

A Detailed Review of Microplastics in Wastewater: Sources, Sampling, Extraction, Analysis, Removal Technologies, and Human Health Implications

Inkiad Anik

Department of Environmental Sciences, Jahangirnagar University, Bangladesh

Submitted: September 15, 2026

Accepted: September 22, 2026

Published: October 10, 2026

Citation: Inkiad Anik (2026). A Detailed Review of Microplastics in Wastewater: Sources, Sampling, Extraction, Analysis, Removal Technologies, and Human Health Implications. *Epistora J. Earth Environ. Sci.* 1(1), 1-18. Article EJEES-2026-101

Abstract

Microplastic (MP) pollution is a worldwide environmental and public health issue owing to its persistence, extensive dispersion, and resistance to wastewater treatment. The entire microplastic management pathway, including sources, environmental distribution, human exposure, sampling and extraction techniques, analytical identification techniques, advanced wastewater treatment technologies, and related risks to human health, is summarized in this review in a thorough and current manner. This study incorporates current developments in detection, removal, and toxicological evaluation into a cohesive framework, in contrast to other evaluations that mainly concentrate on distinct aspects of microplastic contamination. The mechanisms, efficiencies, benefits, and drawbacks of emerging technologies such as advanced spectroscopic techniques, photocatalytic micromotors, bioinspired molecules, metal organic framework (MOF) based adsorbents, biochar filtration, and electrocoagulation for wastewater applications are highlighted. The study also gathers new data from throughout the world on exposure to microplastics via food, drinking water, and the air, connecting long term exposure to oxidative stress, inflammation, endocrine disruption, reproductive damage, and neurological diseases. Furthermore, a critical discussion is held on existing knowledge gaps, such as the lack of standardized analytical techniques, insufficient detection of nanoplastics, and poor comprehension of health effects. This study is unique in that it evaluates analytical, engineering, and toxicological viewpoints in an integrated manner and suggests future research avenues that include health-based risk assessment, sustainable elimination methods, and standardized monitoring. For academics, environmental engineers, legislators, and wastewater treatment professionals looking for practical ways to reduce microplastic pollution and safeguard aquatic ecosystems and public health, this all-encompassing approach offers helpful advice.

Keywords: Microplastics, Wastewater Treatment, Detection Techniques, Removal Technologies, Human Health Risk

Introduction

Microplastics (MPs) pollution poses a significant global environmental challenge, primarily due to their small size, which makes conventional wastewater treatment ineffective. Advanced oxidation processes (AOPs) are increasingly recognized as a potential solution for removing MPs from water. This review highlights various AOPs such as photocatalytic oxidation, ozonation, and hybrid systems, while examining their effectiveness and the molecular mechanisms behind MP degradation (Kumar et al., 2024). (Bhattacharjee et al., 2025) showed millions of tonnes of plastic enter ecosystems annually, disrupting food chains through ingestion by organisms. While marine research is extensive, less is known about terrestrial impacts, where soil types complicate MP detection. Techniques such as spectroscopy and pyrolysis-gas chromatography-mass spectrometry -

are employed for analysis. In order to identify and characterize microplastics (MPs), (Liu et al., 2022) compared sampling, extraction, and analytical techniques for MP occurrence and transfer in wastewater treatment plants (WWTPs). Understanding how soil quality and horticulture eco-toxicological concerns are affected by microplastic pollution: A comprehensive examination were studied by (Gayathri et al., 2024).

Different techniques for eliminating microplastics from water and other media such as prevalence, transportation, toxicity, raw polymers and additives, and cleanup techniques of microplastics were performed. Chemical treatments, biological removal and ingestion, and physical sorption and filtration are examples of removal techniques. The mechanisms, effectiveness, benefits, and disadvantages of different removal techniques are examined (Padervand et al., 2020). (Picó et al., 2022) investigated the presence, movement, and ultimate destination of microplastics (MPs) in several water sources, including untreated water, treated water, tap water, and bottled water, and assessed the potential health effects of MPs on humans. (Dey et al., n.d.) studied a comprehensive evaluation of current and future approaches to microplastic detection and separation from discharged wastewater, which pose the greatest obstacles to microplastic treatment systems. Also included is research that critically examines how microplastics affect marine life and human health. To guarantee a waste discharge standard that minimizes the final possible effect on aquatic habitats, this research offers a comprehensive grasp of full techniques for detecting and removing microplastics and their related difficulties.

(Worek et al., 2025) emphasized the need of keeping an eye on the MPs content of fertilizers made from wastewater treatment byproducts. They also assessed of the Microplastics that Are Present in the stabilized sewage population various methods of sludge analysis and their effects on the environment. (Yousafzai et al., 2025) explored the effects of microplastic buildup, including oxidative stress and bioaccumulation in organisms, and spoke about the drawbacks and difficulties of existing technology. The integration of detection with degradation techniques is emphasized in order to produce transdisciplinary, scalable, and sustainable solutions. The ways in which these MP particles cause cellular toxicity, oxidative stress, and chronic inflammation in several organ systems were described. Particle-induced endothelial dysfunction and plaque instability provide cardiovascular risks, while blood-brain barrier penetration and alteration of neurotransmitters cause neurotoxic consequences (Sutkar et al., 2025). An analysis of the procedures that were used to collect, measure, and characterize microplastics in drinking water was conducted by (Elkhatib & Oyanedel-Craver, 2020). Different methods were used throughout the whole process, beginning with collection and ending with characterisation, in order to quantify microplastics in urban water systems. Sophisticated analytical methods for evaluating and identifying microplastic contamination in wastewater and water systems were studied by (Özgenç, 2024) Particle size distribution analysis, FTIR, Raman, SEM-EDS, and various thermo analytical methods were employed to detect and characterize microplastics (MPs) in water. They emphasized the sources and formations of MPs in environments, evaluating the merits and limitations of advanced analytical techniques compared to traditional ones. (Campanale et al., 2020) discussed the consequences and impacts of dangerous substances on human health. They concentrated on the most hazardous and poisonous chemicals found in all plastic items. Additionally, this study included a comprehensive overview of research that looked at the prevalence of these substances on microplastics. (Aib et al., 2025) summarised recent studies on the environmental fate and effects of microplastics and medicines, highlighting the combined impact on aquatic ecosystems and creatures. They also provide a detailed analysis of their main routes, origins, and distribution, emphasising air deposition, agricultural runoff, and wastewater disposal. By identifying the causes and effects of plastic pollution on people and ecosystems, public awareness and understanding among researchers about the detrimental impacts of plastic pollution on society and the environment were studied by (Karak et al., 2025) .

The origins of marine microplastics and their harmful impact on marine life were thoroughly examined. Additionally, they investigated the movement of microplastics via water and air, among other environmental channels. Various purification methods, including membrane filtration, biological degradation, electrocoagulation, and nanoparticle removal, and summarizes recent research on MP identification and toxicity assessments in vitro and in vivo were outlined by (Park et al., 2020). Exposure to airborne MPs, risks to human, animal health, and ecosystems, notably through sewage contamination was studied by (Zahmatkesh et al., 2023). (Bhardwaj et al., 2024) showed a thorough assessment of microplastic pollution, a new hazard to freshwater environments. (Hechmi et al., 2024) Risks and long-term mitigating techniques for microplastic (MP) contamination of soil caused by treated wastewater and sewage sludge.

In addition to gathering fresh data on cellular and physiological harm due to microplastics, such as oxidative stress, inflammation, hormone disruption, and potential genetic impacts, the study looks at prospective human exposure routes via contaminated seafood, water, and air were studied (Sunny et al., 2025). This review integrates microplastic sources, detection methods, advanced wastewater treatment technologies, and human health impacts into a single comprehensive framework. It provides a comparative evaluation of emerging removal technologies based on their mechanisms, efficiencies, advantages, and limitations while incorporating the latest research (2024–2025). The review also links wastewater-derived microplastic pollution with human exposure pathways and identifies key research gaps, including standardized detection methods, nanoplastic analysis, and sustainable treatment strategies. The primary objective of this review is to provide a comprehensive and up-to-date assessment of microplastic pollution in wastewater by critically examining their sources, environmental distribution, sampling and extraction methods, analytical detection techniques, advanced removal technologies, and associated human health risks. The review further aims to compare the efficiency, mechanisms, advantages, and limitations of conventional and emerging wastewater treatment technologies, identify current research gaps in microplastic detection and risk assessment, and propose future research directions for developing standardized monitoring methods and sustainable strategies to reduce microplastic contamination and protect both aquatic ecosystems and public health.

Sources and Presence of Microplastics

The Fig.1 highlights origins and environmental distribution of microplastics (MPs). It shows that microplastics come from two main pathways: primary sources (small plastics intentionally manufactured such as microbeads, pellets and materials from personal care products or road wear) and secondary sources (produced by the breakdown of larger plastics such as bags, bottles, synthetic textiles, fishing gear and agricultural films). The graphic also displays the distribution of microplastics in various settings such as air, water (oceans and freshwater), ice cores, soil, and the human body. It highlights the pervasive and persistent nature of microplastics as pollutants that threaten ecosystems and human health, and promotes reduction, reuse and recycling to limit contamination (Browne, 2015).

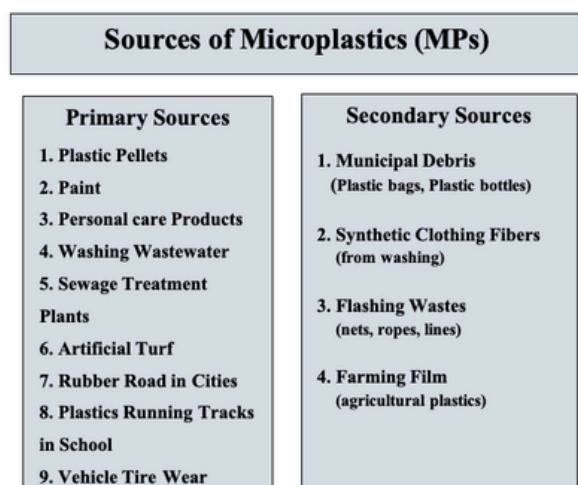


Fig.1. Sources of Microplastics (MPs) and their presence in the environment

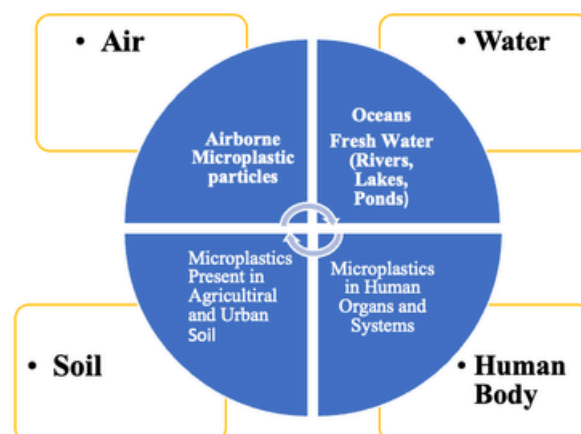


Fig. 2. Presence and Circulation of Microplastics (MPs)

Definition and Sizes of Microplastics:

The size of a plastic particle is the only criterion for classifying it as microplastics. Words like "barely visible particles," "those not visible to the naked eye," "the invisible fraction," and "occasional mention of the fact that they cannot be seen" occur here and there. Although most research provide a specific upper limit, the exact figure is not universally agreed upon. Although some writers argue that particles larger than 1 mm cannot be regarded as microplastics, the National Oceanic and Atmospheric Administration (NOAA) uses the 2008 workshop's recommendations to define microplastics as plastic particles that are 0.5 mm in size. Additionally, other sizes have been provided, and a very subjective definition (0.1 cm). Most writers have advocated the 5-mm restriction in recent years, according to the literature study.

New categories and definitions are being considered by certain groups of workers. The Technical Subgroup on Marine Litter for the implementation of the Marine Strategy Framework Directive (MSFD) suggests further subdividing the "visible size fraction" (.1 mm) into large microplastics (1-5 mm), mesoplastics (5-25 mm), and macroplastics (>25 mm), while the "invisible fraction" (<.1 mm) is called "small microplastics." The Size range section discusses the under-recognized absence of a minimum size requirement for microplastics (Filella, 2015).

Distribution and Transportation of Microplastics:

The Fig. 2 shows the origins, methods of transit and environmental dispersion of microplastics. Microplastics may come from primary sources (tiny particles introduced directly into the environment, e.g. microbeads, industrial pellets) or secondary sources (resulting from the degradation of bigger plastics). These particles reach aquatic systems via urban runoff, wastewater discharge, washing of synthetic fabrics, tire wear, and marine activities. Once in the environment, microplastics may be carried by rivers, ocean currents, wind and by air deposition, allowing them to travel considerable distances. In marine environments they aggregate in ocean gyres, settle into sediments, or are re-suspended in the water column. Microplastics are also taken up by aquatic creatures, leading to their introduction into the food chain. The image therefore represents the extensive dispersion of microplastics in air, water, soil and biota via interlinked transport systems (Leitão et al., 2023).

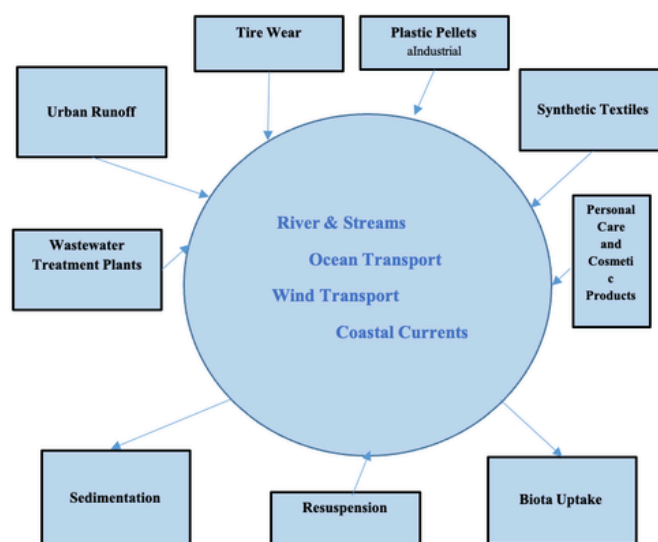


Fig. 3. Distribution and Transportation of Microplastics

Consumption Rate of Microplastics in Different Countries

The consumption rate of microplastics (MPs), expressed in milligrams per person annually across various nations and areas, is shown in Fig. 3. With 37% of all microplastic consumption, the United States is by far the highest percentage, suggesting far more exposure than other areas. China provides 10%, while the European Union comes in second with 12%. Japan and South Korea, both at 8% and Germany at 7%, represent a medium group with modest levels of consumption. Australia (5%), India (4%), Canada (4%), and Brazil (3%), which have comparatively lower microplastic ingestion, are smaller contributors (Karami et al., 2017).

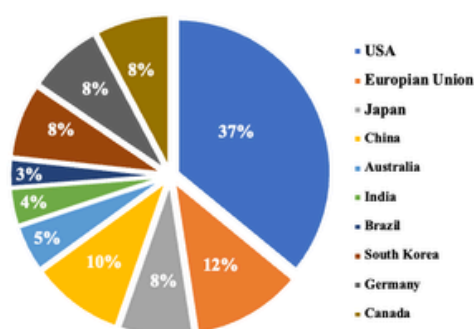


Fig. 4. Consumption Rate of Microplastics in Different Countries (mg/capita/year)

Global Assessments of Human Microplastic Consumption

The main ways that humans are exposed to microplastics (MPs) are via food, drinking water, and inhalation. The amount of microplastic consumed annually by Americans based on a thorough examination of 26 published studies, which included 402 data points and more than 3,600 processed samples. Seafood, sugar, honey, salt, alcohol, bottled and tap water, and airborne particles made up around 15% of the typical American diet. Microplastic concentrations were found to be 94.37 particles/L in bottled water, 4.23 particles/L in tap water, 32.27 particles/L in beer, 1.48 particles/g in seafood, 0.44 particles/g in sugar, 0.10 particles/g in honey, 0.11 particles/g in salt, and 9.80 particles/m³ in air. For female children, the annual food consumption varied from around 39,000 particles to 52,000 particles for adult men. The total yearly exposure rose to 74,060 particles for female children, 81,331 for male children, 98,305 for adult females, and 121,664 particles for adult men when inhaling was taken into account. The source of drinking water had a considerable impact on exposure; those who exclusively drank bottled water consumed almost 90,000 more particles a year, while those who solely drank tap water consumed just 4,000 particles a 22-fold difference (Cox et al., 2019).

Microplastics Sampling Method

Table 1: Comparative Advantages and Limitations of Microplastic Sampling Techniques

I. Manta and Neuston Net Method	
Benefits	Drawbacks
• Simple To Use • Can hold massive amounts of water • Good for comparing various places • Produces enormous amounts of microplastics (MPs) for analysis	• Requires costly equipment • Needs a boat to function • Time consuming • Risk of contamination of vessel & towing rope • Relatively high detection limit (~333 µm)
II. Plankton Net Method	
• Quick and easy to use • Resolution limit (approx. 100 µm) • Good for modest water volumes	• costly equipment • Needs boat • Requires water flow (not for static circumstances) • Can block or break • Collects lesser quantities than manta nets
III. Sifting Method	
• Special equipment not required • No watercraft needed • Collecting samples easy	• It requires a lot of labour and time • Only for medium quantities • Requires manual transfer of water (using buckets, etc.)
IV. Pumping	
• Can hold significant amounts of water • Less hard labour • Flexible choice of mesh size	• Can hold significant amounts of water • Less hard labour • Flexible choice of mesh size
V. Sieving or Filtration (Ex situ)	
• Simple sample collection • Known / Controlled water volume • Easy to choose the mesh size	• Only suitable for low quantities • Need to bring the samples to the laboratory • Contamination hazard while handling

(Mistry et al., 2023)

Microplastics Extraction Techniques

Table 2: Techniques Based on Separation

I. Density Distinguishing	
Principle: Plastics and surrounding materials are separated according to their densities.	
Benefits	Drawbacks
• Plastic pre-concentrates • Makes downstream detection and analysis easier.	• Impacted by residues of soil or sediment • Inefficient in eliminating organic materials
II. Separation of Oil	

Principle: Makes use of polymers' lipophilic properties	
Efficient in the separation of hydrophobic MPs	Recovery rates that are erratic and unpredictable
III. Separation of Vertical Density Gradients	
Principle: Makes use of layered liquids with varying densities, often including magnetic Particles	
Enhanced effectiveness of separation	- Limited access to research - Expensive approach
IV. Electrostatic Distancing	
Principle: Electrical charge differences as the basis for separation	
- Ideal for sand, water, and sediments - gentle approach (no deterioration of plastic)	- Time-consuming - Unsuitable for samples that are wet

(Mistry et al., 2023)

Table 3: Techniques Based on Digestion

I. Acid-Base Digestion	
Benefits	Drawbacks
- Extremely efficient at removing organic matter - Ideal for biological samples and sediments	- Might deteriorate plastics - Time-consuming - May decrease accuracy
II. Fenton's Reagent (H₂O₂ Oxidation)	
- Extensively used in the investigation of soil and sediment - In some situations, more efficient than acid/base digestion	- Might deteriorate plastics - Requires strict temperature control - Results may be impacted by ageing effects.
III. Digestion by Enzymes	
- Mild and maintains the integrity of plastic - Appropriate for marine life and water samples	- Expensive - Soil sample validation is limited

(Mistry et al., 2023)

Table 4: Other Extractions Methods

I. Manual Extraction	
Benefits	Drawbacks
The most straightforward method, which might use other technologies like hot needles	Inaccurate and Time-consuming
II. Extraction of Pressurized Fluid	
- High efficiency at a low cost - Useful for MPs smaller than 30 µm	- Large particles are not acceptable (>30610 µm is probably a mistake; it should be >~300 µm). - May change the shape of particles
III. Extraction by Magnets	
Effective MP isolation	- Non-specific binding - Post-treatment is necessary - Iron particle interference
IV. Flotation of Froth	
Easy and efficient separation	Non-specific binding
V. Extraction of Liquids	
- Quick processing - Adequate for large sample sizes - Able to calculate the mass of polymers	- Restricted to certain kinds of polymers - Sample damage risk

(Mistry et al., 2023)

Microplastic Analytical Techniques

A. Visual Method

Microscopic Counting

Microscopy is used to identify pretreated samples. The particles are immediately counted. The stereomicroscope can identify particles as small as micrometers (mm). This approach may swiftly identify samples with a relatively high quantity of big microplastics, giving a fast and inexpensive image of the abundance of microplastics. The samples' nature cannot be ascertained, hence the identification techniques described below must be used in conjunction with them (Li et al., 2018).

B. Spectroscopic Method

FTIR

The content and molecular structure of a material determine the excitable vibrations that occur when samples are exposed to infrared light within a certain range. Plastic polymers have unique band patterns and very distinctive infrared spectra. ATR-FTIR may be used to investigate particles larger than 500 mm. FTIR combined with microscopy can study particles as small as 20 mm. Techniques based on FTIR are non-destructive. They are dependable, quick, and well-established. The recently developed automated FTIR imaging, like FPA, allows for the quick capture of thousands of spectra within a region with a single measurement and significantly reduces the analysis time. Samples must be IR-active; those that are less than 20 mm may not produce sufficient absorbance for interpretable spectra. It is challenging to evaluate non-transparent particles with this technology. The highly specialized devices are costly and need skilled personnel to operate and analyze data. The environmental matrix (such as biofilm growth on polymer) influences the detection, making data interpretation challenging. To get rid of IR active water, the sample has to be processed (Li et al., 2018).

Raman Spectroscopy

When compared to the irradiating laser, the frequency of the back-scattered light varies due to the interaction of the irradiated laser light with the sample's molecules and atoms. Substance-specific Raman spectra may be obtained by detecting the Raman shift. The Raman Spectroscopy (RS) approach paired with microscopy is appropriate for particles larger than one millimeter. For particles that fall between 1 and 20 mm, it is the only technique accessible. Small particles between 1 and 20 mm may be analyzed with great spatial resolution and comparatively low sensitivity to water thanks to microscopy linked RS. The RS technique may be used to analyze dark and opaque particles; it can also be used for quick chemical mapping, which allows for quick and automated data gathering and processing. The detection of microplastics is hampered by significant fluorescence interference from biological, organic, and inorganic contaminants. Prior to analysis, the sample must be purified; proper Raman acquisition parameters, such as wavelength, laser intensity, and photo bleaching, are crucial. Micro-RS automated mapping is still being developed. RS's analysis takes a lot of time (Li et al., 2018).

Scanning Electron Spectroscopy

In order to quantify the secondary ions, an electron beam interacts with the sample to create the sample pictures. It is possible to investigate particles as small as the microscope. This technique may provide a high-resolution picture of the samples. There is no comprehensive identifying information available, and samples must be coated at high vacuum (Li et al., 2018).

C. Chromatographic Method

Thermo Analytical Methods such as Pyrolysis GC/MS

After thermally treating the samples in ambient circumstances, the liberated gaseous chemicals are captured and moved to a GC column that is connected to a quadrupole-MS. Next, a database of typical plastic kinds is compared to the spectra of the pyrolysis products. Samples larger than 500 mm that can be manually handled with tweezers are appropriate for this approach. Without the need for solvents, the sample and the organic plastic additives may be examined simultaneously, preventing background contamination. The technique is dependable and delicate. There is a collection of common polymer spectra data accessible. Each run can only evaluate one particle with a certain weight. The pyrolysis database is only accessible for certain polymers, including polypropylene and PE (Li et al., 2018).

Liquid Chromatography

Certain solvents are used to dissolve the samples. Size exclusion chromatography is used to assess different molar mass distributions, and HPLC analysis is used for quantification. For the chemical extraction to perform this test, a sufficient sample size of several milligrams is needed. Certain polymers have high recoveries. Its uses are limited to environmental samples due to limitations on polymer kinds and the inability to establish physical features, such as size information. Each run can only evaluate a certain number of samples. This approach can only evaluate certain types of polymers, such PS and PET (Li et al., 2018).

D. Other Methods

Tagging Method

When microplastics are exposed to blue light, hydrophobic dye adsorbs onto their surfaces and causes them to glow. It is possible to see and count microplastics with sample sizes as small as the microscale range. This simple technique enables quick and inexpensive microplastic screening. It is possible to count and identify the fluorescent particles. The dye may also stain other particles, such organic waste. This would cause the amount of microplastics to be overestimated (Li et al., 2018).

Table 4: Comparative Assessment of Analytical Methods for the Detection and Characterization of Microplastics in Wastewater

Detection Method	Detection Limit	Polymer Identification	Particle Size	Advantages	Limitations
FTIR	~20 μm	Excellent	>20 μm	Non-destructive, reliable polymer identification	Limited for particles <20 μm
Raman Spectroscopy	~1 μm	Excellent	1–20 μm	High spatial resolution, suitable for small particles	Fluorescence interference, expensive
Scanning Electron Spectroscopy	<1 μm	Partial (elemental analysis)	Nano–Micro	High-resolution morphology and elemental characterization	Cannot identify polymer type independently
Pyrolysis GC/MS	Bulk sample	Excellent	Bulk sample	Accurate polymer quantification and chemical composition	Destructive, requires complex sample preparation
Liquid Chromatography (HPLC)	Several mg of sample	Good (PS, PET)	Bulk sample	Quantitative polymer analysis with high recovery for selected polymers	Limited to specific polymers, cannot determine particle size or morphology, low sample throughput
Tagging Method	Microscale particles	Moderate	Microscale	Rapid, simple, inexpensive screening and visualization of microplastics	Non-specific dye binding may stain organic matter, leading to false positives and overestimation

Microplastics Removal Techniques

Microplastics are removed from wastewater using physical, chemical, biological, and sophisticated techniques. Skimming and gravity settling remove microplastics from primary, secondary, and tertiary wastewater treatment systems. Conventional methods may remove microplastics greater than 300 µm and 100 µm with up to 99.9% efficiency without increasing operating expenses. They cannot entirely remove microplastics below these sizes. Secondary treatment employing biological degradation and microbial growth systems can remove 95.6% of microplastics bigger than 20 µm (Singh et al., 2021). Biological treatment lowers microplastic content, however numerous tiny particles remain in the effluent, preventing total eradication. Advanced treatment methods enhance microplastic elimination. Techniques including ultrafiltration, microfiltration, nanofiltration, reverse osmosis, and chemical disinfection improve microplastic removal effectiveness, reaching 97.2% for particles bigger than 20 µm. Even with this enhancement, microplastics may not be retained. Microplastic removal is more efficient using membrane bioreactor (MBR) devices. The MBR method use biological treatment and membrane filtration to retain tiny particles and achieve up to 99.4% removal efficiency for particles above 20 µm. A study found that MBR systems eliminated 99.3% of particles above 250 µm and retained more microplastics than activated sludge systems (Acarer, 2023). The different techniques employed for microplastic removal from wastewater are described below:

Wastewater Treatment Plant Process

Wastewater treatment facilities can remove a substantial amount of microplastics successfully, with claimed removal efficiencies often surpassing 95%. Conventional treatment procedures may effectively remove bigger particles (>100–300 µm), but tiny microplastics are more difficult to catch. Advanced technologies like membrane bioreactors provide better removal efficiency because of the membrane filtering with efficiency more than 99%. However, it is still hard to completely remove all the tiny microplastics, suggesting that the technical level of wastewater treatment systems has to be improved (Lares et al., 2018).

Al and Fe salt Technique

Aluminium and iron salts were utilized as coagulants for particles less than 0.5 mm and the removal efficiency was $45.34 \pm 3.93\%$. The coagulation method is straightforward, requires no extra equipment or complicated setup and is suitable in wastewater treatment applications. However, the comparatively poor removal effectiveness is still a major drawback (Ma et al., 2021).

Electrocoagulation

Electrocoagulation (EC), a sophisticated physicochemical treatment method which eliminates pollutants mainly via charge neutralization and flocculation. In the process, sacrificial metal electrodes (usually aluminum or iron) create in situ coagulant species that destabilize suspended particles and encourage their aggregation into bigger flocs that can be readily removed from water. The procedure is very successful across a wide pH range with removal efficiencies of over 90% at pH 3–10 and 99.24% at pH 7.5 under optimized operational parameters. Unlike traditional coagulation procedures, electrocoagulation does not need the constant injection of chemical coagulants or microbes, thereby presenting an ecologically benign and energy-efficient treatment alternative. However, one of the main drawbacks of the method is the relatively lengthy operating period, which can impair the treatment efficiency in large-scale applications and raise the total operational expenses (Perren et al., 2018).

Filtration with biochar

Biochar filtration is a potential and cost-effective approach for eliminating microplastics from wastewater using a morphologically controlled filtering process, in which particles are trapped by adhering, trapping, and tangling inside the porous biochar structure. The approach is especially well-suited for the capture of microplastics on the order of 10 µm in size and can reach removal efficiencies more than 95% under optimized circumstances. The cheap cost of manufacture, great porosity and environmental friendliness make biochar an ideal filtering media. However, this procedure has numerous disadvantages: relatively slow filtering rate and increasing clogging of the filter pores during long-term operation, which leads to reduced treatment efficiency. In addition, regeneration and reuse of biochar filters may be difficult and expensive, which might hinder their large-scale implementation without suitable maintenance procedures (Z. Wang et al., 2020).

Filtration with granular activated carbon (combined with coagulation and sedimentation)

Filtration using granular activated carbon (GAC) is an efficient treatment method for the removal of microplastics from wastewater, and is commonly combined with coagulation and sedimentation. The mechanism focuses on the physical attributes of microplastics, such as form and size, which allow their trapping by adsorption and filtering inside the porous GAC media. It is especially effective for the removal of particles in the 1–5 μm size range. The observed removal efficiencies are around 56.8–60.9 %. GAC filtration may be an important aspect of sophisticated wastewater treatment systems since it has a key benefit of successfully trapping nano-sized plastic particles. However, the process is somewhat sluggish and extended operation might result in pore blockage causing a reduction in filtering effectiveness. Additionally, regeneration of wasted activated carbon is difficult and expensive from a technological standpoint, which may restrict its long-term economic viability for large scale applications (Z. Wang et al., 2020).

Pulse clarification with filtration

The wastewater treatment technique of pulse clarification with filtration mainly eliminates microplastics by trapping in the sludge blanket created by coagulation flocs. During treatment, dispersed microplastic particles are absorbed into the sludge matrix and then removed by filtering. This process is highly efficient for removing microplastics of less than 100 μm and removal efficiency has been reported to be in the order of 85%. One of the main benefits is that its removal performance is similar to sophisticated wastewater treatment technologies and hence may be a feasible choice to improve microplastic removal in traditional treatment facilities. However, a key constraint is the inability to achieve total retention of microplastics since some tiny particles might get through the treatment process requiring further polishing stages to improve overall removal effectiveness (Sadia et al., 2022).

Algal Masses

The use of algal biomass has been developed as an ecologically acceptable and sustainable solution for microplastics removal of wastewater. The removal process is mainly driven by electrostatic interactions, where microplastic particles attach to the surfaces of algal biomass due to electrostatic attraction and subsequent aggregation. The approach is efficient for the capture of microplastics with particle sizes of around 20 μm with removal effectiveness up to 94.5 %. An important benefit of this procedure is that it does not include chemical additives, electrical energy or sophisticated mechanical processes, and is thus a low-cost and environmentally friendly treatment alternative. However, its efficacy may vary significantly depending on the physiological features of the algae and the surface topology (topography) of the seaweed or algal biomass, which might affect the adsorption capacity and total removal efficiency (Sundbaek et al., 2018).

Bioinspired molecules

Bioinspired molecules for microplastics removal from wastewater: a new and unique technique. The technique relies on a mechanical capture mechanism powered by hydrophobic contacts and van der Waals forces that encourage selective adhesion and aggregation of microplastic particles. Unlike traditional treatment approaches, bioinspired molecules have the ability to collect a broad range of plastic particles of varying sizes, shapes and polymer compositions, allowing for great flexibility in wastewater treatment applications. The positive side of this strategy is its flexibility to target different microplastic pollutants in complicated wastewater streams. However, the technology is still in its infancy and its practical use has yet to be completely developed. More study is needed to ascertain if it is suitable for large-scale use, its longevity, cost-effectiveness and overall efficacy for practical wastewater treatment (Herbert & Schuhen, 2017).

Zr metal organic framework (MOF) based foams

Zirconium (Zr) metal–organic framework (MOF)-based foams are a novel kind of sophisticated adsorbent material for the removal of microplastics from wastewater. The main process for the physical removal of microplastics is physical entrapment. The MOF foam is three-dimensional and very porous. During water filtration, the structure physically traps and holds the microplastic particles. The Zr MOF-based foams showed an excellent removal effectiveness of $95.5 \pm 1.2\%$, under optimized circumstances, emphasizing its significant potential for water purification. The materials show great removal ability and remarkable -

durability, mechanical stability and reusability, and are potential candidates for long-term wastewater treatment applications. However, the performance of these MOF foams is determined by the flexibility and structural resilience of the foam, as well as the particle size and zeta potential of the microplastics, which impact the particle–foam interactions and the overall capture efficiency. Hence, more optimization is necessary to provide a consistent performance across a broad variety of wastewater conditions (Chen et al., 2020).

Photocatalytic micromotors

Photocatalytic micromotors are a new and sophisticated method for removing microplastics from wastewater. They are removed via a technique based on phoretic interactions and a shoveling/pushing effect, by which self-propelled micromotors actively transfer and concentrate the microplastic particles by autonomous movement. Unlike traditional passive filtration systems, photocatalytic micromotors create propulsion when irradiated by light, which allows for effective interaction with distributed microplastics without the need for any additional fuel. The self-propelled behaviour increases the collection efficiency of the particles and makes the technique especially promising for the treatment of dilute wastewater streams. One of the primary advantages of photocatalytic micromotors is their autonomous operation and high mobility, which enable them to work effectively and independently of chemical fuels. However, the selectivity of the micromotors for various kinds of microplastics remains a key hurdle, with particle size, surface chemistry and polymer composition all considerably affecting the effectiveness of capture. Hence, more efforts are still required to increase their selectivity, scalability and practical use for large scale wastewater treatment (L. Wang et al., 2019).

Table 5: Comparative Evaluation of Conventional and Advance Technologies for Microplastic Removal from Wastewater

Technology	Removal Efficiency	Performance	Cost	Advantages	Limitations	Reference
Conventional Wastewater	>95% (>100 - 300 μm)	High	Medium	Commercially	Inefficient for very	Lares et al., 2018
Al and Fe Salt	45.34 $\pm$ 3.93%	Low	Low	Simple operation,	Low removal	Ma et al., 2021
Electrocoagulation	>90%; up to 99.24%	Very High	Medium	High removal	Long treatment	Perren et al., 2018
Biochar Filtration	>95%	High	Low	Sustainable, inexpensive,	Filter clogging,	Z. Wang et al., 2020
Granular Activated	56.8–60.9%	Moderate	Medium	Removes small	Moderate efficiency,	Z. Wang et al., 2020
Pulse Clarification	~85%	Moderate–High	Medium	Easy integration	Requires polishing	Sadia et al., 2022
Algal Biomass	Up to 94.5%	High	Low	Sustainable, chemical-	Performance depends on	Sundbaek et al., 2018
Bioinspired Molecules	Not fully established	Promising (Experiment	High	Selective capture of	Early-stage technology,	Herbort & Schuhen,
Zr-MOF-Based	95.5 $\pm$ 1.2%	Very High	High	High efficiency,	High material	Chen et al., 2020)

Impact of Microplastics on Human Health

Inflammation

Exposure to microplastics may cause inflammation in several organs. Both in vitro and in vivo studies reveal that microplastics activate immune cells causing local tissue injury and systemic inflammation. For example, gastrointestinal exposure may result in lesions and altered immune signaling pathways, whereas inhaled microplastics may cause pulmonary inflammation. Wright and Kelly (2017) have pointed out that long-term exposure to airborne and ingested microplastics may worsen pre-existing inflammatory disorders in people. Also, Barboza et al. (2018) emphasized the persistent low-grade inflammation that may be caused by the ingestion of seafood contaminated with microplastics, which has consequences for food safety and human health.

Table 6: Technologies for Different Wastewater Types Based on Microplastic Removal Performance

Wastewater Type	Recommended Technology	Reason	Reference
Municipal	MBR + Biochar	High efficiency and scalability	(Allahkarami et al., 2025)
Textile	Electrocoagulation	High suspended solids	
Industrial	MOF + Membrane	Small particles	
Drinking Water	Activated Carbon + UF	Low residual MPs	
Rural Areas	Biochar	Low cost	

Oxidative Stress

Microplastics stimulate the generation of reactive oxygen species (ROS), resulting in oxidative stress that impairs cellular metabolism and induces DNA damage, lipid peroxidation, and mitochondrial dysfunction. Prata (2018) emphasized the contribution of airborne microplastics to the generation of reactive oxygen species (ROS), which may be implicated in respiratory and cardiovascular disorders. Li, Ding, Cheng, Sheng, Xu, Rong, Wu, Zhao, Ji, Zhang, and Wang (2020) showed that polyethylene microplastics modified gut microbiota and heightened inflammation in mice, directly associating oxidative stress with gastrointestinal diseases.

Endocrine Disruption

Phthalates and bisphenol A (BPA), two chemical compounds often found in plastics, may seep from microplastic particles and disrupt endocrine signaling. These substances cause growth, reproductive, and metabolic problems by imitating or blocking natural hormones. In 2015, Trasande, Zoeller, Hass, Kortenkamp, Grandjean, Myers, DiGangi, Bellanger, Hauser, Legler, Skakkebaek, Heindel, and Sathyanarayana calculated the substantial economic and health costs associated with endocrine-disrupting chemicals in the EU. According to Sharma and Chatterjee (2017), these disturbances may also affect the control of reproductive hormones and thyroid function, which might be dangerous for future generations.

Reproductive Effects

Microplastics have a deleterious effect on reproductive health, according to new research. Microplastic exposure reduces fertility, alters embryonic development, and decreases sperm motility, according to animal research. Prenatal and perinatal exposures to microplastics may cause long-term health problems, according to a review of the literature by Hu, Xu, Huang, Zhou, Zhang, Zhang, and Wang (2024) on the reproductive and developmental toxicity of microplastics in animals. The initial evidence of microplastics in human placental tissues, dubbed "plasticenta," was presented by Ragusa, Svelato, Santacroce, Catalano, Notarstefano, -

Carnevali, Papa, Rongioletti, Baiocco, Draghi, D'Amore, Rinaldo, Matta, and Giorgini (2021), which is highly significant because it raises questions regarding fetal exposure and its potential unknown effects.

Neurological Effects

Inducing neuroinflammation, changing neurotransmitter signaling, and impairing cognitive function may be possible outcomes of microplastics reaching brain tissue, according to recent research. In urban populations in particular, Prata (2018) pointed out that airborne exposure is a significant pathway for neurotoxicity. A group of researchers led by Leslie, van Velzen, Brandsma, Vethaak, Garcia-Vallejo, and Lamoree (2022) found microplastics in human blood, which may be a sign of systemic transport leading to potential exposure of sensitive organs including the brain. In sum, these results point to the fact that microplastics are a serious problem for both the environment and public health. We must immediately and thoroughly investigate their hazardous processes and their long-term health repercussions due to their chronic exposure, bioaccumulation in human tissues, and capacity to generate systemic effects (Thornton Hampton et al., 2022)

Table 7: Impact of Microplastics on Human Health

Health Effect	Mechanism of Microplastic Toxicity	Reported Impacts	Key References
Inflammation	In tissues and organs, microplastics cause inflammatory reactions and immune cell activation.	Lung inflammation, altered immunological signaling, gastrointestinal lesions, and exacerbation of long-term inflammatory diseases.	(Unuofin & Igwaran, 2023)
Oxidative Stress	Reactive oxygen species (ROS) are produced more often when microplastics are present, which damages cells.	Respiratory and cardiovascular conditions, altered gut microbiome, mitochondrial dysfunction, DNA damage, and lipid peroxidation.	(Prata, 2018a) (Talbot & Chang, 2022)
Endocrine Disruption	Hormonal systems are disrupted by chemical additions like BPA and phthalates that seep from microplastics.	Transgenerational dangers, thyroid dysfunction, metabolic imbalance, reproductive issues, and poor hormone control.	(Hu et al., n.d.) (Sharma & Chatterjee, 2017)
Reproductive Effects	Microplastics have an impact on fetal and embryonic development and	Reduced fertility, altered embryonic development, decreased sperm motility, and possible health hazards throughout pregnancy and the postnatal period.	(Devi & Lakshmi, 2025)
Neurological Effects	Microplastics have the ability to get through biological barriers and cause neurotransmitter disruption and neuroinflammation.	Neurotoxicity, systemic distribution via blood circulation, cognitive impairment, and potential buildup of brain tissue.	(Prata, 2018b) Leslie et al., 2022)

Research Suggestions for Characterizing Microplastic Hazards:



Fig. 4. Suggestions for Characterizing Microplastic Hazards

Table 8: Suggestions for Characterizing Microplastic Hazards

Recommendations	Focus	Key References
Suggestions 1. Determine which microplastic properties, via thorough particle characterization and toxicity tests, best predict risks.	Determine which microplastic properties, via thorough particle characterization and toxicity tests, best predict risks.	(Thornton Hampton et al., 2022)
Suggestions 2. Conducting toxicity testing using polydisperse, ecologically realistic distributions of microplastic particles can help better describe microplastic risks.	Conducting toxicity testing using polydisperse, ecologically realistic distributions of microplastic particles can help better describe microplastic risks.	
Suggestions 3. Create trials that provide reliable dose-response data for the formulation of health-based thresholds.	Create trials that provide reliable dose-response data for the formulation of health-based thresholds.	
Suggestions 4. Connect microplastics to current or new adverse outcome pathways (AOPs).	Link microplastics to new or current adverse outcome pathways (AOPs).	
Suggestions 5. By creating a framework for extrapolating in vitro findings to in vivo consequences, you may increase the relevance of in vitro research for hazard characterization.	By creating a framework for extrapolating in vitro findings to in vivo consequences, you may increase the relevance of in vitro research for hazard characterization.	
Suggestions 6. Describe the pathways of understudied microplastic exposure.	Describe the pathways of understudied microplastic exposure.	

Conclusion

The growing prevalence of microplastics in aquatic habitats highlights the urgent need for effective detection methods, modern wastewater treatment technologies, and comprehensive risk assessment frameworks to protect ecosystem and human health. This study shows that although traditional wastewater treatment facilities are successful in removing bigger microplastic particles, they are still unable to remove smaller microplastics and nanoplastics, which permits their ongoing release into natural water bodies. Membrane bioreactors, electrocoagulation, charcoal filtration, photocatalytic systems, metal-organic framework (MOF)-based adsorbents, and bioinspired materials are examples of advanced treatment methods that show significant promise for increasing removal efficiency. However, issues including high operating costs, energy needs, membrane fouling, and poor long-term performance restrict their widespread use. The study also emphasises how difficult it is to accurately identify and quantify microplastics since no one analytical method can fully characterise all particle sizes and polymer types. To increase data dependability and comparability across research, standardised sampling, extraction, and analysis procedures are crucial. Furthermore, the necessity for thorough toxicological studies and health risk assessments is highlighted by mounting data connecting microplastic exposure to inflammation, oxidative stress, endocrine disruption, reproductive toxicity, and neurological diseases. Future wastewater management should transition from single-treatment approaches to integrated intelligent treatment systems combining AI-assisted monitoring, standardized analytical protocols, advanced hybrid removal technologies, and health-based risk assessment to achieve sustainable microplastic and nanoplastic mitigation.

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