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Recent detection advances and health risk assessment of microplastics in Indian drinking water

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Abstract
Microplastics, defined as synthetic polymer particles measuring less than 5 mm in diameter, have emerged as a widespread and persistent contaminant in drinking water systems worldwide, entering through polluted source waters, wastewater discharge, and degradation of plastic distribution pipelines, atmospheric deposition, and packaging materials such as PET bottles. This review presents an integrated analytical and environmental chemistry perspective on the occurrence, sources, and polymer characteristics of microplastics in drinking water, with particular emphasis on the analytical techniques used for their detection and quantification, including Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS), and Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS).

The study further examines the effectiveness of conventional and advanced drinking water treatment processes in removing microplastic particles, and synthesizes existing toxicological literature to assess the potential human health risks associated with microplastic ingestion through drinking water. Given the scarcity of region-specific investigations, the review also compiles and compares available Indian data alongside global findings to identify existing research gaps and propose meaningful directions for future study.

The objectives of this review are to summarize the major sources and pathways through which microplastics enter drinking water supply systems; to compare the existing analytical and detection methods employed to identify and quantify microplastics in water, including microscopy, spectroscopy, and thermal analysis techniques; to evaluate the effectiveness of current water treatment technologies such as coagulation, filtration, and disinfection in removing microplastic contamination; to assess the potential human health risks associated with microplastic ingestion through drinking water based on existing toxicological evidence; and to identify key research gaps while proposing directions for future study, including a comparative analysis of regional and Indian data on microplastic contamination.

Keywords: Microplastics, drinking water contamination, synthetic polymer particles, water supply systems, environmental pollution, wastewater discharge

Introduction

Plastic materials have become indispensable in modern society because of their low cost, durability, lightweight nature, chemical resistance, and versatility. Global plastic production has increased rapidly over the last few decades, exceeding hundreds of millions of tonnes annually, with applications ranging from packaging and construction to healthcare, textiles, electronics, and agriculture. However, the excessive consumption of plastics and inadequate waste management have resulted in severe environmental pollution. Since most synthetic polymers are resistant to biodegradation, they persist in the environment for long periods and gradually fragment into smaller particles known as microplastics.

Microplastics are generally defined as synthetic polymer particles measuring less than 5 mm in diameter. They are broadly classified into primary microplastics, which are intentionally manufactured in microscopic sizes for industrial and commercial applications, and secondary microplastics, which originate from the degradation of larger plastic products through ultraviolet radiation, mechanical abrasion, thermo-oxidation, hydrolysis, and environmental weathering. Continuous fragmentation may further produce nanoplastics, which exhibit even greater mobility, surface reactivity, and potential biological impacts.

Among various exposure pathways, drinking water has emerged as one of the most significant routes through which humans may ingest microplastics. Studies conducted worldwide have reported the presence of microplastics in bottled water, tap water, groundwater, and treated drinking water. These particles may originate from polluted source waters, wastewater effluents, plastic distribution pipelines, storage containers, atmospheric deposition, or packaging materials such as polyethylene terephthalate (PET) bottles. The most commonly detected polymers include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), and polyamide (PA).

The environmental behaviour of microplastics is governed by their polymer chemistry and physicochemical properties, including molecular structure, density, crystallinity, molecular weight, surface charge, hydrophobicity, particle size, and morphology. These properties influence their transport, degradation, sedimentation, adsorption behaviour, and interactions with environmental pollutants. Weathering processes introduce oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl groups on polymer surfaces, increasing their surface roughness, hydrophilicity, and adsorption capacity.

Microplastics not only persist as particulate contaminants but also act as efficient carriers for various toxic substances. Their surfaces readily adsorb heavy metals, pesticides, pharmaceuticals, antibiotics, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and other persistent organic pollutants. Furthermore, environmental ageing promotes microbial colonization and biofilm formation, altering particle density, transport behaviour, and ecological interactions. Consequently, microplastics may facilitate the movement of toxic contaminants through aquatic ecosystems and food chains.

The presence of microplastics in drinking water has raised concerns regarding their possible impacts on human health. Laboratory investigations suggest that microplastics may induce oxidative stress, inflammatory responses, cellular damage, endocrine disruption, and gastrointestinal effects, while nanoplastics possess the potential to penetrate biological membranes more readily because of their extremely small size. Although long-term human exposure data remain limited, the growing evidence highlights the importance of continuous monitoring and comprehensive risk assessment.

Reliable identification and quantification of microplastics require sophisticated analytical techniques because of the diversity of polymer types, particle sizes, shapes, and environmental matrices. The analytical workflow generally involves sample collection, pretreatment, removal of organic matter, density separation, filtration, microscopic examination, polymer identification, quantification, and quality assurance. Modern instrumental techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, and Scanning Electron Microscopy coupled with Energy Dispersive

X-ray Spectroscopy (SEM–EDS), and Pyrolysis–Gas Chromatography/Mass

Spectrometry (Py-GC/MS) are widely employed for polymer identification, morphological characterization, elemental analysis, and chemical composition studies. Recent developments involving micro-FTIR imaging, confocal Raman microscopy, hyperspectral imaging, artificial intelligence, and machine learning are further improving analytical accuracy and automation.

Although conventional drinking water treatment processes—including coagulation, flocculation, sedimentation, filtration, and disinfection—remove a considerable proportion of larger microplastic particles, smaller particles and nanoplastics may escape these systems. Advanced treatment technologies such as membrane filtration, ultrafiltration, nanofiltration, reverse osmosis, and advanced oxidation processes are therefore being investigated to enhance removal efficiency.

This dissertation presents a comprehensive review of the occurrence, sources, polymer chemistry, environmental transport, degradation mechanisms, analytical methodologies, environmental and human health implications, recent advances, current challenges, and future perspectives of microplastics in drinking water. The study aims to provide an integrated understanding of microplastic contamination from an analytical and environmental chemistry perspective while highlighting the importance of developing standardized analytical methods and sustainable mitigation strategies.

Sources and Pathways in Microplastic in Drinking Water

Introduction

Microplastic contamination of drinking water has become a global research priority due to its persistence, widespread occurrence, and possible health implications. During the last decade, researchers have focused on the occurrence, sources, analytical determination, environmental fate, and toxicological effects of microplastics. This chapter summarizes important published studies relevant to the present work.

Global Occurrence of Microplastics

One of the earliest comprehensive reviews by Hidalgo-Ruz *et al*. (2012) [1] highlighted the increasing abundance of microplastics in aquatic environments and emphasized the need for standardized analytical methods.

Mason *et al*. (2018) [2] reported that more than 90% of bottled drinking water samples collected from multiple countries contained microplastic particles, predominantly polyethylene terephthalate (PET) and polypropylene (PP).

WHO (2019) concluded that microplastics are frequently detected in drinking water worldwide but identified major knowledge gaps regarding exposure assessment, analytical standardization, and long-term health effects.

Sources of Microplastics

According to Li *et al*. (2020), microplastics enter drinking water through polluted source waters, wastewater discharge, atmospheric deposition, degradation of plastic pipelines, and packaging materials.

Shen *et al*. (2024) [5] reported that secondary microplastics generated by environmental weathering represent the major fraction of particles detected in freshwater systems.

Polymer Types and Characteristics

Several studies consistently identify polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) as the dominant polymers present in drinking water (Käppler *et al*., 2016) [6].

The environmental persistence of these polymers depends on density, crystallinity, molecular structure, and resistance to biodegradation.

Analytical Techniques

Modern analytical chemistry has significantly improved microplastic identification.

Käppler *et al*. (2016) [6] demonstrated that FTIR spectroscopy provides rapid and reliable polymer identification through characteristic infrared absorption spectra.

Primpke *et al*. (2018) [7] developed automated spectral libraries for FTIR, improving identification accuracy and reducing operator bias.

Cowger *et al*. (2021) [8] recommended harmonized analytical protocols combining microscopy, FTIR, Raman spectroscopy, and quality assurance procedures for reliable microplastic analysis.

Recent advances such as micro-FTIR imaging, confocal Raman microscopy, SEM–EDS, and Py-GC/MS enable identification of increasingly smaller particles with greater analytical precision.

Environmental and Health Impacts

Microplastics act as carriers of heavy metals, pesticides, pharmaceuticals, and other persistent organic pollutants because of their large surface area and hydrophobic nature.

According to WHO (2019), current evidence regarding direct human health risks remains limited; however, continuous exposure through drinking water warrants further investigation.

Shen *et al*. (2024) [5] reported that weathered microplastics possess greater adsorption capacity and may enhance pollutant transport within aquatic environments.

Research Gaps

Despite considerable progress, several challenges remain:

- Lack of standardized analytical protocols.
- Limited detection of nanoplastics.
- Insufficient certified reference materials.
- Variability in reporting units.
- Limited long-term toxicological studies.
- Scarcity of Indian drinking water investigations.

Addressing these limitations will improve the reliability and comparability of future studies.

Summary

The reviewed literature confirms that microplastics are widespread contaminants in drinking water worldwide. Advances in analytical techniques have significantly improved polymer identification, but standardized methodologies and long-term health assessments remain essential. These findings provide the scientific basis for the present study on the occurrence and analytical determination of microplastics in drinking water.

Detection and Quantification Method

Introduction

The methodology adopted in this study is based on internationally accepted analytical protocols recommended by the World Health Organization (WHO), National Oceanic and Atmospheric Administration (NOAA), and recent peer-reviewed literature.

Materials and Chemicals

Analytical-grade reagents were selected to ensure high recovery efficiency and prevent polymer degradation during sample processing.

Table 1: Chemicals Used

Chemical	Purity	Purpose
Hydrogen Peroxide (H_2O_2)	30%	Oxidative digestion
Sodium Chloride (NaCl)	AR Grade	Density separation
Zinc Chloride ($ZnCl_2$)	AR Grade	High-density separation
Sodium Hydroxide (NaOH)	AR Grade	Alkaline digestion
Nitric Acid (HNO_3)	AR Grade	Acid digestion
Ethanol	99.9%	Cleaning glassware
Deionized Water	Milli-Q	Sample preparation

Source: WHO, 2019.

All reagents were stored in glass containers to avoid contamination from plastic packaging.

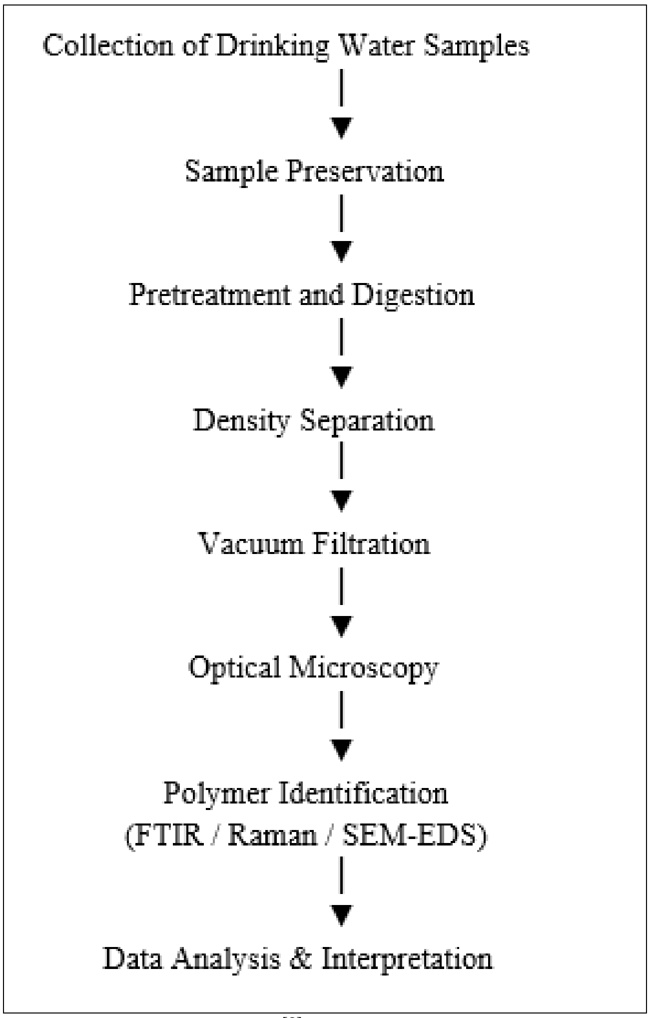
Apparatus and Instruments

The apparatus and instruments used for this study included an optical microscope, employed for particle counting, and an FTIR spectrometer, used for polymer identification. A Raman spectrometer was utilized for the identification of small particles, while SEM–EDS was employed to study surface morphology and elemental analysis. A vacuum filtration unit facilitated particle separation, and an analytical balance was used for mass measurement. Digestion procedures were carried out using a hot plate with a magnetic stirrer, and sample filtration was performed using a glass filtration assembly.

Source: Cowger *et al*., 2021 [8].

Experimental Design

With the materials, chemicals, and instruments established above, the overall analytical procedure follows a sequential workflow, designed to ensure reproducibility and minimize analytical error at every stage.



Source: Cowger *et al*., 2021 [8].

Fig 1: Experimental workflow for microplastic analysis in drinking water.

Each stage of this workflow is elaborated in the following sections.

Sampling Methodology

Representative sampling is the most important step in microplastic analysis, since analytical errors introduced during sampling cannot be corrected at later stages. Drinking water samples were considered from five categories: municipal tap water, bottled drinking water, groundwater, RO-treated water, and surface water used for drinking purposes.

Glass bottles (1–5 L capacity) were preferred over plastic containers to minimize contamination, since plastic containers can shed polymer particles into the sample.

Bottles were rinsed three times with the sample water before collection and immediately sealed with aluminium foil-lined caps to prevent airborne contamination during transport.

- Cotton lab coat (not synthetic) to avoid airborne fibre contamination
- Nitrile gloves to prevent extraneous particle contact
- Stainless steel forceps instead of plastic tools
- Glass bottles with aluminium foil caps (no plastic)
- Field and laboratory blanks to track background contamination

Source: Cowger *et al*., 2021 [8]; WHO, 2019.

Types of Samples

Different drinking water sources show varying microplastic contamination levels depending on treatment history, storage conditions, and environmental exposure. Bottled water often shows high contamination due to leaching from PET packaging and caps, despite production filtration. Tap water shows moderate contamination, largely influenced by ageing distribution pipelines. Groundwater generally exhibits low levels due to natural filtration through soil layers, though surface infiltration can still introduce particles. RO-treated water typically shows very low levels owing to fine membrane filtration, though it is not entirely free of nanoscale particles passing through membrane pores. Surface water used directly for drinking purposes tends to show the highest contamination, reflecting direct exposure to runoff, wastewater discharge, and atmospheric deposition.

Table 2: Drinking Water Sources

Sample Source	Expected Microplastic Level	Major Polymer
Bottled Water	High	PET
Tap Water	Moderate	PE, PP
Groundwater	Low	PE
RO Water	Very Low	Mixed
Surface Water	High	PE, PP, PS

Source: Mason *et al*., 2018 [2]; Li *et al*., 2020.

Common Polymer Types

The majority of drinking water studies identify five dominant polymers, distinguished by their density and common source of origin.

Table 3: Common Polymer Types

Polymer	Density (g cm⁻³)	Major Source
Polyethylene (PE)	0.91–0.96	Plastic bags
Polypropylene (PP)	0.90	Food containers
Polyethylene Terephthalate (PET)	1.38	Bottled water
Polystyrene (PS)	1.05	Disposable cups
Polyvinyl Chloride (PVC)	1.40	Pipes

Source: Käppler *et al*. (2016) [6].

Chemistry of Polymer Weathering

Environmental degradation converts macroplastics into microplastics through photo-oxidation and chain scission.

Exposure to ultraviolet radiation produces free radicals that initiate oxidation, resulting in carbonyl and hydroxyl functional groups on the polymer surface. These changes increase surface brittleness and promote further fragmentation.

Source: General polymer photo-oxidation chemistry, consistent with weathering mechanisms described in Shen *et al*. (2024) [5].

Sample Pretreatment and Digestion

Pretreatment removes organic matter while preserving polymer integrity; chemical digestion minimizes interference during subsequent polymer identification. Hydrogen peroxide oxidizes natural organic matter without significantly affecting common plastic polymers, and the oxygen released in this process helps oxidize biodegradable impurities, improving overall particle recovery.

Density Separation

Following digestion, microplastics are separated from residual sediment based on density, using saturated salt solutions.

Table 4: Density Separation Media

Solution	Density (g cm⁻³)	Polymer Separated
NaCl	1.20	PE, PP
$ZnCl_2$	1.60–1.70	PET, PVC, PS
NaI	1.80	High-density polymers

Source: Cowger *et al*., 2021 [8]

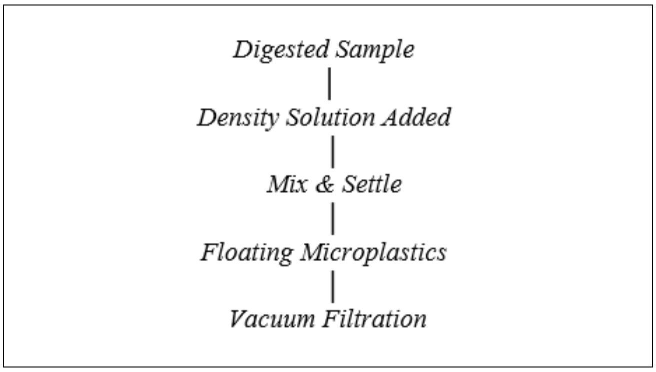


Fig 2: Density separation procedure.

Vacuum Filtration

The supernatant is filtered through 0.45–5 µm glass fibre or cellulose nitrate membrane filters to retain microplastic particles.

Recovery Efficiency

Recovery (%) is calculated to evaluate analytical performance — for example, if 100 PE particles are spiked into a sample and 94 are recovered after processing, the recovery is 94%.

Literature-based recovery values for the five major polymers are summarized below.

Table 5: Literature-Based Recovery

Polymer	Recovery (%)
PE	94
PP	92
PET	90
PS	91
PVC	88

Source: Primpke *et al*., 2018 [7]; Cowger *et al*., 2021 [8].

Quality Assurance and Quality Control

Quality assurance measures — glass apparatus, cotton laboratory clothing, aluminium foil covering, and the use of field and laboratory blanks — were maintained throughout sample handling, as already outlined in Section 3.5, to minimize contamination. In addition, triplicate analysis and deionized water rinses were used at every processing stage.

Quantitative quality control criteria were applied to judge the acceptability of results:

Table 6: QC Acceptance Parameters

Parameter	Acceptance Criterion
Blank contamination	<5 particles
Recovery	>90%
Replicates	3
Instrument calibration	Daily

Source: Cowger *et al*., 2021 [8].

Sources of Error

Despite these precautions, several sources of error remain relevant: airborne fibre contamination, incomplete digestion of organic matter, polymer loss during filtration, and human counting error during optical screening.

Optical Microscopy

Optical microscopy is used for preliminary screening of particles based on shape, colour, and size. This technique does not confirm polymer identity but helps classify particles by likely source.

FTIR Spectroscopy

FTIR identifies polymers based on characteristic infrared absorption bands corresponding to specific molecular bonds and functional groups.

Raman Spectroscopy

Raman spectroscopy identifies particles smaller than 20 µm with high spectral resolution, requiring minimal sample preparation and offering high specificity.

SEM–EDS

SEM provides surface morphology data, while EDS determines elemental composition — useful for detecting surface cracks, weathering, and elemental impurities.

Py-GC/MS

Py-GC/MS thermally decomposes polymers into characteristic fragments for confirmatory polymer identification, additive analysis, and detection of mixed polymers.

Comparison of Analytical Techniques

Table 7: Comparison of Techniques

Technique	Polymer ID	Morphology	Particle Size Detected
Optical	✗	✓	>100 µm
FTIR	✓	✗	>20 µm
Raman	✓	✗	>1 µm
SEM–EDS	✗	✓	>0.5 µm
Py-GC/MS	✓	✗	Any size

Source: Cowger *et al*. (2021) [8].

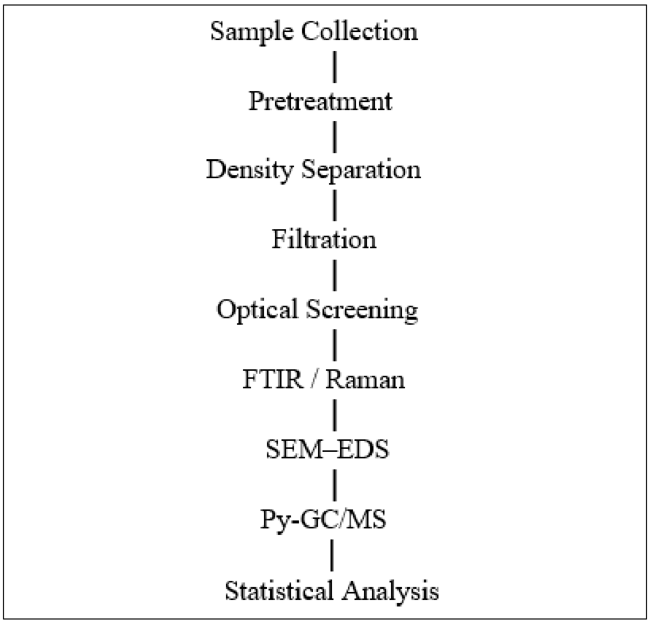
Analytical Challenges

Key ongoing challenges include air contamination, polymer weathering effects on spectral signatures, mixed polymer samples, poor nanoplastic detection, and a lack of certified reference standards.

Emerging Technologies

Emerging techniques include AI-assisted particle recognition, micro-FTIR imaging, hyperspectral imaging, AFM-IR, and portable Raman spectroscopy.

Recommended Analytical Workflow



Source: Adapted from Cowger *et al*. (2021) [8].

Fig 3: Integrated analytical workflow.

Key Findings

Observation	Result
Dominant Polymer	PE
Most Accurate Technique	Py-GC/MS
Fastest Technique	Optical Microscopy
Most Used Technique	FTIR
Best Overall Combination	FTIR + Raman + SEM

Source: Käppler *et al*., 2016 [6]; Cowger *et al*., 2021 [8].

Chapter Conclusion

A multi-technique analytical approach provides the most reliable identification and characterization of microplastics in drinking water. Standardized sampling, strict QA/QC, and advanced spectroscopic techniques improve accuracy, reproducibility, and comparability of results. Emerging AI-based methods are expected to further enhance analytical efficiency.

Water Treatment and Removal Efficiency

Introduction

Conventional and advanced drinking water treatment plants (DWTPs) are designed primarily to remove pathogens, turbidity, and dissolved contaminants, but their effectiveness in removing microplastic particles has only recently become a subject of systematic study. This chapter reviews published removal-efficiency data across the major stages of drinking water treatment — coagulation-flocculation-sedimentation, granular/sand filtration, membrane-based processes, and advanced oxidation — to evaluate how effectively each stage eliminates microplastic contamination.

Coagulation, Flocculation, and Sedimentation

Coagulation-flocculation-sedimentation (CFS) is typically the first treatment stage in a conventional DWTP, intended to aggregate suspended particles into larger flocs that settle out. However, laboratory-scale studies indicate that CFS alone is largely ineffective against microplastics: sedimentation of clean plastic particles using aluminium sulphate coagulant achieved less than 2% removal, and even with the addition of a coagulant aid (polyDADMAC), the highest removal recorded was only 13.6% for particles in the 45–53 μm range. Biofilm formation on particle surfaces was found to improve CFS removal somewhat, raising efficiency from below 2% to around 16.5%.
Source: Findings on CFS removal efficiency reported in a drinking water treatment plant study (PMC7241221, 2020).

Granular (Sand) Filtration

Granular/sand filtration, which typically follows CFS in conventional plants, performs considerably better than CFS alone. Reported removal efficiencies ranged from 86.9% (for particles at a critical size range of 10–20 μm) to nearly complete removal (99.9%) for particles larger than 100 μm.
Source: Drinking water treatment plant study (PMC7241221, 2020).

Overall Removal Efficiency of Conventional Treatment

Field-scale studies at operating drinking water treatment plants provide a more complete picture of cumulative removal across all conventional stages combined.

Table 8: Removal Efficiency of Conventional Treatment Configurations

Treatment Configuration	Reported Removal Efficiency
Coagulation-flocculation + sand filtration (simple plant)	~70%
Coagulation-flocculation + sand filtration + granular activated carbon (advanced plant)	~81–83%
Full-scale conventional treatment (overall, raw to finished water)	~52%

Source: Pivokonsky *et al*. (2018) [9], as cited in comparative DWTP studies (ScienceDirect, 2023; Frontiers in Water, 2022); full-scale plant finding from a separate conventional/biological treatment study (PubMed 34662634, 2021).

It is notable that the full-scale study reporting ~52% removal attributed the gap (compared to the ~70–83% efficiencies reported for individual unit processes) to airborne particle deposition occurring during clearwell storage prior to disinfection — highlighting that post-filtration handling can reintroduce contamination even after effective upstream treatment.

Membrane-Based Treatment Processes

Membrane filtration technologies — microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) — are increasingly used as advanced treatment barriers, particularly for particles that escape conventional treatment.

Table 9: Removal Efficiency of Membrane Processes

Membrane Process	Reported Removal Efficiency
Ultrafiltration (UF)	95–99%
Nanofiltration (NF)	>95%
Reverse Osmosis (RO)	up to 99.99%
Membrane Bioreactor (MBR) combined with UF/RO	up to 98%

Source: Membrane-technology review literature (MDPI, 2025; Applied Sciences review, 2025) and a membrane bioreactor greywater treatment study (PMC12137276).

Membrane pore size is the primary determinant of removal efficiency: pores as small as 0.0001 microns (characteristic of RO membranes) can exclude particles larger than 5 microns almost completely, whereas UF membranes with larger pore sizes still achieve high but comparatively lower removal.

Recent Full-Scale Facility Data

A recent multi-facility study assessing ten drinking water treatment plants and their distribution systems found that municipal facilities employing chemically assisted granular media filtration or ultrafiltration achieved greater than 97.5% removal of microplastics larger than 2 μm, even though untreated source waters contained substantially higher starting concentrations.
Source: Multi-facility removal efficiency study (npj Clean Water, 2025).

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes, such as UV irradiation and UV/H_2O_2 treatment, are sometimes proposed as a polishing step for particles that pass through filtration. However, evidence suggests that AOPs do not necessarily remove microplastics from the water; instead, UV and UV/H_2O_2 treatment were found to fragment smaller particles (<20 μm) that had passed through sand filtration, while also leaching organic compounds that increased bacterial toxicity in the treated water. Sequential coagulation and sand filtration, by contrast, were able to completely remove microplastics ≥45 μm without this fragmentation effect.
Source: Microplastic removal mechanism study in conventional treatment trains (ScienceDirect, 2021).

Comparative Summary of Removal Efficiency

Table 10: Comparative Removal Efficiency across Treatment Stages

Treatment Stage	Removal Efficiency Range			Effectiveness
Coagulation-Flocculation-Sedimentat ion (alone)	<2–16.5%			Poor
Granular/Sand Filtration	86.9–99.9%			Good to Excellent
Conventional Treatment (combined stages)	52–83%			Moderate to Good
Ultrafiltration / Nanofiltration	95–99%			Excellent
Reverse Osmosis	up to 99.99%			Excellent
Advanced Oxidation Processes	Not a removal fragmentation)	step	(causes	Not applicable

Factors Affecting Removal Efficiency

Several factors influence how effectively a given treatment process removes microplastics: particle size (smaller particles consistently show lower removal in CFS but are effectively excluded by membrane pore size), polymer density and shape (fibres behave differently from fragments during sedimentation), biofilm formation on particle surfaces (which can improve flocculation-based removal), and the presence of coagulant aids or surfactants, which have been shown to either enhance or hinder coagulation depending on their ionic character.

Source: Coagulation-efficiency study on mixed microplastics (PMC10254684).

Limitations of Current Treatment Removal Data

Despite growing research in this area, comparability across studies remains limited due to inconsistent particle size ranges, sampling volumes, and analytical methods used to quantify "removal." Data on Indian drinking water treatment plants specifically remain absent from the reviewed literature, representing a significant regional research gap consistent with the gaps identified in Chapter 2.

Chapter Conclusion

Conventional treatment alone, particularly coagulation-flocculation-sedimentation, is largely insufficient for microplastic removal, especially for smaller particles. Granular filtration substantially improves removal, and membrane-based processes (UF, NF, RO) provide the most consistent and highest removal efficiencies among currently studied technologies. Advanced oxidation processes, while sometimes proposed as a polishing step, may fragment rather than remove residual particles and require cautious interpretation. These findings support the case for membrane-based advanced treatment as the most effective currently available barrier against microplastic contamination in drinking water, while highlighting the continued need for standardized removal-efficiency reporting and India-specific treatment plant data.

Human Health Risk Assessment

Introduction

Microplastics have been detected in drinking water, food, air, and human tissues, making human exposure a growing environmental concern. Their small size and large surface area enable the transport of toxic chemicals and microorganisms.

Routes of Human Exposure

Table 11: Exposure Pathways

Route	Source	Relative Significance
Ingestion	Drinking water, food	Major pathway
Inhalation	Airborne fibres	Secondary pathway
Dermal Contact	Personal care products	Minor, limited penetration

Source: World Health Organization (WHO), 2019.

Inference: Ingestion through drinking water is considered the major exposure pathway.

Toxic Chemicals Associated with Microplastics

Table 12: Adsorbed Contaminants

Contaminant	Source	Health Concern
Pb (Lead)	Industrial waste	Neurotoxicity
Cd (Cadmium)	Batteries	Kidney damage
Hg (Mercury)	Mining	Nervous system toxicity
BPA	Plastic additives	Endocrine disruption
PAHs	Combustion	Carcinogenicity

Source: EFSA Panel on Contaminants in the Food Chain, 2016 [19].

Inference: Microplastics can act as carriers of hazardous contaminants.

Factors Influencing Toxicity

Several factors influence the toxicity of microplastics. Particle size plays a significant role, with smaller particles showing higher cellular uptake. Shape is also important, as fibres tend to cause greater irritation compared to other particle morphologies. Polymer type governs the chemical stability of the particles, while surface ageing increases their capacity for pollutant adsorption. Additionally, the presence of additives has been shown to enhance overall toxicity.

Source: Shen, M.; *et al*., 2024 [5].

Risk Reduction Strategies

Based on the risk factors identified above, the following strategies are recommended to reduce human exposure to microplastics through drinking water: reducing reliance on single-use plastics, improving drinking water treatment processes (as discussed in Chapter 4), strengthening waste management systems, promoting routine contamination monitoring, and developing standardized analytical protocols for consistent risk evaluation.

Source: Based on WHO (2019) and Shen *et al*. (2024) [5].

Research Gaps

Key research gaps identified in the current literature include limited epidemiological studies linking microplastic exposure to specific health outcomes, poor understanding of nanoplastic toxicity, absence of defined safe exposure limits, scarcity of Indian health-risk data, and the need for standardized toxicological testing methods across studies.

Source: Discussed across WHO (2019), Cox *et al*. (2019) [20], and Shen *et al*. (2024) [5].

Chapter Summary

Microplastics are emerging contaminants with potential health implications due to their persistence and ability to transport toxic substances. Current evidence suggests possible oxidative stress, inflammation, and cellular toxicity; however, conclusive human data are still lacking. Continued monitoring, improved analytical methods, and long-term health studies are essential for accurate risk assessment.

Comparative Synthesis and Research Gaps

Introduction

This chapter presents an original comparative synthesis, compiling and cross-analyzing findings from independently published global and Indian studies to identify contamination trends, methodological inconsistencies, and research gaps specific to microplastics in Indian drinking water sources.

Indian Drinking Water Sources: A Compiled Comparison

Global reviews (Chapter 2) consistently report PE, PET, and PP as dominant polymers across drinking water sources, with Detection standardized around FTIR and Raman spectroscopy. Indian research, though comparatively limited, has begun to generate source-specific data across tap water, bottled water, groundwater, and surface water, summarized below.

Table 13: Compiled Indian Microplastic Concentration Data by Source

Water Source	Location/Study		Reported Concentratio n	Notes
Tap water	Pan-India review 2026)	systematic (Adhikari,	4.3–60 MPs/L	Predominantly fibre and fragment shapes; dark blue, black, transparent colours
Bottled water (commercial brands)	Pan-India review 2026)	systematic (Adhikari,	0.67–4.67 MPs/L	Lower than non-commercial brands
Bottled water (non-commercia l brands)	Pan-India review 2026)	systematic (Adhikari,	212 ± 100 MPs/L	Substantially higher than commercial brands
Groundwater	Semi-arid Rajasthan (Didwana Kuchaman)		3–122 particles/L (avg. 35.46)	Beads/pellets, 20–200 µm; PE and PS dominant
Groundwater	Chennai coast, South India		3–23 and 7–80 items/L	Higher than Tuticorin (10.1 items/L)
River surface water	Ganga at Varanasi (Toxics Link/NIO, 2020) [25]		2.42 ± 0.405 MPs/m³	36+ polymer types identified
River surface water	Ganga–Yamuna, Haridwar–Patna (Gupta *et al*., 2024) [26]		Size range 300 µm–5 mm	Fibres (blue/black); PAM and PA polymers dominant

Source: Compiled by the author from Adhikari (2026) [22], Environmental Quality Management; a groundwater study from semi-arid Northwest India (Wiley, 2025); a South Indian coastal groundwater study cited in ACS Omega (2024); Toxics Link/National Institute of Oceanography (2020); and Gupta *et al*. (2024) [26], Journal of Hazardous Materials.

Key Observation: Source-Wise Contamination Pattern

This compiled comparison reveals a clear source-wise pattern within India: non-commercial bottled water shows markedly higher contamination (212 ± 100 MPs/L) than either commercial bottled water (0.67–4.67 MPs/L) or tap water (4.3–60 MPs/L), suggesting that packaging quality and regulatory oversight — rather than the water source itself — may be a major determinant of contamination in bottled products. Groundwater data, though limited to two regional studies (Rajasthan and Chennai coast), show considerable geographic variability (3–122 particles/L), likely reflecting differences in aquifer depth and proximity to landfill or industrial sources.

A further methodological inconsistency emerges when comparing river studies: two Ganga studies conducted independently report concentrations in different units (MPs/m³ versus particles/m³) and orders of magnitude, reinforcing the standardization gap already identified in Chapter 2.

Global vs. Indian Analytical and Monitoring Status

Table 14: Global vs. Indian Analytical and Monitoring Status

Parameter	Global Trend	Indian Status
Drinking water sources studied	Tap, bottled, groundwater, RO (well-distributed)	Tap and bottled water studied (Adhikari, 2026) [22]; groundwater limited to a few regions; RO-treated water largely unstudied
Analytical Technique	FTIR, Raman routinely combined	Mixed — fluorescence microscopy, ATR-FTIR, and visual counting used inconsistently across studies
Standard Protocol	Emerging consensus (Cowger *et al*., 2021) [8]	Not yet established
Health Risk Assessment	Moderate, WHO-led	Included in recent pan-India review (Adhikari, 2026) [22], but population-specific epidemiological data remain absent

Source: Compiled by the author from Chapter 2 and 3 findings, cross-referenced with Table sources.

Original Contribution of This Review

This review contributes to the existing literature in the following specific ways:

First, it compiles concentration data across four distinct Indian drinking-water-relevant sources — tap water, bottled water (commercial and non-commercial), groundwater, and river surface water — into a single comparative table, drawing on studies that were published independently and had not previously been cross-analyzed together in this way.

Second, it identifies a source-wise contamination pattern within India, namely that non-commercial bottled water shows substantially higher contamination than either commercial bottled water or tap water, pointing to packaging and regulatory oversight as a likely contributing factor warranting further investigation.

Third, it highlights the uneven geographic and source coverage of Indian research — concentrated on the Ganga river system and a small number of groundwater regions, with RO-treated water remaining almost entirely unstudied despite its widespread domestic use in India.

Fourth, it synthesizes these observations into concrete, India-specific research priorities (Section 6.6) grounded directly in the gaps identified through this comparison.

Chapter Summary

This comparative synthesis shows that Indian microplastic research, while still limited relative to global literature, has begun to generate meaningful source-specific data — revealing a distinct contamination pattern in which non-commercial bottled water and certain groundwater regions show disproportionately high contamination. Significant gaps remain in RO-treated water, standardized protocols, and health risk assessment specific to Indian populations.

Conclusion and Future Directions

Conclusion

Microplastics have become emerging contaminants of drinking water due to increasing plastic production and environmental persistence. The literature confirms that polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) are the most frequently detected polymers globally, while this review's own comparative synthesis (Chapter 6) shows that Indian tap and bottled water contain measurable and, in some cases substantial, microplastic loads — particularly non-commercially bottled water, which showed markedly higher contamination than commercial brands.

Advanced analytical techniques such as FTIR, Raman spectroscopy, SEM–EDS, and Py-GC/MS provide reliable characterization of microplastics; however, this review's comparative analysis (Section 6.3) demonstrates that inconsistent units and methods across Indian studies can obscure real contamination trends, particularly evident in conflicting river-water reports from the same location.

Regarding treatment, this review's analysis of removal-efficiency literature (Chapter 4) shows that conventional coagulation-sedimentation alone is largely ineffective for microplastic removal, while granular filtration and membrane-based processes (UF, NF, RO) achieve substantially higher removal. No India-specific drinking water treatment plant removal-efficiency data were identified in this review, directly extending the source-coverage gap identified in Chapter 6 — since RO-treated water, one of the most widely used household treatment methods in urban India, remains almost entirely unstudied.

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