to specific sample types and applications.

ATR-FTIR is particularly relevant for investigating NMPs because it allows direct analysis of solid or liquid samples with minimal preparation. This technique introduces infrared light directly to the sample, enabling the extraction of structural and compositional information even from complex matrices. FTIR is valued for its ability to quickly generate high-quality spectra, ease of use and reproducibility. Common challenges include potential background contamination, but ATR-FTIR remains a sensitive and cost-effective method, capable of detecting MPs (about 10 µm). When coupled with microscopy (micro-FTIR) [98, 99], it can identify even smaller particles, making it an essential tool in the study of NMPs.

For example, ATR-FTIR showed stronger peak signals with decreasing NMPS diameter at the micrometer scale, successfully detecting NMPs with high sensitivity in the 6–20 µm size range [100]. Jung et al. [101] demonstrated the use of ATR-FTIR for identifying polymers in NMPs ingested by sea turtles; highlighting its ability to perform rapid analysis with minimal sample destruction. Similarly, this technique was used for NMPs detection from sediments and water samples [102].

AFM-IR uses an atomic force tip and infrared laser excitation to simultaneously record high-resolution topography and chemical spectra. It provides resonant modes and high-quality data with excellent sensitivity, unaffected by background interfaces, and matches conventional IR spectra of bulk materials. However, it is relatively slow and complex [103]. A hybrid technique combining the spatial resolution of AFM with the chemical information of IR spectroscopy was employed to study nanoscale PS particles. This approach enabled the detection and quantification of NPs as small as 20 nm in aqueous environments [104]. A pulse tunable IR source with a 10-ns pulse length and broad mid-infrared coverage is localized on AFM tip to investigate nanoscale thermal, mechanical, and infrared properties of TiO_2-pigmented NMPs before and after aging. AFM topography shows unaged NMPs as smooth, while aged MPs exhibit rough, granular surfaces. A combined AFM-mechanics method and photothermal infrared spectroscopy are used to locate, capture, and chemically identify beads in mussel siphons [95].

Figure 6a-c illustrates the efficacy of the AFM-IR technique in detecting 150 nm PS spheres based on surface groups. In Fig. 6b, characteristic sulfonate (S=O) stretching vibrations are observed at 1165 and 1350 cm^{-1} (green line); however, these signals disappear after treating PS spheres with H_2O_2 (red line). The IR spectrum (Fig. 6c) reveals C=C and C–H features. Figure 6a, b displays AFM and IR images, respectively.

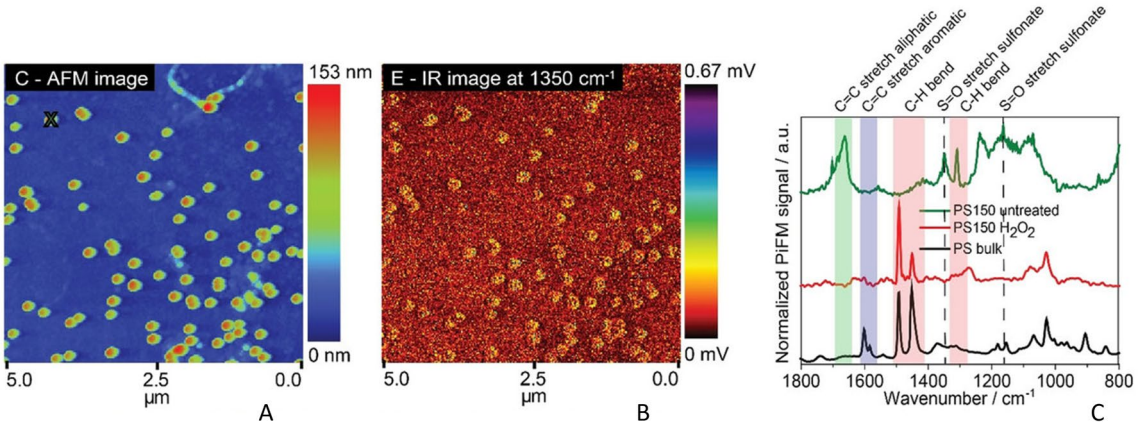

Fig. 6 Typical measurement results by AFM-IR of PE NPs with AFM morphology **A**, IR image **B** and IR spectra **C** [104]

Laser direct infrared (LDIR) spectroscopy technique combines the precision of infrared spectroscopy with the spatial resolution of laser-based imaging [105]. This method allows for the detailed chemical mapping of materials, making it particularly relevant for the investigation of NMPs. LDIR operates by directing a tunable laser across the sample surface, generating high-resolution spectra that reveal the chemical composition of individual particles. Its ability to rapidly scan large areas with minimal sample preparation makes LDIR ideal for identifying and quantifying NMPs within complex environmental matrices. LDIR imaging can analyze up to 10^3 particles/fibers (< 300 µm) in approximately 1–2 h. Over FTIR and Raman imaging, it helps to overcome uncertainties such as subsampling strategies due to long analysis and post-processing times of large datasets [106]. LDIR shows significant potential when combined with automation, offering the possibility of automating both identification and quantification processes. This technique has been successfully applied to detect NMPs larger than 20 µm from water and soil samples [107]. Additionally, LDIR can be further enhanced with a quantum cascade laser (QCL), offering higher radiation power than typical IR sources.

Figure 7 shows the chemical imaging spectra from LDIR technology. The LDIR system automatically identified particles and matched spectra. All MP particles in this study showed over 80% matching with the spectral library. Polymer composition distribution varied based on particle size and sampling methods. LDIR excels in analyzing MPs, but its resolution is limited when it comes to characterizing NMPs, especially those smaller than 1 µm. The spatial resolution of this technique, while higher than conventional IR spectroscopy, may not be sufficient to resolve the smallest particles, leading to potential underestimation of NMPs presence in a sample.

Raman spectroscopy-based advancements

Raman spectroscopy is a vibrational spectroscopic technique that provides detailed molecular information based on the inelastic scattering of light. When light interacts with a material, most photons are elastically scattered, but a small fraction is scattered at different energies, corresponding to the vibrational modes of the molecules [109]. This scattering produces a Raman spectrum that serves as a molecular fingerprint, enabling precise chemical identification. Raman spectroscopy is particularly relevant for the investigation of NMPs due to its ability to non-destructively analyze small particles, even those embedded in complex matrices. This technique is widely recognized as a powerful tool for characterizing NMPs. Compared with IR that has longer wavelength, Raman shows better performance for analysis of NPs. Its effectiveness as a chemical analytical method enables the detection of NMPs in various environmental matrices like sediments [110], bottled waters [111] and mixing between seawater and freshwaters [112]. Micro-Raman is capable of identifying MPs smaller than 1 µm using spectroscopy, while conventional Raman spectroscopy can identify MPs larger than 10 µm. Xie et al. [110] detect and identify NMPs smaller than 1 µm using the surface-enhanced Raman spectroscopy (SERS) technique with Klarite substrate which facilitated the identification and detection of atmospheric/aquatic MPs with size up to 360 nm; and enhancement factor up to 2 orders of magnitude for PS analytes was found [110]. Figure 8a-c illustrates the application of SERS to detect PS NPs, with a resolution limit reaching 50 nm. SERS, a non-invasive molecule-specific technology, enables single-molecule detection through molecular vibration fingerprinting. To ensure the effective detection of NMPs, optimizing plasmonic hotspots is crucial, as

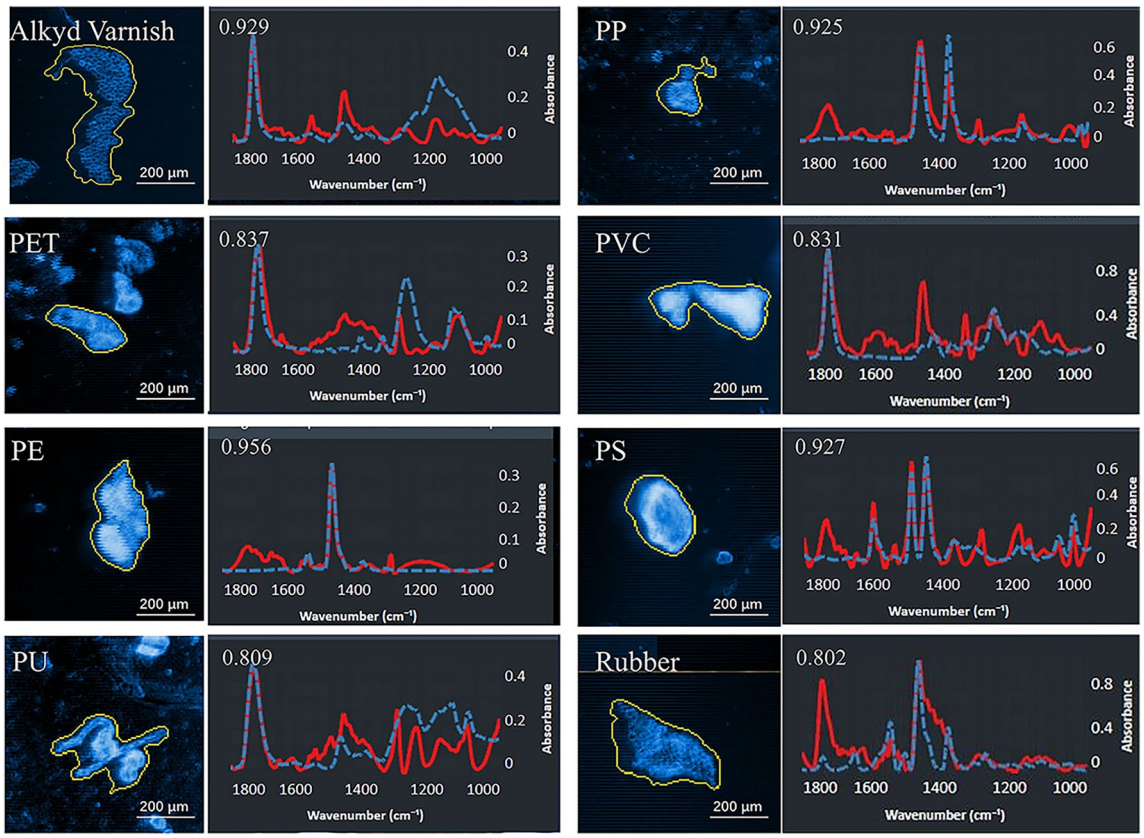

Fig. 7 Typical LDIR chemical imaging spectra of eight MPs identified as alkyd varnish: PET, PE, PU, PP, PVC, PS, and rubber. Blue lines are reference spectra and red lines are experiments. The number on the upper left of the spectrum is the degree of matching with the standard spectrum [108]

variations in the size of NMPs can affect SERS signals. This challenge can be addressed by fabricating SERS substrates with tailored plasmonic nanoparticles in specific sizes and shapes [113].

To prevent sample degradation and luminescence, certain tests were conducted at lower laser power. However, for NPs smaller than 1 µm, more robust analytical techniques are required to ensure accuracy. Figure 8d presents Raman-confocal match analysis of a single fiber (left) and a non-match (right) compared to the standard Raman peak [70].

Tip-enhanced Raman spectroscopy (TERS) merges the chemical sensitivity of SERS with the high spatial resolution of scanning probe microscopy, allowing for nanoscale chemical imaging. A sharp metal or metal-coated tip is placed at the center of a laser focus, where the electromagnetic field at the tip apex is confined and enhanced by localized surface plasmon resonance [115]. TERS provides a powerful technique for analyzing surfaces with nanometer precision [116]. Over the last decade, this technique has been applied in wide range of research areas including carbon nanotubes, graphene, biology, photovoltaics, etc., Yeo et al. [117] conducted nano-scale probing of Raman active mixed polyisoprene and PS thin film to investigate surface composition. Although difficult to operate, this method could investigate films at surface and subsurface levels and tend to enable analysis at nanometer spatial resolution.

Advances in other methodologies

Mass spectroscopy advancements

Matrix-assisted laser desorption/ionization-time-of-flight mass spectrometry (MALDI-TOF MS) uses ionization of sample mixed with matrix molecule via a laser; and the ions are separated by their mass-to-charge ratio in a TOF analyzer for mass analysis. Tang et al. used this technique for sediment samples to identify and quantify NMPs. PS and PET were identified with 0.96 and 0.98 correlation coefficients for low and high molecular weight polymers. Similar research approach was applied for other types of NMPs identification [118] and exploring bioaccumulation of NMPs inside zebrafish [119]. In other work, MALDI-FTICR MS, i.e., a matrix-assisted laser desorption of ionization-Fourier transform ion showed high performance

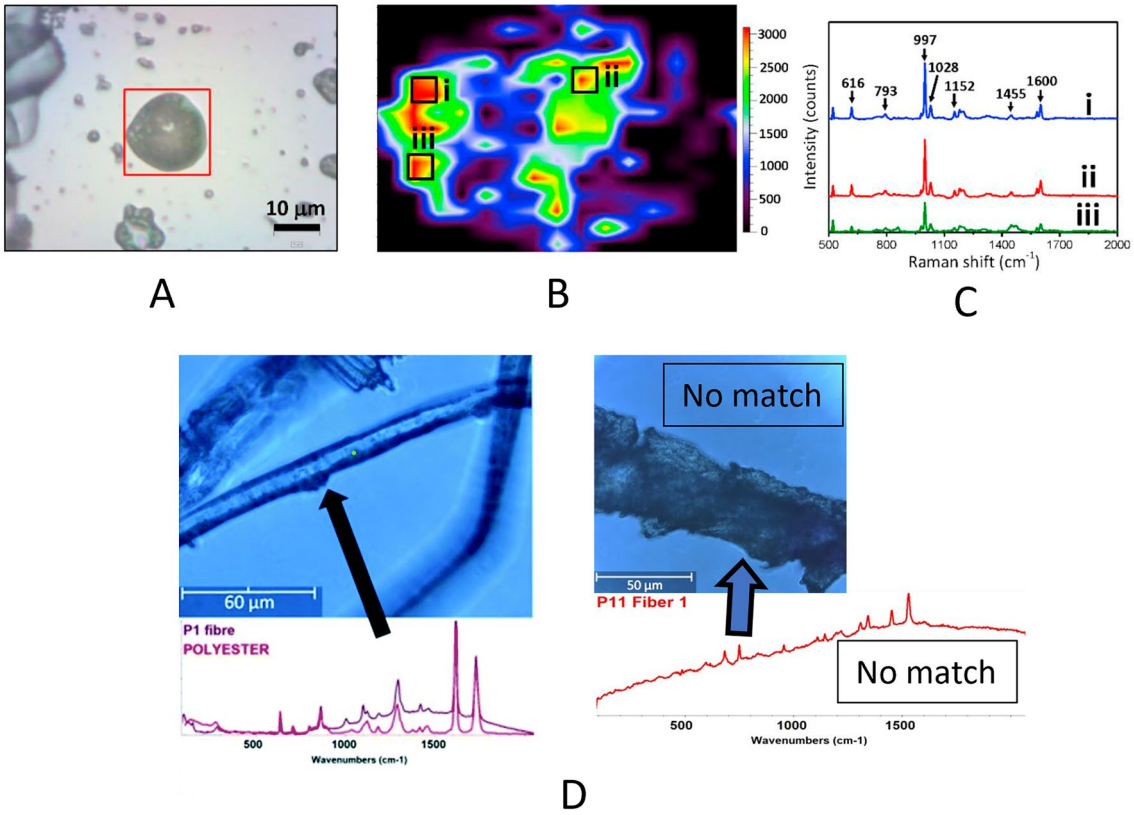

Fig. 8 Identification of 1 µm PS NPs with SERS. **a** Microscopic image of PS NPs deposited on a silicon wafer; **b** Raman intensity map of the 997 cm^{-1} band in the region marked with a red box in panel **A** [114]; **c** Raman spectra obtained from three random sites marked in panel **b**; **d** details of the match analysis product showing the single fiber confocal Raman match analysis, (50 × objective and 80–2060 cm^{-1} Raman shift range) and the confocal Raman no match [70]

for wide-ranged NMPs characterization with improved signal-to-noise ratio [120].

Thermal analysis advancements

Thermogravimetric analysis (TGA) measures the mass of a substance as it changes with temperature or time under controlled temperature procedures and atmospheres. Characterization and quantification of NMPs can be achieved via optimizing parameters in TGA such as heating, analysis of mass and loss, sample preparation and standard calibration [121]. Pyrolysis-gas chromatography–mass spectrometry (Py-GC–MS) involves heating a sample to decompose it into smaller molecules, which are then separated by gas chromatography and identified using mass spectrometry. This technique can detect NMPs via their thermal decomposition into characteristic or signature molecules; and based on unique degradation products a precise detection can be done [122]. Plastic polymers vary in thermal stability and have distinct IR absorption and Raman scattering characteristics. Thermo-analytical techniques identify MPs by analyzing changes in their chemical and physical properties [123]. This process identifies polymers by their decomposition byproducts. Developing thermo-based techniques is critical for characterizing low-solubility MPs and additives that are hard to dissolve, extract, or hydrolyze.

In TG-FTIR and TG-MS, a transfer line or capillary connects the TGA directly with evolved gas analysis. These methods are useful for analyzing known matrix samples with specific MPs and detecting PVC [124]. Thermal extraction-desorption gas chromatography mass spectrometry (TEDGC/MS) can be useful for analyzing unknown matrix samples with unknown variable kinds of MPs and content but the method is complex [125]. Microscale combustion calorimeter (MCC) can be applied for simple and rapid screening to identify potential MP loads of standard polymers in unknown samples, but there is no difference between different polymers, where only PE, PP, PS contribute significantly to the signal and are limited to 5 mg of sample [124]. Py-GC–MS (pyrolysis-gas chromatography–mass spectrometry) can simultaneously locate and measure the most prevalent MPs in complex samples.

Light scattering technique advancements

Many studies use light scattering to characterize NMPs. In dynamic light scattering (DLS), a monochromatic light beam incident on a solution scatter in all directions, providing information about the size, shape, molecular weight, and radius of gyration of macromolecules [86]. While light scattering techniques can assess a wider variety of particle sizes, they only measure average hydrodynamic sizes, which may be biased towards larger particles due to their stronger scattering. This can mask signals from smaller particles and be affected by contaminants like dust fibers or aggregates. Strict sample preparation is crucial for accurate results, especially in foods, beverages, inhaled particles, and personal care products. This is addressed by multi-angle light scattering (MALS), which analyzes scattered light at various angles and provides molecular weight and size distribution data. MALS is often used as an online detector in size-based separation methods like size exclusion chromatography (SEC) and asymmetrical flow-field flow fractionation.

AI-based technologies advancements

Data analysis, the final stage of scientific research, is frequently used to collect and represent results and find correlations. When large datasets are involved, a new class of algorithms is necessary to find hidden correlation and simplify data analysis. Indeed, artificial intelligence (AI) has emerged as a transformative tool in the analysis of NMPs, offering enhanced precision and scalability. NMPs may be automatically detected, categorized, and quantified from complicated datasets thanks to AI-based techniques like computer vision, deep learning, and machine learning. These techniques can process large volumes of imaging and spectral data, identifying subtle patterns and correlations that conventional approaches might miss. In NMPs research, AI-based analysis accelerates the identification of plastic particles, enhances the accuracy of differentiating between polymer kinds, and aids in understanding their environmental behavior [126]. Machine learning is a branch of artificial intelligence that focuses on developing algorithms capable of learning from data and making decisions or predictions without needing explicit instructions. It is a fundamental approach to enabling intelligent behavior in AI systems. Machine learning can help to detect and identify nanomaterials by analyzing data to recognize patterns and classify material types, improving research efficiency and accuracy [127].

For example, Guo et al. [126] linked laboratory data about metal ions sorption on NMPs with environmental monitoring using neural networks for prediction. However, limitations in the size of the dataset for absorption, variability in NMPs properties and areas of sampling can make this prediction difficult. As a subclass of neural networks, convolutional neural networks (CNN) are invariant by roto-translation, making them performant for image recognition. Ng et al. [127] applied this algorithm to classify the extent of NMPs contamination in soil samples where visible–near-infrared (vis–NIR) reflectance spectra were used as 1D input. Support vector machine (SVM) is a supervised machine learning class that classifies data by finding a hyperplane that maximize the distance between different groups of data. It is used for general-purpose classification, and it requires long-term training, making it unsuitable for large datasets. Shan et al. combined hyperspectral imaging (HSI) with SVM to quantify NMPs contamination in sea water filtrates [128]. Random forest and decision tree are ML methods used for classification and regression. They can identify or detect features and patterns, as well as anticipate categories and continuous values. Hufnagl et al. used these methods for automatic analysis of μFTIR images of MPs for monitoring applications [129]. Table 2 presents a summary of these publications pertaining to different approaches in terms of methodology, approach, advantages, and drawbacks. This table provides a comprehensive information about various ML methods.

Despite numerous reports, developing new algorithms and databases for NMPs detection and analysis utilizing ML-based approaches remains essential. Raman spectroscopy, widely used for NMPs detection, covers various ranges: soil (150–200 μm), marine (> 10 μm), plastic microbeads (> 4 μm), and spectral analysis (< 1 μm). For instance, Xie et al. [133] reported Raman spectroscopy with an ML-based automatic identification platform for NMPs. In this work, NMPs were identified with 98.8% accuracy through steps like establishing a Raman spectroscopy dataset, peak extraction, data processing, and random forest model building. Challenges include weak Raman spectra and complex environmental samples. In another similar attempt, Weber et al. [134] developed an NMPs analysis platform via combining ML with μ-Raman, where they created a data set consisting of $> 6.4 \times 10^4$ Raman spectra, including 10.7% polymer spectra extracted from 47 water samples.

Perspectives

Emerging solutions for detecting NMPs are centered on advanced technologies that offer high sensitivity and specificity. Innovations such as microfluidic systems and nanoparticle tracking analysis are streamlining sample preparation and analysis, enhancing detection capabilities. For instance, microfluidics coupled with electrochemical cells has shown potential for NMP detection. However, it is important to consider that NMPs are not inherently electroactive, and microfluidic systems are generally not suitable for processing large sample

Table 2 Various ML algorithms their applicability, advantages and drawbacks over NMPs detection

Method	Approach	Advantage	Drawback	Refs.
ANN	Predicting sorption capacity of heavy metal ions on NMPs	Highly potential case study linked to lab experiments	Limited sorption data are inhibiting wider applicability	[126]
CNN	Classification of IR spectral data inputs	Potential rapid NMPs soil contamination screening	Lacking ability to differentiate intermediate cases	[127]
CNN	GoogLeNet architecture as a model trained and tested for image analysis	Potential automatic NMPs classification using micrographs	Limited to microbeads	[130]
SVM	To identify MPs from the hyperspectral image	Ability to quantify and identify NMPs from seawater and seawater filtrates	Particle size, polymer type and organic impurity can affect accuracy	[128]
SVM	Repfile-EasyTL model: Transfer learning strategy realizing transference from HIS system to NIR sensor	Rapid, accurate, less complex	Interference from organic matter, alkali-hydrolyzable nitrogen, and available phosphorus	[131]
SVM	3D coherent imaging combined with ML for NMPs detection	Holographic signatures of NMPs	At the moment limited to water samples	[132]
RF	μFTIR images analysis for identification and monitoring NMPs	Can differentiate polymer types, their abundance and size distribution	Label noise and different dimensions can affect	[129]

volumes. Future directions may focus on integrating diverse analytical techniques to provide more comprehensive detection, developing portable, field-deployable tools for on-site monitoring, and establishing standardized protocols to ensure consistent and comparable results. The development of regulatory frameworks could further drive research and technological innovation, enabling more effective management of NMP pollution and its environmental and health impacts.

Advanced functional nanomaterials may play a crucial role in separating NMPs, with potential for designing materials that specifically target these particles. However, the lack of unique markers on NMPs (similar to biomarkers on cell surfaces) presents a significant challenge for targeted separation and detection. Addressing this limitation is essential for advancing detection methods. In terms of detection and identification techniques discussed in this manuscript, optical microscopy is unable to detect NMPs smaller than 200 nm, whereas electron microscopy methods can detect NMPs at the nanoscale but lack the ability to chemically identify them. Techniques such as FE-SEM and TEM are powerful tools for high-resolution imaging and for analyzing the morphology, structure, and elemental composition of NMPs. However, sample preparation for these methods is challenging, as it requires avoiding contamination and distinguishing NMPs from other materials in complex samples. Atomic force microscopy (AFM) can characterize NMPs at the nanoscale and provides detailed surface information, but it is expensive and time-consuming, limiting its practicality for routine detection. Spectro-microscopic tools demonstrate significant potential for simultaneously achieving morphological and chemical identification of NMPs. IR and Raman spectroscopies, when coupled with microscopic techniques (e.g., AFM-IR and Raman-confocal microscopy), are indeed promising due to their ability to provide both visualization and chemical identification of NMPs. Among these, Raman spectroscopy is especially effective at detecting particles down to the sub-micrometer scale, a range where IR spectroscopy often struggles due to weak signals caused by trace concentrations and the limitations of spatial resolution imposed by longer wavelengths. Mass spectrometry, while highly precise, sensitive, and capable of multi-component analysis, is limited in detecting particles smaller than 50 nm and requires complex, costly sample preparation. Thermogravimetric analysis (TGA), though useful for assessing thermal properties, cannot provide molecular or chemical information, a limitation that can be addressed by coupling it with complementary techniques. Dynamic light scattering (DLS) offers rapid and non-destructive analysis for particles in the nano- to micro-meter range, but is restricted to suspended particles and struggles with poly disperse samples.

AI plays an important role in the detection or identification of NMPs by improving data analysis, accuracy, and efficiency. AI algorithms, particularly machine learning and deep learning, can process complex spectroscopic and imaging data to accurately identify and classify NMPs. Consequently, automated feature extraction and signal enhancement further improve identification capabilities, while predictive modeling aids in contamination assessment and environmental impact analysis. These algorithms facilitate the creation of comprehensive libraries or databases of NMP signatures, enabling efficient identification across various sample types and environments. AI can also be integrated with sensor technology to enable adaptive sensing and monitoring.

One notable example is digital holography (DH), which offers great potential for NMP detection. Unlike

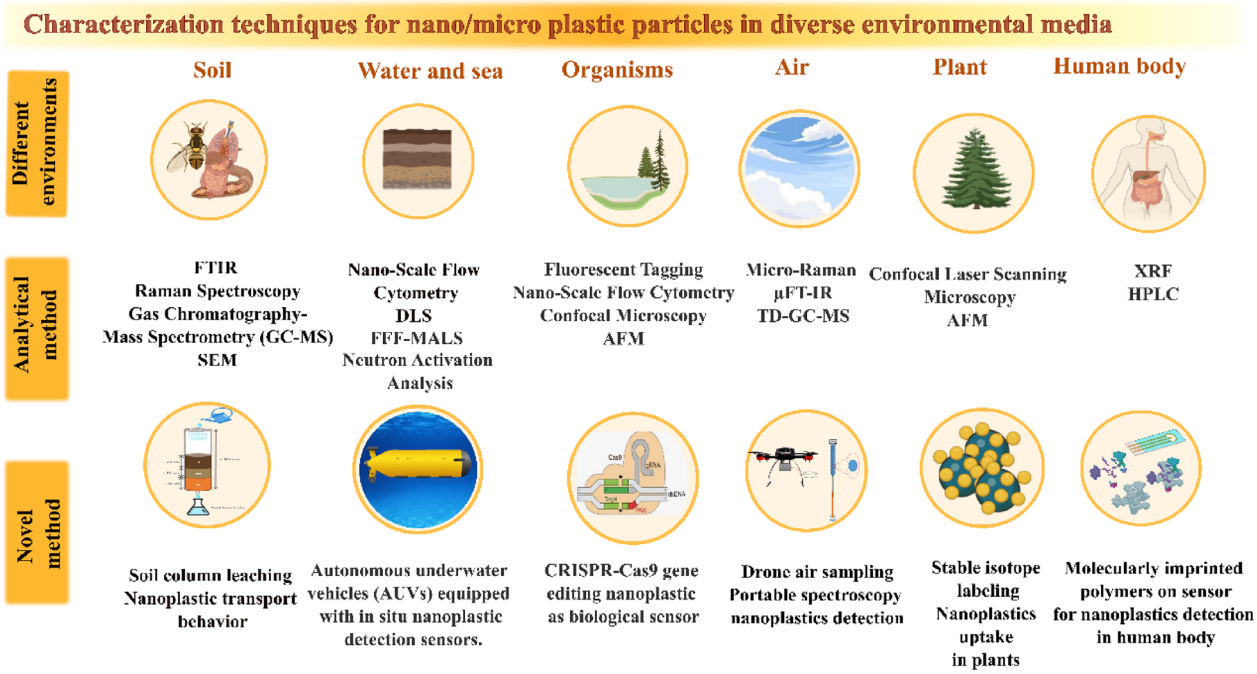

Fig. 9 Possible new technological aspects for NMPs detection

traditional methods, DH uses a sensor to display holograms, enabling the identification of tens of thousands of items per hour. When combined with AI, DH becomes highly suitable for in situ water quality analysis, offering unparalleled efficiency in high-throughput applications [132]. Despite these advancements, challenges remain, particularly in standardizing sample pretreatment procedures. Factors such as sample type, source, and quantity must be carefully considered to avoid altering the intrinsic properties of NMPs. For example, while AFM demonstrates extraordinary detection capabilities at the nanoscale, it cannot identify the chemical species of NMPs. This limitation can be addressed by coupling AFM with other techniques, such as AFM-IR or TERS, to provide both morphological and chemical characterization. LDIR spectroscopy has also shown promise as a versatile tool for detecting, identifying, and classifying NMPs. However, achieving high resolution at the nanoscale remains a challenge, requiring advancements in nanoscale microscopy and the integration of material-specific investigations. With continued innovation and the application of AI, these challenges can be overcome, paving the way for more effective and scalable solutions in NMP analysis.

Figure 9 outlines potential approaches that can be developed for the detection of NMPs in various scenarios, offering a comprehensive insightful framework for advancing new technologies. While no single approach is effective for every scenario, recent studies highlight complementary strategies and multi-properties analysis on path to resolve the detection of NMPs at the nanoscale. The development of reliable, novel methods is essential for the continued progress in NMPs detection and analysis. Effective policy and decision-making to overcome NMPs problem requires key scientific, regulatory, and societal needs. Ongoing research directions should fill knowledge gaps to ensure comprehensive policy development against NMPs[135].

Conclusion

Critical review of literature reveals that plastic waste severely impacts freshwater and terrestrial ecosystems, as well as human health. Adopting a life cycle approach, including end-of-life disposal, recovery, reuse, and recycling, is crucial. The reprocessing of recycled plastics for new applications and their recovery from waste streams can reduce greenhouse gas emissions and conserve resources. Future research should focus on the impact of NPs and MPs on biological organisms and critically examine their toxicity to humans, animals, and plants. Understanding the mechanisms and effects of these particles is crucial. Advancing computational and mathematical modeling can significantly improve risk assessments and inform preventive strategies. The development of sustainable protocols and tools for the quantification and

identification of MPs and NPs is essential for their effective management. A robust detection and identification method for NMPs must be established to address these challenges. Additionally, the success of such methods depends on the standardization of sample pretreatment and separation techniques. Therefore, the detection of NMPs encompasses three key aspects: sampling, sample pretreatment, separation and detection as well as identification. Overall, greater efforts are needed across these areas to advance current knowledge and technologies in the detection of NMPs.

Author contributions
A. N.: writing–original draft, conceptualization; S. S.: writing–original draft, conceptualization; S.V.: writing–review and editing; W. Y.: writing–review and editing; U. P. U.: writing–review and editing; A. K.: writing–review and editing, supervision, conceptualization; X. L.: writing–review and editing, supervision; P. S.: writing–review and editing; M. G.: writing–review and editing, supervision, funding acquisition.

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Availability of data and materials
No datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare no competing interests.

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References

1. Ter Halle A, Ghiglione JF (2021) Nanoplastics: a complex, polluting terra incognita. Environ Sci Technol 55:14466–14469. https://doi.org/10.1021/acs.est.1c04142
2. Cai H, Xu EG, Du F, Li R, Liu J, Shi H (2021) Analysis of environmental nanoplastics: progress and challenges. Chem Eng J 410:128208. https://doi.org/10.1016/j.cej.2020.128208
3. Kokilathasan N, Dittrich M (2022) Nanoplastics: detection and impacts in aquatic environments—a review. Sci Total Environ 849:157852. https://doi.org/10.1016/j.scitotenv.2022.157852
4. Ng EL, Huerta Lwanga E, Eldridge SM, Johnston P, Hu H, Geissen V, Chen D (2018) An overview of microplastic and nanoplastic pollution in agroecosystems. Sci Total Environ 627:1377–1388. https://doi.org/10.1016/j.scitotenv.2018.01.341
5. Ullah R, Tsui MTK, Chow A, Chen H, Williams C, Ligaba-Osena A (2023) Micro(nano)plastic pollution in terrestrial ecosystem: emphasis on impacts of polystyrene on soil biota, plants, animals, and humans. Environ Monit Assess 195:252. https://doi.org/10.1007/s10661-022-10769-3
6. Lai H, Liu X, Qu M (2022) Nanoplastics and human health: hazard identification and biointerface. Nanomaterials 12(8):1298. https://doi.org/10.3390/nano12081298
7. Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang JH, Abu-Omar M, Scott SL, Suh S (2020) Degradation rates of plastics in the environment. ACS Sustain Chem Eng 8:3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635
8. Pérez-Reverón R, Álvarez-Méndez SJ, González-Sálamo J, Socas-Hernández C, Díaz-Peña FJ, Hernández-Sánchez C, Hernández-Borges J (2023) Nanoplastics in the soil environment: analytical methods, occurrence, fate and ecological implications. Environ Pollut 317:120788. https://doi.org/10.1016/j.envpol.2022.120788
9. Delre A, Goudriaan M, Morales VH, Vaksmaa A, Ndhlovu RT, Baas M, Keijzer E, de Groot T, Zeghal E, Egger M, Röckmann T, Niemann H (2023) Plastic photodegradation under simulated marine conditions. Mar Pollut Bull 187:114544. https://doi.org/10.1016/j.marpolbul.2022.114544
10. Yu J, Wang S, Zhang HQ, Song XR, Liu LF, Jinag Y, Chen R, Zhang Q, Chen YQ, Zhou HJ, Yang GP (2024) Effects of nanoplastics exposure on ingestion, life history traits, and dimethyl sulfide production in rotifer *Brachionus plicatilis*. Environ Pollut 344:123308. https://doi.org/10.1016/j.envpol.2024.123308
11. Ouda M, Kadadou D, Swaidan B, Al-Othman A, Al-Asheh S, Banat F, Hasan SW (2021) Emerging contaminants in the water bodies of the Middle East and North Africa (MENA): a critical review. Sci Total Environ 754:142177. https://doi.org/10.1016/j.scitotenv.2020.142177
12. Pedrotti ML, Petit S, Eyheraguibel B, Kerros ME, Elineau A, Ghiglione JF, Loret JF, Rostan A, Gorsky G (2021) Pollution by anthropogenic microfibers in North-West Mediterranean Sea and efficiency of microfiber removal by a wastewater treatment plant. Sci Total Environ 758:144195. https://doi.org/10.1016/j.scitotenv.2020.144195
13. Ryan AC, Allen D, Allen S, Maselli V, LeBlanc A, Kelleher L, Krause S, Walker TR, Cohen M (2023) Transport and deposition of ocean-sourced microplastic particles by a North Atlantic hurricane. Commun Earth Environ 4:442. https://doi.org/10.1038/s43247-023-01115-7
14. Allen S, Allen D, Phoenix VR, Le Roux G, Jiménez PD, Simonneau A, Binet S, Galop D (2019) Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat Geosci 12:339–344. https://doi.org/10.1038/s41561-019-0335-5
15. Viaroli S, Lancia M, Re V (2022) Microplastics contamination of groundwater: current evidence and future perspectives. A Rev Sci Total Environ 824:153851. https://doi.org/10.1016/j.scitotenv.2022.153851
16. Mitrano DM, Wick P, Nowack B (2021) Placing nanoplastics in the context of global plastic pollution. Nat Nanotechnol 16:491–500. https://doi.org/10.1038/s41565-021-00888-2
17. Wahl A, le Juge C, Davranche M, El Hadri H, Grassl B, Reynaud S, Gigault J (2021) Nanoplastic occurrence in a soil amended with plastic debris. Chemosphere 262:127784. https://doi.org/10.1016/j.chemosphere.2020.127784
18. Wang W, Zhang J, Qiu Z, Cui Z, Li N, Li X, Wang Y, Zhang H, Zhao C (2022) Effects of polyethylene microplastics on cell membranes: a combined study of experiments and molecular dynamics simulations. J Hazard Mater 429:128323. https://doi.org/10.1016/j.jhazmat.2022.128323
19. Barcelo D, Pico Y (2020) Case studies of macro- and microplastics pollution in coastal waters and rivers: Is there a solution with new removal technologies and policy actions? Case Stud Chem Environ Eng 2:100019. https://doi.org/10.1016/j.cscee.2020.100019
20. Barchiesi M, Chiavola A, Di Marcantonio C, Boni MR (2021) Presence and fate of microplastics in the water sources: focus on the role of wastewater and drinking water treatment plants. J Water Process Eng 40:101787. https://doi.org/10.1016/j.jwpe.2020.101787
21. Chia RW, Lee JY, Jang J, Cha J (2022) Errors and recommended practices that should be identified to reduce suspected concentrations of microplastics in soil and groundwater: a review. Environ Technol Innov 28:102933. https://doi.org/10.1016/j.eti.2022.102933
22. Huang J, Chen H, Zheng Y, Yang Y, Zhang Y, Gao B (2021) Microplastic pollution in soils and groundwater: characteristics, analytical methods

and impacts. Chem Eng J 425:131870. https://doi.org/10.1016/j.cej.2021.131870
23. He D, Luo Y, Lu S, Liu M, Song Y, Lei L (2018) Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC. Trends Anal Chem 109:163–172. https://doi.org/10.1016/j.trac.2018.10.006
24. Mahapatra S, Maity JP, Singha S, Mishra T, Dey G, Samal AC, Banerjee P, Biswas C, Chattopadhyay S, Patra RR, Patnaik S, Bhattacharya P (2024) Microplastics and nanoplastics in environment: sampling, characterization and analytical methods. Groundw Sustain Dev 26:101267. https://doi.org/10.1016/j.gsd.2024.101267
25. Zheng K, Wang P, Lou X, Zhou Z, Zhou L, Hu Y, Luan Y, Quan C, Fang J, Zou H, Gao X (2024) A review of airborne micro- and nano-plastics: sampling methods, analytical techniques, and exposure risks. Environ Pollut 363:125074. https://doi.org/10.1016/j.envpol.2024.125074
26. Choi S, Lee S, Kim MK, Yu ES, Ryu YS (2024) Challenges and recent analytical advances in micro/nanoplastic detection. Anal Chem 96:8846–8854. https://doi.org/10.1021/acs.analchem.3c05948
27. Thomas C, Spatayeva T, Yu D, Loh A, Yim UH, Yoon JY (2024) A comparison of current analytical methods for detecting particulate matter and micro/nanoplastics. Appl Phys Rev 11:011313. https://doi.org/10.1063/5.0153106
28. Xue Y, Song K, Wang Z, Xia Z, Li R, Wang Q, Li L (2024) Nanoplastics occurrence, detection methods, and impact on the nitrogen cycle: a review. Environ Chem Lett 22:2241–2255. https://doi.org/10.1007/s10311-024-01764-w
29. Saha N, Shourie A (2024) Detection and characterization of micro- and nano-plastics in wastewater: current status of preparatory & analytical techniques. Environ Qual Manage 34(2):e22267. https://doi.org/10.1002/tqem.22267
30. Casella C, Vadivel D, Dondi D (2024) The current situation of the legislative gap on microplastics (MPs) as new pollutants for the environment. Water Air Soil Pollut 235:778. https://doi.org/10.1007/s11270-024-07589-1
31. Jakubowicz I, Enebro J, Yarahmadi N (2021) Challenges in the search for nanoplastics in the environment—a critical review from the polymer science perspective. Polym Test 93:106953. https://doi.org/10.1016/j.polymertesting.2020.106953
32. Viaroli S, Lancia M, Lee JY, Ben Y, Giannecchini R, Castelvetro V, Petrini R, Zheng C, Re V (2024) Limits, challenges, and opportunities of sampling groundwater wells with plastic casings for microplastic investigations. Sci Total Environ 946:174259. https://doi.org/10.1016/j.scitotenv.2024.174259
33. Lee JY, Jung J, Raza M (2022) Good field practice and hydrogeological knowledge are essential to determine reliable concentrations of microplastics in groundwater. Environ Pollut 308:119617. https://doi.org/10.1016/j.envpol.2022.119617
34. Lee JY, Cha J, Ha K, Viaroli S (2024) Microplastic pollution in groundwater: a systematic review. Environ Pollut Bioavailabil 36:2299545. https://doi.org/10.1080/26395940.2023.2299545
35. Chia RW, Lee JY, Cha J, Rodríguez-Seijo A (2024) Methods of soil sampling for microplastic analysis: a review. Environ Chem Lett 22:227–238. https://doi.org/10.1007/s10311-023-01652-9
36. Lai Y, Dong L, Li Q, Li P, Liu J (2021) Sampling of micro- and nanoplastics in environmental matrixes. TrAC Trends Anal Chem 145:116461. https://doi.org/10.1016/j.trac.2021.116461
37. Azari A, Vanoirbeek JAJ, Van Belleghem F, Vleeschouwers B, Hoet PHM, Ghosh M (2023) Sampling strategies and analytical techniques for assessment of airborne micro and nano plastics. Environ Int 174:107885. https://doi.org/10.1016/j.envint.2023.107885
38. Nguyen B, Claveau-Mallet D, Hernandez LM, Xu EG, Farner JM, Tufenkji N (2019) Separation and analysis of microplastics and nanoplastics in complex environmental samples. Acc Chem Res 52:858–866. https://doi.org/10.1021/acs.accounts.8b00602
39. Vaughan R, Turner SD, Rose NL (2017) Microplastics in the sediments of a UK urban lake. Environ Pollut 229:10–18. https://doi.org/10.1016/j.envpol.2017.05.057
40. Schütze B, Thomas D, Kraft M, Brunotte J, Kreuzig R (2022) Comparison of different salt solutions for density separation of conventional and biodegradable microplastic from solid sample matrices. Environ Sci Pollut Res 29:81452–81467. https://doi.org/10.1007/s11356-022-21474-6
41. Razeghi N, Hamidian AH, Mirzajani A et al (2022) Sample preparation methods for the analysis of microplastics in freshwater ecosystems: a review. Environ Chem Lett 20:417–443. https://doi.org/10.1007/s10311-021-01341-5
42. Merga LB, Redondo-Hasselerharm PE, Van den Brink PJ, Koelmans AA (2020) Distribution of microplastic and small macroplastic particles across four fish species and sediment in an African lake. Sci Total Environ 741:140527. https://doi.org/10.1016/j.scitotenv.2020.140527
43. Shruti VC, Jonathan MP, Rodriguez-Espinosa PF, Rodríguez-González F (2019) Microplastics in freshwater sediments of Atoyac River basin, Puebla City. Mexico Sci Total Environ 654:154–163. https://doi.org/10.1016/j.scitotenv.2018.11.054
44. Turner S, Horton AA, Rose NL, Hall C (2019) A temporal sediment record of microplastics in an urban lake, London. UK J Paleolimnol 61:449–462. https://doi.org/10.1007/s10933-019-00071-7
45. Savino I, Campanale C, Trotti P, Massarelli C, Corriero G, Uricchio VF (2022) Effects and impacts of different oxidative digestion treatments on virgin and aged microplastic particles. Polymers 14(10):1958. https://doi.org/10.3390/polym14101958
46. Peng L, Mehmood T, Bao R, Wang Z, Fu D (2022) An overview of micro(nano)plastics in the environment: sampling, identification. Risk Assess Control Sustain 14(21):14338. https://doi.org/10.3390/su142114338
47. Keerthana Devi M, Karmegam N, Manikandan S, Subbaiya R, Song H, Kwon EE, Sarkar B, Bolan N, Kim W, Rinklebe J, Govarthanan M (2022) Removal of nanoplastics in water treatment processes: a review. Sci Total Environ 845:157168. https://doi.org/10.1016/j.scitotenv.2022.157168
48. Yang Q, Zhang S, Su J, Li S, Lv X, Chen J, Zhan LY (2022) Identification of trace polystyrene nanoplastics down to 50 nm by the hyphenated method of filtration and surface-enhanced raman spectroscopy based on silver nanowire membranes. Environ Sci Technol 56:10818–10828. https://doi.org/10.1021/acs.est.2c02584
49. Li Y, Wang Z, Guan B (2022) Separation and identification of nanoplastics in tap water. Environ Res 204:112134. https://doi.org/10.1016/j.envres.2021.112134
50. Hildebrandt L, Mitrano DM, Zimmermann T, Pröfrock D (2020) A nanoplastic sampling and enrichment approach by continuous flow centrifugation. Front Environ Sci 8:89. https://doi.org/10.3389/fenvs.2020.00089
51. Ali I, Tan X, Mustafa G, Gao J, Peng C, Naz I, Duan Z, Zhu R, Ruan Y (2024) Removal of micro- and nanoplastics by filtration technology: performance and obstructions to market penetrations. J Clean Prod 470:143305. https://doi.org/10.1016/j.jclepro.2024.143305
52. Juraij K, Ammed SP, Chingakham C, Ramasubramanian B, Ramakrishna S, Vasudevan S, Sujith A (2023) Electrospun polyurethane nanofiber membranes for microplastic and nanoplastic separation. ACS Appl Nano Mater 6(6):4636–4650. https://doi.org/10.1021/acsanm.3c00112
53. Lapointe M, Kurusu RS, Hernandez LM, Tufenkji N (2023) Removal of classical and emerging contaminants in water treatment using superbridging fiber-based materials. ACS EST Water 3:377–386. https://doi.org/10.1021/acsestwater.2c00443
54. Grause G, Kuniyasu Y, Chien MF, Inoue C (2022) Separation of microplastic from soil by centrifugation and its application to agricultural soil. Chemosphere 288:132654. https://doi.org/10.1016/j.chemosphere.2021.132654
55. Modak S, Kasula M, Esfahani MR (2023) Nanoplastics removal from water using metal-organic framework: investigation of adsorption mechanisms, kinetics, and effective environmental parameters. ACS Appl Eng Mater 1:744–755. https://doi.org/10.1021/acsaenm.2c00174
56. Surette MC, Mitrano DM, Rogers KR (2023) Extraction and concentration of nanoplastic particles from aqueous suspensions using functionalized magnetic nanoparticles and a magnetic flow cell. Microplast Nanoplast 3:2. https://doi.org/10.1186/s43591-022-00051-1
57. Liang Y, Hu S, Zhang Q, Zhang D, Guo G, Wang X (2022) Determination of nanoplastics using a novel contactless conductivity detector with controllable geometric parameters. Anal Chem 94:1552–1558. https://doi.org/10.1021/acs.analchem.1c02752
58. Liu P, Wu L, Guo Y, Huang X, Guo Z (2024) High crystalline LDHs with strong adsorption properties effectively remove oil and micro-nano

plastics. J Clean Prod 437:140628. https://doi.org/10.1016/j.jclepro.2024.140628
59. Wang H, Zhou Q (2024) Bioelectrochemical systems—a potentially effective technology for mitigating microplastic contamination in wastewater. J Clean Prod 450:141931. https://doi.org/10.1016/j.jclepro.2024.141931
60. Ebnesajjad S (2014) Surface and Material Characterization Techniques. Surface Treatment of Materials for Adhesive Bonding. 39–75. https://doi.org/10.1016/B978-0-323-26435-8.00004-6
61. Song YK, Hong SH, Jang M, Han GM, Rani M, Lee J, Shim WJ (2015) A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. Mar Pollut Bull 93:202–209. https://doi.org/10.1016/j.marpolbul.2015.01.015
62. Forte M, Iachetta G, Tussellino M, Carotenuto R, Prisco M, De Falco M, Laforgia V, Valiante S (2016) Polystyrene nanoparticles internalization in human gastric adenocarcinoma cells. Toxicol in Vitro 31:126–136. https://doi.org/10.1016/J.TIV.2015.11.006
63. Maes T, Jessop R, Wellner N, Haupt K, Mayes AG (2017) A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Sci Rep 7:44501. https://doi.org/10.1038/SREP44501
64. Maxwell SH, Melinda KF, Matthew G (2020) Counterstaining to separate nile red-stained microplastic particles from terrestrial invertebrate biomass. Environ Sci Technol 54:5580–5588. https://doi.org/10.1021/acs.est.0c00711
65. Nguyen B, Tufenkji N (2022) Single-particle resolution fluorescence microscopy of nanoplastics. Environ Sci Technol 56:6426–6435. https://doi.org/10.1021/acs.est.1c08480
66. Lee JJ, Kang J, Kim C (2024) A low-cost TICT-based staining agent for identification of microplastics: Theoretical studies and simple, cost-effective smartphone-based fluorescence microscope application. J Hazard Mater 465:133168. https://doi.org/10.1016/j.jhazmat.2023.133168
67. Tarafdar A, Choi SH, Kwon JH (2022) Differential staining lowers the false positive detection in a novel volumetric measurement technique of microplastics. J Hazard Mater 432:128755. https://doi.org/10.1016/j.jhazmat.2022.128755
68. Silva AB, Bastos AS, Justino CIL, da Costa JP, Duarte AC, Rocha-Santos TAP (2018) Microplastics in the environment: challenges in analytical chemistry—a review. Anal Chim Acta 1017:1–19. https://doi.org/10.1016/J.ACA.2018.02.043
69. Shang L, Gao P, Wang H, Popescu R, Gerthsen D, Nienhaus GU (2017) Protein-based fluorescent nanoparticles for super-resolution STED imaging of live cells. Chem Sci 8:2396–2400. https://doi.org/10.1039/c6sc04664a
70. Munoz LP, Baez AG, Purchase D, Jones H, Garelick H (2022) Release of microplastic fibres and fragmentation to billions of nanoplastics from period products: Preliminary assessment of potential health implications. Environ Sci Nano 9:606–620. https://doi.org/10.1039/d1en00755f
71. Valsesia A, Parot J, Ponti J, Mehn D, Marino R, Melillo D, Muramoto S, Verkouteren M, Hackley VA, Colpo P (2021) Detection, counting and characterization of nanoplastics in marine bioindicators: a proof of principle study. Microplast Nanoplast 1:5. https://doi.org/10.1186/s43591-021-00005-z
72. Sommer F, Dietze V, Baum A, Sauer J, Gilge S, Maschowski C, Giere R (2018) Tire abrasion as a major source of microplastics in the environment. Aerosol Air Qual Res 18:2014–2028. https://doi.org/10.4209/aaqr.2018.03.0099
73. Riboni N, Ribezzi E, Nasi L, Mattarozzi M, Piergiovanni M, Masino M, Bianchi F, Careri M (2024) Characterization of small micro-and nanoparticles in antarctic snow by electron microscopy and raman micro-spectroscopy. Appl Sci 14(4):1597. https://doi.org/10.3390/app14041597
74. Yang T, Xu Y, Liu G, Nowack B (2024) Oligomers are a major fraction of the submicrometre particles released during washing of polyester textiles. Nat Water 2:151–160. https://doi.org/10.1038/s44221-023-00191-5
75. Bhat MA (2024) Airborne microplastic contamination across diverse university indoor environments: a comprehensive ambient analysis. Air Qual Atmos Health 17:1851–1866. https://doi.org/10.1007/s11869-024-01548-9
76. Fu W, Zhang W (2017) Hybrid AFM for nanoscale physicochemical characterization: recent development and emerging applications. Small 13:1603525. https://doi.org/10.1002/smll.201603525
77. Cheng S, Bryant R, Doerr SH, Wright CJ, Williams PR (2009) Investigation of surface properties of soil particles and model materials with contrasting hydrophobicity using atomic force microscopy. Environ Sci Technol 43:6500–6506. https://doi.org/10.1021/es900158y
78. Nguyen T, Petersen EJ, Pellegrin B, Lam GJM (2017) Impact of UV irradiation on multiwall carbon nanotubes in nanocomposites: formation of entangled surface layer and mechanisms of release resistance. Carbon 116:191–200. https://doi.org/10.1016/J.CARBON.2017.01.097
79. Zhang W, Crittenden J, Li K, Chen Y (2012) Attachment efficiency of nanoparticle aggregation in aqueous dispersions: modeling and experimental validation. Environ Sci Technol 46:7054–7062. https://doi.org/10.1021/es203623z
80. Dussud C, Meistertzheim AL, Conan P, Pujo-Pay M, George M, Fabre P, Coudane J, Higgs P, Elineau A, Pedrotti ML, Gorsky G, Ghiglione JF (2018) Evidence of niche partitioning among bacteria living on plastics, organic particles and surrounding seawaters. Environ Pollut 236:807–816. https://doi.org/10.1016/j.envpol.2017.12.027
81. Dussud C, Hudec C, George M, Fabre P, Higgs P, Bruzaud S, Delort AM, Eyheraguibel B, Meistertzheim AL, Jacquin J, Cheng J, Callac N, Odobel C, Rabouille S, Ghiglione JF (2018) Colonization of non-biodegradable and biodegradable plastics by marine microorganisms. Front Microbiol 9:1571. https://doi.org/10.3389/FMICB.2018.01571
82. Ducoli S, Federici S, Nicsanu R, Zendrini A, Marchesi C, Paolini L, Radeghieri A, Bergese P, Depero LE (2022) A different protein corona cloaks "true-to-life" nanoplastics with respect to synthetic polystyrene nanobeads. Environ Sci Nano 9:1414–1426. https://doi.org/10.1039/d1en01016f
83. Akhatova F, Ishmukhametov I (2022) Nanomechanical atomic force microscopy to probe cellular microplastics uptake and distribution. Int J Mol Sci 23(2):806. https://doi.org/10.3390/ijms23020806
84. Luo H, Xiang Y, Li Y, Zhao Y, Pan X (2021) Photocatalytic aging process of Nano-TiO2 coated polypropylene microplastics: combining atomic force microscopy and infrared spectroscopy (AFM-IR) for nanoscale chemical characterization. J Hazard Mater 404:124159. https://doi.org/10.1016/J.JHAZMAT.2020.124159
85. Dazzi A, Prater CB, Hu Q, Chase DB, Rabolt JF, Marcott C (2012) AFM–IR: combining atomic force microscopy and infrared spectroscopy for nanoscale chemical characterization. Appl Spectrosc 66:1365–1384. https://doi.org/10.1366/12-06804
86. Stetefeld J, Mckenna SA, Patel TR (2016) Dynamic light scattering: a practical guide and applications in biomedical sciences. Biophys Rev 8:409–427. https://doi.org/10.1007/s12551-016-0218-6
87. Austin J, Minelli C, Hamilton D, Wywijas M, Jones HJ (2020) Nanoparticle number concentration measurements by multi-angle dynamic light scattering. J Nanopart Res 22:108. https://doi.org/10.1007/s11051-020-04840-8
88. Grubbs J, Tsaknopoulos K, Massar C, Young B, O'Connell A, Walde C, Birt A, Siopis M, Cote D (2021) Comparison of laser diffraction and image analysis techniques for particle size-shape characterization in additive manufacturing applications. Powder Technol 391:20–33. https://doi.org/10.1016/J.POWTEC.2021.06.003
89. Keck CM, Müller RH (2008) Size analysis of submicron particles by laser diffractometry—90% of the published measurements are false. Int J Pharm 355:150–163. https://doi.org/10.1016/J.IJPHARM.2007.12.004
90. Gross J, Sayle S, Karow AR, Bakowsky U, Garidel P (2016) Nanoparticle tracking analysis of particle size and concentration detection in suspensions of polymer and protein samples: Influence of experimental and data evaluation parameters. Eur J Pharm Biopharm 104:30–41. https://doi.org/10.1016/J.EJPB.2016.04.013
91. Huang G, Xu B, Qiu J, Peng L, Luo K, Liu D, Han P (2020) Symmetric electrophoretic light scattering for determination of the zeta potential of colloidal systems. Colloids Surf A 587:124339. https://doi.org/10.1016/J.COLSURFA.2019.124339
92. Carvalho PM, Felicio MR, Santos NC, Goncalves S, Domingues MM (2018) Application of light scattering techniques to nanoparticle characterization and development. Front Chem 6:237. https://doi.org/10.3389/fchem.2018.00237

93. Mariano S, Tacconi S, Fidaleo M, Rossi M, Dini L (2021) Micro and nanoplastics identification: classic methods and innovative detection techniques. Front Toxicol 3:636640. https://doi.org/10.3389/ftox.2021.636640
94. Prata JC, Paço A, Reis V, da Costa JP, Fernandes AJS, da Costa FM, Duarte AC, Rocha-Santos T (2020) Identification of microplastics in white wines capped with polyethylene stoppers using micro-Raman spectroscopy. Food Chem 331:127323. https://doi.org/10.1016/J.FOODCHEM.2020.127323
95. Merzel RL, Purser L, Soucy TL, Olszewski M, Colón-Bernal I, Duhaime M, Elgin AK, Banaszak Holl MM (2019) Uptake and retention of nanoplastics in quagga mussels. Global Chall 4(6):1800104. https://doi.org/10.1002/gch2.201800104
96. Yeo BS, Stadler J, Schmid T, Zenobi R, Zhang W (2009) Tip-enhanced raman spectroscopy—its status, challenges and future directions. Chem Phys Lett 472:1–13. https://doi.org/10.1016/j.cplett.2009.02.023
97. Khan SA, Khan SB, Khan LU, Farooq A, Akhtar K, Asiri AM (2018) Fourier transform infrared spectroscopy: fundamentals and application in functional groups and nanomaterials characterization. Handbook Mater Char 10:317–344. https://doi.org/10.1007/978-3-319-92955-2_9
98. Asamoah BO, Uurasjärvi E, Räty J, Koistinen A, Roussey M, Peiponen KE (2021) Towards the development of portable and in situ optical devices for detection of micro and nanoplastics in water : a review on the current status. Polymers 13(5):730. https://doi.org/10.3390/polym13050730
99. Chen Y, Wen D, Pei J, Fei Y, Ouyang D, Zhang H, Luo Y (2020) Identification and quantification of microplastics using fourier- transform infrared spectroscopy: current status and future prospects. Curr Opin Environ Sci Health 18:14–19. https://doi.org/10.1016/j.coesh.2020.05.004
100. Othman AM, Elsayed AA, Sabry YM, Khalil D, Bourouina T (2023) Detection of Sub-20 µm microplastic particles by attenuated total reflection fourier transform infrared spectroscopy and comparison with raman spectroscopy. ACS Omega 8:10335–10341. https://doi.org/10.1021/acsomega.2c07998
101. Jung MR, Horgen FD, Orski SV, Rodriguez CV, Beers KL, Balazs GH, Jones TT, Work TM, Brignac KC, Royer SJ, Hyrenbach KD, Jensen BA, Lynch JM (2018) Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. Mar Pollut Bull 127:704–716. https://doi.org/10.1016/j.marpolbul.2017.12.061
102. Liong RMY, Hadibarata T, Yuniarto A, Tang KHD, Khamidun MH (2021) Microplastic occurrence in the water and sediment of miri river estuary. Borneo Island Water Air Soil Pollut 232:342. https://doi.org/10.1007/s11270-021-05297-8
103. Jafari M, Nowak DB, Huang S, Abrego JC, Yu T, Du Z, Hammouti B, Jeffali F, Touzani R, Ma D, Siaj M (2023) Photo-induced force microscopy applied to electronic devices and biosensors. Mater Today Proc 72:3904–3910. https://doi.org/10.1016/j.matpr.2022.10.216
104. ten Have C (2021) Photoinduced force microscopy as an efficient method towards the detection of nanoplastics. Chem Methods 1:205–209. https://doi.org/10.1002/cmtd.202100017
105. Carruthers H, Clark D, Clarke FC, Faulds K, Graham D (2022) Evaluation of laser direct infrared imaging for rapid analysis of pharmaceutical tablets. Anal Methods 14:1862–1871. https://doi.org/10.1039/d2ay00471b
106. Hildebrandt L, El Gareb F, Zimmermann T, Klein O, Kerstan A, Emeis KC, Pröfrock D (2022) Spatial distribution of microplastics in the tropical Indian Ocean based on laser direct infrared imaging and microwave-assisted matrix digestion. Environ Pollut 307:119547. https://doi.org/10.1016/j.envpol.2022.119547
107. Ivleva NP (2021) Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives. Chem Rev 121:11886–11936. https://doi.org/10.1021/acs.chemrev.1c00178
108. Bao M, Huang Q, Lu Z, Collard F, Cai M, Huang P, Yu Y, Cheng S, An L, Wold A, Gabrielsen GW (2022) Investigation of microplastic pollution in Arctic fjord water: a case study of Rijpfjorden, Northern Svalbard. Environ Sci Pollut Res 29:56525–56534. https://doi.org/10.1007/s11356-022-19826-3
109. Ribeiro-Claro P, Nolasco MM, Araújo C (2017) Characterization of microplastics by raman spectroscopy. Comprehensive Anal Chem 75:119–151. https://doi.org/10.1016/BS.COAC.2016.10.001
110. Xie L, Gong K, Liu Y, Zhang L (2023) Strategies and challenges of identifying nanoplastics in environment by surface-enhanced raman spectroscopy. Environ Sci Technol 57:25–43. https://doi.org/10.1021/acs.est.2c07416
111. Zhang J, Peng M, Lian E, Xia L, Asimakopoulos AG, Luo S, Wang L (2023) Identification of Poly(ethylene terephthalate) nanoplastics in commercially bottled drinking water using surface-enhanced raman spectroscopy. Environ Sci Technol 57:8365–8372. https://doi.org/10.1021/acs.est.3c00842
112. Gillibert R, Balakrishnan G, Deshoules Q, Tardivel M, MagazzùA DMG, Maragò OM, de La Chapelle ML, Colas F, Lagarde F, Gucciardi PG (2019) Raman tweezers for small microplastics and nanoplastics identification in seawater. Environ Sci Technol 53:9003–9013. https://doi.org/10.1021/acs.est.9b03105
113. Mogha NK, Shin D (2023) Nanoplastic detection with surface enhanced raman spectroscopy: present and future. TrAC - Trends Anal Chem 158:116885. https://doi.org/10.1016/j.trac.2022.116885
114. Zhou XX, Liu R, Hao LT, Liu JF (2021) Identification of polystyrene nanoplastics using surface enhanced Raman spectroscopy. Talanta 221:121552. https://doi.org/10.1016/j.talanta.2020.121552
115. Cao Y, Sun M (2022) Tip-enhanced Raman spectroscopy. Rev Phys 8:100067. https://doi.org/10.1016/j.revip.2022.100067
116. Kumar N, Mignuzzi S, Su W, Roy D (2015) Tip-enhanced Raman spectroscopy: principles and applications. EPJ Tech Instrum 2:9. https://doi.org/10.1140/epjti/s40485-015-0019-5
117. Yeo BS, Amstad E, Schmid T, Stadler J, Zenobi R (2009) Nanoscale probing of a polymer-blend thin film with Tip-enhanced Raman spectroscopy. Small 5:952–960. https://doi.org/10.1002/smll.200801101
118. Lin Y, Huang X, Liu Q, Lin Z, Jinag G (2020) Thermal fragmentation enhanced identification and quantification of polystyrene micro/nanoplastics in complex media. Talanta 208:120478. https://doi.org/10.1016/j.talanta.2019.120478
119. Habumugisha T, Zhang Z, Fang C, Yan C, Zhang X (2023) Uptake, bioaccumulation, biodistribution and depuration of polystyrene nanoplastics in zebrafish (Danio rerio). Sci Total Environ 893:164840. https://doi.org/10.1016/j.scitotenv.2023.164840
120. Liu S, Zhao H, Liu Z, Zhang W, Lai C, Zhao S, Cai X, Qi Y, Zhao Q, Li R, Wang F (2022) High-performance micro/nanoplastics characterization by MALDI-FTICR mass spectrometry. Chemosphere 307:135601. https://doi.org/10.1016/j.chemosphere.2022.135601
121. Mansa R, Zou S (2021) Thermogravimetric analysis of microplastics: a mini review. Environ Adv 5:100117. https://doi.org/10.1016/j.envadv.2021.100117
122. Picó Y, Barceló D (2020) Pyrolysis gas chromatography-mass spectrometry in environmental analysis: focus on organic matter and microplastics. TrAC - Trends Anal Chem 130:115964. https://doi.org/10.1016/j.trac.2020.115964
123. Majewsky M, Bitter H, Eiche E, Horn H (2016) Determination of microplastic polyethylene (PE) and polypropylene (PP) in environmental samples using thermal analysis (TGA-DSC). Sci Total Environ 568:507–511. https://doi.org/10.1016/J.SCITOTENV.2016.06.017
124. Goedecke C, Dittmann D, Eisentraut P et al (2020) Evaluation of thermoanalytical methods equipped with evolved gas analysis for the detection of microplastic in environmental samples. J Anal Appl Pyrolysis 152:104961. https://doi.org/10.1016/j.jaap.2020.104961
125. Duemichen E, Eisentraut P, Celina M, Braun U, Wiesner Y, Schartel B, Klack P, Braun U (2019) Automated thermal extraction-desorption gas chromatography mass spectrometry: a multifunctional tool for comprehensive characterization of polymers and their degradation products. J Chromatogr A 1592:133–142. https://doi.org/10.1016/J.CHROMA.2019.01.033
126. Guo X, Wang J (2021) Projecting the sorption capacity of heavy metal ions onto microplastics in global aquatic environments using artificial neural networks. J Hazard Mater 402:123709. https://doi.org/10.1016/j.jhazmat.2020.123709
127. Ng W, Minasny B, McBratney A (2020) Convolutional neural network for soil microplastic contamination screening using infrared spectroscopy. Sci Total Environ 702:134723. https://doi.org/10.1016/j.scitotenv.2019.134723

128. Shan J, Zhao J, Zhang Y, Liu L, Wu F, Wang X (2019) Simple and rapid detection of microplastics in seawater using hyperspectral imaging technology. Anal Chim Acta 1050:161–168. https://doi.org/10.1016/j.aca.2018.11.008
129. Hufnagl B, Steiner D, Renner E, Löder MGJ, Laforsch C, Lohninger H (2019) A methodology for the fast identification and monitoring of microplastics in environmental samples using random decision forest classifiers. Anal Methods 11:2277–2285. https://doi.org/10.1039/C9AY00252A
130. Yurtsever M, Yurtsever U (2019) Use of a convolutional neural network for the classification of microbeads in urban wastewater. Chemosphere 216:271–280. https://doi.org/10.1016/j.chemosphere.2018.10.084
131. Zhao S, Qiu Z, He Y (2021) Transfer learning strategy for plastic pollution detection in soil: calibration transfer from high-throughput HSI system to NIR sensor. Chemosphere 272:129908. https://doi.org/10.1016/j.chemosphere.2021.129908
132. Bianco V, Memmolo P, Carcagnì P, Merola F, Paturzo M, Distante C, Ferraro P (2020) Microplastic identification via holographic imaging and machine learning. Adv Intell Syst 2:1900153. https://doi.org/10.1002/aisy.201900153
133. Xie L, Luo S, Liu Y, Ruan X, Gong K, Ge Q, Li K, Valev VK, Liu G, Zhang L (2023) Automatic Identification of individual nanoplastics by Raman spectroscopy based on Machine Learning. Environ Sci Technol. https://doi.org/10.1021/acs.est.3c03210
134. Weber F, Zinnen A, Kerpen J (2023) Development of a machine learning-based method for the analysis of microplastics in environmental samples using µ-Raman spectroscopy. Microplast Nanoplast 3:9. https://doi.org/10.1186/s43591-023-00057-3
135. Duncan TV, Khan SA, Patri AK, Wiggins S (2024) Regulatory science perspective on the analysis of microplastics and nanoplastics in human food. Anal Chem 96:4343–4358. https://doi.org/10.1021/acs.analchem.3c05408

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