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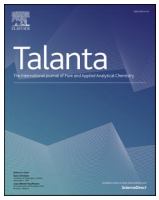

Laser Direct Infrared Spectroscopy: A cutting-edge approach to microplastic detection in environmental samples

Prince Jebedass Isaac Chandran, S. Veerasingam *

Environment Science Center, Qatar University, Doha, P.O Box 2713, Qatar

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ABSTRACT

Microplastic pollution has emerged as a significant global environmental concern, affecting marine, terrestrial, and atmospheric ecosystems. As microplastic contamination continues to intensify, the need for precise, efficient, and scalable detection method is growing. This review highlights recent advancements in microplastic detection technologies, with a particular focus on Laser Direct Infrared (LDIR) spectroscopy. Utilizing a Quantum Cascade Laser (QCL), LDIR offers rapid, sensitive, and automated detection capabilities. It significantly reduces analysis time compared to conventional techniques such as Fourier Transform Infrared (FTIR) and Raman spectroscopic techniques, making it ideal for large-scale environmental monitoring. Its ability to identify particles as small as 10 μm, combined with enhanced wavelength accuracy, positions LDIR as a promising tool for microplastic analysis across various environmental matrices. Despite some limitations, such as a narrower spectral range, LDIR's superior speed and precision make it a critical advancement for understanding and addressing the global microplastic crisis.

1. Introduction

Plastics have become integral to modern society due to their lightweight properties, durability, and cost-effectiveness [1]. Global plastic production is projected to reach approximately 445.25 million metric tons annually by 2025, with further increases expected to 590 million metric tons by 2050 [2]. Common plastics such as polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polypropylene (PP) dominate production, collectively accounting for a significant portion of global plastic output [3]. However, this widespread usage has raised growing environmental concerns, particularly regarding plastic waste.

Plastics discarded into the environment fragment through mechanical wear, weathering, and biological degradation, forming secondary microplastics—particles smaller than 5 mm [4–7]. In contrast, primary microplastics, often found in cosmetic products are directly released into the environment as minute plastic particles [8]. Over time, microplastics degrade further into nano plastics, as small as 100 nm, adding complexity to plastic pollution [9].

Microplastics have been detected across various ecosystems, including marine and terrestrial environments [10–13]. In marine systems, plastic debris primarily originates from coastal areas, rivers, and wastewater discharge, often exacerbated by stormwater runoff [14–16]. While concerns about plastic pollution date back to the 1970s [17,18], recent studies highlight the growing prevalence of microplastics, with more than 80 % of marine plastic debris originating from land-based sources [19–22].

Microplastics have been found in various environments, including beaches, sediments, rivers, seawater, and even remote regions such as the Arctic [23]. Their widespread presence poses risks to biodiversity and human health, particularly through the consumption of contaminated terrestrial and aquatic organisms. Addressing this issue requires reliable and efficient detection techniques for identifying and quantifying microplastics.

Traditional methods such as Fourier Transform Infrared (FTIR) and Raman spectroscopy are widely used for microplastic identification but are time-consuming and often require labor-intensive sample preparation, making them less practical for large-scale environmental monitoring [24]. To overcome these challenges, innovative approaches such as Laser Direct Infrared (LDIR) spectroscopy have emerged. Powered by Quantum Cascade Laser (QCL) technology, LDIR offers rapid and high-resolution analysis, producing a reflectance spectrum in just 1 s [25]. This makes a significant advancement over traditional techniques and offers considerable potential for large-scale environmental monitoring and microplastic detection [26].

* Corresponding author.
E-mail address: v.subramanian@qu.edu.qa (S. Veerasingam).

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This review provides a comprehensive analysis of current microplastic detection techniques, with a particular focus on the transformative potential of LDIR spectroscopy. By examining its applications in microplastic analysis, this review highlights how LDIR can enhance the speed, accuracy, and efficiency of environmental monitoring, addressing the limitations of conventional methods and contributing to a better understanding of microplastic pollution.

2. Comparative evaluation of microplastic detection techniques: the superiority of LDIR spectroscopy

2.1. Optical microscope

Optical microscope has been commonly used to visually identify microplastics based on their physical characteristics such as size, color, and shape. However, this method is limited by its reliance on visual interpretation and resolution, particularly for smaller particles. While microplastic particles in the 1–5 mm range can be identified using light microscopy, the technique struggles to detect particles smaller than 200 nm due to the diffraction limit [27]. Additionally, the process is labor-intensive and time-consuming, requiring manual analysis.

In contrast, LDIR eliminates the need for manual inspection through high-resolution, automated imaging, enabling the rapid detection and characterization of particles. By integrating infrared spectroscopy with imaging, LDIR provides precise chemical identification without the limitations inherent in traditional optical microscopy [28].

Optical microscopy is limited by the diffraction of visible light, which constrains its resolution to approximately 200 nm [20]. Although it is a cost-effective preliminary tool for particle identification, it requires complementary techniques, such as FTIR or Raman spectroscopy for accurate polymer characterization. Sierra et al. (2020) emphasize its practicality for quick assessments but also underscore its limitations in resolving submicron particles.

2.2. Fluorescence microscope

Fluorescence microscope uses chemical reagents, such as fluorescent dyes, to induce fluorescence in microplastics under specific lighting conditions [29]. This method can detect smaller microplastic particles and facilitate image analysis; however, it is limited by the non-specific nature of fluorescent dyes. The interaction between dyes and different polymer types is not always selective, potentially leading to inaccuracies [30].

In contrast, LDIR does not rely on chemical markers, which may introduce variability in analysis. Instead, LDIR uses infrared light to directly identify the chemical structure of microplastics, allowing for more reliable and efficient analysis without the need for additional reagents. This makes LDIR particularly suitable for real-time monitoring of microplastic contamination, especially in complex marine environments where multiple polymer types coexist.

2.3. Fourier-transform infrared spectroscopy (FTIR)

FTIR is widely used to analyze microplastics by leveraging the infrared spectral properties of polymers to determine their chemical composition [31,32]. While FTIR is effective, especially when combined with a well-established polymer spectral library [33], it is limited by its slow speed and low resolution. Micro-FTIR, which is necessary for smaller microplastics, can take several hours to process a single sample [34].

FTIR spectroscopy measures the absorption of infrared radiation by molecular bonds, providing unique spectra for the identification of polymer types. Focal Plane Array (FPA)-based FTIR imaging significantly enhances analysis by allowing simultaneous high-resolution mapping and rapid data acquisition across a sample surface [2,10]. FTIR has proven effectiveness in analyzing particles as small as 20 μm when combined with ATR (attenuated total reflectance) technique and down to 2 μm using transmission technique [35]. It is particularly suitable for environmental matrices like sediment, water, and biota due to its compatibility with spectral libraries that enable automated polymer identification (Baker et al., 2014). FTIR spectroscopy consistently performs well in inter-laboratory studies, owing to its standardized protocols and reproducible results. Käppler et al. (2016) emphasized robustness of FTIR in detecting common polymers such as polyethylene (PE) and polypropylene (PP).

In contrast, LDIR offers a significant improvement over FTIR, capturing detailed chemical information within seconds per particle, thereby greatly enhancing throughput. This makes LDIR particularly suitable for large-scale environmental monitoring. Moreover, LDIR's automated system reduces the need for labor-intensive sample preparation, making it a more efficient alternative to FTIR [36].

2.4. Raman spectroscopy

Raman spectroscopy has become increasingly popular in microplastic research due to its ability to provide a unique molecular fingerprint for each polymer. Unlike FTIR, Raman spectroscopy is highly sensitive and can analyze smaller particles with broader spectral coverage [37]. However, this method is time-consuming and less efficient when dealing with complex environmental samples. Its reliance on a laser spot size of 1 mm may fail to capture the full extent of contamination [38,35].

Raman spectroscopy identifies molecular vibrations through the inelastic scattering of monochromatic light. Its primary advantage lies in its ability to detect smaller particles (<1 μm), making it critical for addressing the challenges of micro- and nanoplastic pollution. Unlike FTIR, Raman spectroscopy can analyze particles in complex matrices with minimal sample preparation. Its molecular fingerprinting capability allows highly specific polymer identification, even in multicomponent systems [35]. However, Raman spectroscopy is sensitive to fluorescence interference, which can obscure spectral results. Advanced techniques, such as surface-enhanced Raman spectroscopy (SERS), address these limitations by improving signal-to-noise ratios. Both FTIR and Raman spectroscopy have been extensively validated in inter-laboratory studies. For instance, Käppler et al. (2016) demonstrated their reliability in quantifying and identifying microplastics in sediments and water samples.

In contrast, LDIR surpasses Raman spectroscopy by efficiently processing larger sample volumes in less time. Using a tunable infrared quantum cascade laser, LDIR can simultaneously scan multiple particles, providing both chemical composition and spatial distribution. This capability is advantageous in several environmental matrices, where microplastics are often found in mixed forms [39].

2.5. Thermal analysis

Thermal analysis methods, such as differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) are useful for identifying microplastics by analysing their thermal properties [40]. These techniques provide insights into the thermal stability and decomposition profiles of microplastics. However, thermal analysis cannot easily differentiate between similar polymers and requires extensive sample preparation. Additionally, these methods are often destructive, meaning that samples cannot be recovered after analysis [41].

In contrast, LDIR offers a non-destructive alternative, preserving samples for further study while delivering detailed chemical information that thermal methods lack. The speed and precision of LDIR further enhance its suitability for routine environmental monitoring, making it a more efficient solution for microplastic analysis.

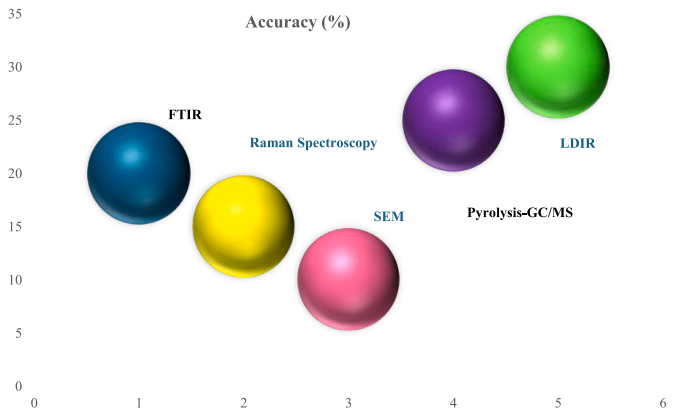

Fig. 1. Comparison of detection accuracy (%) among various microplastic detection techniques.

2.6. Pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS)

Pyr-GC/MS is a powerful technique for characterizing microplastics at the molecular level, offering detailed information about the composition of polymers in environmental samples [42]. However, Pyr-GC/MS requires strict experimental conditions, extensive sample preparation, and sophisticated equipment, limiting its practicality for routine monitoring [43]. Additionally, the method is time-consuming and unsuitable for large-scale sample analysis due to its lower throughput.

In comparison, LDIR surpasses Pyr-GC/MS in terms of speed and ease of use. While Pyr-GC/MS provides highly detailed molecular information, LDIR strikes a balance between chemical specificity and operational efficiency, making it ideal for high-throughput screening in environmental samples. Its ability to rapidly process large datasets with minimal sample preparation makes LDIR a more accessible and efficient tool for environmental monitoring.

2.7. Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (SEM-EDS)

SEM-EDS is an advanced imaging technique that provides high-resolution images of microplastics along with their elemental composition [44]. However, SEM-EDS requires complex sample preparation, including drying, coating, and embedding, which can introduce artifacts and alter the morphology of microplastics [45]. Furthermore, SEM-EDS is labor-intensive and time-consuming, making it less suitable for routine monitoring.

In contrast, LDIR provides rapid, automated imaging combined with chemical analysis without the need for extensive sample preparation. Its non-destructive nature allows for more efficient sample processing, making LDIR a practical choice for analyzing microplastics across diverse environmental matrices, including sediments, water, air, and biota.

2.8. Liquid chromatography/mass spectrometry (LC/MS)

LC/MS is useful for detecting specific plastic types, particularly in complex environmental matrices such as dust and wastewater. While this method provides accurate quantification, it is destructive and requires large sample sizes for meaningful results. Moreover, LC/MS is limited to detecting known polymers and may not provide comprehensive data on the full range of microplastics present in a sample (Fig. 1). This graph compares the accuracy of various analytical techniques used for microplastic detection. Among the techniques, LDIR (Laser Direct Infrared) demonstrates the highest accuracy, making it the most effective for detecting microplastics, especially smaller particles.

In contrast, LDIR offers a more comprehensive analysis by identifying a wide range of polymer types simultaneously, without requiring large sample sizes or complex sample preparation. Its rapid scanning capability makes it ideal for detecting and quantifying microplastics in large datasets, providing more detailed insights into the diversity and abundance of microplastics in environments.

The terms “precision” and “accuracy” must align with the Guide to the Expression of Uncertainty in Measurement (GUM). Precision refers to the reproducibility of measurements under unchanged conditions, whereas accuracy reflects the closeness of a measurement to the true value. These metrics are vital for validating spectroscopic methods like LDIR, ensuring both repeatability and correctness in polymer identification [20,46].

3. Introduction of LDIR

In recent years, LDIR imaging has emerged as a transformative tool for detecting and analyzing microplastics across various environments, including oceans, groundwater, soil, and biological tissues. LDIR stands apart from traditional methods by utilizing a high-magnification visible camera capable of detecting particles as small as 10 μm. Powered by a proprietary quantum cascade laser (QCL), LDIR offers unprecedented speed and wavelength accuracy, surpassing conventional Raman and FTIR spectroscopy. It can acquire a complete infrared spectrum for microplastics in just 1 s per particle, whereas traditional methods can take hours [47,48]. LDIR excels in rapid scanning and imaging of large areas, offering significant advantages in terms of automation and sample throughput. Unlike traditional methods such as μ-FTIR or Raman, which analyze predefined sample sections and may spend time on non-relevant areas, LDIR scans the entire sample to locate microplastics before

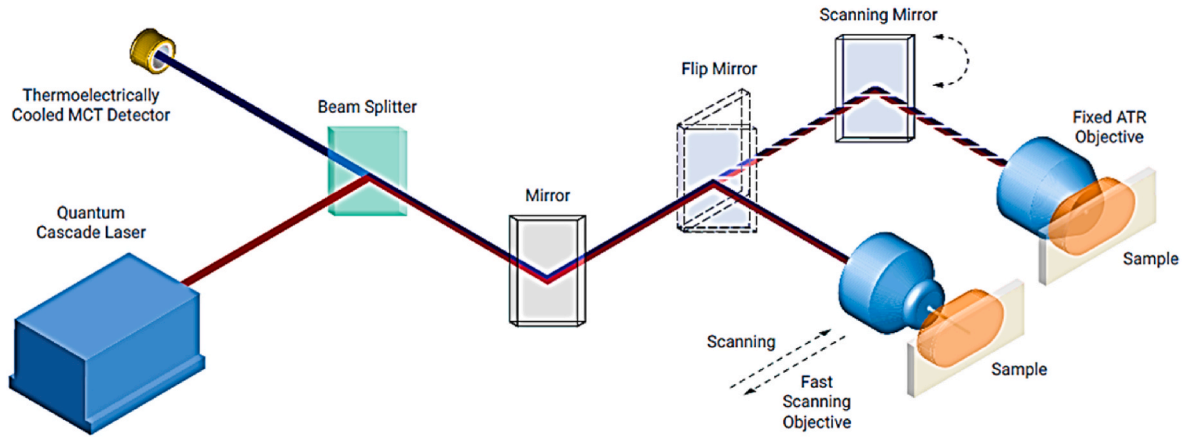

Fig. 2. Fig. 2. Schematical representation of QCL based LDIR instrumentation [51].

Table 1
Comparison of various methods for detection of microplastic.

S. No	Techniques	Principle	Available Data	Detection Limit	Advantage	Limitations
1	Optical Microscopy	Micro Plastics are counted based on shapes, colours, thickness, sheen, and/or using a hot pin.	Number Shape Colour	>500 μM	Non-destructive Inexpensive	Low automation Polymer type can't identify
2	Fluorescence Microscope	Micro Plastics are counted based on shapes, colours, thickness, sheen, and/or using a hot pin.	Number Shape Size	>500 μM	Non-destructive Inexpensive	Low automation Polymer type can't identify
3	μ-FTIR	Pre-selected Micro Plastics or a proportion of pretreated samples are identified according to the changes in the dipole moment of functional groups in the MPs.	Number Shape Size Polymer Type	>100 μM	Non-destructive High automation Quick analysis	Relatively low identification of MP types A limited quantity of ambiguous particles can be analyzed under a single-point analysis mode.
4	μ-Raman	Pre-selected Micro Plastics are identified based on the changes in a molecular bond's polarizability	Number Shape Size Polymer Type	>10 μM	Non-destructive High automation Quick analysis	Liquid nitrogen cooling is required. Background fluoresces are caused by other biological materials.
5	TGA/DSC	The mass changes of samples subjected to thermal decomposition in an inert atmosphere are measured. The DSC measures the temperature difference between the sample and a reference.	Polymer Type Total Mass	>5 mg	1–20 mg is required for analysis Capable of analysis in a short period	Cannot provide any insight into the MPs themselves, including MP number, size, and colour Only PP and PE polymers can be analyzed
6	Pyr-GC-MS	Samples are thermally decomposed in an inert atmosphere and are separated by a GC column, then passed to the mass spectrometer for detection.	Polymer types Total mass	>5 mg	Destructive Less sample preparation	Only a small amount of sample can be analyzed at a time Only limited types of polymers can be analyzed
7	LC/MS	Samples are solvent phase separated by LC and then passed to the mass spectrometer for detection.	Polymer types Total mass	>5 mg	Destructive Less sample preparation	Only a small amount of sample can be analyzed at a time
8	SEM-EDX	Electron microscopy imaging combined with EDS offers the elemental composition	Number Shape Size Polymer Type	2 nm at 2Kv	High resolution	Time-consuming; can't show colours
9.	LDIR	Rapid imaging and full-spectrum analysis via quantum cascade laser (QCL).	Number, Shape, Size, Polymer Type	>20 μM	Non-destructive, High automation, Fully integrated workflow, Fast, No liquid nitrogen needed, Ability to analyze large areas, Comprehensive data on multiple particles simultaneously	Expensive, but significantly more efficient for large-scale environmental studies

imaging. This significantly reduces analysis time and enhances efficiency, especially for samples with fewer particles, making LDIR particularly valuable for large-scale environmental monitoring.

One minor limitation of LDIR is that its imaging process may merge adjacent particles into a single detection, unlike μ-FTIR, which can distinguish closely located particles by analyzing their entire surface area. However, LDIR's rapid throughput, minimized redundancy, and ability to efficiently process large sample areas compensate for this limitation. Although its infrared band range is narrower (1800–900 cm^{-1}), this is offset by its superior speed and automation capabilities [49].

3.1. Instrumentation

LDIR technology leverages advancements in infrared (IR) imaging, particularly using QCLs, which provide a highly collimated, bright, and narrow-linewidth light source without the need for a spectrometer. This represents a significant shift from traditional Fourier Transform Infrared (FTIR) microscopy. QCL-based systems, such as LDIR enable high-resolution imaging and microplastic analysis without the need for liquid nitrogen-cooled detectors, simplifying the process and reducing operational costs [50] (Fig. 2). Schematical representation of QCL based LDIR instrumentation [51]. Traditional FTIR systems, rely on large detectors and lengthy analysis times for pixel-by-pixel spectra collection, often produce redundant data and require hours of processing. In contrast, LDIR utilizes rapidly scanning optics paired with a QCL and a thermoelectrically cooled mercury cadmium telluride (MCT) detector. This combination acquires spectra only at relevant points, reducing both data processing time and file size, while maintaining high sensitivity and accuracy in identifying microplastics [52]. Comparison of various methods for detection of microplastic is shown in Table .1.

Advances in infrared microscopy, such as folding reflective optics and new detector technologies, have further enhanced LDIR capabilities, enabling large-scale environmental studies with unparalleled precision [53].

LDIR technology overcomes many of the limitations associated with FTIR and other traditional methods. FTIR systems typically collect a complete spectrum for every pixel in the scanned area, leading to extensive data collection and lengthy processing times. For example, analyzing a 10 mm in diameter sample can take over 3 h and generate data files larger than 30 GB, with processing times of up to 10 h. Much of this data is redundant, as spectra are collected even in areas without microplastics [54].

In contrast, LDIR operates using a two-mode system scan mode and sweep mode. In scan mode, a single wavelength rapidly scans the sample to detect particles and gather information on their size and shape. During the sweep mode, the system pauses over detected particles to collect a full spectrum for each, allowing for precise identification and characterization without wasting time on irrelevant areas.

This targeted approach drastically reduces analysis time, cutting it from 10 h to less than one. Moreover, LDIR workflows are highly automated, making them ideal for large-scale environmental studies

where high throughput is essential [55–58]. With its high level of spectral detail, LDIR is the most efficient and effective tool for rapid microplastic detection and analysis [59].

The integration of automated workflows, rapid detection, and detailed imaging makes LDIR the superior method for microplastic analysis. It offers unmatched speed, precision, and efficiency, particularly when compared to labor-intensive techniques like μ-FTIR and Raman spectroscopy, making it the preferred choice for researchers studying the environmental impact of microplastics in different environmental ecosystems.

3.2. Light source (QCL)

Recent advancements in the band-structure engineering of semiconductor lasers have greatly improved infrared (IR) microscopy, particularly with the development of Quantum Cascade Lasers (QCLs). These lasers consist of repeated stacks of multiple quantum well heterostructures, typically made from III-V semiconductor materials such as GaAs–AlGaAs and InGaAs–InAlAs–InP. The quantum wells enable precise control over the lasing wavelengths, ranging from 2.75 μm to as long as 161 μm, by adjusting the well depths during fabrication. The mid-IR region (3.5–12.8 μm) is especially targeted due to its relevance in biochemical fingerprinting and molecular analysis [60–63]. A key feature of QCL technology is its single-mode emission, which offers high spectral resolution and flexibility for imaging applications. LDIR systems utilize four multiplexed QCL modules to cover the entire biochemical fingerprint region (800–1900 cm^{-1}), providing more detailed and customizable analysis compared to conventional thermal emitters like globars [63–67]. Additionally, QCL's polarized and high-intensity illumination is ideal for advanced techniques such as spectroscopic polarimetry and vibrational circular dichroism measurements, improving signal-to-noise ratios and spatial resolution [67–73]. This represents a significant advancement in microplastic detection and characterization.

3.3. Detector (MCT)

Mercury–Cadmium-Telluride (MCT) detectors are crucial components of LDIR systems due to their exceptional performance and sensitivity in the mid-IR range. These thermoelectrically cooled detectors can cover wavelengths up to 18 μm, with band gap energies as low as 0.07 eV, making them ideal for the precise detection of microplastic particles [63]. Single-element MCT detectors, commonly used in LDIR, offer excellent spectral characteristics with high detectivity ($D^* \geq 2 \times 10^9$), enabling fast readout rates and cost-effective operation. The integration of high-refractive-index microlenses further enhances detector performance by increasing the effective optical area [74]. This advancement allows LDIR to surpass traditional methods, providing faster data acquisition, improved sensitivity, and greater spatial accuracy for high throughput microplastic analysis in environmental samples.

3.4. Optics

The optics in LDIR systems are crucial for relaying light from the QCL source to the sample and then to the detector. To achieve optimal performance, LDIR requires specially designed refractive optics capable of diffraction-limited imaging. While QCLs can be adapted to existing IR microscopes, significant redesigns of the refractive optics are necessary to prevent degradation in image quality [75–79]. Early LDIR designs used reflective relay optics and standard Schwarzschild objectives, which, although functional, reduced image quality due to central obscuration. Modern systems have shifted to more advanced refractive optics, which enhance image clarity and resolution, enabling better spatial localization and accurate identification of microplastic particles [80,81]. In contrast, traditional IR techniques often face limitations in imaging resolution and require more time for analysis.

LDIR spectroscopy has demonstrated exceptional reliability in inter-

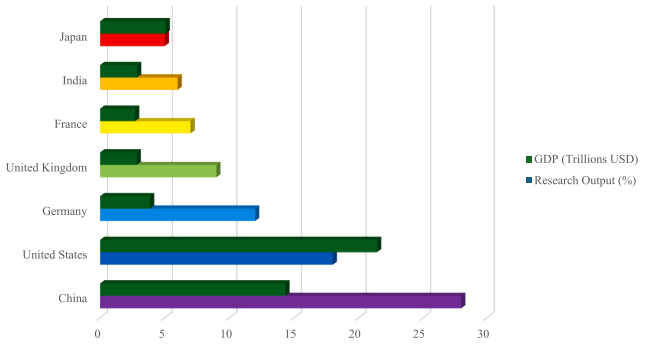

Fig. 3. "Microplastic Research Output vs. GDP by Country (2024)" highlights the relationship between the scientific contributions to microplastic research and the economic capacity of various nations. The chart illustrates that China leads with 28 % of the global research output on microplastic pollution, followed by the United States at 18 %, and Germany at 12 %. Notably, China's rapid growth in this field is driven by its increasing focus on environmental research, as evidenced by its significant share of publications. The figure also shows the economic context through GDP values, revealing that while nations like the United States and Japan have higher GDPs, countries such as Germany and France demonstrate substantial contributions relative to their economic size. This suggests that economic strength is a contributing but not definitive factor in research output, as nations with smaller economies still play a critical role in advancing global environmental science.

laboratory studies and validations using certified reference materials. Whiting et al. (2022) conducted inter-laboratory ring tests, highligthing LDIR's precision and reproducibility in identifying a wide range of polymers across laboratories. The study utilized certified reference materials, such as polystyrene and polyethylene standards to ensure that the results adhered to accepted benchmarks in microplastic analysis. Moreover, Ghanadi et al. (2024) highlighted the application of LDIR in environmental matrices, demonstrating its high accuracy and automation in analyzing microplastics in sediments and water samples. These studies underscore LDIR's robust performance in collaborative research settings and its capability for high-throughput, consistent quantification of microplastics.

4. Recent reports on microplastic analysis in environmental samples using LDIR

The Laser Direct Infrared (LDIR) technique (Agilent 8700, USA) has proven to be a highly effective method for identifying polymer types, shapes, and sizes of microplastics in various environmental samples. LDIR enables non-destructive analysis, preserving the chemical and physical integrity of the samples. Unlike traditional techniques, LDIR requires no chemical pre-treatment, enabling rapid detection and analysis without altering the properties of microplastic particles. Due to its high sensitivity, LDIR can detect even trace amounts of microplastics by analysing infrared spectra [82]. Additionally, this technique uses an automated process to collect the mid-infrared spectrum of each particle and compare it to a plastic library, covering particle sizes ranging from 20 to 500 μm [83,84]. Fig. 3. Microplastic Research Output vs. GDP by Country (2024).

The effectiveness of LDIR in microplastic research has been demonstrated in multiple studies. For example, Whiting, Q.T. et al. (2022) [55] evaluated the performance of LDIR for the analysis of microplastics in various environmental matrices. The researchers developed an optimized protocol using an 8 μm porosity polycarbonate filter (If the study used SEM, it may involve gold or aluminium coating to enhance imaging quality), which enabled efficient pre-concentration and quantification of microplastics. This method identified 11 polymer types across different sample types, including water, sediment, and biota, with recovery rates

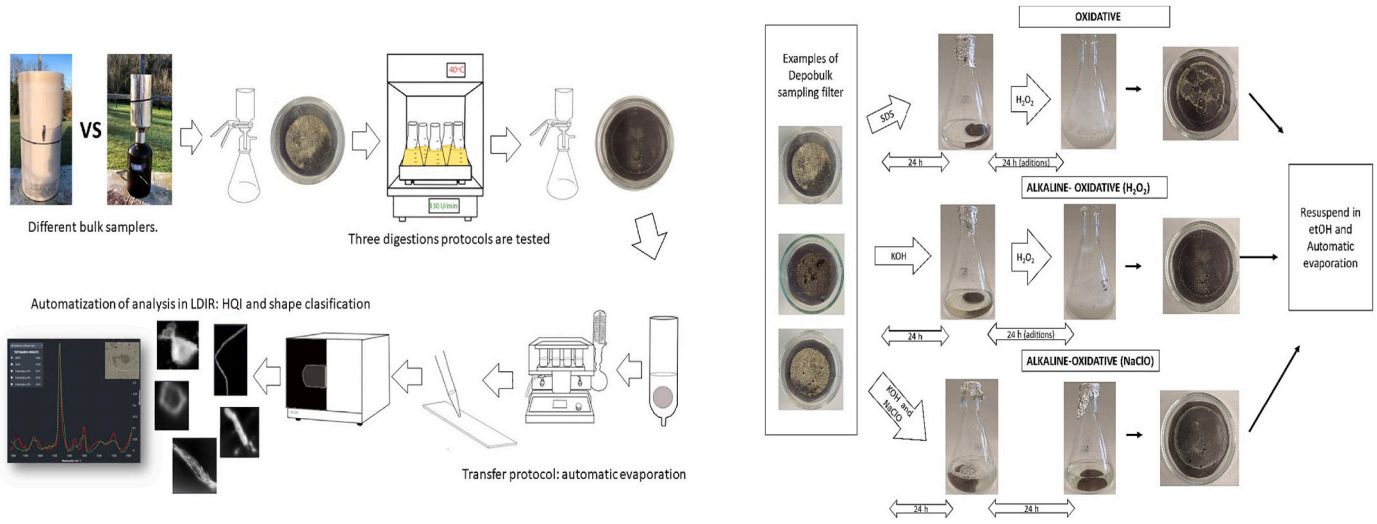

Fig. 4. Advanced LDIR-Based Microplastic sample preparation, detection and shape classification [91].

of 80–100 % for particle sizes between 200 and 500 μm. Additionally, the analysis time was significantly reduced to about 3 h per sample, a substantial improvement over traditional methods [85–87].

In another study, López-Rosales et al. (2022) employed LDIR to analyze microplastics in fish gastrointestinal tracts. The study compared several digestion protocols, finding that an enzymatic-oxidative digestion method combined with an automatic evaporation system and LDIR was a reliable and relatively fast approach for microplastic analysis. This method achieved nearly 100 % recovery for large particles (>500 μm) and about 75 % recovery for smaller fibers (10 μm thick), demonstrating LDIR's capability to handle various microplastic sizes with high precision [88].

LDIR has also been used to assess microplastic concentrations in environmental samples. Researchers found microplastic concentrations ranged from 8 to 132 particles/m^3, with 96 % of particles having a diameter greater than 100 μm [6]. This study demonstrated the high efficiency of LDIR for identifying and quantifying microplastics in environmental samples, including a wide range of polymer types such as polyurethane (PU), polyethylene terephthalate (PET), and polypropylene (PP) [89].

Hildebrandt et al. (2022) expanded LDIR's applications by coupling microwave-assisted enzymatic-oxidative matrix digestion with LDIR imaging to analyze microplastics in various environmental samples, identifying 20 different polymer types. The most common were PET (20 %) and PU (15 %), with 93 % of microplastics being smaller than 100 μm. This method revealed the presence of microplastics in diverse environments, with significant spatial and temporal variability, highlighting LDIR's adaptability and efficiency in large-scale environmental monitoring [90]. Overall, these studies emphasize LDIR's superiority as an analytical technique for the rapid, accurate, and non-destructive identification and quantification of microplastics in diverse environmental samples. The sample preparation process, especially digestion protocols, is a critical factor in microplastic detection using LDIR spectroscopy. The accuracy of LDIR depends on the effective isolation of microplastics from complex matrices, such as fish tissue, without altering their properties. Errors in digestion can lead to false negatives or incorrect quantification. Given LDIR's superior precision in microplastic identification, preserving the integrity of the sample is paramount for achieving reliable results. This paper highlights the importance of optimized sample preparation to fully harness the advanced capabilities of LDIR in detection of microplastics from environmental samples. (Fig. 4 Advanced LDIR-Based Microplastic sample preparation, detection and shape classification).

Zhao et al. (2021) used LDIR to evaluate the ecological risks associated with microplastics (MPs) in sediment samples from the Yellow River and Yellow Sea. Their results showed that microplastics were 2.9 times more prevalent in the Yellow Sea compared to the Yellow River, with concentrations averaging 54,813.2 ± 19,355.9 particles per kilogram of dry sediment in the Yellow Sea and 18,780.2 ± 9951.8 particles per kilogram in the Yellow River. The dominant polymers found in sediments from both regions were silicone, fluoro rubber, and polypropylene (PP). More than 90 % of the microplastics were 100 μm or smaller, underscoring the significant presence of micro-sized particles. The risk assessment identified high ecological threats from microplastics in both environments, emphasizing the urgent need for ongoing environmental monitoring and mitigation strategies [92].

Li et al. (2022) investigated how crushed and washed sea salt (CWSS) processing affected microplastic residues in sea salt. The study found an average of 256 ± 26 microplastic particles per 10 g of crude sea salt, which originated from seawater crystallization. The CWSS process significantly reduced microplastic content, with removal rates ranging from 56.25 % to 97.66 %. However, both crude and commercial salts still contained microplastic contaminants, with polyamide (PA) and polyurethane (PU) being the most common types. Polypropylene (PP) contamination was primarily introduced during the CWSS process, particularly in the packaging stage, suggesting that further improvements to the process could reduce plastic contamination even more [93].

Nowak et al. (2020) studied the abundance and characteristics of microplastics in sediments from the Rzeszow Dam Reservoir. Microplastics with irregular, jagged, or thread-like shapes were predominant. Particles larger than 50 μm accounted for 91 % of the total microplastics, with 27 % ranging between 3 and 6 μm. Fibers and irregular fragments were the most common forms, with polyurethane (PU) and polyamide (PA) identified as the dominant polymers. Microplastic accumulation was notably higher near the reservoir inflow, where the average surface area of microplastics was greater than in other sections. These findings raise concerns about the ecological health of the reservoir and highlight broader environmental implications for microplastic pollution in freshwater systems [94].

Xiang et al. (2022) [48] utilized LDIR to analyze microplastics and phthalate esters (PAEs) in soil samples from agricultural regions in China. Microplastic levels ranged from 380 to 3786 pieces/kg, while PAE concentrations varied between 0.30 and 1.58 mg/kg. Greenhouse soils exhibited significantly higher microplastic levels than non-greenhouse soils, though PAE concentrations varied by region. Studies show that microplastic concentrations were primarily influenced by external input sources, whereas PAEs were affected by both input and removal processes [95–98].

Table 2
Application of LDIR technique to assess the level of microplastics in environmental samples from the literature reports.

S. No	Techniques	Sample	Type of Micro Plastics	Average Particles	Major Micro Plastics Found	Size	Reference
1	LDIR	Marine	11	–	PP, PE, PS, PVC, PET	200–500 μm	[102]
2	LDIR	Fish gastrointestinal	NA	–	PS, PP, PVC, PET, PE and PA	≤10 μm	[103]
3	LDIR	Tropical Indian Ocean	10	–	PU, PA, PET, PP, PE, EVA	20–50 μm	[32]
4	LDIR	Altantic Ocean	20	500 ± 700 particles/m^3 water	PET (20 %), and PU (15 %)	93 % < 100 μm	[29]
5	LDIR	Yellow river and yellow sea	26	54813.2 ± 19355.9 18780.2 ± 9951.8 Particles/1 kg	Silicone, fluor rubber, and PP	<100 μm (90 %)	[76]
6	LDIR	Sea salt	13	256 ± 26 Particles/10 gm	PA, PU, PP	0 and 140 μm	[56]
7	LDIR	Rzeszów Reservoir	9	–	PU & PA	20–470 μm	[74]
8	LDIR	Guiana dolphins	8	7.77 ± 1.25	PU, PET and EVA	0.08–4.24 mm	[67]
9	LDIR	Coastal Environment	9	1200 to 3400 particles/kg	PET, PA, PE, PU, PC	<100 μm (90 %)	[26]

Table 3
Literature reports used LDIR to characterize microplastics in terrestrial water samples

S. No	Techniques	Sample	Type of Micro Plastics	Average Particles	Major Micro Plastics Found	Size	References
1	LDIR	Agriculture soil	12	380–3786 Particles/Kg	PE, PP, PA, PET	20–100 μm	[47]
2	LDIR	Lake Sediment	9	520 Particles/gm	PA, PE, PTFE, POM	<100 μm (84 %)	[16]
3	LDIR	Surface waters	21	10000 Particles/Lit	PVC, PVA, GP, AV, PE, PET	20–250 μm	[55]
4	LDIR	Agricultural soils	26	3.20 ± 0.41 × 10^5 particles/kg	PE, PP, PVC, PA, PTFE	10–500 μm	[34]
5	LDIR	Urban river network area	22	104.6 ± 5.6 particles/L	Silicone, Rubber, PTFE, PPE	<330 μm	[53]
6	LDIR	Groundwater aquifer	21	16 to 97 particles/L	PE, PVC (59)	18–491 μm	[48]
7	LDIR	Groundwater	16	2103 particles/L	PET, PU	20–471 μm	[75]
8	LDIR	Pearl River	30	290 particles/L	PU, PET	10–500 μm	[104]
9	LDIR	Yangtze River Delta Region	20	1974 particle/kg	Rubber, PER	20–50 μm	[64]

Ghanadi et al. (2024) [26] focused on sediment samples, revealing microplastic concentrations of approximately 520 and 430 particles/g. Most microplastics were smaller than 100 μm, and a power-law distribution suggested that smaller microplastics likely resulted from the breakdown of larger plastics. The major polymers identified included PA, PE, PTFE, and PAC, with microplastics categorized into fragments, beads, and fibres [99].

Fan et al. (2022) [6] implemented LDIR to study microplastics in urban freshwater environments. Results showed that only 8–14 % of detected particles were confirmed as microplastics, with a recovery rate of 88.3 % ± 1.2 %. The system detected MPs as small as 20 μm with precision comparable to FTIR and Raman spectroscopy [100].

In farmland soils, a combined LDIR and FTIR method detected microplastic concentrations as high as 3.20 × 10^5 particles/kg, particularly in soils subjected to film mulching for over 30 years. The majority of microplastics (96.5–99.9 %) fell within the 10–500 μm range, with 26 polymer types identified, including PE, PP, PVC, PA, and PTFE [80].

Effluent from wastewater treatment plants (WWTP) was analyzed, revealing microplastic concentrations between 2.3-1.2 and 10.46–5.6 particles/L, with seasonal variation. Larger microplastics (>330 μm) were more abundant, with silicone, rubber, PTFE, and PU being the dominant polymers. Commercial areas contributed significantly to microplastic load in WWTP effluent [101]. (Table 2. Environmental samples literature reports) (see Table 3).

Samandra et al. (2022) [49] examined microplastic contamination in groundwater, detecting microplastics in all seven boreholes analyzed. PE, PP, PS, and PVC were prevalent, with an average microplastic size of 89 ± 55 μm. Microplastic concentrations reached 38 ± 8 particles/L, with PE and PVC being the most common polymers across all sites [105].

Mu et al. (2022) [97] conducted LDIR analysis of groundwater samples from Jiaodong Peninsula, revealing an average microplastic abundance of 2103 particles/L. PET and PU polymers dominated the samples, with over 90 % of microplastics measuring smaller than 100 μm, suggesting common sources or degradation processes for these contaminants [106].

Wu et al. (2023) [102] used LDIR to analyze microplastics in the sediments and surface waters of the Pearl River, China. The study identified 30 different polymers across 38 samples, with an average concentration of 1974 particles/kg in sediment and 290 particles/L in surface water. Higher concentrations of polyurethane (PU) and polyethylene terephthalate (PET) were found near areas with heavy ship activity, indicating pollution from antifouling coatings [107].

Van Cauwenberghe et al. (2015) [103] studied the transport of microplastics in the atmosphere of a coastal city was analyzed, distinguishing between terrestrial and marine air masses. LDIR detected 20 different types of microplastics, with rubber (16.7 %) and PFR (14.8 %) being the dominant components. Terrestrial air masses contained 32.0 items/m^3, compared to 14.7 items/m^3 in marine air masses. Terrestrial sources mainly contributed rubber microplastics, while marine sources were rich in PFR microplastics [108]. These studies highlight the superior detection capabilities of LDIR for microplastic analysis, providing rapid and reliable identification across various environmental matrices. Its high sensitivity, ability to detect a wide range of polymer types, and non-destructive nature make it an invaluable tool for assessing microplastic contamination in terrestrial and aquatic environments.

4.1. Microplastics in human samples

Zhu et al. (2023) [104] investigated the presence of microplastics in human placentas, finding that all 17 samples contained microplastics, with an average of 2.70 ± 2.65 particles/g, ranging from 0.28 to 9.55 particles/g. The study identified 11 distinct polymer types, with polyvinyl chloride (PVC) (43.27 %), polypropylene (PP) (14.55 %), and polybutylene succinate (PBS) (10.90 %) being the most common. Microplastic sizes ranged from 20.34 to 307.29 μm, with the majority (80.29 %) being smaller than 100 μm. Most of the PVC and PP particles were under 200 μm, raising concerns about the presence of small plastic particles in human tissues [109].

Sun et al. (2024) [55] examined microplastic exposure in the human endometrium using LDIR. The analysis identified 13 types of microplastics, with six types showing high abundance and detection rates. Microplastic levels ranged from 0 to 117 particles/100 mg, with a median of 21 particles/100 mg. A significant proportion (88.35 %) of the detected microplastics were smaller than 100 μm, with ethylene-acrylic

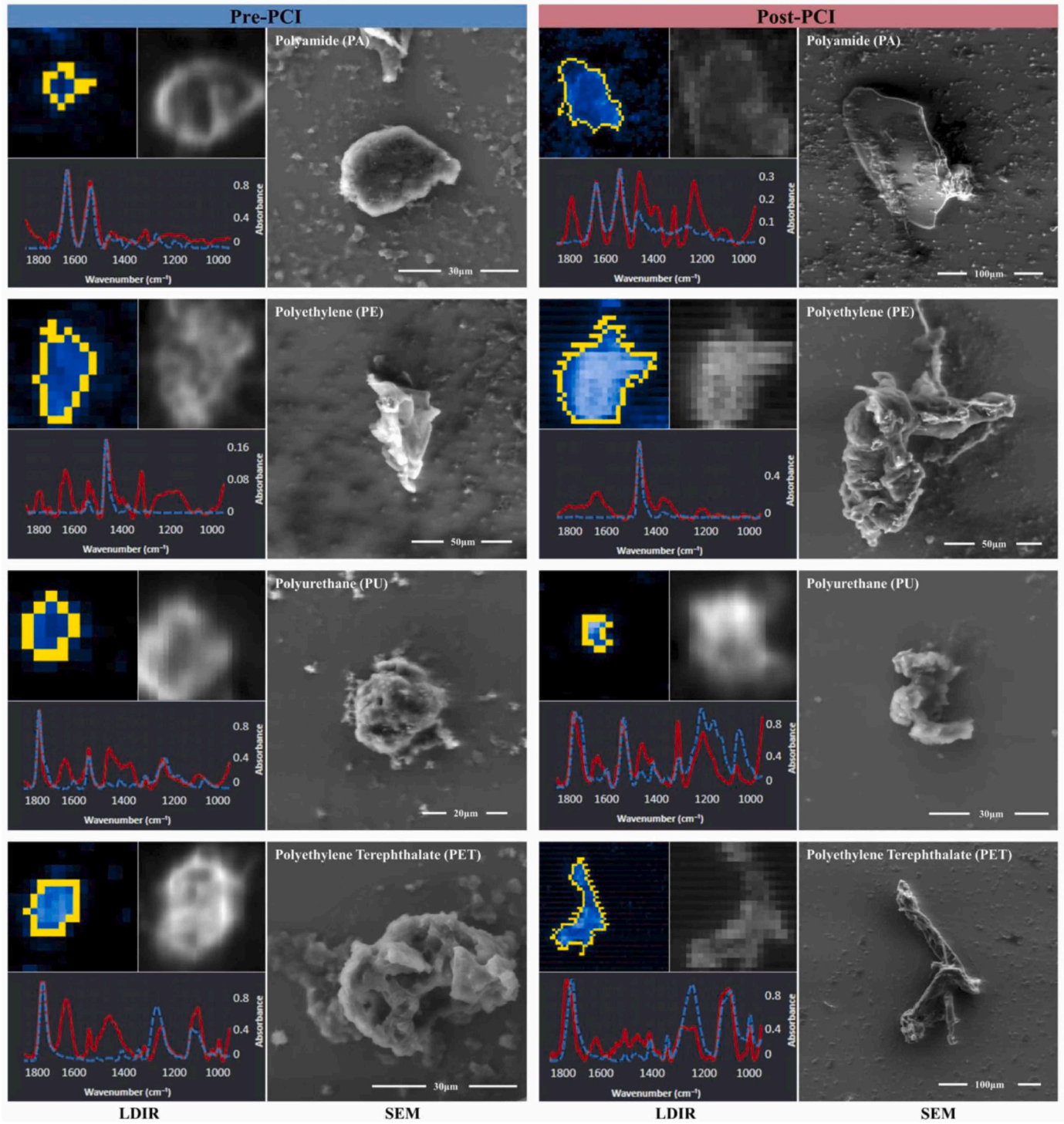

Fig. 5. Enhanced microplastic detection in blood samples using LDIR and SEM imaging [112].

acid copolymer being the most prevalent among smaller microplastics, while polyether amide (PEA) dominated the larger microplastics (100–500 µm) [110].

LDIR was also employed to investigate the inhalation of microplastics by humans, focusing on particles ranging between 20 and 500 µm [77]. The study identified 21 types of microplastics, with polyurethane (78.36 %) being the most abundant, followed by polyethylene, chlorinated polyethylene, and alkyd varnish. Most of the detected microplastics were smaller than 500 µm, suggesting that humans are involuntarily inhaling microplastics, raising concerns about potential health risks associated with long-term exposure to airborne microplastics [111] (Fig. 5 Enhanced Microplastic Detection in Blood Samples Using LDIR and SEM Imaging). [112].

Recent research by Codrington et al. (2024) [113] demonstrated the application of LDIR imaging for detecting microplastics in human penile tissue. The study identified seven distinct microplastic types, predominantly polyethylene terephthalate and polypropylene, within tissue samples. These findings highlight LDIR's precision in biomedical research and its potential to elucidate the health impacts of microplastic exposure on male reproductive health.

Table 4
LDIR based research studies in different organs of human

S. No	Techniques	Sample	Type of Micro Plastics	Average Particles	Major Micro Plastics Found	Size	References
1	LDIR	Human placenta	17	2.70 ± 2.65 Particles/g	PVC (43.27 %), PP (14.55 %), PBS (10.90 %)	20.34–307.29 μm	[114]
2	LDIR	Human endometrium	13	0 to 117 particles/100 mg	PU, PE, PVC, PET	100–500 μm	[54]
3	LDIR	Human sputum	21	39.5 particles/10 ml	PU, PE, CPE,	45–210 μm	[33]

This highlights the critical role of LDIR in detecting and characterizing microplastics in human tissues. Its ability to identify a wide range of polymer types with high sensitivity and precision positions LDIR as a superior technique for assessing human exposure to microplastics, especially in studies related to human health (Table 4: Human samples literature reports).

LDIR was employed to identify the sources of microplastics released from disposable face masks (DFMs) [37]. The study revealed that 24.5 % of microplastics originated from polypropylene (PP), while 57.1 % came from polyurethane (PU). The airborne fraction, comprising polyethylene terephthalate (PET), polyamide (PA), polyethylene (PE), and polystyrene (PS), accounted for 18.4 % of the total microplastics. Disposable medical masks were shown to release an average of 1043 ± 155 microplastics/mask into clean water, with medium fibres (100–500 μm) and fine particles (≤100 μm) being the dominant forms [46,115–118].

Liu et al. (2022) [8] conducted an LDIR-based study, detecting 2803 microplastic particles/g of dry sludge in septic tanks, with 36 different types of microplastics found in the tanks and 26 types present in both sediments and scum. Interestingly, the variety of microplastics in scum was 21 % higher than in the sediments. The most common polymers identified were PET, PE, PS, PVA, and PA, which made up 86.3 % of the microplastics in sediments and 91.2 % in scum. Four types of microplastics fibres, beads, granules, and fragments were detected in the tanks [119].

Dust samples from houses in Japan's Kanto region were analyzed using both FTIR and LDIR techniques, confirming the presence of microplastics in indoor environments. FTIR analysis revealed that cellulose, polyester, and PET were present in 60–90 % of the samples, while LDIR analysis detected PU, cellulose, PVAL, and PET in 40–90 % of samples. The combination of these methods allowed for efficient and complementary analysis across different particle sizes [104].

LDIR was also used to assess microplastic particles in domestic and fetal pig lungs in their natural environment. Domestic pig lungs were found to contain 180 particles/g, ranging in size from 20.34 μm to 916.36 μm, which was twice the amount found in fetal pig lungs. Polyamide (PA) was the most prevalent polymer in domestic pig lungs (46.11 %), whereas polycarbonate (PC) was the dominant polymer in fetal pig lungs (32.9 %) [102].

López-Rosales et al. (2024) [120] used LDIR to evaluate microplastics in atmospheric bulk deposition collected from a suburban area in NW Spain. The study identified PE, PP, and PET as the most common polymers, with deposition rates ranging from 98 to 1220 microplastics/m^2/day. The majority of microplastics were in the 20–50 μm range, while fibres were primarily in the 50–500 μm range [103].

These studies highlight the versatility of LDIR in identifying and characterizing microplastics across diverse domestic environments. Its high sensitivity and rapid analysis make it superior to traditional methods, particularly in detecting a wide range of polymer types and microplastic sizes in everyday settings [120,114].

5. Conclusion and Future Prospective

In the past decade, notable advancements have been achieved in the detection and quantification of microplastics in environmental samples, driven by the development of various analytical techniques. Each method has its own strengths and limitations, making the choice of technique dependent on the specific research objectives. For instance, large-scale environmental monitoring requires different methodologies than those needed for investigating emission pathways or analyzing polymer composition in organisms.

One of the most transformative emerging techniques is LDIR chemical imaging. By utilizing a focused QCL, LDIR achieves rapid spectral acquisition, reducing measurement time to as little as 1 s per spectrum. This speed allows for the identification of numerous particles over large areas, providing substantial improvements compared to traditional techniques like Raman and FTIR spectroscopy. Additionally, the integrated visible camera in LDIR systems enhances the detection of particles as small as 10 μm, positioning LDIR as a key tool in advancing microplastic research.

Despite its superior capabilities, LDIR has some limitations, particularly its restricted spectral range (975–1800 cm^{-1}), which may limit the identification of certain polymer types. Nevertheless, its fast, non-destructive, and highly sensitive nature renders it an ideal technique for analyzing microplastics across a variety of environments, including marine ecosystems (seawater, fish gastrointestinal tracts, and sea salt), terrestrial environments (freshwater, soil, and even human biological tissues) as well as atmospheric systems.

The increasing adoption of LDIR in environmental research points to a promising future for its applications. Expanding its spectral range could unlock broader applications in detecting and analyzing microplastics in more complex matrices. Furthermore, automation in LDIR systems offers exciting potential for high-throughput screening, enabling large-scale monitoring of microplastics across diverse ecosystems. Ongoing advancements in quantum cascade laser technology and detector sensitivity are expected to boost LDIR's analytical capabilities, establishing its role as an essential tool in global efforts to understand, quantify, and address the growing issue of microplastic pollution.

CRediT authorship contribution statement

Prince Jebedass Isaac Chandran: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Veerasingam:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of Abbreviations

PP – Polypropylene
PE – Polyethylene
PS – Polystyrene
PU - Polyurethane
PVC - Polyvinyl Chloride
PET - Polyethylene Terephthalate
PSB - Polybutylene Succinate
PTFE – Polytetrafluoroethylene
POM – Polyoxymethylene
EVA - Ethylene-Vinyl Acetate
PVA – Poly Vinyl Alcohol

Data availability

Data will be made available on request.

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