Advancing Micro Plastic Analysis: A Comprehensive Review of Detection and Characterization Techniques

Abstract

This review paper critically evaluates the current state of micro plastic detection and characterization methods, highlighting the significant environmental and health risks posed by microplastics. Microplastics, categorized into primary and secondary types, are ubiquitous in various ecosystems, raising concerns about their impacts on aquatic life and human health. The paper discusses the diverse characteristics of microplastics and the challenges associated with their detection in complex environmental matrices. An overview of existing detection methods, including visual identification, spectroscopic techniques, and emerging technologies such as automated imaging and machine learning, is provided. Additionally, the review addresses the environmental fate and transport of microplastics, their interactions with biota, and the socio-economic implications of pollution. Emphasizing the need for standardized methodologies and innovative solutions, the paper calls for enhanced public awareness and policy initiatives to mitigate the pervasive threat of microplastics, thereby contributing to global environmental sustainability efforts.

Keywords: Micro plastics, Detection Methods, Environmental Impact, Pollution Mitigation

1. Introduction

Micro plastics, which are categorized into primary and secondary types, pose a significant threat to ecosystems and human health. Primary microplastics are released into the environment as microbeads, plastic pellets, and fibers, while secondary microplastics are formed from the breakdown of larger plastic items due to factors like UV light and weathering (Avinash, 2023). As illustrated in Figure 1, microplastics can originate from various sources, including landfills, agriculture, and urban stormwater runoff.

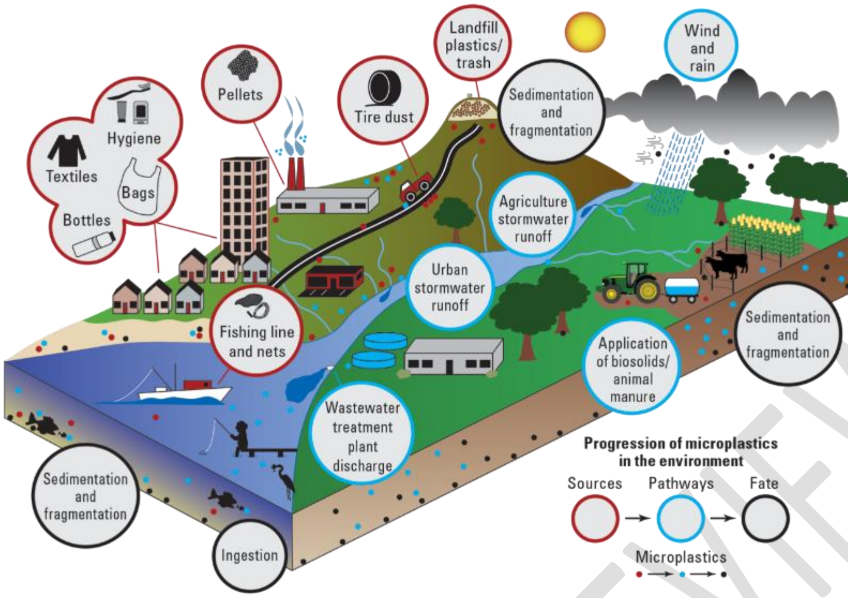

Figure 1 : *Sources and pathways of microplastic pollution. Source: (Nash et al., 2023)*

The widespread occurrence of microplastics is evident in various environments, with studies showing high prevalence rates, such as 93.7% in marine fish from the South China Sea (Koongolla et al., 2022). These microplastics, being ubiquitous, not only contaminate aquatic environments but also find their way into food sources like omega-3 oil supplements, raising concerns about human exposure and health impacts (Kim, 2024).

Accurate detection and characterization of microplastics are crucial for understanding and mitigating their pollution. Despite efforts to develop standardized monitoring methods and substitutes for microplastics, research on the adverse effects of these pollutants on humans remains limited(Lee et al., 2023). Microplastics have been identified as a significant environmental concern due to their harmful effects on ecosystems and potential risks to human health("Microplastics in Aquatic Environments: Sources, Ecotoxicity, Detection &Amp; Remediation," 2021). Techniques for sampling and quantifying microplastics in various environments, including beach sand and sediments, have been standardized to assess their presence and potential harm(Besley et al., 2017). The presence of microplastics in different ecosystems, from freshwater to marine environments, underscores the need for comprehensive detection and assessment methods(Koelmans et al., 2019).

In conclusion, the prevalence of microplastics in diverse environments highlights the urgency of accurate detection and characterization to address the environmental and health risks associated with these pollutants. Research efforts must focus on developing effective methods for monitoring and mitigating microplastic pollution to safeguard ecosystems and human well-being.

2. Microplastic Characteristics and Challenges

Microplastics are defined as small plastic particles less than 5 mm in size, categorized into primary microplastics that are intentionally manufactured at a small size and secondary microplastics that result from the breakdown of larger plastic items(Cole et al., 2011). They come in various shapes such as fibers, fragments, and spheres, and are composed of different polymers like polyethylene, polypropylene, and polystyrene (Syberg et al., 2015). The diverse nature of microplastics, including their size, shape, and polymer composition, poses challenges for their detection in complex matrices like soil, water, and biota (Soo et al., 2021). The small size of microplastics, their abundance in the environment, and the potential presence in various matrices make their detection and characterization difficult (Dey et al., 2021).

Environmental factors such as degradation and aggregation influence micro plastic detection. Microplastics can undergo degradation processes, breaking down into smaller particles that are harder to detect (He, 2024). Aggregation of microplastics with other particles can further complicate their identification and quantification in environmental samples(Hampton et al., 2022). The presence of a complex mixture of physical and chemical characteristics in microplastics, including sizes, morphologies, polymer types, and sorbed chemicals, adds to the challenge of determining which particle characteristics are most relevant for understanding their toxicity to aquatic organisms (Hampton et al., 2022).

The characteristics of microplastics, their challenges in detection, and the environmental factors affecting their identification are crucial considerations in understanding the impact of these contaminants on ecosystems. The unique properties of microplastics, coupled with their ubiquity and potential harm to organisms, highlight the importance of developing effective detection methods and mitigation strategies to address this global environmental issue.

3. Current Detection Methods:

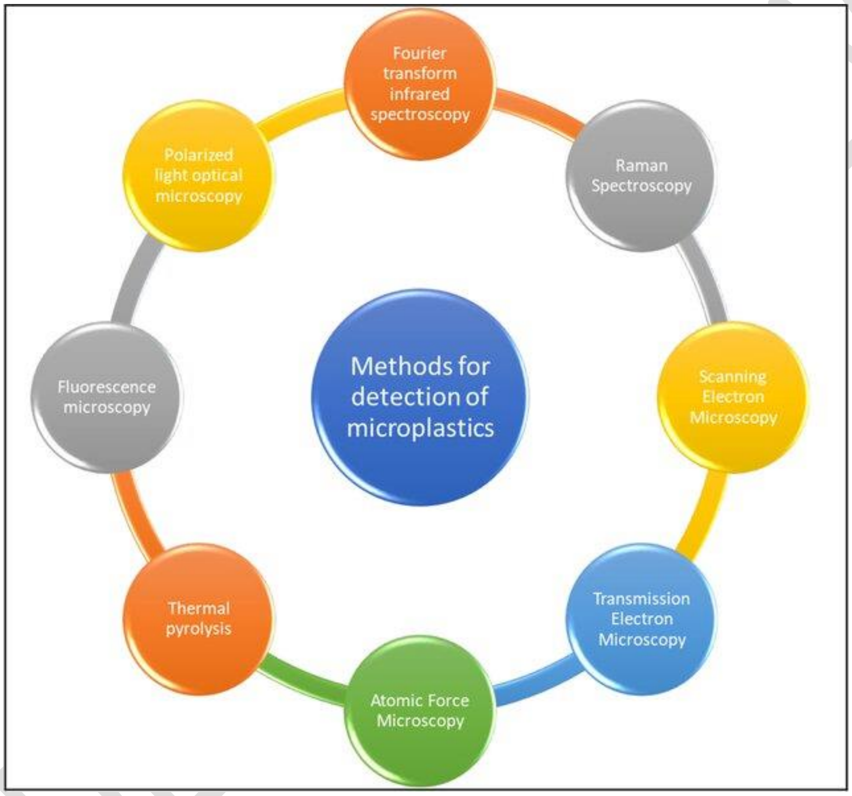

Figure 2 illustrating the various methods for detecting microplastics, highlighting the decision-making process for selecting appropriate techniques based on sample characteristics. Source: (Muthulakshmi et al,2023)

Microplastic detection methods **(As seen in table 1)** encompass a variety of techniques aimed at identifying and quantifying these pervasive pollutants.

Table 1 summarizes various microplastic detection methods, highlighting their descriptions, advantages, limitations, and relevant references.

Method	Description	Advantages	Limitations	References
Visual Sorting	Identification of microplastics using microscopes or the naked eye	Simple, cost-effective, minimal equipment required	Subjective, time-consuming, potential for misidentification	(Baruah et al., 2022) (Biyik & Baycan, 2021)

Fourier Transform Infrared Spectroscopy (FTIR)	Analyzes chemical composition by measuring infrared absorption	Accurate polymer identification, non-destructive	Expensive equipment, limited to particles >20 μm	(Baruah et al., 2022) (Jin et al., 2022) (Biyik & Baycan, 2021)
Raman Spectroscopy	Identifies polymers based on molecular vibrations	High spatial resolution, can detect particles <1 μm	Time-consuming, fluorescence interference	(Baruah et al., 2022) (Biyik & Baycan, 2021) (Jin et al., 2022)
Pyrolysis Gas Chromatography-Mass Spectrometry (Pyr-GC-MS)	Thermal decomposition followed by chemical analysis	Highly accurate, can identify additives	Destructive method, complex data interpretation	(Baruah et al., 2022) (Goedecke et al., 2020)
Scanning Electron Microscopy (SEM)	High-resolution imaging of particle surface morphology	Detailed surface characterization, size measurement	Cannot identify polymer type, expensive equipment	(Baruah et al., 2022) (Biyik & Baycan, 2021)
Thermal Extraction Desorption Gas Chromatography-Mass Spectrometry (TED-GC-MS)	Thermal extraction of organic compounds followed by analysis	High sensitivity, can detect trace amounts	Destructive method, complex sample preparation	(Goedecke et al., 2020)
Nile Red Staining	Fluorescent dye that selectively stains plastic particles	Rapid, cost-effective for large sample sizes	Potential false positives, limited polymer discrimination	(Biyik & Baycan, 2021) (Sürme & Maraş, 2022)
Surface-Enhanced Raman Scattering (SERS) with Machine Learning	Uses 3D-plasmonic gold nanopocket structure for MP detection	Improved sensitivity, can detect MPs without pretreatment	Requires specialized equipment and ML algorithms	(Sürme & Maraş, 2022)

Visual identification, a common method, is hindered by subjectivity and observer bias(Li et al., 2020). Filtration techniques, such as membrane filtration and centrifugation, are utilized with size limitations depending on the method employed (Faramarzi, 2024). Spectroscopic techniques like Raman and Fourier-transform infrared (FTIR) spectroscopy offer specificity in analysis but can be costly and complex (Baryalay, 2024; Zhang, 2024). Microscopy, including optical and electron microscopy, allows for detailed characterization of microplastics (Cao, 2024). Chemical analysis methods like pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS) aid in polymer identification (Hermabessière & Rochman, 2021)

Current research emphasizes the importance of standardizing detection methods for microplastics (Nguyen et al., 2019; Renner et al., 2021). Techniques like Raman spectroscopy and FTIR are pivotal in individual particle analysis and visual identification of microplastics(Zhang, 2024). Despite advancements in automation for spectroscopic methods, challenges remain in terms of time consumption, cost, and spectral resolution(Sturm et al., 2021). Additionally, fluorescence-based methods like Nile Red offer novel approaches for detecting small microplastics (Erni-Cassola et al., 2017; Sturm et al., 2021)

In summary, the field of microplastic detection is evolving, with a range of methods available. Each method has its strengths and limitations, highlighting the need for continued research to refine and standardize detection techniques for accurate and efficient identification of microplastics in various environmental samples.

Table 2 summarizes various methods for detecting microplastics, highlighting their detection limits, advantages, and disadvantages. This overview underscores the diversity of techniques available, each with unique strengths and challenges, emphasizing the need for standardization and refinement in microplastic detection methodologies.

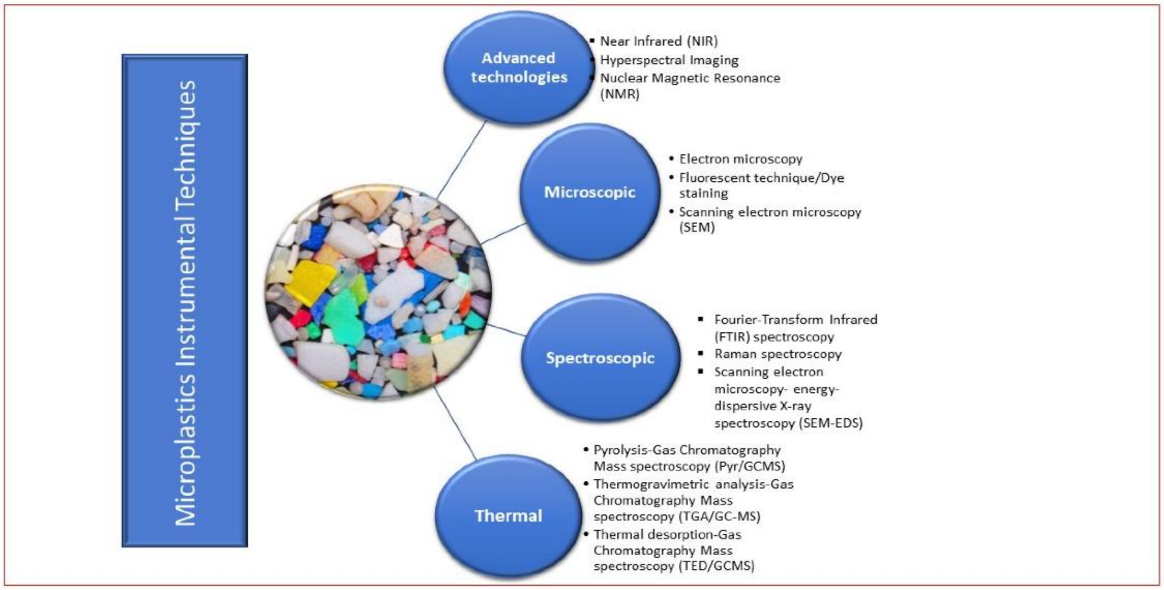

Figure 3 shows a comprehensive diagram illustrating various analytical methods used for detecting and characterizing microplastics, categorized into Advanced, Microscopic, Spectroscopic, and Thermal technologies. Source: (Adelugba, A. and Emenike, C., 2023)

4. Characterization Techniques:

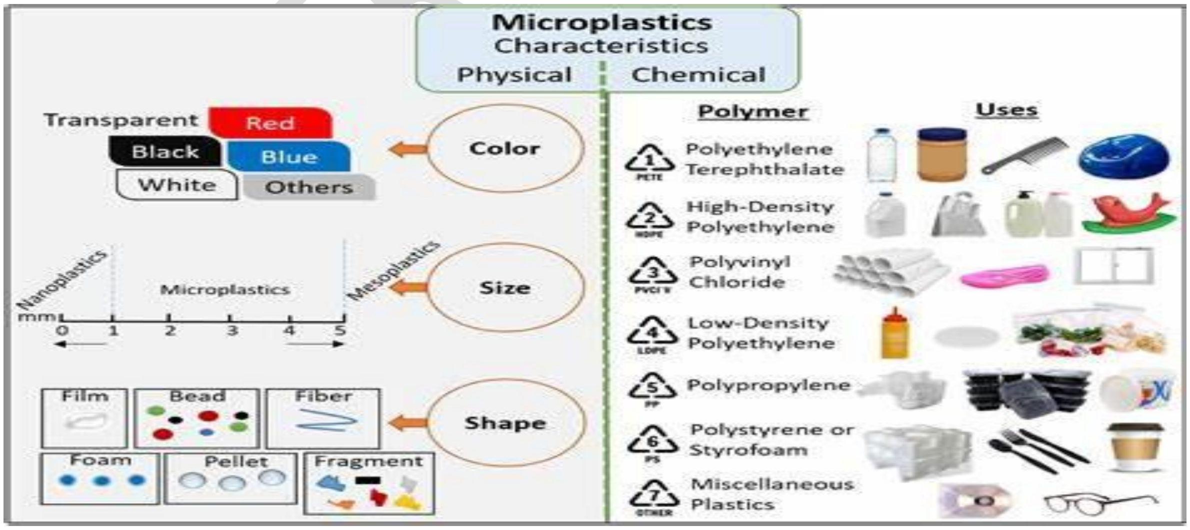

Figure 4 shows an infographic detailing the physical and chemical characteristics of microplastics, including color, size, shape, polymer types, and common uses. Source: (Raza, M., Lee, J.Y. and Cha, J., 2022)

Characterization techniques are essential for understanding polymers thoroughly, providing detailed information on size, shape, polymer type, and the presence of additives or contaminants. Various techniques are employed for this purpose, each offering unique advantages. Flow cytometry is particularly valuable for rapid analysis and size discrimination, allowing for efficient assessment of polymer characteristics (Arrua et al., 2014). Image analysis, especially automated methods, facilitates particle counting and size measurement, aiding in comprehensive polymer characterization(Lin et al., 2021). Pyrolysis-GC/MS is notable for its detailed capabilities in identifying polymers and copolymers, offering in-depth insights into their composition(Kusch, 2014).

Additionally, techniques like atomic force microscopy (AFM) provide high-resolution surface profiling, enhancing the advanced characterization of polymer materials(Magonov, 2000). Time-of-flight secondary ion mass spectrometry (ToF-SIMS) offers compound-specific surface analysis, distinguishing it from other techniques and making it a preferred tool for polymer characterization (Prasad et al., 2022). Moreover, matrix-assisted laser desorption ionization time of flight mass spectrometry (MALDI-TOF MS) is advantageous for polymer identification due to its ability to provide mass spectra with individual n-mer resolution within polymer distributions (Payne & Grayson, 2018).

Furthermore, infrared spectroscopy is widely used for chemical reaction monitoring and structure identification in cross-linked polymers, showcasing its significance in polymer characterization(Narasimhaswamy & Reddy, 1991). Laser-induced breakdown spectroscopy (LIBS) assisted by machine learning is employed for discriminating and identifying different polymeric samples with varying additives, contributing to effective polymer analysis(Stefas et al., 2019). Overall, the combination of these diverse characterization techniques offers a comprehensive approach to understanding and optimizing polymer properties as seen in Table 2.

Table 2: Overview of characterization techniques used for material analysis, highlighting their target parameters and associated limitations.

Characterization Technique	**Target Parameters**	**Limitations**
Flow Cytometry	Rapid analysis, size discrimination	Limited to particles that can be suspended in a fluid
Image Analysis (Automated)	Particle counting, size measurement	Dependent on image quality and resolution
Pyrolysis-GC/MS	Polymer and copolymer identification	Destructive method, requires complex instrumentation
Atomic Force Microscopy (AFM)	High-resolution surface profiling	Limited to surface analysis, slow scanning process
Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS)	Compound-specific surface analysis	Surface-sensitive, requires high vacuum environment
Matrix-Assisted Laser Desorption Ionization Time of Flight MS (MALDI-TOF MS)	Polymer identification, mass spectra resolution	Limited to polymers that can be ionized
Infrared Spectroscopy	Chemical reaction monitoring, structure identification	Limited resolution for complex mixtures, requires calibration
Laser-Induced Breakdown Spectroscopy (LIBS) with Machine Learning	Discrimination and identification of polymers	Requires extensive calibration, may be affected by matrix effects

5. Emerging Technologies in Microplastic Detection

Automated Imaging and Machine Learning: Discuss recent advancements in automated image analysis Recent advancements in automated image analysis and machine learning have significantly enhanced the accuracy and efficiency of microplastic detection and identification. Technologies like deep learning algorithms have been integrated to classify particles based on various features such as shape, size, and polymer type(Liu et al., 2020). Studies have shown that the key physicochemical properties play a crucial role in dictating the gastrointestinal bioaccessibility of microplastics-associated xenobiotics, highlighting the importance of understanding these properties for effective detection (Liu et al., 2020). Additionally, the use of technologies like Faster-RCNN-FPN and spectroscopic imagery under ultraviolet light has enabled high precision and recall in classifying microplastics based on polymer type(Thammasanya, 2024).

Furthermore, the integration of a liquid–solid triboelectric nanogenerator and deep learning methods has shown promise in detecting microplastics, although there are challenges such as single detection, low efficiency, complex sample processing, and high costs that need to be addressed for wider applicability(Huang et al., 2023). Techniques utilizing spatial heterodyne microscopic differential Raman spectroscopy have been introduced for microplastic detection, showcasing the continuous innovation in detection methodologies(Yang et al., 2023). Moreover, the development of microscopic image datasets with segmentation and detection labels has facilitated the analysis of morphological and elemental characteristics of microplastics, aiding in their identification and classification(Lee, 2024).

Researchers have also explored the rapid classification of microplastics using convolutional neural networks, involving stages like density separation, organic digestion, and polymer type characterization through spectroscopy techniques(Akkajit & Sukkuea, 2023). Deep learning approaches have been applied for automatic microplastics counting and classification, demonstrating the potential for advanced automation in this field(Lorenzo-Navarro et al., 2021). Machine learning-based methods, such as the k-nearest neighbor classification, have been developed for the analysis of microplastics in environmental samples, showcasing the versatility of these technologies in different contexts(Weber et al., 2023).

Moreover, the design and implementation of microplastic detection and classification systems supported by deep learning algorithms have shown promising results in detecting microplastics in various environmental matrices(Dal, 2024). These systems often combine traditional detection methods with deep learning algorithms to enhance the accuracy and efficiency of microplastic detection. The continuous evolution of detection technologies, including the utilization of deep learning algorithms, has led to significant improvements in the detection and identification of microplastics in different environmental samples(Zhong, 2023).

The integration of automated imaging and machine learning techniques has revolutionized the field of microplastic detection. Technologies like deep learning algorithms have enabled the classification of microplastics based on various characteristics, enhancing the accuracy and efficiency of detection processes. Despite some challenges such as complex sample processing and high costs, ongoing research and advancements in this area continue to drive innovation towards more effective and reliable microplastic detection methods.

Next-Generation Spectroscopy Techniques:

Terahertz spectroscopy is a cutting-edge spectroscopic method that shows promise for the analysis of microplastics due to its high sensitivity and rapid processing speeds compared to traditional techniques. Research has demonstrated the effectiveness of terahertz spectroscopy in detecting microplastic particles in various matrices, underscoring its potential for environmental monitoring and analysis(Park & Ahn, 2022). The utilization of surface-functionalized terahertz microfluidic metamaterials has facilitated the detection of polystyrene microplastic particles in water, highlighting the precision of terahertz spectroscopy in identifying specific types of microplastics(Park & Ahn, 2022).

Additionally, terahertz spectroscopy has found applications in a wide range of fields such as materials science and biology, showcasing its versatility and relevance for microplastic analysis(Zhong et al., 2020). Studies have explored the use of terahertz time-domain spectroscopy for non-destructive testing of materials, emphasizing its high signal-to-noise ratio and real-time detection capabilities(Yang et al., 2022). This technology offers advantages over traditional infrared spectroscopy by directly measuring the electric field's amplitude without requiring sample contact, making it a promising tool for sensitive and rapid microplastic detection(Yang et al., 2022).

Moreover, terahertz spectroscopy has been effective in detecting defects in composite materials, demonstrating its ability to identify subtle variations and anomalies with high precision(Luo, 2023). The non-destructive nature of terahertz time-domain spectroscopy makes it valuable for analyzing complex materials like composite insulators, where traditional methods may be inadequate(Luo, 2023). Furthermore, terahertz spectroscopy has been successfully applied to detect microplastics in various samples, including salts, indicating its potential for investigating microplastics in different environmental matrices(Im et al., 2021).

The integration of terahertz spectroscopy with advanced technologies like convolutional neural networks has enabled the detection of quality attributes in agricultural products, illustrating the versatility of terahertz technology in various applications(Sun, 2024). By combining terahertz spectroscopy with machine learning algorithms, researchers have achieved high sensitivity and accuracy in detecting defects and impurities in various materials, including microplastics(Sun, 2024). This approach offers a promising pathway for improving the efficiency and reliability of microplastic analysis in complex environmental samples.

Terahertz spectroscopy emerges as a next-generation spectroscopic technique with significant potential for microplastic analysis. Its high sensitivity, non-destructive characteristics, and real-time detection capabilities make it a valuable tool for identifying and characterizing microplastics in diverse environmental samples. By leveraging advancements in terahertz technology and integrating it with innovative methodologies, researchers can enhance the accuracy and efficiency of microplastic detection, contributing to the progress of environmental monitoring and sustainability endeavors.

Portable and On-Site Detection Tools:

Portable microplastic detectors, such as handheld Raman or FTIR spectrometers, have emerged as valuable tools for on-site detection in field studies, offering numerous advantages in providing real-time data for environmental monitoring and analysis. These portable devices enable researchers to conduct immediate assessments of microplastic contamination levels in various environmental samples, including soils, sediments, water bodies, and biota, without the need for extensive sample preparation or transportation to a laboratory setting(Unnimaya et al., 2023). The convenience and efficiency of these tools make them particularly suitable for conducting rapid surveys and monitoring activities in remote or challenging field locations where access to laboratory facilities may be limited(Möller et al., 2021).

One significant application of portable microplastic detectors is in soil analysis, where researchers have developed protocols to purify soil samples for spectroscopic analysis using FTIR spectrometers(Möller et al., 2021). These tools allow for the assessment of the size and number of microplastic particles present in soil samples, providing valuable insights into the extent of contamination and the types of polymers involved. Similarly, in studies focusing on beach sand and sediment cores, portable FTIR spectrometers have been utilized to identify and characterize microplastics, such as PET and PP, highlighting the versatility of these devices in different environmental matrices (Chaisanguansuk et al., 2023; Sajorne et al., 2022).

The use of handheld Raman spectrometers has also been instrumental in detecting microplastics in various field studies, including mangrove sediment cores and water column samples (Chaisanguansuk et al., 2023; Fox et al., 2022). These portable devices offer the advantage of rapid analysis and identification of microplastics based on their unique spectral signatures, allowing researchers to quantify and characterize the abundance of microplastics in different environmental compartments. Additionally, the development of low-cost methods for quantifying microplastics in soils and compost using near-infrared spectroscopy demonstrates the potential of portable spectroscopic tools for widespread environmental monitoring applications(Wander et al., 2022).

Furthermore, the integration of portable FTIR spectrometers with advanced technologies like machine learning has enabled the classification and quantification of microplastics in complex samples, enhancing the efficiency and accuracy of detection processes(Çebi et al., 2023). By combining spectroscopic analysis with data processing algorithms, researchers can streamline the identification of microplastics and generate real-time data for immediate decision-making in environmental management and conservation efforts. These advancements underscore the importance of portable microplastic detectors in facilitating on-site detection and analysis, contributing to a better understanding of microplastic pollution in diverse ecosystems(Cho et al., 2023).

Portable microplastic detectors, such as handheld Raman and FTIR spectrometers, play a crucial role in field studies by providing rapid and reliable data on microplastic contamination levels in various environmental samples. These tools offer the advantage of on-site detection, enabling researchers to conduct real-time assessments and monitoring activities in remote or challenging field locations. The integration of portable spectroscopic devices with advanced technologies enhances the efficiency and accuracy of microplastic analysis, contributing to the ongoing efforts to mitigate the environmental impact of microplastic pollution.

6. Environmental Fate and Transport of Microplastics

To comprehensively address the environmental fate and transport of microplastics, it is essential to consider various aspects such as modeling and predicting microplastic distribution, biodegradation and fragmentation pathways, sorption and desorption dynamics, and the role of microplastics as vectors for pollutants.

Modeling and predicting microplastic distribution in aquatic environments involve the use of computational models that consider factors like particle size, shape, and density(Hassan et al., 2024). These models help in understanding how microplastics move within water bodies and their potential accumulation in specific areas. Additionally, hydrodynamic models play a crucial role in predicting the transport of microplastics in aquatic systems(Hassan et al., 2024).

Biodegradation and fragmentation pathways of microplastics are influenced by environmental conditions, with studies exploring the rate of degradation under different scenarios(Kim, 2024). Research on novel enzymes or bacteria capable of breaking down plastic polymers sheds light on potential solutions to mitigate the persistence of microplastics in the environment(Kim, 2024).

Sorption and desorption dynamics highlight the role of microplastics as vectors for pollutants, where contaminants can adhere to microplastic surfaces, affecting their environmental impact and bioavailability(Kalčíková & Bundschuh, 2021). Understanding how microplastics interact with pollutants is crucial in assessing the overall environmental risks associated with their presence.

Moreover, the formation of biofilms on microplastics has been identified as a critical factor influencing the fate, behavior, and bioavailability of microplastics in aquatic environments(Kalčíková & Bundschuh, 2021). Biofilms, consisting of microorganisms attached to surfaces, can alter the properties of microplastics and impact their interactions with the surrounding environment.

Addressing the environmental fate and transport of microplastics requires a multidisciplinary approach that integrates computational modeling, biodegradation studies, and an understanding of sorption dynamics. By considering these factors, researchers can develop effective strategies to manage and mitigate the impacts of microplastics on aquatic ecosystems.

7. Microplastic Interactions with Biota

Recent research has elucidated the complex interactions between microplastics and biota, with a focus on bioaccumulation, biomagnification, toxicological effects, and physiological impacts. Studies have demonstrated that microplastics can indeed bioaccumulate within food webs, potentially leading to biomagnification in higher trophic levels(Miller et al., 2020). This bioaccumulation can happen through various pathways, including ingestion by marine and terrestrial organisms (Hamilton et al., 2021; Nabila & Patria, 2021). Microplastics have been identified as carriers for harmful chemicals, such as persistent organic pollutants and heavy metals, which can exert toxic effects on living organisms(Amelia et al., 2021; Pennati et al., 2022). Moreover, the ingestion of microplastics by various species has been associated with physiological impacts like oxidative stress, tissue damage, and impaired reproduction(Gouin, 2020).

The transfer of microplastics through trophic levels has been well-documented, with evidence of bioaccumulation and biomagnification along the food web (Pennati et al., 2022).Microplastics can be ingested by a wide array of organisms, from zooplankton to fish, potentially resulting in biomagnification of plastics in higher predators(Fulfer & Menden-Deuer, 2021; Hamilton et al., 2021). Additionally, research has underscored the significance of microplastics in the bioavailability and accumulation assessment of various aquatic organisms, emphasizing the need to comprehend the pathways of microplastic uptake (Kuehr et al., 2022; Roch et al., 2020).

Furthermore, studies have shown that microplastics can have negative impacts on soil fauna while stimulating microbial activity, indicating intricate ecological consequences(Lin et al., 2020). The widespread presence of microplastics in diverse ecosystems, including freshwater and marine environments, highlights the urgent necessity to tackle the challenges posed by microplastic pollution(Faleti, 2022; Mm et al., 2021). Understanding the sorptive properties of microplastics and their role as vectors for major ocean pollutants is crucial for evaluating their hazards to marine ecosystems and human health (Amelia et al., 2021; Praveena & Aris, 2020)

The body of research on microplastic interactions with biota emphasizes the multifaceted nature of this environmental concern. From bioaccumulation and biomagnification studies to toxicological effects and physiological impacts, the evidence points to the pervasive influence of microplastics on various organisms and ecosystems. Addressing these challenges necessitates a comprehensive understanding of the pathways, mechanisms, and impacts of microplastic pollution on biota.

8. Mitigation and Remediation Strategies

Innovative Filtration and Cleanup Technologies:

Recent advancements in microplastic filtration systems for wastewater treatment plants have focused on the development of innovative technologies to effectively remove microplastics from water sources. These technologies include the use of advanced filtration membranes, such as polyhydroxyalkanoates (PHA), which are biodegradable and can be produced from renewable carbon resources(Hanik et al., 2019). Additionally, research has highlighted the importance of cleanup technologies like The Ocean Cleanup project, which aims to remove plastic debris from the oceans using innovative systems (Meshram & Mhatre, 2024)

Biodegradable Plastics as a Solution:

The effectiveness of biodegradable plastics, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), in reducing microplastic pollution has been a subject of ongoing research. Biodegradable plastics offer a potential solution to the issue of plastic pollution by degrading more readily in various environmental conditions compared to traditional plastics(Hanik et al., 2019). However, there are concerns about the generation of microplastics from biodegradable plastics, indicating the need for further investigation into their overall impact on reducing pollution (Permana et al., 2023).

Policy and Regulatory Developments:

Global and regional policy initiatives aimed at controlling microplastic pollution have been implemented to address the issue. These initiatives include microbead bans and extended producer responsibility (EPR) programs, which hold manufacturers accountable for the end-of-life disposal of their products(Gregory et al., 2023). While these regulations are essential steps in reducing microplastic emissions, there is a need for continuous evaluation of their effectiveness and enforcement to ensure significant progress in mitigating plastic pollution.

9. Socioeconomic Impacts and Public Awareness

Economic Costs of Microplastic Pollution:

Microplastic pollution presents a significant economic burden on various industries such as fisheries, tourism, and public health. Studies have demonstrated that microplastics can contaminate marine organisms like green mussels (Malto et al., 2021)and crustaceans(Parvaresh et al., 2024), affecting their market value and potentially leading to economic losses. The presence of microplastics in water bodies, as evidenced in rivers like the Citarum River

(Hermana et al., 2024) and the Banger River (Despasari et al., 2023), is often associated with anthropogenic activities and inadequate waste management practices, impacting industries reliant on clean water sources.

The long-term economic implications of uncontrolled microplastic pollution are concerning. If not addressed, the continuous input of microplastics into freshwater ecosystems, as highlighted in studies on runoff and discharge pathways(Wang et al., 2022), could result in lasting damage to aquatic life and ecosystems, affecting industries dependent on these resources. Additionally, the persistence of microplastics in marine environments, such as in the Persian Gulf(Parvaresh et al., 2024), can have cascading effects on fisheries and tourism, further exacerbating economic challenges.

Efforts to tackle microplastic pollution necessitate increased public awareness and education, as emphasized in studies focusing on the necessity for awareness programs in countries like Chile (Paredes-Osses et al., 2021) and Iran (Parvaresh et al., 2024). Public awareness is crucial in promoting behavioral changes that reduce plastic usage and enhance waste management practices, ultimately mitigating the economic costs associated with microplastic pollution.

The economic costs of microplastic pollution on industries like fisheries, tourism, and public health are substantial and could have long-term implications if not effectively mitigated. Public awareness, coupled with strategic interventions to reduce plastic pollution and improve waste management, is essential to alleviate the economic burden imposed by microplastics on various sectors

Public Awareness and Citizen Science Initiatives:

Citizen science initiatives are pivotal in advancing microplastic research by involving the public in sampling and monitoring efforts. Projects engaging public participation, particularly those focused on collecting and identifying microplastic pollution in various environments (Teddiman, 2021), have significantly contributed to increasing awareness and understanding of the issue. These initiatives not only gather valuable data but also empower individuals to participate in environmental research and conservation efforts(Paradinas et al., 2021).

Enhanced public awareness through citizen science projects can lead to changes in behavior concerning plastic use and disposal practices. Active involvement in monitoring microplastic pollution can make individuals more conscious of their plastic consumption habits and the potential environmental impact of plastic waste(Felipe-Rodriguez et al., 2022). This increased awareness can drive shifts towards reducing single-use plastic consumption, promoting recycling, and advocating for sustainable practices in daily life.

Furthermore, citizen science initiatives can influence policy support by providing robust data and evidence of microplastic pollution to policymakers and regulatory bodies. By engaging the public in data collection and monitoring, these projects generate comprehensive datasets that can inform decision-making processes and policy development aimed at mitigating microplastic pollution(Bosker et al., 2017). The collaborative nature of citizen science fosters a sense of shared responsibility among participants, policymakers, and researchers, leading to a more holistic approach to addressing environmental challenges.

Public awareness and citizen science initiatives are crucial components in combating microplastic pollution. By involving citizens in research activities, raising awareness about the impacts of microplastics, and influencing behavioral changes and policy decisions, these initiatives significantly contribute to advancing our understanding of microplastic pollution and promoting a more sustainable relationship with the environment.

10. Critical Evaluation and Future Directions:

To critically evaluate and propose advancements in microplastic detection and characterization, it is essential to consider the strengths and weaknesses of existing methods. Various techniques have been employed, such as instrumental methods(Hermabessière & Rochman, 2021), convolutional neural networks (CNN) (Huang et al., 2023), and spectroscopic approaches(Weber et al., 2023). These methods offer different levels of sensitivity, accuracy, cost, and ease of use.

Instrumental techniques, such as microwave-assisted extraction and pyrolysis–gas chromatography/mass spectrometry, provide high-resolution characterization of microplastics (Sturm et al., 2021). However, these methods may require complex sample preparation and expensive equipment, impacting their practicality and cost-effectiveness. On the other hand, CNN-based approaches offer rapid classification of microplastics(Huang et al., 2023), but they may lack the precision needed for detailed characterization.

Spectroscopic methods, including Raman spectroscopy and near-infrared spectroscopy, have been used for microplastic detection(Lee, 2024; Paradinas et al., 2021). These techniques provide valuable information on the composition and characteristics of microplastics but may have limitations in terms of spatial resolution and sensitivity.

Despite the advancements in detection methods, there are gaps and limitations that need to be addressed. Standardization of sampling and analysis protocols is crucial to ensure the comparability of results (Cao, 2024; Hermabessière & Rochman, 2021). Additionally, the development of cost-effective and portable devices for on-site detection is essential for widespread monitoring of microplastics (Fox et al., 2022; Huang et al., 2023).

Future research should focus on advancements in technology for improved microplastic detection and characterization. For instance, the integration of machine learning algorithms with spectroscopic techniques can enhance the accuracy and efficiency of microplastic analysis (Gouin, 2020; Weber et al., 2023). Moreover, the development of novel detection methods, such as terahertz spectroscopy and hyperspectral imaging, can offer new insights into microplastic identification.

The field of microplastic detection and characterization is rapidly evolving, with a wide range of methods available. By addressing the current limitations and focusing on innovative technologies, researchers can advance the field and contribute to a better understanding of the environmental impact of microplastics.

11. Conclusion:

This review highlights the critical importance of developing robust and reliable methods for the detection and characterization of microplastics. These methods are essential to advancing our understanding of microplastic pollution and informing effective mitigation strategies. While significant progress has been made, ongoing research and innovation are needed to standardize and enhance these techniques. A call to action is warranted for further development in microplastic detection technologies, which will be pivotal in addressing the environmental and health challenges posed by microplastics as seen in Table 3 below.

Table 3 provides a concise summary of the critical areas discussed in the review, emphasizing the need for continued research and innovation in micro plastic detection methods to effectively address the environmental and health challenges posed by micro plastics.

Area	Key Findings
Importance of Detection	Developing robust and reliable methods for detecting and characterizing microplastics is crucial. These methods are essential for understanding the extent and impact of microplastic pollution, which in turn is needed to develop effective mitigation strategies.
Progress and Challenges	Significant progress has been made in developing various detection and characterization methods, ranging from visual sorting and spectroscopic techniques to advanced methods like automated imaging and machine learning. However, ongoing research is needed to standardize these techniques, enhance their sensitivity and accuracy, and address limitations such as cost and complexity.
Call to Action	Further development of microplastic detection technologies is urgently needed. Improved and standardized methods are crucial for

	addressing the environmental and health challenges posed by microplastics. This includes focusing on innovative technologies and approaches to enhance detection capabilities and address the limitations of existing methods.
Specific Areas for Improvement	The review highlights the need for: * Standardization of sampling and analysis protocols to ensure comparability of results across studies. * Development of cost-effective and portable devices for on-site detection to enable widespread monitoring. * Integration of machine learning algorithms with existing techniques to improve accuracy and efficiency. * Exploration of novel detection methods like terahertz spectroscopy and hyperspectral imaging.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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