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*Review Article*

# Optical Sensing Techniques for Microplastic Identification: Comparative Evaluation, Limitations, and Future Recommendations

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## ABSTRACT

Microplastics (MP) have actively polluted various water sources, including oceans, rivers and lakes. MPs are tiny plastic particles, typically less than 5 millimetres in size. They originate from degraded larger plastics or microbeads in products. It can enter human bodies through ingestion or inhalation. Their small size allows them to penetrate tissues and organs, potentially causing inflammation. In the environment, MP accumulates in soil, water, and air. They can disrupt ecosystems by entering the food chain, affecting aquatic life. The objective of this paper is to provide a comprehensive review of established MP identification methods and to recommend new technologies for future environmental monitoring. The methodology employed a comprehensive literature review and comparative analysis of current MP detection techniques. The non-optical analytical tools, such as Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), Nuclear Magnetic Resonance (NMR), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), and Scanning Electron Microscopy (SEM), alongside prominent optical methods, include standard Fourier Transform Infrared (FTIR), Attenuated Total Reflection Fourier-Transform Infrared Spectroscopy (ATR-FTIR), Raman spectroscopy, Nile Red fluorescence, and UV-Visible (UV-Vis) spectroscopy. The results obtained conclude that no single method is

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perfect, but Micro-Fourier Transform Infrared (μ-FTIR) spectroscopy is highly recommended as the primary optical sensing approach for standardised monitoring due to its optimal balance of speed, reliability, and accessibility. The study also highlights that the integration of Artificial Intelligence (AI) and Machine Learning (ML) is the future of optical MP detection, capable of automating complex spectral matching and noise reduction. Potential applications of the research proposed multi-modal framework can be directly applied to large-scale, cost-effective environmental monitoring, enabling broader geographical coverage and aiding policymaking, particularly in developing nations.

*Keywords:* Analytical method, artificial intelligence, environmental pollution, microplastics, optical sensing techniques, polymer identification

## INTRODUCTION

Plastic is highly valued by both manufacturers and customers due to its versatility, lightweight nature, durability, and affordability. As a result, plastic production has greatly increased (Jung et al., 2023). At present, packaging makes up around 40% of all plastic produced, and most packaging is made to be used just once before being thrown away. Tragically, this increase in plastic use has resulted in a huge rise in the number of plastic products that are accidentally or purposefully lost and end up in the environment. It is estimated that nearly 60% of all produced polymers have gathered in junkyards or the environment (Geyer et al., 2017; Zhao et al., 2023). As plastic can be made in various sizes and shapes, the tiniest sizes (less than 5 mm) of manufactured plastic products are referred to as "microplastics".

MPs are classified into two types, primary MP and secondary MP (Pham et al., 2023). The differences between these classes need to be thoroughly examined to properly tackle the problem of MP pollution (Bermúdez & Swarzenski, 2021). Primary MP are produced in small sizes to serve a functional purpose. They include microbeads that are being added to cosmetic and personal care formulations, plastic pellets that are used in manufacturing processes in various industries, and MP that are added to cleaning products in households (Singh & Mishra, 2023). On the contrary, secondary MPs are created when larger plastic particles break down and disintegrate (Contreras-Llin & Díaz-Cruz, 2024). Plastic bottles, bags and containers that are exposed to environmental stressors such as UV radiation, temperature variations, and physical abrasion eventually diminishes them into smaller fragments over time.

One of the most concerning environmental problems in Malaysia is the high level of MP contamination in the country's aquatic environment, affecting the freshwater and marine ecosystems of the country and has the potential to affect human beings (Landrigan, 2020). The issue has its roots in the intensive use of plastics in different industries and in everyday life, thus contributing to the discharge of MP into rivers, lakes, and coastal zones.

These tiny, barely noticeable plastic pieces may linger in the environment for a long time, endangering aquatic life and making it simple for them to make it into the food chain (Zambrano-Pinto et al., 2024). Environmental exposure causes significant surface degradation and cracking on plastic polymers. Ageing alters spectral signatures, which can complicate accurate optical detection. These structural changes also increase the potential for toxic chemical absorption. Degradation creates microscopic cracks and pores on the plastic surface. Degradation also alters the physicochemical properties of the MP. This expanded surface area allows more pollutants to attach to particles (Ge et al., 2023).

There is empirical data of MP contamination that can be recorded along with the populations of brachyuran crabs that live within the Setiu Wetlands, Malaysia. Environmental effects like UV radiation and tidal forces break macroplastics into fragments. Biological activities and wave action further degrade these plastics into micro-sized particles. Land-derived materials frequently move between locations through daily tides and water currents (Jansen et al., 2024). These natural processes facilitate the heavy accumulation of MP within mangrove areas. A species of crab that is prevalent in the area is exposed to MP via the environment it lives in, as the wetlands are increasingly polluted with plastic trash (Abd Rahim et al., 2023). Brachyuran crabs are filter feeders; therefore, consuming tiny particles, such as MP, as food sources. These ingestions may lead to several harmful outcomes on their health and survival, such as poor feeding efficiency, poor nutrient uptake, and physical damage to their digestive tracts. It is recommended that future research pairs optical detection with controlled laboratory feeding trials to distinguish between incidental ingestion and selective feeding behaviours in Brachyuran crabs. In addition, the build-up of MP in the bodies of crabs may pose a potential threat to further trophic levels, hence influencing the overall ecological integrity of the Setiu Wetlands. The Department of Environment monitors river data to evaluate regional pollution controls. The outcome of the estuary of the Terengganu River is utilised to give guidance on municipal limits on the industrial discharge. Such results affect the ideas of Integrated River Basin Management (IRBM) plans that state governments implement. Certain River Basin Management plans are also required by the European Union Water Framework Directive (WFD). Both models provide systematic avenues where the local communities can mitigate plastic pollution. Localised coordinated control ensures that all the nearby ecosystems have cleaner water. The compliance with such international standards improves the accuracy of environmental protection operations (Lim et al., 2023).

The identification of MP is often based on the various methods of analysis, covered by microscopy, stereoscopy, and Liquid Chromatography-Mass Spectrometry (LCMS). Microscopy, e.g. electron microscopy, allows observation and localisation of MP according to size, shape and colour. The use of stereoscopic microscopy increases the depth perception, which enhances the precise detection and measurement of MPs in the specimens of the environment (Feld et al., 2021; Lee et al., 2023).

LCMS is an effective analytical method that can distinguish and quantify the various forms of MP according to their chemical composition. These techniques are inevitable in the determination of the degree of MP pollution, as well as the development of effective mitigation measures, which will consequently lower the environmental pollution and protect the health of people against possible damage.

Various optical sensing methods are also used in MP analysis, such as UV-Visible (UV-Vis) spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, and Nile Red staining. UV-Vis spectroscopy quantifies the absorbance of light by the sample molecules, and thus it is possible to determine the concentration of MP based on their specific absorption properties (Jiao et al., 2022). FTIR spectroscopy determines the chemical composition of MP through the analysis of molecular vibrations of the sample, therefore, providing information about the type of plastic which is present. Like the FTIR, Raman spectroscopy complements chemical composition information, but it functions using different principles, thus increasing the strength of the analysis. Nile red staining is a fluorescence technique that specifically stains MP, making them easily observed under a fluorescent microscope. Figure 1 illustrates the annual publication expenses of research on MP between 2020 and 2024.

The most dominant source in all the years is journal articles. In the year 2020, there were around 1,200 reports of journal publications. This number steadily grew to a high of 2,500 in the year 2023. There is a minor decrease in 2024, and approximately 900 journal publications. There was also an increase in generic publications, which, however, showed a significant growth in 2023. Sections of books and conference proceedings corresponded to similar tendencies, only in much smaller amounts. There were stable outputs in each category, indicating the same level of scholarly interest. The least contribution was given by the book category every year. The highest in 2023 could be the result of the increased global anxiety or additional investments. The decline in 2024 shows the effect of COVID-19 towards academic research. The lockdown in 2020 and 2021 halted the research and publications in 2024 because most organisations and schools closed to encourage everyone to stay home. Only essential emergency services like medical and food supplies remained operational (Rume & Islam, 2020). In addition, complex identification methods also create significant labour bottlenecks for modern researchers. Labour-intensive sampling procedures naturally limit the total volume of published studies. Strict analytical requirements have increased the time needed to complete research (Debraj & Mulky, 2025). Although the increase in publications in this field is declining in 2024, it has considerable scientific and practical relevance. In addition, the current research aims to fill the research gap that has occurred recently and spur further research in the field. This tendency is a sign of good academic activity and peer-reviewed work. These include generic works, probably policy documents or institutional reports. The statistics show growing awareness of MP pollution in the world. The further increase in the number confirms the necessity of environmental urgency of the problem.

Figure 2 illustrates the number of studies utilising optical methods for MPs identification from 2020 to 2024. Primary databases were searched with Figure 2 in the search of Web of Science, Scopus and Google Scholar with an aim of building a strong base for this review. Besides, as inclusion criteria, the studies were included when they presented primary experimental information on the characterisation of MP or when they implied a new analytical workflow. In the event literature was not written in English, the preliminary screening was done on titles and abstracts, then a comprehensive eligibility check of the full text was done.

Research activity gradually increased from 2020 to 2023. In 2020, 17 studies were recorded on this topic. The number rose to 21 in 2021 and 24 in 2022. A peak of 25 studies occurred in 2023. This growth indicates rising interest in optical-based techniques. Optical methods are valued for their non-destructive nature. In 2024, the count dropped significantly to only 10 studies. Although there is a decreasing trend, the importance of MP identification in securing the healthiness of biodiversity (Tan & Mohd Zanuri, 2023). It also suggests the difficulties and complexities of handling, preparing and identification of MP samples (Cutroneo et al., 2020).

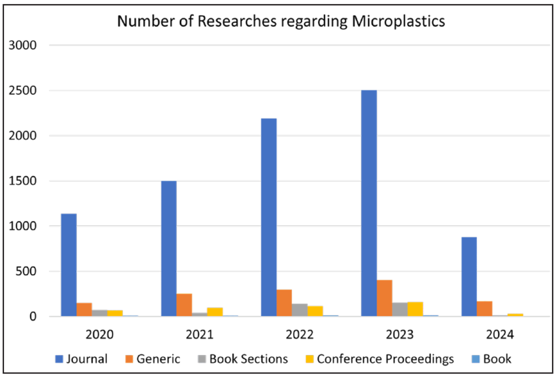


*Figure 1.* Number of research papers regarding MPs

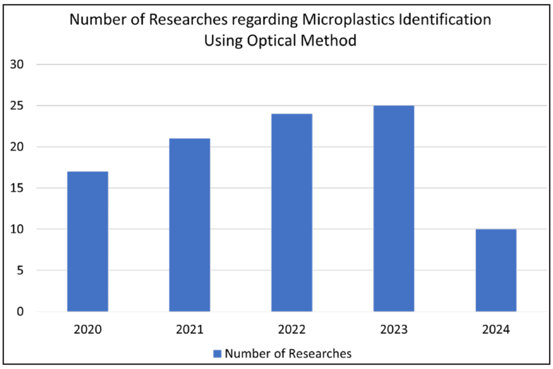


*Figure 2.* Number of research papers about MPs identification using optical methods

## Microplastics

Microplastics (MPs), a term that has gained widespread recognition in recent years, are plastic particles ranging from 5 mm to 25 mm is considered mesoplastics, and the bigger ones (after 25 mm) are macroplastics (Grini et al., 2022; Recabarren et al., 2025). Such minute pollutants have gathered significant interest due to their level of occurrence in many ecosystems. The damage they can cause to wildlife and humans calls for proper management of the environment. The sources, types, distribution and consequences of MPs are important issues that need to be analysed to comprehend the phenomenon.

MPs have many sources, mostly obtained because of the wear of bigger plastic objects like bags, packaging products and bottles. Also, the fibres produced by the textile during the laundry process are synthetic, personal care products contain microbeads, and industrial processes generate them as well, further increasing the number of these particles. When emitted to the environment, they are long-lasting, do not degrade in nature and build up in the environment in oceans and rivers as well as on land.

Figure 3 shows the prevalent types of MP identified by researchers, which are polyethene terephthalate (PET), Polyvinyl chloride (PVC), polypropylene (PP), Polystyrene (PS), HDPE and LDPE. PVC is commonly used in pipes, window fittings and flooring. PS is a common polymer which is frequently used in foam containers.

Figure 4 shows the structure of MPs, where MPs are divided into two components, primary MPs and secondary MPs.

The distribution and breakdown of larger plastic objects are secondary MP. However, primary MP may be deposited directly into the water bodies in case they are carried in the drainage system to the surface water. The deliberate introduction of MP into consumer goods presents a direct danger to aquatic life, as the organisms consume the particles, which can potentially cause trophic interactions to be broken.

Secondary MP are the apportionment and disintegration of bigger plastic objects. Larger plastics, such as bottles, bags, and containers, are exposed to natural pressures like UV radiation, temperature fluctuations, and mechanical abrasiveness, which have an impact on how quickly these plastics break down into smaller pieces over time (Fakhri et al., 2024). Secondary MP tend to be geometrical anomalies and are found in a size range; hence, contributing to a large portion of MP pollution in aquatic and terrestrial environments. They can live decades or even centuries as secondary MPs and present long-term environmental problems.

A variety of MP types were found in the Penang tropical estuarine mangrove ecosystems of Malaysia. Polymer types that were identified were polyacetal (19%), polybutadiene (6%), polychloroprene (CR) (6%), polyethene (PE) (30%), polyformaldehyde (4%), PS (19%), PP (9%), PVC (2%), polyamide 6/6 (PA6) (2%), and polyethene oxide. Sampling was done in coastal surface waters, coastal sediment cores and estuarine sediment layers (Tan & Mohd Zanuri, 2023). Even though the differences in the sampling sites resulted in the density of MP differing between sites, the composition of the MP types was similar across sites.

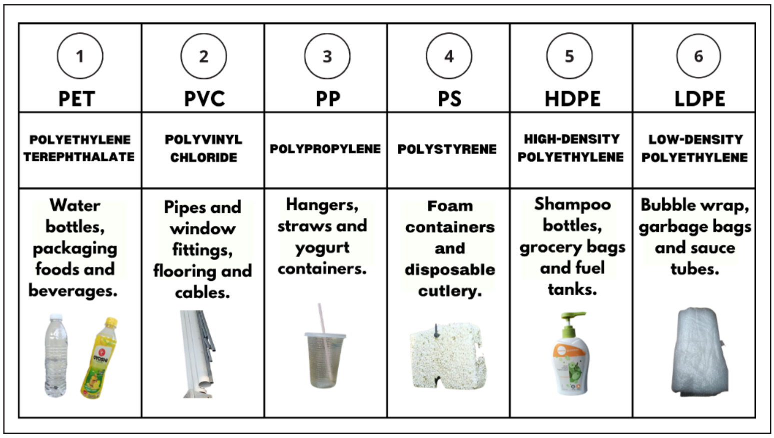


*Figure 3.* Common types of MPs

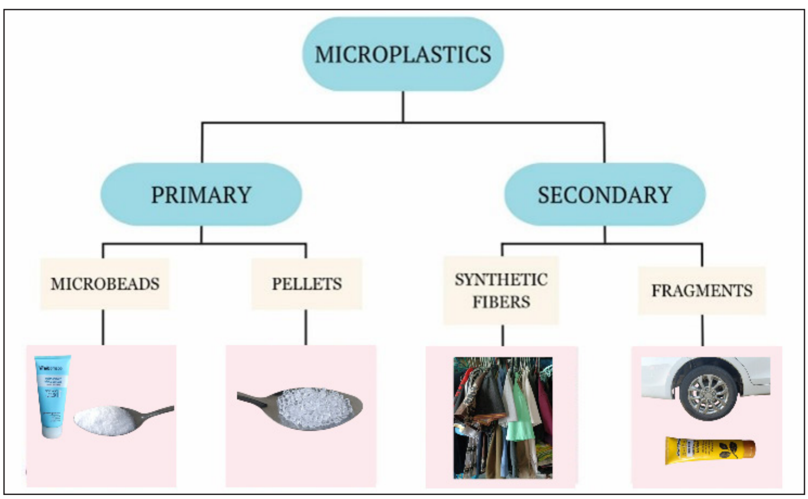


*Figure 4.* Types of MPs

## Present Techniques of Microplastic Detection

The modern MP detection methods are a combination of sophisticated analysis tools. These are Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) that breaks down MP samples to enable chemical interrogation of every element; Nuclear Magnetic Resonance (NMR), which distinguishes the type of MP based on their molecular architecture; X-ray Diffraction (XRD), which identifies and analyses crystalline polymeric structures; Thermogravimetric Analysis (TGA), which measures thermal degradation behaviour; and Scanning Electron Microscopy (SEM), which provides high-resolution images to.

### *Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS)*

Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) is an analytical method used to recognise and describe MP. The principal entails exposing an MP sample to high temperatures (pyrolysis), thus breaking it down into smaller pieces (Rosso et al., 2023). Gas chromatography (GC) is used to separate and further analyse the pyrolysis products based on their chemical properties, and mass spectrometry (MS) is used to identify and quantify each component (Kadac-Czapska et al., 2023). Many high-impact studies integrate Py-GC-MS as a confirmatory tool to calibrate optical sensors and minimise false-positive identifications caused by environmental biofilms or organic debris. While optical sensing techniques offer rapid, non-destructive screening, cross-validation remains essential for absolute polymer confirmation. Py-GC-MS allows identification of MP using discrete chemical fingerprints, and has been successful in identifying specific types of MP, such as PVC, PMMA, PP, PS, PE, PET, and PA.

### *Nuclear Magnetic Resonance (NMR)*

The idea underlying the use of Nuclear Magnetic Resonance (NMR) is that certain atomic nuclei have a magnetic moment, which causes them to align with a magnetic field when they are subjected to it. By responding to radiofrequency pulses, the nuclei absorb and consequently release energy, thus giving important information about the molecular environment of the sample (Giaganini et al., 2023). NMR can also be used in the identification and characterisation of different types of polymers in terms of their unique molecular structure within the framework of MP identification. This technique is particularly applicable in the detection of MP, like acrylonitrile-butadiene-styrene MP (ABS-MP), and in such a system, the distinctive polymer chains produce certain NMR spectra.

### *X-ray Diffraction (XRD)*

X-ray diffraction (XRD) is an analytical methodology that is rigorous in nature, based on the interaction of periodic lattice structures of crystalline materials with the collimated X-ray beams. In an XRD experiment, a beam of monochromatic radiation is incident on the specimen, and the resultant diffraction pattern is measured by an array of detectors. The crystal lattice produces constructive and destructive interferences that produce different diffractive peaks that could be quantitatively examined to explain the arrangement of atoms in the sample. When XRD is used to differentiate between crystalline polymers and amorphous ones, it is utilised as part of MP identification, thus improving the specifics of MP shapes.

Examples of representative polymer classes that are routinely interrogated by XRD are PE, high-density polyethene (HDPE), and polyvinyl alcohol (PVA); each of the above has a distinct diffraction signature, which is determined by the crystalline lattice parameters. As a result, XRD is an obligatory instrument for determining MP composition and complements our understanding of their impact on the environment (Dey et al., 2023).

### *Thermogravimetric Analysis (TGA)*

Thermogravimetric analysis (TGA) is one of the thermal analyses, which is used to gauge how a sample's mass changes over a regulated temperature gradient. TGA is used to gauge the thermal degradation characteristic of polymeric particles when it is used to determine MP. In this technique, an MP specimen is subjected to a programmed temperature curve under constant monitoring of its weight loss (Bensharada et al., 2022; Zainuddin & Syuhada, 2020). TGA can be used to identify MPs as the species degrade at discrete degradation rates, where each species has a unique onset temperature at which mass loss initiates. Common polymers that are examined using TGA include PE, PP and PET, and each of them will exhibit a characteristic weight-loss curve that can be utilised to conduct compositional discrimination. The method proves to be, therefore, useful in explaining the thermal stability and the composition of MP in the matrix, thus integrating the strategies to be employed in effective environmental monitoring and mitigation.

### *Scanning Electron Microscopy (SEM)*

Scanning Electron Microscopy (SEM) is an effective imaging technique in the detection of MP in the environmental matrices. SEM is based on a scanning of a narrowly focused electron beam on the specimen surface to excite the emission of secondary electrons, as well as other types of signals that are capable of being processed and yielding images of the surface topography. In MP analyses, the electrons released into the surface of conductively coated surfaces with noble metals like gold or palladium are gathered to form the micrographs. A common set of preparation procedures includes the collection of environmental samples (e.g., aqueous or sedimentary fractions), their filtration and subsequent exposure to dehydration, mounting on stubs, and sputter-coating with a thin conductive layer, usually gold, palladium or carbon, to reduce the charging effects and improve the image resolution (Mateos-Cárdenas et al., 2022). Some of the common polymers studied using SEM are PE, PP, and PET. SEM is the superior method for morphological differentiation. It provides high-resolution imaging of surface topography, allowing researchers to classify primary and secondary plastic through morphological differentiation.

## Advantages and Limitations

### *Nuclear Magnetic Resonance*

Nuclear magnetic resonance (NMR) spectroscopy provides useful structural data, which is useful in MP analysis. However, its extensive use is limited by the fact that it requires advanced instrumentation and highly trained people, which can be a hindrance during regular utilisation. The separation of polymeric compounds or the identification of trace amounts of MP may be difficult, which may undermine the quality of analysis. Furthermore, the process of NMR is laborious and time-consuming, as it requires a lot of sample preparation and complicated interpretation of data. The cost of capital involved in the NMR instrumentation also limits its availability in the routine MP characterisation. Spectral data are sometimes subject to fluctuating data, which may require additional extraneous analysis to eliminate inconsistencies, thus compromising the reliability of the results (Seghers et al., 2023).

### *Nile Red Fluorescence*

The detection of MP is commonly done using Nile red fluorescence, but its practical implementation is limited by the complexity of the sample preparation and the interference of the matrix. Environmental samples may have heterogeneous components that may undermine the specificity of Nile red stain, giving false positives or negatives. The method is also quite expensive, requiring the use of special fluorometric equipment and reagents (Mazlan et al., 2022). Moreover, it is time-consuming because it is a series of steps- sample isolation, staining, incubation and microscopic examination. Such accruing limitations reduce the effectiveness and practicability of Nile red fluorescence for use in a complicated environmental matrix.

### *Thermogravimetric Analysis (TGA)*

Thermogravimetric analysis (TGA) is a type of thermal analysis which is used to measure changes in the mass of a sample during a controlled temperature gradient. TGA is used to gauge the thermal degradation characteristic of polymeric particles when it is used to determine MP. In this technique, an MP specimen is subjected to a programmed temperature curve under constant monitoring of its weight loss (Zainuddin & Syuhada, 2020). TGA can be used to identify MPs as the species degrade at discrete degradation rates, where each species has a unique onset temperature at which mass loss initiates. Common polymers that are examined using TGA include PE, PP and PET, and each of them will exhibit a characteristic weight-loss curve that can be utilised to conduct compositional discrimination. The method proves to be, therefore, useful in explaining the thermal stability and the composition of MP in the matrix, thus integrating the strategies to be employed in effective environmental monitoring and mitigation.

## Potential of Optical Sensing Technique

One of the main electromagnetic radiation categories that is frequently employed in modern scientific research is optical light, which consists of ultraviolet (UV), visible, and infrared light. UV radiation has shorter wavelengths and thus, contains more photon energy as compared to visible light. The visible light, which is characterised by the wavelengths that can be seen by human eyes, is widely used in microscopy, spectroscopic analysis, and imaging processes. Infrared radiation, characterised by wavelengths longer than those of visible light, has diverse applications including remote sensing, thermography, and spectroscopic study of chemical compositions. The ability of optical light to couple with matter in unique ways is the foundation of its central place in scientific discovery, which allows a very broad range of methodological strategies in a broad range of fields. The current areas of research work still believe in the optical light method in control as a potential area of future research since it is relatively simplified, faster and less intrusive than other more conventional methods.

### *Fourier-Transform Infrared Spectroscopy (FTIR)*

Fourier-Transform Infrared Spectroscopy (FTIR) falls under the category of the most widespread analytical procedures used to determine the presence of MP. This method is achieved by separating aqueous samples with fine mesh sieves or filters of carefully determined pore sizes, thus trapping MP with water and other extraneous contents between the sieves. The retained particles are then irradiated with infrared light to give transmitted spectra, which are then obtained with a detector. The spectral data obtained are computed using the Fourier-transform analysis to identify the identity of the polymer shown in Figure 5. The FTIR method is a fast method of data collection, compared to other traditional methods, because it can scan a wide spectral range in minutes. The technique is non-destructive and leaves samples intact, which is a beneficial characteristic, especially when analysing rare or precious materials. To improve this, the samples need to be dried to reduce water interference (Fomina et al., 2023). Furthermore, for complicated substances, FTIR can only offer a limited amount of information about the whole chemical structure. To get more thorough molecular information, include FTIR with additional methods like mass spectrometry, NMR, or Raman Spectroscopy. Figure 5 shows the working principle of FTIR.

An example result of the FTIR spectrum of PVC is referred from Yaseen et al. (2021). The analysis uses infrared light to monitor how Poly (vinyl chloride) breaks down over time. They observed the growth of some chemical indicators, like carbon and carbonyl double bonds. These are definite indications of structural degradation of the plastic subjected to UV conditions. The experiment shows that new tin complexes can be used to delay degradation by comparing the heights of the peaks to compare them. All spectral measurements were referred to the constant carbon-hydrogen bond.

The highest peak is created at 1722 cm-1, and this shows the presence of carbonyl (C=O) groups. The other important peak is at 1602 cm-1, and it shows the formation of carbon-carbon double bonds (C=C) (Wu et al., 2024). The two peaks are on the rise as the polymer chain breaks and loses the hydrogen chloride in the presence of UV. Another peak that the researchers observed was the 1328 cm-1 peak, which is attributed to C-H bonds in the PVC (Ahmed et al., 2021). This C-H peak was not affected, and therefore it was used as an internal standard to measure degradation indices. With the quantification of these precise spectral variations, the study gives a mathematical demonstration of the efficiency of the stabiliser.

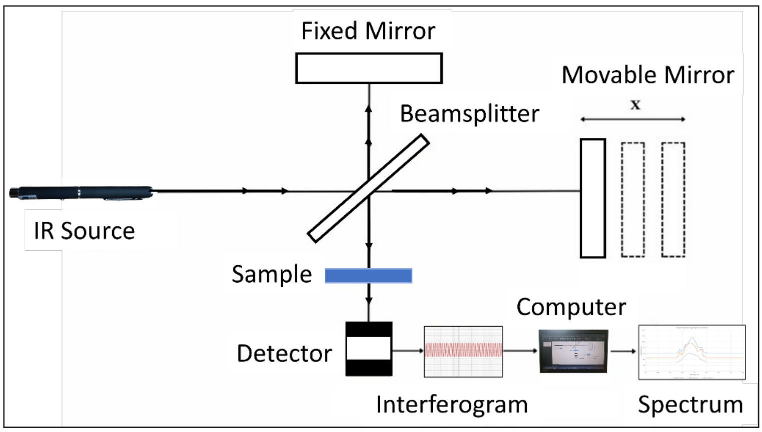


*Figure 5.* Principle of FTIR

### *ATR-FTIR (Attenuated Total Reflection Fourier-Transform Infrared Spectroscopy)*

Attenuated Total Reflection Fourier-Transform Infrared Spectrophotometry (ATR-FTIR) is also one of the main methods of MP analysis. In this configuration, the beam of infrared is passed through a high-index crystal, which comes in direct contact with the MP surface. The resulting evanescent wave allows one to measure surface absorption, which gives an idea of functional groups existing within the material and thus helps in characterising and identifying it. In contrast, the standard FTIR quantifies the transmission or reflection of infrared light of a specimen. ATR-FTIR enables faster, direct surface probing compared to FTIR. ATR-FTIR can be used for a wide range of sample types, such as gels, films, solids, liquids, powders, and surface analyses, and has increased sensitivity to trace elements, able to detect small amounts of material (Van Haaren et al., 2023). Though it is a widely used and adaptable method, ATR-FTIR has several flaws. ATR-FTIR is quite similar to diamonds in terms of their high index of refraction. The square root term is negative, the ATR impact is absent, and the ratio of indices is close to one if the sample index and crystal index are too identical.

Moreover, compared to conventional transmission FTIR, the ATR approach could have a smaller spectrum range, especially in the low wavenumber range. To cover the entire spectral range, the ATR-FTIR method can be combined with additional IR approaches, if required. Table 1 shows the comparison table between FTIR and ATR-FTIR.

Table 1 shows a comparison table between standard FTIR and ATR-FTIR. In environmental monitoring, the shift from standard FTIR to ATR-FTIR is driven by the need for speed and the ability to analyse particles recovered from the field. Although standard FTIR remains the scientific foundation, the hardware configuration of ATR-FTIR makes it a more practical choice for rapid MP identification.

The samples collected in fields are mixed with types of MP. These MPs can be isolated depending on the type of MP using the method of the Sequential Density Separation (SDS). Sequential density separation is an efficient technique to isolate all forms of MP in sample water. The density of the liquid is gradually increased to suspend some plastic polymers. Low-density plastics such as PE will first be collected on the surface. Adding salt solutions in turn causes the heavier materials, like PS, to rise. It is a methodical method that could be employed to classify various forms of polymers in a proper order. The former advantage is that high-purity plastic fractions can be collected. The process is cost-effective and has high research analytical integrity. It can manage complicated environmental blends without destroying the polymer structures (Rivoira et al., 2020).

Table 1
*Comparison between standard FTIR and ATR-FTIR*

| Feature | Standard FTIR (Transmission) | ATR-FTIR |
|---|---|---|
| Physical Mechanism | The IR beam passes directly through the entire sample. | An IR beam reflects inside a crystal, creating an evanescent wave. |
| Sampling Depth | Probes the entire bulk (thickness) of the sample. | Probes only the surface layer (0.5 to 5 um deep). |
| Sample Preparation | Requires grinding samples into thin KBr pellets. | Samples are pressed directly onto the crystal surface. |
| Light Path | The sample must be transparent or very thin to let light pass. | Light never travels through the sample; it only touches the surface. |
| Data Processing | Produces a "standard" spectrum immediately. | Requires an ATR Correction algorithm to adjust peak intensities. |
| Key Advantage | Good for bulk chemical analysis of pure materials. | Superior for weathered surfaces and irregular environmental shapes. |

### *Raman Spectroscopy*

While different from traditional spectroscopy, Raman spectroscopy is a valuable tool for MP identification. It provides molecular information about the material being analysed. A unique Raman spectrum is produced when a laser beam interacts with an MP particle, which enables the kind of plastic polymer to be identified. The benefits of Raman spectroscopy include high sensitivity and quick result acquisition, making it most appropriate in polymer differentiation and investigation of MPs as small as submicron sizes (Pashaei et al., 2023). Also, Raman spectroscopy can be used to characterise polymers by interrogating specific vibrational modes of the molecular structure. Raman and u-FTIR are excellent in distinguishing primary and secondary MP by their chemical markers and additive detection, as they can detect "oxidative weathering" signatures (Su et al., 2024). Raman instrumentation (portable) can be used to do field analysis with a variety of applications. The method has lower sensitivity to water, thus increasing its aptitude for the analysis of biological tissues and water bodies.

However, there are several drawbacks and difficulties. Raman scattering is generally a very weak process, where only about one in every $10^8$ photons undergoes spontaneous scattering. The strength of the achievable Raman signal is constrained by this intrinsic weakness. The sample may get heated when high-intensity laser sources are used. This might result in thermal progression or change the sample's characteristics. For delicate or thermally unstable materials, this is specifically cumbersome. Raman spectroscopy is more sensitive to the analysis of metallic (metal-containing materials or metal oxides such as iron oxide and titanium oxide) and other material components. But pure metals such as pure gold, pure silver, pure aluminium and pure copper normally show no observable Raman lines since their lattice vibrations do not significantly change polarisability. To address these drawbacks, several new sophisticated methodologies have been devised. An example is the Surface Enhanced Raman Spectroscopy (SERS), which can reduce by many orders the interference of fluorescence by enhancing the Raman signal by metallic nanostructures several times. This method also effectively masks organic fluorescence without using harsh chemical treatments.

### *Nile Red Fluorescence*

The effect of fluorogenic dye Nile Red assumes that fluorogenic dyes, including Nile Red, are strongly emitted when interacting with nonpolar components, in particular, the lipidic components of MP (MP). Under this protocol, Nile Red is incubated with MP samples, where it is allowed to adsorb on the hydrophobic surfaces of the plastic particles. The stained MPs can then be visualised and determined in terms of fluorescence after subsequent illumination at certain excitation wavelengths, which can be achieved using a fluorescence microscope. The method is especially effective in the identification of MPs in environmental samples.

Polymers regularly recognised by the Nile Red fluorescence assay include polylactic acid (PLA), PVC, expanded polystyrene (EPS), two versions of HDPE, polyamide-6 (PA6), PE, PET, three types of PP, and two types of PS; these polymers are hydrophobic polymers that are vital in the flu. Nile Red has not gone with use without its limitations. The fluorescence sensitivity of the dye is highly affected by the polarity of the surrounding medium, which may result in great spectral changes and attenuation, complicating the quantitative measurements. Moreover, Nile Red is also photobleached, which is a slow process of the loss of fluorescence due to a long-lasting impact with excitation light (Sha et al., 2023). By using shorter exposure periods and lower light intensity settings to minimise the amount of time and intensity of light exposure during imaging.

### *UV-Vis Spectroscopy*

Ultraviolet-Visible (UV-Vis) spectroscopy is used to identify the absorption of photons in the ultraviolet and visible fields by new species. As light of distinct wavelengths passes through a sample, characteristic absorption bands form, and there is attenuation of the intensity of light passing through at those wavelengths. Within the framework of MP detection, the UV-Vis spectroscopy can be utilised to characterise the absorption profiles of the polymers that are commonly used in MP. Spectral range 200-780nm on a v-650 spectrometer (Jasco) with a spectral bandwidth of 0.5nm and a spectral resolution of 2nm. Different types of MP, such as low-density polyethene (LDPE), HDPE, PE, PP, and PET, PVC, exhibit distinct absorption spectra in the UV-Vis range (200nm to 780nm). By comparing the absorption patterns of unknown samples to reference spectra of known polymers, scientists can identify and quantify the presence of specific MP in environmental samples using UV-Vis spectroscopy. UV-Vis spectroscopy is a common method in various fields and is widely used for both qualitative and quantitative analysis in laboratories. Due to their broad dynamic range, UV-Vis spectrometers can calculate absorbance across several orders of magnitude (Fakayode et al., 2024). Therefore, samples with different concentrations can be analysed (Paul et al., 2024). UV-Vis spectroscopy is non-invasive towards the sample, hence enabling the sample to be repeatedly examined. Despite this method being commonly used, it also has several issues. Due to UV-Vis spectroscopy having limited sensitivity and detection limitations, it may not be able to detect very low quantities of analytes. To overcome this difficulty, cuvettes with longer path length can be used as they can contain more analytes. The analyte's concentration can also be raised by pre-concentrating materials by methods like solid-phase extraction or evaporation. Moreover, baseline drift, particle scattering, and turbidity in the sample may cause inaccurate absorbance readings. To solve this problem, adjust for baseline drift by using reference samples or baseline correction methods.

To minimise the scattering effects and eliminate particles, either filter or clear the samples. Advanced calibration methods, including partial least squares regression (PLSR), allow the system to adjust for matrix effects and background interference (Nnachi, 2024). Optical methods have been highly used in research as it is non-invasive, rapid, accurate and many more. Optical light methods are trending now as it complies with future characteristics. Figure 6 illustrates the principle of working of UV Vis spectroscopy.

For instance, Klempová et al. (2023) used UV-VIS on PVC to study the effect of degradation on the absorbance. The UV–VIS spectrum of PVC shows characteristic absorption in the near-visible region. A distinct absorbance band appears around 390 nm due to conjugated polyene formation. This peak indicates progressive degradation of PVC under thermal and UV exposure. Increased absorbance intensity reflects the growth of chromophoric sequences within the polymer matrix. These conjugated structures arise from dehydrochlorination reactions during ageing processes (Liu et al., 2026). The spectral shift toward longer wavelengths suggests an extended conjugation length (Bononi et al., 2020). UV–VIS analysis provides a sensitive approach for monitoring optical and chemical changes. This method enables non-destructive evaluation of PVC degradation behaviour.

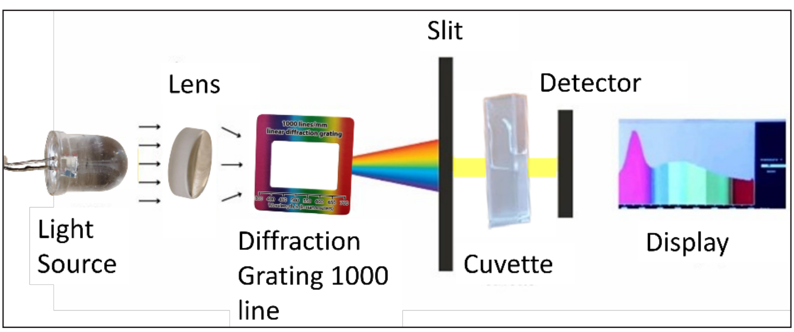


*Figure 6.* Principle of UV-Vis

## Comparison Between Optical Sensing Techniques

Table 2 shows a comparison table of the top common optical sensing techniques for MP identification. No single method fits every research budget or goal perfectly. High-accuracy tools like Raman spectroscopy detect the smallest particles. However, advanced equipment often involves much higher financial costs. Nile Red staining offers a faster, cheaper way to count particles (Shruti et al., 2022). Standard monitoring typically relies on the chemical reliability of FTIR. Researchers must balance precision against available time and resources.

Table 2
*Comparative table of optical sensing techniques*

| Method | Sensitivity (Min. Size) | Specificity (Polymer ID) | Relative Cost | Throughput (Samples/Day) |
|---|---|---|---|---|
| μ-FTIR | High (~5~10 μm) (0.1~1.0 ppm) | Excellent | Moderate to High | Low (1~5 samples) |
| Raman Spectroscopy | Very High (<1 μm) (< 0.1 ppm) | Excellent | High | Very Low (1~2 samples) |
| Nile Red Staining | Moderate (~100 μm) (1.0 – 10 ppm) | Low (non-specific) | Low | High (20~50 samples) |
| UV-Vis Spectroscopy | Low (5.0 – 50 ppm) | Moderate | Low | Very High (>50 samples) |
| Fluorescence Microscopy | Moderate (0.5 -5.0 ppm) | Moderate | Moderate | Moderate (10~20 samples) |

## Recommended Optical Approach for Future Monitoring

Despite the abundance of existing analytical methods, μ-FTIR spectroscopy is recommended as the primary optical method to employ for MP monitoring. Despite other techniques like Raman spectroscopy being in a better position to deliver the optimum spatial resolution of sub-micron-sized particles, μ-FTIR offers the most suitable trade-off between speed and reliability, as well as the availability to environmental researchers. Being sensitive to 5 um to 10 μm, μ-FTIR is a promising technique to detect MP accurately (Olivatto et al., 2024). The high-throughput strategies to analyse complex organic substrates present in tropical ecosystems, such as the Malaysian mangroves, have a huge knowledge gap (Tan & Mohd Zanuri, 2023). The application of μ-FTIR as a reference point has enabled scientists to employ large polymer spectral libraries to obtain high-confidence identification, which can be a bottleneck in large-scale environmental measures. Moreover, external contamination should also be detected with the help of blank filters in the case of MP analysis. Researchers subtract these background counts to have tremendous accuracy in the data. Such a stringent procedure ensures that the findings of environmental research have analytical integrity. The blanks used are also efficient in preventing excess assertion of the plastic levels of ocean samples. This might contribute to more laborious and time-consuming procedures as more procedures and protocols must be followed. One of the examples recommended is by obligating the use of blank filters to increase the level of certainty in the analytical results. This underscores the essential care every researcher must take during their routine procedures.

Careful contamination management is vital for maintaining the integrity of all scientific findings. Precise results depend entirely on avoiding external plastic fibres during the sample processing. The implementation of the Airborne Contamination Control (ACC) Protocol significantly mitigated airborne microplastic (MP) contamination, thereby increasing the confidence that identified particles originated solely from the samples. These findings underscore the necessity of rigorous laboratory hygiene and demonstrate that accessible, low-cost interventions can drastically enhance the reliability and data quality of future environmental and biological MP assessments (Paiva et al., 2022). Hydrogen Peroxide must also be used for oxidative digestion as it is one of the most common and effective methods for removing natural organic matter (NOM), such as microorganisms, algae, and biofilms, from environmental samples. This is needed in the case of Nile Red, because otherwise, this dye will stain organic debris and produce false results (Castillo & Dumale, 2024).

Moreover, the use of a multi-modal optical sensing structure is proposed in future research to solve the weaknesses of the individual sensors. This approach suggests that Nile Red fluorescence staining must be performed as a low-cost and rapid screening protocol to determine the total number of particles in the field in a short time, and μ-FTIR to profile a representative subset chemically (Corami et al., 2021). The hybrid method is the answer to the essential issue of the cost-effective monitoring of the developing regions and the necessity to maintain the high scientific standards of the process of policymaking. This type of monitoring system would allow one to monitor greater geographical regions without the extreme costs of the expensive spectroscopic imaging of individual samples. Finally, the optical sensing MP detection will be capable of integrating with the existing optical hardware and combining it with Machine Learning (ML) and Artificial Intelligence (AI) to apply more functions (Kalatzis et al., 2025). The weakness in the data processing of data, i.e., the time-intensive manual interpretation of spectra, remains a severe obstructive factor to real-time monitoring. Optical sensing accuracy can be enhanced significantly by developing AI-based automated spectral matching and noise-removal algorithms that will specifically work with environmentally damaged plastics (Cowger et al., 2025; Jin et al., 2024; Mikmekova et al., 2024). The technological solution will transform the MP detection technology, which is a tedious and lab-intensive process, into a high-impact and streamlined environmental monitoring tool on a global scale. The implementation of AI in the process of MP identification will form another system of decision-making. To conclude, standardised u-FTIR is the most plausible baseline that can be used to map global MP pollution. Intimate measures, blank filters and oxidative digestion guarantee high levels of analysis. Hybrid Nile Red systems with hydrogen peroxide and spectroscopy offer a rather cheap monitoring system. Additionally, spectral analysis that is time-consuming will eventually be automated with the addition of Artificial Intelligence. Laboratory research becomes a useful tool of environmental policy because of this development. Evidence-based choices will eventually save our delicate ecosystems for the coming generations.

## CONCLUSION

Lastly, the high pollution of water bodies with MP has attracted numerous studies that aim at defining and identifying and defining them. Scientists use different methodologies, which can be broadly divided into non-optical and optical, each of which have their drawbacks and merits. The examined methodologies provide priceless information about MP properties, which improves our knowledge regarding their interactions with the environment and biological outcomes. The optical methods that are explained to have little perturbation to the sample will be proven as future-proof against the future need of analysing the sample, and the future techniques will need improvement to combat the negative impact of MP on aquatic life. The recommendations for the future are aimed at the construction of a high-impact, multi-modal model, comprising low-cost screening and highly developed automation. Nile Red staining is proposed by scientists because of its quick and accurate counts of particles in the field. Standardised 3mu-FTIR spectroscopy should then be used to determine the chemical characterisation of representative subsets in detail. Most importantly, the data processing will transform due to the AI and ML integration process. Automated algorithms can be used to spectral match and remove noise on plastics which have been environmentally degraded. This advancement alters the detection techniques of MP that depend on the tedious effort in the laboratory to real-time global monitoring. This type of streamlined approach will give the sound information required in making effective environmental policies.

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