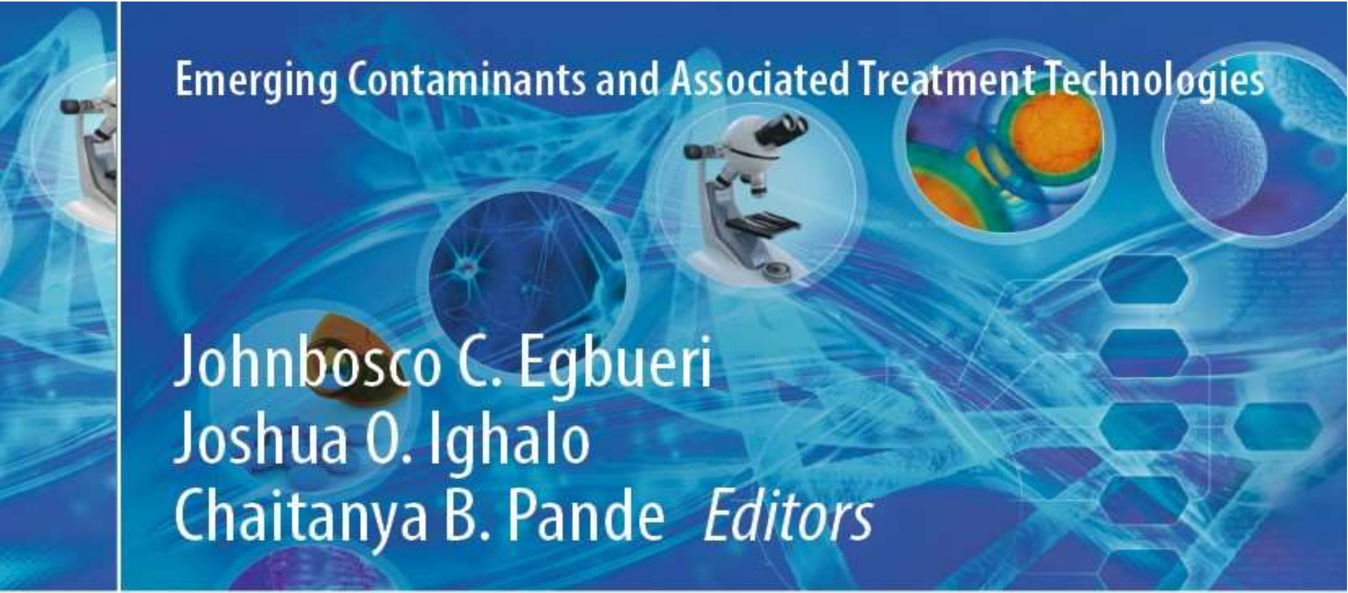

Emerging Contaminants and Associated Treatment Technologies

Johnbosco C. Egbueri
Joshua O. Ighalo
Chaitanya B. Pande *Editors*

Microplastics in African and Asian Environments

The Influencers, Challenges, and Solutions

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Johnbosco C. Egbueri · Joshua O. Ighalo ·
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Editors

Microplastics in African and Asian Environments

The Influencers, Challenges, and Solutions

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Justification for the Chapter Ordering

This order would allow readers to gradually build their understanding of microplastics, starting from basic concepts and expanding into more complex issues and potential solutions:

1. Introduction and Overview: Chapters "Overview of Microplastics and Their Environmental Occurrences"–"Invisible Threats in Himalayan Region: Unmasking the Impact of Microplastic Pollution on Human Health Today and Tomorrow" provide an introduction to microplastics, their distribution, and initial impacts across different regions, including Africa and Asia.
2. Regional Perspectives: Chapters "Plastic Litter Pollution on the Beaches of Lakshadweep Island: An Assessment of their Abundance and Transport"–"Microplastic Pollution in the Changing Climate" go deeper into specific regional issues and challenges related to microplastic pollution, covering areas like airborne microplastics, pollution in India, and the impact of climate change on microplastic distribution.
3. Transport and Environmental Impact: Chapters "Considerations and Perspectives on Microplastics in Air as an Emerging Challenge"–"Food Security Challenges and Microplastics: A Comprehensive Review" focus on the mechanisms of microplastic transport, their presence in different environments such as air soils, sediments, and wetlands, and their ecological impacts on food security and human health.
4. Human Health Implications: Chapters "Environmental Risks and Human Health Impact of Microplastic Pollution"–"Microplastics in Animals – A Global Concern to Food Safety and Human Health" explore the direct and indirect effects of microplastic pollution on human health, covering topics such as ingestion, toxicological effects, and overall health impacts.
5. Analytical Techniques and Methodologies: Chapters "Modeling of Microplastic Contamination Using Soft Computational Methods: Advances, Challenges, and Opportunities"–"Raman Spectroscopy Based Approaches for Microplastics Investigations" discuss various analytical techniques, modeling approaches,

and monitoring methods used in microplastic research, including GIS, remote sensing, spectroscopy, and computational modeling.

6. Mitigation and Future Directions: Chapters "A Review on Microplastics Migration from Sources Through Wastewater to the Environments: Classifications, Impacts and Removal Techniques"–"A Call to Action for Addressing Microplastic Pollution: Mitigation and Solutions" conclude the book by discussing strategies for mitigation, future research directions, and the broader implications of microplastic pollution on global ecological and human health.

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Monitoring and Assessment Techniques for Microplastics

Chenhao Zhou, Zhonghao Chen, Mahmoud Nasr, Ahmed I. Osman, Zhi Ying Lai, Chung Loong Yiin, Bridgid Lai Fui Chin, and Pow-Seng Yap

Abstract The pervasive presence of microplastics in the environment has raised significant concerns regarding their impact on ecosystems and human health. This chapter begins by introducing the concept of microplastics, emphasizing their role as emerging pollutants and their detrimental effects on the environment. The core of this chapter focuses on the practical aspects of monitoring microplastics. It covers

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sampling and collection techniques, discussing considerations for different environmental matrices such as water, sediments, soils, and biological tissues. Furthermore, it investigates the various analytical methods, encompassing microscopy-based techniques, spectroscopy, and chemical methods. A thorough discussion of the strengths and limitations of these methods is provided, enabling readers to make informed choices for their specific monitoring needs. Data analysis and interpretation are crucial for drawing meaningful conclusions from monitoring efforts, and this chapter provides insights into best practices in data processing. It addresses the importance of data quality, statistical methods, and data visualization in understanding the extent of microplastic contamination. In addition, it offers a compilation of real-world case studies showcasing the application of monitoring and assessment techniques in diverse environmental settings, illustrating the relevance of these techniques in addressing the challenges of microplastic contamination. The chapter concludes by addressing current challenges and limitations in microplastic monitoring, presenting emerging trends and innovations in the field, and suggesting future research directions. Overall, this chapter underscores the paramount significance of monitoring and assessment techniques in understanding and mitigating the effects of microplastics on our environment, thereby contributing to a more sustainable and less polluted future.

Keywords Microplastics · Collection · Monitoring · Data analysis · Challenges

1 Introduction

Plastic products are highly favored worldwide due to their durability and low production costs. The widespread use of plastic products has also created many conveniences for modern life (Chen et al., 2020a). However, the high durability and non-degradability of plastic products often lead to serious pollution caused by plastic debris to the global ecological environment (Dissanayake et al., 2022). Microplastics are typically defined as any plastic fragment with a size less than 5 mm, and the lower limit is uncertain (Picó & Barceló, 2019). Microplastic particles can be divided into large microplastics, small microplastics, and nano microplastics according to their size. Particles with sizes between 1 and 5 mm are called large microplastics, particles with sizes between 1 μm and 1 mm are called small microplastics, and particles with sizes less than 1 μm are called nano-plastics (Tirkey & Upadhyay, 2021). Meanwhile, microplastic particles have different shapes, such as fibers, particles, fragments, flakes, and beads (Sharma & Chatterjee, 2017).

In recent years, microplastic particles have been observed in soil ecosystems, surface water, coastal sediments, freshwater sediments, and various deep environments worldwide (Ivar do Sul & Costa, 2014; Wong et al., 2020), and microplastic pollution has become very common. Microplastics often have high durability and easy diffusion, and can quickly spread and fix in the global biosphere (Osman et al., 2023; Tang et al., 2021). The issue of microplastic pollution has gradually become a central topic of discussion around the world (Chia et al., 2021). Microplastic particles can be classified into two types based on their own sources: primary and secondary (Gupta et al., 2023b). The primary microplastic particles usually refer to particles used in industry or commerce, such as cosmetics used in the beauty industry and microbeads used in the medical industry. The secondary microplastic particles mainly come from the natural weathering and degradation of plastic products, and indirectly from the oxidation process of larger microplastic particles in industries such as construction, textile, and agriculture (Gupta et al., 2023b). Considering the continuous increase in synthetic polymer products, it is expected that the concentration of microplastic particles will continue to increase in the coming decades, which will also expand the risks posed to the ecological environment and human health (Petersen & Hubbart, 2021).

Due to their small size, microplastic particles are easily ingested by organisms, causing direct physical damage and potential toxic effects (Silva et al., 2018). On the one hand, the adverse effects of ingesting microplastics on organisms can accumulate and amplify through the food chain (Razeghi et al., 2021c). On the other hand, microplastics can adsorb various pollutants and evolve into transport carriers for persistent organic pollutants and heavy metals present in the environment (Deng et al., 2021). For example, in soil and sediment, microplastic particles can act as transport media for harmful substances and interact with organisms or other non-biological factors (Wong et al., 2020). This will have extremely adverse effects on the health and various functions of soil, and in the absence of proper treatment, microplastic particles may exist in soil and sediment for thousands of years. In addition, freshwater systems such as river water are important carriers of microplastics, and the presence of microplastics in urban water bodies may pose risks to aquatic organisms and humans. When high concentrations of microplastics are released into the aquatic environment, they may pose significant risks to zooplankton, fish, and others (Du et al., 2021). At the same time, human consumption of organisms from this environment will have adverse effects on their own health (Anuar et al., 2023). At the same time, microplastics from different sources are collected and transported together with water flow, ultimately arriving and accumulating in the marine system (Sun et al., 2022). In addition, microplastic particles will also be transported through the atmosphere to remote and primitive areas. For example, microplastics have been reported in regions such as the Arctic, Antarctica, and the Alps, but in fact, there has been no direct human input into these regions (Zhang et al., 2022a).

At present, our understanding and awareness of microplastic pollution is not perfect, and there is still a significant gap and development space (Shruti et al., 2021). Therefore, it is necessary to adopt reliable and effective monitoring and evaluation techniques to carry out comprehensive statistics of key data collected from samples, which can provide practical and useful information data for further understanding the propagation characteristics of microplastics, and provide effective evidence for the comprehensive and adverse effects of microplastic pollution on the ecological environment (Cho et al., 2021). Monitoring and evaluating the uptake of microplastics by biological communities is a challenging and complex task, as research on microplastics is still in its early stages. The purpose of conducting microplastic monitoring and evaluation in the environment is to quantify the correlation and trends of microplastic pollution, and to determine in detail the main types and dispersion levels of microplastic particles (Morgado et al., 2021). The characteristics of microplastics usually depend on their own physical and chemical properties, which mainly include color, shape, size, and density, while chemical properties are mainly based on the type of plastic (Morgado et al., 2021). Compared with medium and large plastics, the ingestion of small microplastics often has a more profound impact on organisms. In other words, the adverse effects of microplastics on organisms are extremely significant (Wesch et al., 2016).

In fact, there is no standardized procedure established for monitoring and evaluating microplastics, which may lead to inconsistent quality and accuracy of microplastic statistical data (Rodrigues et al., 2018), thereby causing significant interference in data comparison and analysis between different microplastic studies. For example, in the study of microplastics in water environments, sample collection and analysis methods often exhibit heterogeneity and non- standardization, which can lead to ineffective and reliable data comparison for microplastic studies conducted in different rivers, and even the microplastic data collected in the same river lacks comparability (Skalska et al., 2020). Similarly, in the process of monitoring and evaluating microplastics in the atmosphere, factors such as the location of sample collection areas, organic matter extraction methods, quality control analysis, etc. often lead to different quality results and seriously affect the accuracy of the study (dos Santos Galvão et al., 2022).

Therefore, on the one hand, it is necessary for us to continue to search for real and reliable monitoring tools to define and examine the formulation of implementation plans in the monitoring and evaluation process, so that they have a considerable degree of standardization. On the other hand, we need to develop multi-modal monitoring and evaluation strategies tailored to local conditions based on the characteristics of different target areas and microplastic characteristics (Vandermeersch et al., 2015).

This chapter provides relevant and effective information for the monitoring and evaluation techniques of microplastics. Discussions were conducted on sampling and collection techniques for water, sediment, soil, and biological tissues in four different environments, and detailed explanations were provided on the challenges and precautions that may be encountered during sample collection and preservation. At the same time, we also provide an overview of various analytical techniques for identifying and quantifying microplastics, including microscopy-based techniques, spectroscopy, and chemical methods, and provide a detailed description of the applicable types, advantages, and limitations of these techniques. In addition, this chapter provides a systematic introduction on how to process and analyze data obtained from monitoring work, and demonstrates the application of monitoring, and evaluation techniques in different environments through real work case studies. It is noteworthy that in order to avoid potential redundancy of information with case studies as shown in chapters 17 and 18, which focus on case studies in Africa and Asia, this chapter features case studies from North and South America. Additionally, it discusses the challenges and limitations of microplastic monitoring technology, explores emerging trends and innovations in this field, and suggests potential future research directions.

2 Sampling and Collection Techniques

The durability of plastics and human attitudes towards their use and disposal have led to the gradual intensification of plastic waste disposal management issues, as well as the accumulation and diffusion of such pollutants on a global scale (Courtene-Jones et al., 2017b). Microplastics (MPs) are a subgroup of plastics with an effective diameter of less than 5 mm (Kang et al., 2019), which often pose potential harm to human life and the ecological environment (Gao et al., 2022). MPs have become an emerging pollutant (Muthukumaran et al., 2023). At present, the sampling and collection technology of MPs is a research hotspot. An overview of methods and equipment for collecting MPs in various environments is shown in Fig. 1. While providing specific explanations of the challenges and precautions in collecting and preserving MP samples, this section also illustrates the effectiveness of these sampling techniques through practical cases.

2.1 Collection Methods and Equipment for MPs in Various Environments

2.1.1 Water Environment

The collection of MPs in water is influenced by their distribution, as well as the sampling location and depth, which together determine the quantity and quality of

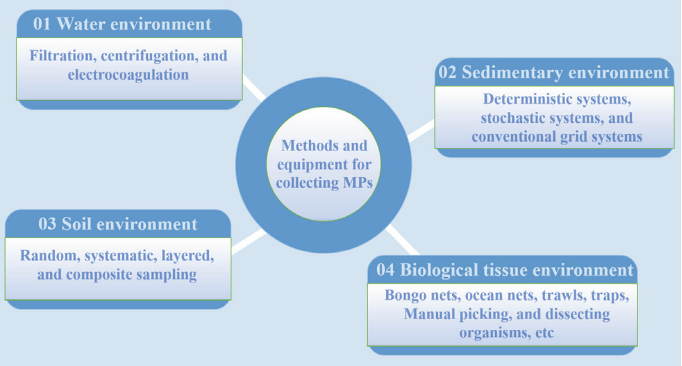

Fig. 1 Systematical illustration of the methods and equipment for collecting MPs in various environments

the samples (Gupta et al., 2023a). The following will introduce common collection techniques, mainly including filtration, centrifugation, and electrocoagulation (Osman et al. 2024; Sacco et al., 2023).

Filtration refers to the process of passing water through a filter that filters MPs based on their size characteristics, effectively capturing MPs in the water environment (Akarsu et al., 2021). Trawl, as the most common filtering method, refers to the arrangement of a trawl on a ship, which is submerged in water at a fixed time or route at a constant speed for towing (Sighicelli et al., 2018). The main types of trawl nets include Manta nets, Neuston nets, Bongo nets, Plankton nets, etc. (Razeghi et al., 2021a). In the actual sampling process, it is necessary to determine the appropriate sampling device based on the characteristics of the water body, for example, when collecting surface water samples, the Manta network or Neuston network is generally selected (Schönlau et al., 2020).

Centrifugation is the process of rotating water at high speeds, which generates centrifugal forces that can cause MPs to move outward at the edges, thereby distinguishing and collecting MP samples based on density (Grause et al., 2022). Centrifuge can complete the separation and sampling of MPs in a relatively short period of time. At present, continuous flow centrifugation technology is regarded as a technology that can efficiently complete the sampling and collection of MPs from water bodies (Hildebrandt et al., 2019). At the same time, this technology can selectively collect and sample MPs from the dimensions of particle size and self-density (Hildebrandt et al., 2020).

Electrocoagulation is the process of applying an electric current to disrupt the stability and polymerization of MP particles, followed by the collection of MPs in water through processes such as filtration or precipitation (Liu et al., 2023). Researchers have made significant breakthroughs and discoveries in collecting MPs through electrocoagulation. In terms of efficient collection of MPs, better electrocoagulation reaction conditions include an electrolyte concentration of 0.05 M, an applied voltage density of 10 V, and an aluminum anode (Shen et al., 2022). In addition, MPs have a better collection efficiency when the pH value reaches 7.5 (Perren et al., 2018).

2.1.2 Sedimentary Environment

The MP particles in sediment are very abundant (Cózar et al., 2014). Although extensive sampling techniques have been applied to extract MPs from sediment (Rocha-Santos & Duarte, 2015), there is no unified standardized approach in sampling and sample processing methods (Van Cauwenberghe et al., 2015).

Considering sampling accuracy, frequency, and economy, sampling strategies can be divided into three different types, namely deterministic systems, stochastic systems, and conventional grid systems (Adomat & Grischek, 2021). Among them, deterministic systems are sampling work based on specific locations. Stochastic systems are selective sampling of each subregion based on statistical foundations while constructing similar subregion random patterns. A conventional grid system utilizes conventional patterns to randomly or deterministically select sampling areas (Adomat & Grischek, 2021).

In addition, to reduce the impact of pollution, instruments made of stainless steel or glass are often used during the sampling process (Razeghi et al., 2021a). For example, a shovel, spoon, trowel or spatula can be used to sample river sediment on the riverbank. However, equipment such as shovels or spatulas often cannot accurately define the sampling depth and sediment volume (Wang & Wang, 2018), so using standardized sediment samplers would be more appropriate. Among numerous sediment sampling devices such as dredgers, grab samplers, and corers, corers have stronger development potential (Brander et al., 2020a). This device can not only accurately collect samples on land and underwater in designated areas but can also be used on hard surfaces where the claws of the sampler are often limited (Adomat & Grischek, 2021).

2.1.3 Soil Environment

The content of MPs in soil is relatively high (Zhang et al., 2022b). However, the current understanding of MPs in soil is not comprehensive (Huang et al., 2020), and there is also a lack of standardization in sampling and collection techniques (Zhang et al., 2020a).

The commonly used sampling techniques can be divided into random, systematic, layered, and composite sampling (Barahona & Iriarte, 2001). Among them, random sampling can reduce errors caused by human factors and ensure that each region has the same selection opportunity. System sampling is based on a regular sampling point pattern to cover the sampling area uniformly. Layered sampling takes into account the differences between different soil layers. Composite sampling refers to the process of combining different numbers of sub-samples into a single sample (Junhao et al., 2021). Taking sampling in farmland as an example, since microplastics are unevenly distributed on farmland and are susceptible to human cultivation, composite sampling methods are often chosen (Möller et al., 2020). In addition, to obtain accurate sampling data, it is often possible to combine multiple types of sampling methods (Junhao et al., 2021).

The sampling tools for soil are similar to those used in sediment, mostly stainless-steel shovels and soil augers (Zhou et al., 2020), as well as stainless steel corers and Lenz samplers (Yang et al., 2021).

2.1.4 Biological Tissue Environment

Biological tissues can ingest MPs at different nutritional levels (Wang & Wang, 2018), thus MPs are abundant in biological tissues (Frias et al., 2014). When sampling MPs ingested by biological tissues, various methods can be used, and the choice of these methods will depend on the target species and their habitat (Miller et al., 2021). For example, various planktonic animals, including jellyfish and algae, can be collected using the Bongo net (Desforges et al., 2015), while different types of fish can be obtained using tools such as ocean nets and trawls (Zhang et al., 2017). Crustaceans, including shrimp, can be obtained through bottom trawls or traps (Lusher et al., 2017), and bivalves represented by oysters can be obtained through trawls or manual picking (Vandermeersch et al., 2015). MPs in biological tissues can be obtained by dissecting organisms and separating the liver, gills, and intestines (Mai et al., 2018). In addition, when there are significant differences between samples of different biological tissues, the reliability of the results can be ensured by increasing the sample size (Hermsen et al., 2018). Comprehensive composite sampling can not only significantly reduce the differences between detection sites and species but also reasonably evaluate statistical differences (Miller et al., 2021).

2.2 Challenges and Precautions in the Collection and Preservation of MP Samples

In the process of collecting and storing MP samples, if appropriate preventive measures are not taken, it is easy to cause cross contamination. Cross-contamination refers to the uncontrolled release of microplastics into environmental samples during the collection and preservation process (Bogdanowicz et al., 2021).

Take the nets used in the collection of microplastic samples as an example, such as Bongo nets, Manta trawl nets, etc. (Hidalgo-Ruz et al., 2012a). The core parts of these networks are often made of synthetic fibers, which may exist in the final collected materials (Mu et al., 2019). In addition, uncleaned sample collection containers located at the end of the network may also be a source of cross-contamination (Bogdanowicz et al., 2021).

In addition, special attention should be paid to the storage environment in which the samples are stored. Due to the presence of a large number of microfiber particles in the air and their deposition phenomenon (Bogdanowicz et al., 2021), it is necessary to carry out deep cleaning work on the surfaces of various workbenches with substances such as ethanol, acetone, and distilled water before use. In addition to cleaning the instruments and equipment, the hands of the staff should also be wiped (Zhao et al., 2015). During laboratory work, it is also recommended that experimenters wear cotton coats or work clothes to avoid fiber interference caused by clothing (Courtene-Jones et al., 2017a). To achieve a clean working environment, fume hoods have also been applied in laboratories and processing samples inside fume hoods will effectively reduce cross-contamination by nearly 50% (Wesch et al., 2017).

2.3 Case Study

Currently, the collection of MPs is being carried out in an orderly manner around the world. Effective sampling techniques are introduced using the collection of MPs in Dongting Lake and Honghu Lake in China as examples.

Dongting Lake and Honghu Lake are the second and seventh largest freshwater lakes in China, respectively, located on the south and north banks of the middle reaches of the Yangtze River. The average depth and maximum depth of Dongting Lake are 6.39 m and 18.67 m, respectively. Transportation, aquaculture, and tourism are the main human activities in Dongting Lake (Wang et al., 2018). The average depth of Honghu Lake is only 1.5 m, and human activities in the lake are mainly aquaculture (Wang et al., 2018). The sampling equipment used for efficient microplastic collection in Dongting Lake and Honghu Lake is mainly a 12 V DC Teflon pump. Although trawl nets with sizes exceeding 300 μm are widely used to collect microplastics in water (Syberg et al., 2015), considering that they often cannot capture larger MP particles, this will also cause significant interference in the assessment of MP particle abundance in the study area. Therefore, the extracted surface water will be filtered through a stainless-steel sieve with a size of 50 μm (Wang et al., 2017a), and the collection of MPs will be completed.

3 Analytical Methods

To accurately identify and quantify microplastics in diverse sample types like water (Johnson et al., 2020; Lee & Chae, 2021; Choran and Oermeci, 2023), sediment (Bauerlein et al., 2023; Parga Martinez et al., 2023; Soursou et al., 2023), soil (Fan et al., 2023; Hossain et al., 2023), and biological samples (Malafaia et al., 2022; Wang et al., 2023a), specialized techniques are essential. In this section, we explore various analytical methods used for microplastic analysis in detail. These include microscopy-based approaches such as optical microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Additionally, we will explore spectroscopic techniques, specifically Fourier transform infrared spectroscopy (FT-IR) and Raman spectroscopy, as well as chemical methods such as pyrolysis–gas, chromatography-mass spectrometry, and thermal analysis.

This comprehensive examination of analytical techniques is crucial for understanding the abundance, composition, and sources of microplastics. By assessing the advantages and limitations of each method, we gain insights into their suitability for different sample types. This multifaceted approach enables researchers and environmental scientists to enhance their ability to detect and characterize microplastics in various environmental matrices.

3.1 Microscopy-Based Methods

Microscopy-based methods play a pivotal role in the identification and analysis of MPs, microscopic plastic particles that pose environmental challenges. In the quest to understand the impact of MPs on various ecosystems, researchers employ sophisticated techniques that offer insights into the characteristics of these minute contaminants.

3.1.1 Optical Microscopy

Optical microscopy stands as a foundational method for estimating the number, color, size, and shape of MPs in various sample types like water, sediment, soil, and biological tissues. Dissection microscopes, preferred over compound microscopes, offer a greater distance between the specimen and the objective, enabling the use of tools like tweezers and probes for further analysis of suspected plastic particles. Guidelines for visual MPs identification, including the hot needle test, are often referenced in studies analyzing MPs in food. However, the lack of chemical recognition can compromise accuracy and precision, leading to the potential misclassification of natural organic and inorganic particles as MPs (Vitali et al., 2022).

Selective staining techniques, such as Nile Red, partially address the chemical blindness of optical microscopy, enhancing the detection of synthetic polymers (Maes et al., 2017; Prata et al., 2021). Despite the theoretical resolution limit of 200 nm, optical microscopy studies on MPs in food rarely report detecting particles smaller than 20 μm (Devriese et al., 2015; Panebianco et al., 2019; Rochman et al., 2015; Sparks, 2020). Notably, Renzi and Blaskovic (2018) reported particles as small as 4 μm. Optical microscopes are extensively used for identifying smaller plastic particles in environmental samples, offering magnification and detailed surface texture analysis (Fu et al., 2020a; Ghanadi et al., 2024; Jung et al., 2021; Kang et al., 2015). The highest lateral resolution achievable with optical instruments, following Abbe's theory, is defined as $D = \lambda/2NA$ (Vitali et al., 2022). While the theoretical limit is 200 nm, practical operation limits hover around 1 μm. Optical microscopy provides crucial information on size distribution, morphology, thickness, topography, degradation stage, and color. However, misidentification challenges persist, especially in distinguishing microplastics from marine minerals (Girão, 2022).

The advantages of optical microscopy include cost-effectiveness and widespread availability, enabling visual identification and size distribution analysis. However, it has limitations in detecting small-sized microplastics and identifying polymer composition. Wang et al. (2017b) emphasized the morphological classification capabilities of optical microscopy, facilitating the quantification of particle size ranges and fiber lengths in samples. Nevertheless, caution is advised, as ordinary visual sorting may lead to misidentification, and factors like sources, types, shape, degradation stage, and color must be carefully considered, making the process time-consuming (Hidalgo-Ruz et al., 2012b; Ngozi et al., 2019). Overall, optical microscopy remains a valuable tool with certain advantages and limitations in the comprehensive analysis of microplastics.

3.1.2 Scanning Electron Microscopy/Energy-Dispersive X-ray Spectroscope (SEM/EDX)

Utilizing a SEM in microplastic analysis provides visualization of nanometer-sized particles (Jung et al., 2021). Adding an energy-dispersive X-ray spectroscope (SEM/EDX) enhances the technique's capabilities by offering information on the elemental composition of both organic and inorganic species. Analyzing elemental components aids in the identification of plastics in environmental samples, with discrimination of surface structures enabling their distinction from other materials. While EDX analysis reveals inorganic species, it does not provide hydrogen content, a major plastic component. Optical microscopy's resolution limitation at high magnifications has led to the adoption of electron microscopy (EM), which, with a wavelength smaller than light radiation, achieves a theoretical resolution of 0.02 nm (Huang et al., 2023; Jung et al., 2021).

In SEM, the highly energetic electron beam interacts with the specimen, resulting in inelastic and elastic scattering. Secondary electrons, emitted when part of the electron beam energy transfers to the specimen, are commonly used in SEM imaging. Backscattered electrons, resulting from collisions with atoms, vary with the atomic number, aiding in atomic number-based imaging. Additionally, X-ray emission, critical for analytical purposes, offers qualitative and quantitative insights through EDX (Girão, 2022; Reimer, 2013). In studies conducted by Pan et al. (2019), it was disclosed that elemental analysis using EDX on microplastics demonstrated prominent nitrogen peaks on the surfaces of polystyrene, polypropylene, and polyethylene. This heightened nitrogen presence was identified as a potential indicator of biomass. The substantial nitrogen content in microplastic samples pointed towards bioaccumulation, highlighting a robust interaction between living organisms and microplastics.

SEM–EDX facilitates fast screening of plastic vs non-plastic pellets, detecting small particles missing visually. Blair et al. (2019c) demonstrated that plastic pellets exhibit a strong carbon peak, while non-plastic pellets lack this feature. SEM provides high-resolution topography images, revealing embrittlement due to weathering. Environmental scanning electron microscopy (ESEM) allows the analysis of wet samples, preserving them in a low-pressure nitrogen atmosphere. ESEM-EDX, without sample coating, ensures artifact-free subsamples for further analysis (Tirkey & Upadhyay, 2021). Wagner et al. (2017) utilized ESEM-EDX as a screening tool, identifying microplastic residue amidst non-microplastic components. The technique revealed microplastics with surface-adhered biofilm, mineral crust, and marine organisms, distinguishing them from mineral particles through the presence of a strong carbon peak. The integration of these advanced techniques contributes to a comprehensive understanding of microplastics in diverse environmental matrices.

Advantages of this method include the generation of high-resolution images of samples with a resolution of less than 0.5 nm. On the other hand, SEM, while successful in microplastic identification, is a time-consuming process in terms of sample preparation and observation. Consequently, it is not well-suited for efficiently identifying a large number of microplastics (Chen et al., 2020b).

3.1.3 Transmission Electron Microscopy (TEM)

The TEM serves as a valuable technique for the identification of microplastics, offering advantages and drawbacks in its application. Unlike SEM, TEM provides high-resolution images with a resolution as fine as 0.1 to 0.2 nm, enabling the observation of ultrastructures below 0.2 μm, which are beyond the capability of optical microscopes. This technique involves transmitting an accelerated and focused electron beam through a thin sample, allowing for the assessment of chemical properties, crystal orientation, electronic structure, and general electron absorption (Caldwell et al., 2022; Zhang et al., 2023b).

TEM has found recent integration with fluorescent dyes, providing valuable fluorescent data overlaid on TEM images for chemical characterization (Samanta et al., 2022). While TEM has advantages, such as a resolution of tens of thousands to millions of times magnification, it has limitations in terms of expense and time consumption (Zhang et al., 2023b). Additionally, the technique requires delicate sample preparation and may introduce artifacts. The electron beam interacts with the sample, generating elastically or inelastically scattered electrons, and detectors collect this signal to produce detailed images (Bonfanti et al., 2021).

Despite its numerous applications in morphological characterization and size determination of nanomaterials, TEM has limited utility in detecting microplastics due to the amorphous nature and elementary composition of polymers. Organic elements exhibit weak contrast in TEM analysis, requiring the staining of microplastics with heavy elements to enhance detection efficiency. However, these stains may impact the chemical composition and structure of polymers. Moreover, TEM has constraints related to the restricted thickness of particles for valid analysis, leading to its infrequent use in microplastic characterization (Kalaronis et al., 2022; Mariano et al., 2021a).

Despite these capabilities, challenges persist in the identification of different types of plastics, as many share similar electron densities (Singh & Kumar, 2024). In conclusion, while TEM is a powerful technique for high-resolution microplastic characterization, researchers must navigate its advantages and limitations, addressing factors such as expense, time consumption, and sample preparation intricacies.

3.2 Spectroscopy-Based Methods

Spectroscopy-based methods are pivotal in the precise analysis of microplastics, offering detailed insights into their chemical composition. Two prominent techniques are Fourier transform infrared spectroscopy (FT-IR) and Raman spectroscopy. These methods, with their distinct advantages and applications, play a crucial role in unravelling the complexities of microplastic pollution, contributing significantly to environmental research and understanding of plastic contaminants.

3.2.1 Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR spectroscopy, a widely employed analytical technique for identifying organic materials, has recently gained prominence in MP pollution research. FT-IR proves invaluable in determining the chemical composition of unknown plastic fragments, comparing IR spectra for reliable identification. This technique becomes particularly valuable in assessing changes in chemical bonds typical of MP aging, offering insights into weathering indexes representing polymer degradation (Campanale et al., 2023; Losacco et al., 2022; Veerasingam et al., 2020). For instance, the carbonyl index serves as a vital indicator, reflecting carbonyl group formation during polypropylene (PP) and polyethylene (PE) photo or thermo-oxidation. These groups, particularly the main photo-absorbing species ($C = O$), trigger reactions due to UV exposure (Almond et al., 2020; Campanale et al., 2023).

Thompson et al. (2004) first utilized FTIR spectroscopy for analyzing microplastics in marine sediment samples, demonstrating its efficacy in identifying and characterizing microplastics and differentiating between polymers. Over time, FT-IR has become a cornerstone for detecting microplastics in various environmental samples (Chen et al., 2020d; Kedzierski et al., 2019; Xu et al., 2019). Environmental studies extensively employ FTIR to identify and quantify microplastics in water, sediment, and biota samples (Kedzierski et al., 2019; Miserli et al., 2023; Rathore et al., 2023; Yu et al., 2019). While FT-IR has proven efficacy, it does have limitations, particularly in identifying mixtures of different plastic types and very small microplastics. The method requires expertise and proper equipment maintenance (Andoh et al., 2024). Several methodologies, including focal plane array (FPA)-based reflectance FT-IR (FPA/FT-IR) (Tagg et al., 2015), attenuated total reflectance (ATR)/FT-IR spectroscopy (Tsang et al., 2017), and micro-FT-IR (Cai et al., 2017), have been employed to surmount these challenges. These investigations not only highlight the adaptability of FT-IR but also underscore its efficiency and speed in detecting and characterizing microplastics across diverse environmental samples, as evidenced by their valuable findings (Cai et al., 2017; Tagg et al., 2015; Tsang et al., 2017).

In conclusion, FT-IR spectroscopy stands as a robust tool in microplastic research, contributing significantly to the understanding and identification of these environmental contaminants. Its applications extend across various environmental matrices, making it a cornerstone in the field. The technique's continuous refinement and adaptation demonstrate its vital role in addressing environmental challenges related to microplastics.

3.2.2 Raman Spectroscopy

Raman spectroscopy, a non-destructive analytical technique, has emerged as a precise method for identifying MPs in various environmental samples. By leveraging the frequency shift of inelastically scattered light based on the Raman effect, this technique accurately determines the chemical composition of unknown plastic fragments, showcasing its high reliability. The vibrational modes of polymers obtained through Raman spectroscopy allow for the identification of MPs, and their applicability extends to subcellular levels in biological tissues (Murugan et al., 2023).

Raman spectroscopy studies have demonstrated its efficiency in swiftly analyzing MPs in different contexts. Zada et al. (2018) efficiently identified 88 MPs among 12,000 particles per kg in Rhine estuary sediments in less than five hours, utilizing stimulated Raman scattering. Wolff et al. (2019) identified MPs in the form of particles and fibers through Raman micro-spectroscopy after chemical and physical purification steps. Kniggendorf et al. (2019) employed Raman spectroscopy to identify MPs in tap water, while Schymanski et al. (2018) found MPs in packaged drinking water and beverage cartons using micro-Raman spectroscopy. Despite its advantages, Raman spectroscopy has some drawbacks. The fluorescent nature of samples may render Raman spectra interpretation challenging, and baseline variations induced by the laser's fluorescence effect could occur. Purification of environmental samples is recommended to mitigate these challenges (De-la-Torre et al., 2023).

Additionally, Surface Enhanced Raman Spectroscopy (SERS) enhances the weak Raman signal by utilizing nanoscale roughened metal surfaces. The technique combines plasmonic and Raman scattering, allowing for the amplification of Raman signals. SERS is particularly advantageous in quantifying microplastics, providing molecular information about polymeric composition with cost-effectiveness. However, it has some limitations, such as potential damage to particles by the laser beam, susceptibility to interference from biological material, and time-consuming procedures (Dey, 2022).

In conclusion, Raman spectroscopy and its advanced applications, like SERS, offer valuable insights into the identification and quantification of microplastics. Despite some limitations, their unique capabilities make them indispensable tools in environmental research, contributing significantly to our understanding of plastic pollution.

3.3 Chemical Methods

Chemical methods play a pivotal role in microplastic analysis, offering detailed insights into their composition, polymer types, and additives. Techniques like pyrolysis gas chromatography-mass spectrometry (Pyr-GC/MS) and Thermal Analysis contribute to a comprehensive understanding of microplastics in diverse environmental samples.

3.3.1 Pyrolysis Gas Chromatography-Mass Spectrometry (Pyr-GC/MS)

Pyr-GC/MS stands out as a valuable method for microplastic analysis across diverse environments. Offering advantages like minimal sample preparation and high sensitivity, it enables the identification of microplastics' chemical composition, polymer types, and additives. The technique involves the analysis of thermal degradation products unaffected by additives, distinguishing it from Raman spectroscopy (Fries et al., 2013; Löder & Gerdts, 2015; Kappler et al., 2018; Lee et al., 2023).

Being a destructive thermo-analytical method, Pyr-GC/MS thermally decomposes microplastic samples under defined conditions, allowing simultaneous analysis of multiple particles and the detection of plastic additives with high sensitivity. However, its application involves complex data processing, exhibits variable limits of detection, and necessitates sample preconcentration due to the small sample amounts used (Huang et al., 2023; Lee et al., 2023; Picó & Barceló, 2020; Santos et al., 2023).

To ensure the reliability of Pyr-GC/MS for quantifying microplastics, studies have used virgin microplastic standards to correct matrix effects and develop identification and quantification methods. This involves selecting specific markers or indicator ions for the plastic types under investigation and interpolating peak areas to determine microplastic concentrations in environmental samples (Okoffo et al., 2020; Toapanta et al., 2021). However, the influence of weathering on the accuracy of microplastic quantification using Pyr-GC/MS has not been fully investigated. Weathering can alter the chemistry, crystallinity, and morphology of polymers, potentially leading to over- or under-estimation of microplastic concentrations (Toapanta et al., 2021).

The integration of pressurized liquid extraction (PLE) with Pyr GC/MS is a promising method for extracting polymers such as polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), poly-(methyl methacrylate) (PMMA), and polyethylene (PE) from complex environmental samples. In addressing interference challenges with environmental samples, double-shot pyrolysis coupled with PLE is employed, involving two temperature ranges in GC operation. The lower temperature step facilitates the examination of low molecular components, while the higher temperature enables the total fragmentation of higher molecular weight polymers. Incorporating size fractionation before extraction enhances precision by providing size profile distributions, which are crucial for eliminating unnecessary matrix particle backgrounds and segregating samples based on sizes (>500 and < 500 μm). This combined approach offers a robust solution for precise environmental sample analysis, allowing specific polymer extraction and detailed examination of molecular components and size variations (Dierkes et al., 2019; Fuller & Gautam, 2016; Okoffo et al., 2020; Adhikari et al., 2022).

3.3.2 Thermal Analysis

Thermal analysis techniques, such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), can be used to characterize microplastics based on their thermal properties. Thermal analysis can complement other identification techniques and provide additional information about microplastic samples. However, it does not offer direct identification of polymer types and is more suitable for bulk analysis rather than individual particle identification.

TGA is a powerful thermal analysis method that gauges sample weight loss during controlled heating in a programmed gaseous environment (Yu et al., 2019). When combined with instruments like FTIR (Cho et al., 2023), DSC (Abbasi et al., 2023), and GC–MS (Duemichen et al., 2014), TGA becomes a robust tool for characterizing thermal properties and decomposition products of samples. Dumichen et al. (2015) devised a pretreatment-free method for quantifying PE microplastics in complex environments using TGA-GC–MS. TGA-FTIR, employed in material and biomass studies, continuously scans pyrolysis gas products to monitor compositional changes (Odochian et al., 2013). Coupling TGA with DSC offers advantages from both thermal techniques (Chabros et al., 2019). Furthermore, the combination of TGA with solid-phase extraction (SPE), subsequently linked to thermal desorption gas chromatography-mass spectrometry (TDS-GC–MS), provided improved resolution and accommodated larger sample sizes in comparison to DSC and Pyr-GC–MS. This approach also aids in overcoming the limitations associated with Raman spectroscopy (Samanta et al., 2022).

DSC is a thermal analysis technique employed to investigate physical and chemical changes, such as melting, crystallization, and glass transition, due to phase transformations and exothermic or endothermic phenomena. It boasts easy calibration, high sensitivity for analyzing thermodynamic properties, and applicability in plastic identification (Majewsky et al., 2016; Zhang et al., 2023a). Requiring only a small sample (about 1 to 20 mg) and avoiding complex data processing, DSC stands as a valuable method in thermal analysis. It examines thermodynamic properties, transition temperatures, and enthalpy/entropy changes to verify polymer characteristics, which is particularly useful for identifying specific primary microplastics like PP and PE microbeads with available reference substances (Zainuddin & Syuhada, 2020). While capable of measuring microplastic mass, DSC has limitations when overlapping peaks occur or when analyzing plastics with varied melting temperatures like PS, Polycarbonate (PC), acrylonitrile butadiene styrene (ABS), and PMMA.

In conclusion, the monitoring and assessment of microplastics require specialized techniques to identify and quantify these particles in various environmental matrices accurately. The analytical methods discussed in this section provide valuable insights into the abundance, composition, and sources of microplastics. Each method has its advantages and limitations, and researchers must carefully consider their suitability for different sample types. By employing a multifaceted approach, scientists can enhance their ability to detect and characterize microplastics, contributing to a comprehensive understanding of their impact on ecosystems.

4 Data Analysis and Interpretation

The data obtained from the monitoring process regarding microplastics (MPs) is crucial for monitoring and assessing the risks of MPs in the environment (Hermsen et al., 2018). However, faced with the large amount of data provided by modern analytical methods, manual evaluation by experts is already at a disadvantage (Renner et al., 2019). At the same time, many problems are often encountered in the process of data analysis and interpretation, which may affect the accuracy or information value of the final results (Underwood et al., 2017). Therefore, it is necessary to consider the data processing methods and evaluation strategies fully. This section provides an overview of the extraction and processing of data obtained in monitoring work, as well as the different statistical methods applied in sample data processing, as shown in **Fig. 2**, and discusses the importance of data quality and accuracy in drawing meaningful conclusions.

4.1 Data Extraction and Processing

Characterizing MPs is crucial for the reliable interpretation of analysis results in order to better understand the potential environmental impacts of MPs in ecosystems (Moura et al., 2023). The characterization of MPs can be roughly divided into four categories, namely polymer identification, particle size comparison, surface area estimation, and evaluation of crystallinity and glassiness. The above characterization will obtain thermal performance parameters, including MP type, particle size range, particle simulated surface area, and crystallinity, melting temperature, etc.

The identification of polymers can determine their composition, and different types of MPs can be evaluated based on their composition. At the same time, polymer components play an important role in determining the adsorption of organic compounds (Guo et al., 2019). Often, different types of MPs will involve different adsorption mechanisms of organic compounds (Atugoda et al., 2021). The comparison of MP particle size is mainly used to determine the range of particle sizes that

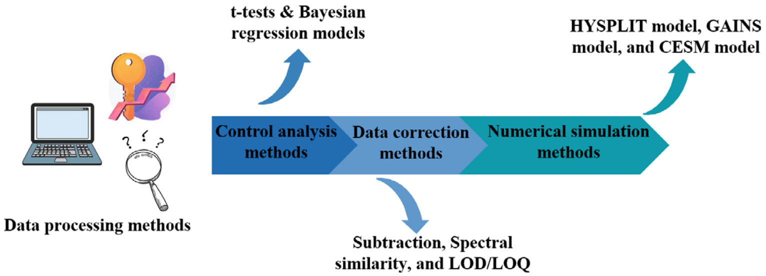

Fig. 2 A detailed representation of different statistical methods applied in sample data processing

make up MPs. The size of MP particles plays a significant role in adsorbing micropollutants (Pestana et al., 2021), and usually, smaller particles have better adsorption capacity compared to larger MP particles. Therefore, the importance of MP size in data interpretation is self-evident. The estimation of the surface area of MPs is mainly used to determine the strength of the interaction between organic compounds and MPs. Materials with larger surface areas typically exhibit better adsorption capacity for organic compounds, as larger surface areas often have more binding points (Moura et al., 2023). In terms of evaluating crystallinity and glassiness, MP polymers produced in amorphous regions often have stronger adsorption properties compared to crystalline MP polymers. X-ray diffraction technology can usually be used to evaluate the crystallinity inside MPs. If this technology finds that the higher the peak, area, and other indices, the higher the crystallinity of such MP materials.

In addition, the standard error between samples is often included in the calculation, which is the arithmetic square root of the variance of the samples. This parameter can well reflect the degree of dispersion of MP samples. If there is a significant difference in the amount of MPs in different samples, it will increase the variance value of this group of samples, leading to a relatively large standard error value. Similarly, under the condition of consistent variance values, the smaller the sample size, the greater the standard error. Therefore, the more samples collected, the more accurate the monitoring and evaluation of MPs in the target area can be.

When analyzing standard error results, two types of errors usually occur (Underwood et al., 2017). The first mistake is to assume that two samples are inconsistent based on the differences between them, but in fact, there is no significant difference in the MP content in the area where these samples were collected. Simultaneously, it was determined that there were differences in the conditions between these samples, such as in aquaculture areas and non-aquaculture areas. On the contrary, the second error is due to the inability to accurately identify subtle differences between samples, leading to the erroneous belief that there is no difference in MP content between aquaculture and non-aquaculture areas. In fact, there may be differences in MP content between the two regions. When the sample cannot represent the true situation of the collected area, such as large sample variance and small sample size, the above two errors may occur simultaneously. In addition, monitoring and evaluating MPs will involve multivariate data. Multivariate data is a synchronous analysis of several environmental variables, which often have complex connections between them. It is usually possible to conduct accurate univariate analysis to make better judgments based on the assessment of expected differences.

4.2 *Data Processing Methods*

4.2.1 Control Analysis Methods

The control analysis method based on statistical analysis is widely used for comparison and control between sample data (Akoueson et al., 2020). The commonly used control analysis methods are t-tests and Bayesian regression models.

The t-test is mainly used to identify the abundance of MP particles between the sample group and the control group (Su et al., 2019). Normally, independent Welch t-tests can be used to analyze normally distributed data. On the one hand, the Mann–Whitney test can be used to analyze abnormal data, and on the other hand, the Shapiro–Wilk normality test can be used to evaluate normality (Dawson et al., 2023). In addition, data analysis work can be carried out using software such as GraphPad Prism and RStudio.

Bayesian regression analysis allows for direct calculation of the color, shape, size, and various related uncertainties of MP particles between the sample group and the control group. The shape and size evaluation of MP particles can usually be evaluated using models with gamma distribution and logarithmic linkage, while color and polymer evaluation can be evaluated using models with classification and logical linkage (Dawson et al., 2023).

4.2.2 Data Correction Methods

In the analysis of control data, data correction methods are usually used, and common data correction strategies include subtraction, spectral similarity, and detection limit/quantification limit method (LOD/LOQ).

Subtraction can be divided into total subtraction and average subtraction. Total subtraction refers to the total number of sample items minus the number of items in the control, while average subtraction refers to the average value of total sample items minus the average value of items in the control.

The spectral similarity method typically requires highly consistent polymer purity to generate relatively high-quality spectra. However, when analyzing environmental MPs, the applicability of the spectral similarity method in data correction is often not high due to factors such as biological pollution, self-degradation, and non-standard size (Zvekic et al., 2022).

LOD is usually used to test low-content MP samples, which can to some extent measure the lowest parameter values of the samples, while LOQ refers to the stable and accurate testing ability of various parameter values of MP sample groups.

4.2.3 Numerical Simulation Methods

Various numerical simulation-based models have been continuously proposed to address the emission issues of MPs. According to the concept of the MP cycle (Rochman & Hoellein, 2020), the emission and transportation of atmospheric MPs are important components of the global MP cycle. Therefore, current numerical models mainly focus on the MPs present in the atmosphere. The commonly used models include the Hybrid Single Article Lagrangian Integrated Trajectory model (HYSPLIT model), Greenhouse Gas Air Pollution Interactions and Synergies model (GAINS model), and Community Earth System model (CESM model).

The HYSPLIT model is mainly used to simulate the trajectory of atmospheric envelope movement. This model can analyze the sources of MPs in the atmosphere and numerically and proportionally evaluate various sources (Wang et al., 2020). However, when facing complex atmospheric dynamics problems, the simulation results of the HYSPLIT model often have a lot of uncertainty.

The simulation of atmospheric MPs using the GAINS model is mainly based on the statistical data of energy and industry provided globally, as well as the air pollutant emission inventories of various countries. Taking the calculation of road MP emissions as an example, the GAINS model can effectively carry out simulation calculations based on emission data of the target area, vehicle operating distance, and specific emission ratios (Evangeliou et al., 2020). The CESM model is mainly used to evaluate the deposition of MPs in the global atmosphere, and its resolution is high (Brahney et al., 2021).

In the CESM model, to address the size variation caused by differences in the lifespan of MP particles, MPs are classified into six different diameter tracer categories and added to the model library. These six diameters are 0.3, 2.5, 7, 15, 35, and 70 μm, respectively (Brahney et al., 2021). The CESM model is considered to have a strong guiding role in the study of atmospheric MPs, especially in remote areas where sampling is difficult (Luo et al., 2022a).

4.3 The Significance of Data Quality and Accuracy

When analyzing MP samples in the environment, the lack of standard protocols and corresponding quality assurance frameworks can lead to unreliable and non-repeatable research results (Lu et al., 2021). Relevant quality standards should be established in sampling, laboratory sample analysis, analysis methods, and other aspects to ensure the effectiveness of each study. At present, our understanding of MPs is not perfect, and the lack of quality assurance data often means that different quality data will be generated (Löder & Gerdts, 2015). The spread of erroneous data will affect various MP data reporting and evaluation standards. Only under the premise of ensuring data accuracy can standardized documents on the effectiveness evaluation of MPs be generated, which facilitates researchers to conduct fair and detailed evaluation work (Kase et al., 2016).

5 Case Studies

5.1 San Francisco Bay

In year 2015, San Francisco Bay had conducted an initial screening investigation into microplastics (Sutton et al., 2016). It was proposed that the contamination level had exceeded those observed in other larger developed water bodies and concluded that it is mandatory to conduct a critical regional study to depict the microplastic in the Bay, and having an in-depth understanding of the entry pathways, analyse the circulation patterns influencing the spatial variations, and assess the transport of microplastics to the ocean. To launch the essential baseline data and propose solutions, the San Francisco Estuary Institute and the 5 Gyres Institute collaborated with the analytical expertise from the Rochman Lab at the University of Toronto to conduct an extensive regional study on microplastic pollution in the main estuary (Klasios et al., 2021; Miller et al., 2021; Rebecca et al., 2019; Zhu et al., 2021). This project was conducted in 3 years employed different sampling and analysis techniques to have an in-depth understanding of the anthropogenic microplastics in the area of the San Francisco Bay and next to National Marine Sanctuaries.

In year 2021, Miller et al. (2021) provided an overview of suggested optimal approaches derived from the thorough evaluation of microplastics in various components of the San Francisco Bay ecosystem inclusive of water, dement, biota, urban stormwater runoff, and wastewater sewage. Additionally, the discussion covers the present microplastic which was present in the shallow water within the three National Marine Sanctuaries that are hydrologically connected to the bay. Standard methods, quality assurance or control practices for the microplastics evaluation was initiated by these following authors (Brander et al., 2020b; Hermsen et al., 2018; Koelmans et al., 2019; Silva et al., 2018). The standard method is used to categorize and compare the concern area and trends to formulate policy and necessary action plans. Implementing quality assurance and quality control measures allows researchers to scrutinize disparities in microplastic analyses, differentiating between statistically significant variations detected in the field and those that merely result from variances in collection and analysis methods. The adoption and adherence to standardised procedures and quality assurance and quality control protocols support a comprehensive evaluation of management actions, guaranteeing their efficient execution in locations where they can have the most substantial influence. The advantage of this study is that it allows multiple sampling and various analysis techniques to be used such as for better understanding and having various characterization on the microplastics in this location (Miller et al., 2021). Figure 3 illustrates the location of the San Francisco Bay and Tomales Bay where the monitoring and sampling tests were conducted for this research. In this figure, the surface water trawls were conducted in both wet and dry seasons as part of the trawl samples. meanwhile, the watershed samples for stormwater were indicated in the figure.

The lesson learnt from this research were on the sample site selection and field sampling, laboratory analysis, and reporting results. For the sample site selection,

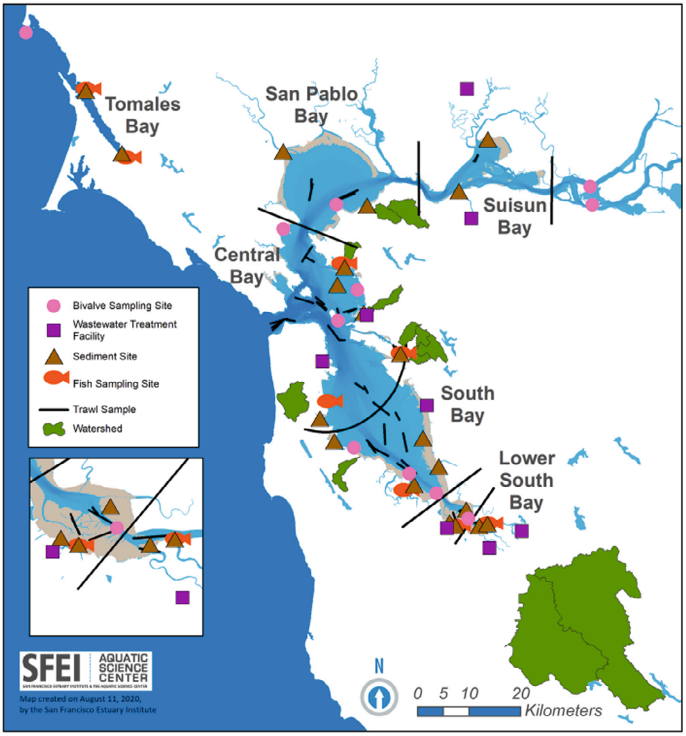

Fig. 3 Site location of San Francisco Bay where the assessment of the microplastic were investigated. Reproduced with permission from Miller et al. (2021). Copyrights 2021 Elsevier

it was proposed to have a truly representative sampling via probabilistic sampling with sufficient number of sample size meanwhile the trend analysis would be suitable for targeted sampling. Nevertheless, the high cost for laboratory analysis on the microplastic is still the primary concern in such research. Hence, thoughtful planning on maximizing the utility of a limited number of samples. This analysis on cost and benefit aspect becomes even more crucial, particularly when accounting for the substantial amount of quality assurance samples recommended, emphasizing the necessity for computerized methods. To resolve this, a well-planned design for trend monitoring is essential which considering the various variables such as the season, tidal stage, current, and other spatial and temporal aspects that are anticipated to impact concentrations. Hence, in this research, their main goal is to an initial dataset to serve as a foundation for subsequent monitoring. This dataset will serve as a reference for future sampling endeavors aimed at identifying variations among sites and over time. Meanwhile, for the field sampling, it was suggested by Miller et al. (2021) that the evaluation of the smaller particles is more essential to relate the observation of the toxicity testing existence. This is further explained that more particles will be accumulated in the provided sample volume based on the smaller range of particle size (Coverton et al., 2019). It is also emphasized the mesh size of sieves along the different matrices is essential to enable evaluations using uniform operational size groups. For comparison with other earlier measurements, it is crucial to employ methods that align with those used in prior studies or the ones that were reported in relevant literature review. It was also suggested to employ bulk grab samples when collecting fibers to simplify the collection and analysis process, minimizing the risk of sample contamination and ensuring that fiber samples do not pass through filters with small pore sizes. It was also learnt that performing small-scale pilot studies before implementing methods is crucial for calibration and improvement by establishing expected microplastic concentrations. And also, assessing the variability in observed concentrations can be improved by taking duplicate samples at approximately the same time and location. For the laboratory analysis, the investigation of the microplastics in environmental samples requires laboratory expert owing to the widespread presence of related contamination sources and the necessity for chemical identification, frequently requiring multiple techniques. For the past few years, analysis methods have rapidly advanced from visually identifying probable plastic particles to adopting material identification methods such as spectroscopy, for more accurate microplastic identification. Few authors such as Cowger et al. (2020); Hung et al. (2021); Primpke et al. (2020) had conducted intensive review on the various analytical techniques involving microplastic measurement and analysis. For the reporting results, it was concluded that there are still not fix methods for microplastic analysis particularly for the environmental media (Miller et al., 2021). Miller et al. (2021) had incorporated the proposed reporting guidelines that was established by Cowger et al. (2020) with the addition of the particle count instead of the total mass or volume which was commonly used in the larger trash above 5 mm in the reporting. This reporting approach had provided information on the current analytical methods, facilitating the relationship with the toxicity studies by enabling the particle types concentration calculations. Nevertheless, Miller et al. (2021) had recommended to provide ample of information for others to convert data into commonly used units. And also, it was also highlighted that the development of the toxicity studies and real-world exposures relationship is essential, however, many current monitoring studies lack details on lower or upper size limits, often focusing solely on the focused size class (Koelmans et al., 2019).

The key recommendations from this case study by Miller et al. (2021) were highlighting the importance of a collaborative, multi-stakeholder approach to address the global issue of microplastic pollution. Furthermore, the accurate measurement and understanding of microplastic sources, sinks, and reservoirs are emphasized to gauge the extent of the problem and prioritize effective mitigation strategies. Moreover, the continuous evolution of methods for characterizing microplastic contamination is deemed essential, particularly in addressing challenges related to ubiquitous microfiber contamination (Barrows et al., 2017). And also, the urgent attention is directed towards establishing standardized quality assurance and quality control methods, inclusive of reporting of blanks and addressing background contamination issues. The improved insights into various sources of microplastics, especially in urban stormwater, are highlighted for the development of targeted solutions.

Additionally, recommendations include further research on airborne deposition, the fate of microplastics in water bodies, and ecotoxicological studies to assess their effects at environmentally relevant concentrations. Finally, recognizing the difficulties involved in assessing risks, there is a plea for a thorough examination that takes into account the varied characteristics of microplastics and their intricate interactions with other substances in aquatic settings.

5.2 Amazon River

Rico et al. (2023) investigated on the monitoring initiative to evaluate the occurrence and potential hazards associated with microplastics in freshwater ecosystems within the Amazon region. Their study examined the pollution of microplastics in a total of 40 samples obtained over a span of 1,500 km in the Brazilian Amazon, encompassing the Amazon River, three primary tributaries, and various streams adjacent to major urban centers. Microplastics within the size array of 55–5000 μm were analyzed based on the characteristics of size, shape, colour through microscopy and identified in terms of polymer composition using infrared spectroscopy.

As shown in Fig. 4, the Amazon River and its tributaries were sampled from bigger passenger boats that moved continuously or from stationary small boats that stayed in one place for as long as possible. Meanwhile, for the urban areas, both bridges or small boats was utilized to conduct the sampling test. In the mid-way of the river area, a specific amount of water was extracted and filtration was conducted on the plankton net. The samples that were filtered will be transferred to a glass container and filtered using the filter paper with the following specification of GF/A, Ø 47 mm, pore size 0.7 μm. Thereafter, the filter used for sampling was folded and placed into aluminum envelopes for subsequent analysis. The quantity of sampled water varied from 0.3 to 4.6 m^3, determined based on the anticipated level of anthropogenic impact at the sampling location (Rico et al., 2023) (Fig. 4).

For the microplastics extraction, several processes were involved in the sample processing, depending on what was shown on the filters. In the event that organic matter made up the majority of the filter content, the material was washed into Erlenmeyer flasks using filtered reverse osmosis water, allowed to settle for a night, and then the water on top was filtered. After the material had sedimented, it was sieved, the organic debris was removed using hydrogen peroxide (H_2O_2), and two density separations were performed using a sodium iodide solution. Sand-filled samples underwent two density separations, drying, and filtering before the extracts were saved for further examination.

For the microplastic analysis, the particles were analyzed using a Perkin Elmer Spotlight 400 μFTIR in transmission mode. To enhance spectral quality, the particles were initially compressed using a diamond compression cell (DC-3, Perkin Elmer) before being loaded onto the machine. Meanwhile, for the quality assurance or quality control, the field materials involved were non-plastic, prewashed, and used with organic cotton clothing. The samples packed in aluminum foil envelopes, were

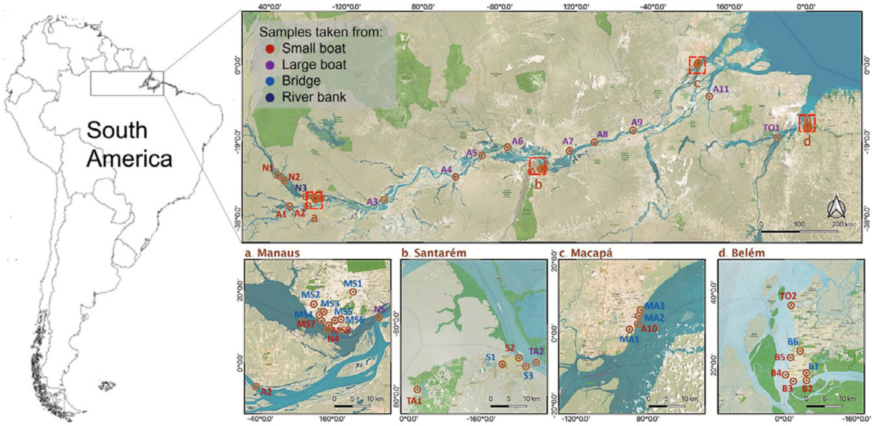

Fig. 4 The specified site location and sampling locations in small boats conducted by Rico et al. (2021, 2023). The dots represent where the sampling initiated in this research. Reproduced with permission from Rico et al. (2021, 2023). Copyright 2023 and 2021 The Authors. The figure is obtained from open access article which is under a Creative Commons licence Attribution-Noncommercial-Noderivs 4.0 International

processed in a controlled environment at the Norwegian Institute for Water Research. To avoid contamination, necessary steps were involved by using the natural fiber clothing, lint rollers, and laminar flow cabinets. Pre-filtered water and solutions, along with rinsed glass containers and polyethylene tubes, were employed. Blank samples were included in each set, and suspected microplastics were characterized visually and chemically similarly like the field samples. The methodology was validated with spiked samples, with the efficiency of extraction and rates of recovery documented in previous studies (Crossman et al., 2020; Hurley et al., 2018). In order to determine the microplastics mass estimation, the calculation involving the particle volume and the density of the identified polymers were involved. Particle volume was computed using distinct shapes for various types: spheres for beads, cylinders for fibers, and ellipsoids for films, fragments, and glitter. The choice of shapes was based on the morphology and size of the analyzed axes. For the estimation of microplastic exposure concentrations in various samples, the count of particles (MPs/L) and the mass of microplastic particles (mg/L) were involved. This calculation involved dividing the number of microplastic particles or the total mass by the volume of water that passed through the sampling nets. The ecological risk assessment was determined using the approach prepared by Koelmans et al. (2020b).

According to this study, there may be ecotoxicological hazards to aquatic life in the Amazon's small rivers and streams that are close to urban areas due to higher quantities of microplastic. Even though only 7–23% of species are impacted, the results are consistent with earlier research by these authors (Besseling et al., 2019); Koelmans et al. (2020b); (Schell et al., 2022) that identified metropolitan areas with inadequate sewage treatment as microplastic hotspots. In order to reduce plastic pollution in Amazonian freshwater habitats, sewage treatment infrastructure and increased public awareness are essential. It is anticipated that the demographic rise may increase microplastic emissions.

6 Challenges and Future Directions

With the rising concerns on the abundance of microplastics in the environment, the techniques employed to monitor microplastics need to be easily accessible, efficient, and accurate. The variety of microplastics and their interaction with the surrounding due to the dynamic properties of the environment and the existing limitations of the current microplastic research techniques have posed challenges to the advancement in this field.

The current microplastics monitoring is lack of standardized protocols (Koelmans et al., 2020a; Zhang et al., 2020b; Lv et al., 2021; Adhikari et al., 2022; Chen et al., 2023), resulting in difficult data analysis and comparison between studies. The ocean is the main reservoir of microplastics originating from terrestrial and fresh water environments that provide the transportation pathway from various sources to the ocean (Zhang et al., 2020b). Thus, reliable water sampling method is crucial in microplastic studies to minimize contamination and ensure final data reliability. The protocols of microplastic separation by sieving and filtration can be established by standardizing the mesh and pore sizes (Lv et al., 2021), which is important in water sampling by using trawls and nets that requires multiple mesh sizes to avoid clogging. Razeghi et al. (2021b) explained that the varying depth of immersion, caused by wind, waves, and boat movement, makes tracking the volume of water filtered difficult and hereby affects the sample representativity. This promotes the combination of net-based and bulk sampling methods, complexifying the sampling process.

MP studies are complicated by their export from surface water to deep-sea sediments. This necessitates the assessment of various environmental compartments to investigate the distribution of microplastics (Simon-Sánchez et al., 2022). Surface sediment in shore areas serves as an indicator of the prolonged interfacial interaction between water terrestrial environments (Razeghi et al., 2021b). According to Sajjad et al. (2022), the higher complexity of separating microplastics from soil than water arises from its ecosystem and microplastic properties. Besides, they noted that the common techniques for extracting microplastics from soil samples, such as air flotation, density suspension, and heating at 130 °C for 3–5 s, suffer from long duration, low recovery, inability to capture three-dimensional heterogeneity, and limitations in extracting nano- and picoplastics, while also being restricted to small-scale applications. Residual matrices in sediment samples, including organic particles, minerals, small particles ($<50\ \mu m$), and those insoluble in organic solvents, cannot be easily removed by different purification processes and may interfere further analyses (Bouzid et al., 2022).

In microplastic separation from biota or biota-rich samples, the main challenge is minimizing the destructive effects of chemicals on the susceptible polymers, resulted by prolonged exposure or unsuitable reaction conditions. Schrank et al. (2022) reported the severe fragmentation of polyethylene terephthalate (PET) and the weight losses of polyamide (PA) 6 and polyurethane (PUR) up to 100% with hot nitric acid and peroxymonosulfuric acid. Elevating temperatures to enhance digestion efficiency increases the vulnerability of polymers to mild chemicals such as hydroxide solutions (90 °C) (Gulizia et al., 2022) and hydrogen peroxide (60–70 °C) (Pfeiffer & Fischer, 2020). Fenton reagent that exerts negligible effects on synthetic polymers, needs to be coupled with enzymatic digestion to remove a large amount of organic matters (Möller et al., 2020). In contrast, an increase of sample weight is probable with certain chemical digestion protocols due to outer surface degradation, internal structural modification, volume increase, structure relaxation, water entrapment, and salt residues (Pfeiffer & Fischer, 2020).

Apart from purification efficiency, inherent limitations of microscopic techniques also constrain the accuracy of microplastic visual studies. Stereomicroscopy used for preliminary screening must be followed by more sophisticated techniques, owing to its limited magnification and low accuracy to detect microplastics with low opacity, small sizes (<100 μm), and definite shapes, in addition to the interference of remaining organic particles that are failed to remove by digestion (Kalaronis et al., 2022; Mariano et al., 2021b). Fluorescence microscopy has high error rate in the presence of blended chemicals like dyes or plasticizers, which are hard to eliminate (Fu et al., 2020b). Polymers that can be detected are limited to fluorescent polymers, such as PET, polypropylene (PP), polystyrene (PS), polyethylene (PE), nylon, polyester, and elastane (Kalaronis et al., 2022). Scanning electron microscopy-energy dispersive X-ray (SEM–EDS), known for eliminating visual characterisation errors by providing high resolution images and elemental composition, is not effective in differentiating microplastic fibers and non-plastic microfibres because of the small discrepancies in structural properties and carbon signals (Blair et al., 2019b). Fu et al. (2020b) highlighted that its constraints also include time-consuming sample preparation and potential risk of alteration or destruction of thermally unstable polymers, including polyvinyl acetate (PVAc) and polyvinyl chloride (PVC), when exposed to high-energy electron beam.

Therefore, vibrational spectroscopies, particularly Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy are used after SEM–EDS analysis. They are able to differentiate microplastic fibres, non-plastic fibres, and suspended fragments, such as titanium, bromine, and silicon, which produce strong carbon signals that are difficult to distinguish from the peaks caused by microplastics with solely SEM–EDS (Blair et al., 2019b). Raman spectroscopy is preferred to detect extremely small microplastics (>1 μm) when compared with FTIR that is limited to < 20 μm (Snega Priya et al., 2022). Unlike FTIR, Raman spectra would not be altered by the water content and sample thickness (Adhikari et al., 2022), but paint particles could dominate a Raman spectrum due to their stronger scattering effect than polymeric matrix, causing fluorescence (Xu et al., 2019). In accordance with Cabernard et al. (2018), despite the size limitation, attenuated total reflectance-FTIR (ATR-FTIR) performs better than μ-Raman spectroscopy in identifying coloured microplastics that cause absorbance, fluorescence, and band overlay. Still, their findings show that both techniques could not effectively identify black coloured or fibrous microplastics. For a large field size, the time consumed for measurement is significantly extended (Primpke et al., 2018).

In microplastic quantification, various factors, such as resolution limit, misidentification of natural particles as plastics, and limitations of purification, lead to high error rates in conventional counting method with microscopic techniques (Zarfl, 2019). This encourages the use of mass spectroscopy that offers fast analysis of smaller particles by yielding data about the polymer types and mass per volume (Chun et al., 2022), as well as addressing the issue of underestimating plastics based on the particle sizes (Adhikari et al., 2022). However, since the common mass spectroscopic techniques, namely pyrolysis gas chromatographic mass spectrometry (Pyr-GC–MS) and liquid chromatography tandem mass spectrometry (LC–MS/MS) destroy samples during analysis, size categorization by sieving and filtering shall be done prior to the experiment in ecotoxicology studies. Plus, the pyrolysis products of certain polymers, including PE, PET, PVC, and others, lack distinctive characteristics and hence cannot be readily identified (Li et al., 2021). This potentially results in an underestimation of these polymers. Furthermore, a challenge exists in assessing the applicability of various calibration method for use across a broader array of polymers. Lauschke et al. (2021) reported the potential interference posed by PS-d_5, a common polymer for creating internal standard in microplastic quantification, due to H–D exchange during pyrolysis catalysed by residual inorganic fraction in the samples. The study by Bouzid et al. (2022), concerning the quantification of PE, PET, PP, PS, and PVC with Pyr-GC–MS, implies that external calibration curve shall be avoided for sediment samples as the presence of residual organic particles and minerals in the sample was found accelerating PET depolymerization during pyrolysis, resulting in inaccurate signals.

Crucially, integrated analysis with multiple analytical techniques that aims to improve characterisation and quantification of microplastics increases the time and cost for regular application. Consequently, the development and adoption of automated analyses become a trend in microplastic monitoring researches. According to Primpke et al. (2018), automated analysis pipeline for FTIR was created in the past study, overcoming the drawbacks of manual FTIR analysis, such as human bias, long measurement time, and size limitation. Automating analyses is viable, yet there is a notable barrier caused by the substantial scale demands (Adhikari et al., 2022). The absence of benchmark information for different regions and materials presents another challenge in automating microplastic analyses. Standardisation of automated analyses requires a specially designed database for various materials and a detailed clustering of spectra (Primpke et al., 2018). Neelavannan and Sen (2023) emphasized the significance of developing a database for weathered plastics to ease the determination of unknown microplastics in environmental samples, which is often impeded by variable Raman spectra. A few attempts have been made to develop a database for weathered plastics under different conditions, which are natural degradation (Dong et al., 2020; Marica & Pînzaru, 2023) and fire (Luo et al., 2022b). Enhanced data availability contributes to the accurate estimation of microplastic transport in computer vision and machine learning deployed to automate monitoring and data collection (Phan & Luscombe, 2023).

Moreover, there is a notable transition in recent research emphasis. Intertidal mangrove wetlands gain growing attention in MP studies due to their ecological values and the detected pollution in the mangrove sediments (Chen, 2022). MP researches concerning freshwater bodies between 2018 and 2022 prioritise investigating the environmental implications over the earlier focus on characterising microplastics (Wang et al., 2023b). MPs have been associated with the toxicological effects on aquatic organisms, pollutant adsorption, and risks posed to human health through trophic transfer. Domestic wastewater, increasingly recognised as a major microplastics contributor in freshwater and ocean environments, has been studied comprehensively, encompassing the assessment of microplastic removal efficiency in wastewater treatment schemes comprising the usual primary and secondary processes, which ranges between 73 and 99% (Blair et al., 2019a; Conley et al., 2019; Gündoğdu et al., 2018; Hernández Fernández et al., 2022; Lares et al., 2018; Meng et al., 2023). However, several problems to be tackled are sludge management, microplastic emission from sludge-based fertiliser, standardisation of research methods, exploring membrane technology, evaluating small microplastics (<20 μm), examining specific types of microplastics in industrial wastewater, and implementing control measure at the household levels (Dey et al., 2021; Hassan et al., 2023; Liu et al., 2021; Sun et al., 2019).

MP particle transport is a vital topic in microplastic researches, particularly concerning the life cycle and distribution of microplastics. Currently, there is a challenge in defining and describing the dynamics of atmospheric transfer over a long distance (Zhang et al., 2020b). Although the identification of microplastic sources and atmospheric trajectory travelled is facilitated with the Lagrangian atmospheric models, such as HYSPLIT, additional researches on their fate and transport mechanism in the air, resuspension from aquatic and terrestrial compartments, and entrainment into these compartments via dry and wet atmospheric precipitation are necessary and currently deficient (Abad López et al., 2023). Since atmospheric deposition is not the only source of microplastics in the air, the results of passive and active sampling methods are hardly comparable without the consideration on the sampling location, height, period, weather, and sampling methods (Chen et al., 2020c). Importantly, microplastic transport researches across different environmental compartments are hindered by the differences in the metrics of reporting and comparing. Microplastic transport poses threat by aiding the spreading of organic and inorganic pollutants and increasing the risk of exposure to these substances. Recent studies have proven that the association of contaminants on micro-sized debris of various materials, namely high density polyethylene (HDPE), PVC, polylactic acid (PLA), and polybutylene succinate (PBS), is affected by the plastic hydrophobicity, physical and chemical properties, as well as biofilm formation (Cui et al., 2023; Torres et al., 2021; Tourinho et al., 2019). The future investigation should highlight sorption dynamics on weathered and degradable plastics, the fate of pollutants, single and combined ecotoxicity of microplastics and chemical pollutants, and bioaccumulation.

A comprehensive strategy in sampling, monitoring, quantification, and study of underlying impacts on environment and organisms could deepen the knowledge of the environmental implications of microplastics. Overcoming the challenges brought by global microplastic pollution needs the awareness and interdisciplinary collaboration among scientists, policymakers, and industry stakeholders.

7 Conclusion

Microplastics have posed a serious threat to ecosystems and human health globally due to their high durability and ease of dispersion. Filtration, centrifugation and electrocoagulation are commonly used to collect microplastics in aqueous environments. The accuracy, frequency and economy of microplastic collection in sedimentary environments are currently ensured through the use of deterministic, stochastic and conventional grid systems. To improve the accuracy of sampling microplastics in soil, a combination of sampling techniques (random, systematic, stratified and composite) is required. Full composite sampling is more suitable to be employed in biologically organized environments. In addition, to further analyze the abundance and composition of microplastics from different sources, this book chapter analyzes the advantages and disadvantages of various analytical methods and data processing methods as shown in Table 1.

This chapter uses the San Francisco Bay and Amazon River cases to further explore local techniques for microplastic collection and analysis. Current monitoring and analytical techniques, there is still a lack of standardized protocols, the complexity of the collection environment, the harmfulness of the separation chemicals, the detection technology still has the limitation of low accuracy, the researchers will be committed to ensure the accuracy of the data at the same time, the assessment of the effectiveness of microplastics to create a standardized document and a fair assessment of the work. Furthermore, the development of automated analysis and machine learning to improve the characterization and quantification of microplastics provides scale-up assistance for the separation of microplastics in wastewater, soil, and atmosphere.

Table 1 Advantages and disadvantages of analytical methods and data analysis methods for microplastics

Analytical methods	Advantages and disadvantages
Microscopy-based methods	Optical microscopes are cost-effective and widely available, but cannot accurately identify microplastics below 0.2 microns
	SEM–EDX can help identify microplastics, generating images at 0.5 nm, but is not effective for mass identification
	TEM provides 0.1–0.2 nm graphics and valuable fluorescence data, but suffers from high cost and time-consuming drawbacks
Spectroscopy-based methods	FT-IR improves efficiency in detecting microplastics
	Raman spectroscopy provides highly reliable and accurate determination of the chemical composition and polymer molecular information of unknown plastic fragments
Chemical method	Pyr-GC/MS is highly sensitive for microplastics and analyses thermal degradation products independent of additives. To favour the extraction of plastic components, the method needs to be combined with pressurised liquid extraction
	Thermal analysis methods do not allow direct identification of the polymer type, are more suited to batch analysis of microplastics and are limited by the different melting temperatures of microplastics
Data analysis methods	
Control analysis methods	The t-test and Bayesian regression models were applied to identify the abundance, colour, shape and size of microplastics, respectively
Data correction methods	Subtraction, Spectral Similarity and LOD/LOQ to Improve Data Corrections
Numerical simulation methods	HYSPLIT simulates microplastic trajectories in the atmosphere with large uncertainties
	The GAINS model simulates global atmospheric microplastic emissions based on global energy and industry data and air pollutant emission inventories
	The CESM model primarily assesses atmospheric microplastic deposition

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