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Recent occurrence of microplastics in freshwater and efficiency of available treatment technologies

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ABSTRACT

This review assesses microplastic occurrence in freshwater systems globally between 2018 and 2024, examining spatial distribution patterns across rivers, lakes, groundwater, and wastewater treatment plants, alongside treatment technology efficiency. Studies were selected following PRISMA guidelines, with inclusion criteria requiring spectroscopic confirmation using ATR-FTIR or Raman spectroscopy and compliance with ISO/TR 21960 and GESAMP quality control protocols. Microplastics were detected across five continents with notable spatial variations: riverine systems showed mean concentrations of 0.5–5 particles/L, lakes exhibited 0.1–2.5 particles/L, while groundwater demonstrated significantly lower levels at 0.01–0.5 particles/L. The most prevalent polymers were polyethylene and polypropylene, primarily linked to secondary microplastic formation from consumer packaging degradation and agricultural film, while fibres (predominantly polyester and polyamide) originated from textile washing effluents, representing primary microplastic sources. Conventional drinking water treatment plants achieved 85–95% removal efficiency for particles >50 μm but declined to 40–60% for smaller fractions, with analytical limitations persisting below 5 μm. Emerging technologies, including photocatalytic degradation, have demonstrated up to 70% polypropylene removal; however, scalability challenges include high energy requirements (2–5 kWh/m^3) and the potential formation of toxic intermedia. Health implications include endocrine disruption, inflammatory responses, and oxidative stress, with nanoplastics (<1 μm) potentially 10–100 times more prevalent than microplastics, though detection capabilities remain critically limited. Legislative frameworks, including the EU Single-Use Plastics Directive, have shown measurable reductions (20–40%) in targeted polymer types; however, enforcement gaps and limited scope continue to hamper comprehensive pollution control. Standardised international monitoring protocols remain integral for effective contamination assessment.

1. Introduction

Emerging pollutants are not necessarily new environmental contaminants; rather, they are naturally occurring or manmade chemicals that are not routinely surveilled in the environment, but have the tendency to contaminate various components of the environment and can consequently cause damage to both humans and other constituents of the biotic ecosystem [1,2]. A major reason they are not routinely monitored is because they require highly sensitive analytical methods to detect their presence in the environment.

Emerging contaminants like pharmaceuticals and microplastics have been detected in various freshwater sources in recent times. These pollutants have most definitely been in the environment for a longer period, however were undetected due to their relatively low detection limits and the unavailability of analytical facilities to suitably detect them in water [3–5]. Notable progress has been made in development of analytical methods to detect and quantify emerging pollutants like pharmaceutical residues in water compared to microplastics whose methods of

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quantification are still in the early stages [6,7].

While early research priorities centred predominantly on marine environments, the freshwater microplastic research landscape has expanded substantially in recent years. Although the proportional focus on freshwater systems historically represented approximately 4% of total microplastic studies as of 2018 [8], the field has experienced exponential growth, with over 500 peer-reviewed freshwater microplastic articles published between 2020 and 2024 alone. This represents a nearly 10-fold increase compared to the preceding five-year period. Technological advances, particularly in spectroscopic analysis and automated particle recognition, have transformed detection capabilities, enabling identification and quantification of microplastics down to 10 μm with increasing reliability [9]. The oldest dedicated freshwater microplastic study emerged in 2011, with systematic investigations gaining momentum from 2015 onwards [10]. Microplastic contamination of marine water remains extensively documented globally; however, the growing body of freshwater research reveals equally concerning contamination levels with distinct source profiles and transport mechanisms.

Furthermore, not much was known about the prevalence of this class of pollutants in freshwater before 2010. Contemporary research now encompasses diverse freshwater matrices including rivers, lakes, reservoirs, groundwater, wastewater treatment plant effluents, and tap water systems, revealing complex spatial and temporal contamination patterns influenced by hydrological dynamics, anthropogenic pressures, and wastewater discharge regimes.

Microplastics are typically tiny (<5 mm) byproducts of plastic waste inappropriately disposed into the environment [11]. Over three-quarters of plastics that are produced end up as waste [12]. They are commonly classified into primary and secondary MPs.

Primary microplastics possess dimensions below 5 mm from the point of manufacture, including microbeads in cosmetics, pre-production plastic pellets (nurdles), and synthetic textile fibres released during washing [13]. Secondary microplastics result from the progressive weathering, fragmentation, and photodegradation of larger plastic items through environmental processes including UV radiation exposure, mechanical abrasion, and microbial activity [14,15]. This distinction carries significant implications for pollution source identification and control strategies: primary microplastics often trace to point sources (e.g., industrial discharges, wastewater treatment plants), while secondary microplastics reflect diffuse sources including agricultural plastics, littering, and improper waste management. Understanding this source differentiation is crucial for implementing targeted policy interventions and developing effective remediation frameworks.

The widespread use of plastic materials in day-to-day life has made it obtain a ubiquitous status in the modern era. However, due to the inappropriate management of plastic waste, it has become a global menace. The United Nations recently estimated that the quantity of plastics in the world's Oceans would exceed the number of fish by year 2050 if a ban is not placed on single use of plastics [16,17].

Over the past half-century, the rate of plastic production increased by over 20-fold and has been tipped to double over the next couple of decades [16]. With such projections, it can only be expected that the environmental burden of microplastic on the environment is bound to increase over time if active measures are not taken. Table 1 indicates a substantial increase in plastic waste generation from 1950 to 2050, with a substantial amount ending up in landfills or the environment. Despite efforts to recycle, a considerable proportion of plastic rubbish remains mishandled. Future estimates suggest that without action, plastic pollution will continue to rise, stressing the need for improved waste management systems and regulations to prevent environmental damage.

Recent toxicological evidence highlights concerning health implications associated with microplastic exposure through freshwater consumption and aquatic food chains. Microplastics function as vectors for chemical pollutants including phthalates, bisphenol A, and persistent organic pollutants (POPs), which leach from plastic matrices upon ingestion [22]. Moreover, nano-sized plastic particles (<1 μm) demonstrate capacity to translocate across biological barriers, including intestinal epithelia and potentially the blood-brain barrier, raising alarms about systemic distribution and organ accumulation [23]. Due to their diminutive size, these particles can bypass the body's initial respiratory defenses and enter lung alveoli, where they may cause various negative health effects, including respiratory issues and systemic health problems [24].

Table 1
Global trends in plastic waste generation, disposal, and future projections (1950–2050).

Year Range	Cumulative Plastic Waste Generation (Mt)	Disposal Methods and Percentages	Refs.
1950-2020	1420.8 Mt	24.7% recycled, 18.8% incinerated, 39.6% landfilled, 16.8% discarded	[18]
1950-2018	1479 Mt produced in the US	75 Mt recycled domestically, 139 Mt exported	[19]
1950-2015	6.3 billion tonnes (76% of production)	79% in landfills or environment	[20]
2018-2050	Plastic pollution could double from 37 Mt to 86 Mt	Additional measured needed to improve recycling and reduce landfilling	[19]
2020-2050	In-use stocks in China to double by 2050	Focus on sustainable production and consumption	[18]
2020-2050	Mismanaged plastic waste could nearly double to 121 Mt annually	Policies could reduce mismanaged waste by 91%	[21]

Emerging research has established links between microplastic exposure and endocrine system disruption, with experimental studies demonstrating altered hormone levels, reproductive dysfunction, and developmental abnormalities in aquatic organisms chronically exposed to environmentally relevant concentrations (0.1-10 μg/L) [25]. In mammalian models, micro and nanoplastic exposure has been associated with oxidative stress, inflammatory responses, gut microbiome alterations, and immune system modulation [26]. In vivo exposure to MNPs increases inflammatory markers such as TNF-α, IL-6, IL-1β, and NF-κB, leading to apoptosis, inflammation, and oxidative stress that impact the gonads, thyroid glands, and hormone secretion from the pituitary and hypothalamus [27,28]. While definitive human health thresholds remain undefined, the ubiquity of microplastics in drinking water supplies (detected in 83% of global tap water samples) necessitates urgent risk assessment and regulatory consideration. Recent comprehensive reviews have elucidated the profound impacts of nano and microplastics on endocrine health, documenting disruptions across thyroid, reproductive, and metabolic hormone axes [27].

Additionally, atmospheric microplastic deposition represents an underappreciated exposure pathway, with airborne particles infiltrating freshwater systems through precipitation and dry deposition. Characterisation of airborne microplastics in the Mahshahr special economic zone revealed concentrations ranging from 0.47 ± 0.06 particles/m^3 in residential areas to 0.85 ± 0.09 particles/m^3 in industrial areas, with the majority identified as black-gray fibers (69.2-81.6%) predominantly composed of polyethylene (PE), polystyrene (PS), polypropylene (PP), and nylon [24]. Inhalation risk assessment demonstrates significant disparity across age groups, with newborns and infants facing the highest exposure (0.44 MP/kg body weight/day for newborns, 0.23 for infants, and 0.07 for adults), attributable to their higher respiratory rates and lower body weights [24]. Occupational and environmental exposure in areas with intensive plastic manufacturing or waste processing activities warrants heightened monitoring, as demonstrated in studies from industrial economic zones.

1.1. Scope and methodology of review

This review synthesises empirical studies published between 2018

and 2024 focusing on microplastic occurrence in freshwater systems and treatment technology efficacy. The temporal scope was deliberately selected to capture the most recent methodological advances and contamination trends, addressing the rapidly evolving nature of microplastic research. Literature was systematically identified through comprehensive database searches (Web of Science, Scopus, PubMed) using keyword combinations including "microplastics", "freshwater", "rivers", "lakes", "groundwater", "drinking water", "wastewater treatment", and "remediation". Inclusion criteria: (1) peer-reviewed empirical research, (2) quantitative microplastic data with size distribution, (3) polymer identification using spectroscopic methods (ATR-FTIR, Raman, Py-GC-MS), (4) adequate quality control measures including procedural blanks and contamination prevention protocols. Studies relying solely on visual identification without spectroscopic confirmation were excluded due to established risks of misidentification and overestimation.

The review framework addresses four key dimensions: (1) spatial distribution and concentration patterns across freshwater environments (rivers, lakes, groundwater, wastewater), (2) analytical methodologies and their limitations, (3) source attribution and transport mechanisms, and (4) treatment technology performance with critical assessment of scalability and economic viability. Each reviewed study was evaluated for methodological rigour, data comparability, and alignment with emerging international standards including ISO/TR 21960 (2020) guidelines for sampling and analysing microplastics in water.

2. Occurrence of microplastic in freshwater

2.1. Microplastics in rivers

Riverine systems serve as primary conduits for microplastic transport from terrestrial sources to marine environments, while simultaneously functioning as temporary sinks through sediment deposition. Comprehensive surveys across 47 river systems spanning five continents reveal pervasive contamination with marked spatial heterogeneity driven by population density, industrial activity, wastewater discharge volumes, and hydrological characteristics.

Concentration ranges in surface waters vary widely, from 0.01 particles/L in remote headwater streams to exceeding 10 particles/L in heavily urbanised river reaches receiving wastewater effluents [29,30]. The Yangtze River system, China's longest waterway, exemplifies acute anthropogenic pressure, with microplastic densities reaching 4.1×10^3 particles/m^3 in industrial sections, predominantly comprising polyethylene (42%), polypropylene (28%), and polyester fibres (18%) [31,32]. Source apportionment analysis indicates wastewater treatment plant effluents contributes to riverine microplastic loading in urban catchments, with agricultural runoff and stormwater overflow representing secondary inputs [33]. Seasonal variations are pronounced, with monsoon periods demonstrating 2-5 fold concentration increases attributed to surface runoff mobilisation and combined sewer overflow events.

European river systems show comparatively lower but still concerning contamination levels. The River Thames yields mean concentrations of 12.27 - 5.92 particles/L, with fragments and films dominating (65%), followed by fibres (28%) and microbeads (7%). Polymer composition reflects regional consumption patterns, with polyethylene and polypropylene from packaging waste predominating alongside polyester textile fibres [34]. Longitudinal profiling demonstrates concentration gradients, with progressive downstream accumulation moderated by dilution effects below tributary confluences and seasonal discharge variations.

North American river surveys reveal similar contamination patterns, with the Great Lakes tributary systems showing mean microplastic abundances of 0.10 to 35.22 particles/L [35]. Size distribution analysis indicates a dominance of particles in the 100-500 μm range, though advanced analytical methods suggest particles <100 μm may comprise 70-85% of total counts when adequately sampled. The biological implications are considerable, as organisms with filter-feeding strategies (bivalves, zooplankton) exhibit selective retention of particles in this size fraction, facilitating bioaccumulation and potential trophic transfer.

Sediment compartments act as long-term sinks for microplastics, often containing concentrations 10–1,000 times higher than those in the overlying water column due to particle settling and accumulation [36,37]. Sediment core analyses from marine and freshwater environments consistently reveal sharp increases in microplastic deposition since the 1950s, paralleling the exponential rise in global plastic production [38–40]. Particle morphology plays a major role in their transport and retention; fibres, being elongated and less dense, exhibit much lower settling velocities and can remain suspended from days to several months compared to heavier fragments and films [41,42]. Hydrodynamic and sedimentological factors such as flow velocity, turbulence, and sediment grain size govern deposition and resuspension processes [43,44]. During low-flow periods, microplastics tend to settle and accumulate in benthic layers, whereas flood and high-discharge events increase bed shear stress, remobilizing previously deposited particles and enhancing downstream transport, thereby elevating exposure risks within aquatic food webs [45,46].

2.2. Distribution of recent literature

Among the papers evaluated, the occurrence of MPs in freshwater has been reported by surveys across Asia (12), Europe (9), North America (2), Oceania (2), and Africa (2) as shown in Fig. 1. The concentration of majority of these surveys in Europe and Asia is similar to the trend observed in another review that examined microplastic contamination of water over a seven year period [8]. Study areas in China accounted for over one-third of the surveys. This is likely attributed to China being the world's largest plastic manufacturer, while Europe is the second largest [47]. Furthermore, of the 27 surveys, over 74% assessed MPs in surface water sources, around 18% assessed groundwater or groundwater associated sources (DWTP with groundwater as source), while the remainder assessed drinking water taps across their respective cities. The paucity of studies assessing microplastic contamination in groundwater sources when compared to surface water surveys was also corroborated by another study [48]. The distribution and abundance of microplastics in freshwater systems are driven by a combination of spatial and temporal factors, including land use, hydrological connectivity, and seasonal flow regimes (Fig. 1).

2.3. Methods of MP characterization

The use of stereomicroscopes was the major means of visual inspection in this study. However, solely using this method to identify the MPs is not encouraged as it can be highly subjective, thereby leading to over or underestimated results [49]. Also, smaller particles are not easily identified which is why further characterization is encouraged. The Fourier transform infrared spectrometer (FTIR) and Raman spectroscopy (RS) have been appraised to detect MPs as small as 20 μm and 1 μm respectively [50]. The most common method of MP characterization employed was Attenuated total reflectance-FTIR (ATR-FTIR) spectroscopic analysis, which was also reported in other reviews [8]. While in other occasions, scanning electron microscopy (SEM), micro-RS and florescence microscope were used. However, findings from another review identified both FTIR and RS to be majorly employed [50].

2.4. Concentration of MPs in freshwater

The MPs were commonly measured in particles/L and particles/m^3. Other forms of measurements employed were n/L and mg/kg. Notably, the Yellow River had a high burden of microplastic, which averaged 930 items/L in the dry season and 497 items/L in the wet season [51]. Also, an urban stream in Johannesburg South Africa had a range of 160

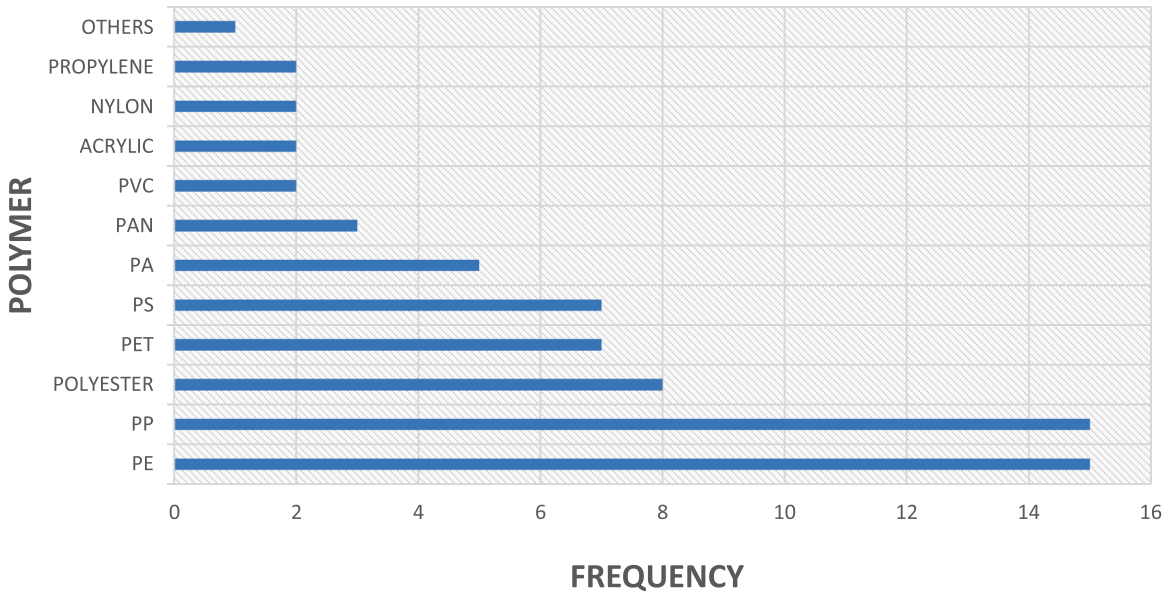

Fig. 1. Spatial and temporal drivers influencing microplastic distribution and abundance in freshwater environments. This schematic illustrates how land use (urban, agricultural, and natural zones), hydrological processes (stormwater runoff, wastewater discharge, baseflow transport, flooding), and seasonal events (wet vs. dry season, storm pulses) affect the movement and deposition of microplastics in riverine and lacustrine systems. The diagram highlights both spatial (source proximity, land use type) and temporal (flow variability, seasonality, episodic events) dimensions contributing to microplastic accumulation in sediments and water columns.

particles/m^3 to 2080 particles/m^3 and an average of 705 particles/m^3 [52]. MPs were also detected in water from drinking water treatment plants (DWTPs). An assessment of a DWTP in Skane, Sweden, whose source was from a lake and a DWTP in Plzeň Czech Republic whose source was from a river reported average concentrations of 174±405 particles/L and 151±4 particles/L respectively [53]. Generally, groundwater sources had lower occurrence of MP in water, compared to surface water sources and even processed drinking water. This is likely because groundwater sources typically tend to be more naturally protected from anthropogenic pollutants than surface water. The variation in the concentration of micropollutants across the different freshwater sources is not only attributed to the differences in the sampling location, but is also dependent on the sampling methodology, method of sampling processing and the type of analytical methods employed [54].

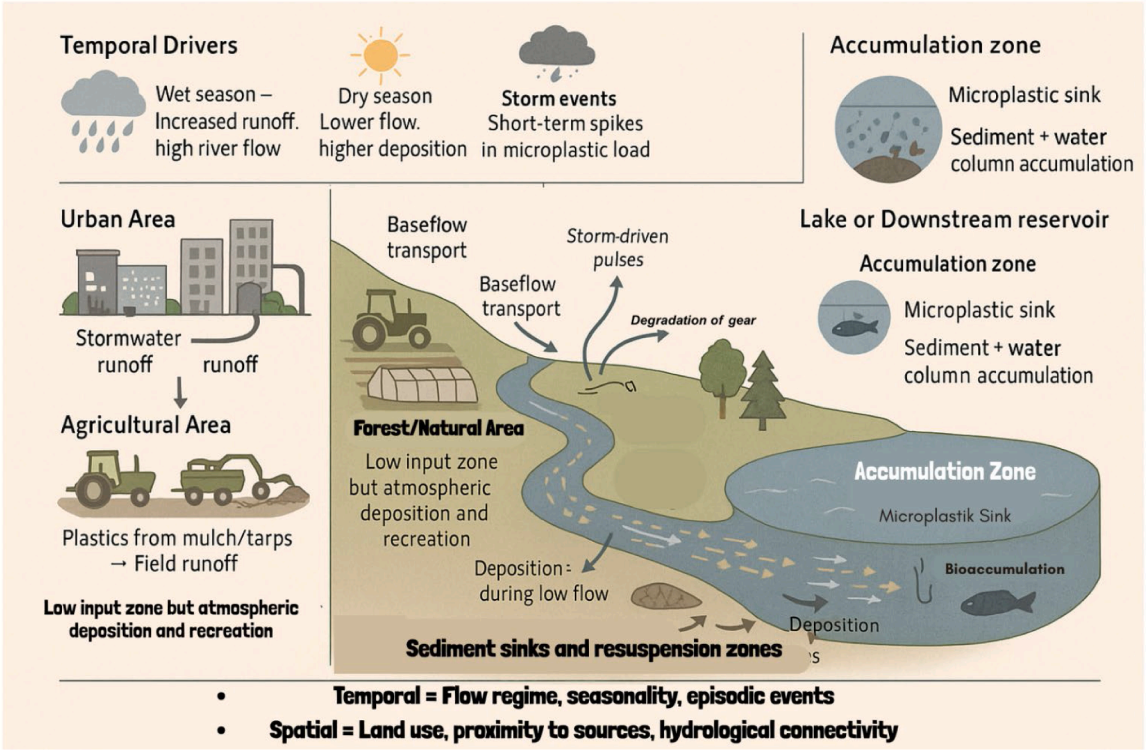

Fig. 2. Prevalence of polymers across the various study settings.

2.5. Prevalent polymers detected in freshwaters

Considering the types of MPs detected in the various freshwater sources, polyethylene (PE) and polypropylene (PP) were found in majority of the studies. A similar trend was also reported in a past review papers, one of which posited that the high prevalence of PE and PP were as a result of their global demand and respective densities [8,55]. Studies have revealed that PE has the highest demand globally, followed by PP [56,57]. In addition, densities of both PE (0.92-0.97 g/cm^3) and PP (0.9-0.91 g/cm^3) are below that of water, causing them to float rather than sink in water [58]. Fig. 2 shows the prevalence of MP polymers across the selected papers, while Table 2 provides a summary of the MP occurrence from each study Table 2.

3. Treatment technologies

3.1. Conventional water treatment processes

3.1.1. Coagulation-flocculation-sedimentation systems

Conventional drinking water treatment plants employing coagulation-flocculation-sedimentation (CFS) processes demonstrate variable microplastic removal efficiency, primarily influenced by particle size, morphology, and operational parameters. Experimental investigations using alum-based coagulation reveal removal efficiencies above 80% for microplastics exceeding 50 μm in diameter, declining substantially to 40-60% for particles in the 10-50 μm range, and below 20% for fractions smaller than 10 μm [86,87]. This size-dependent performance reflects the fundamental limitations of gravitational settling processes, as smaller particles possess lower settling velocities and remain suspended longer, evading removal.

Coagulant type and dosage significantly influence capture efficiency. Polyaluminium chloride (PACl) generally performs slightly better than conventional alum at comparable doses due to enhanced floc formation and charge neutralization [88]. Moreover, polymer type affects removal, with polyethylene and polypropylene particles tending to show higher capture rates than polyester and polyamide fibres, reflecting differences in density and surface hydrophobicity [88,89].

3.1.2. Filtration systems

Advanced filtration technologies provide enhanced microplastic removal beyond conventional CFS processes. Granular media filtration, including sand and anthracite filters, typically achieves removal efficiencies of 60–85% for particles larger than 20 μm, with efficiency decreasing for smaller size fractions [90,91]. Multi-media filters incorporating activated carbon layers have demonstrated improved overall removal, reaching 80–95% across broader size ranges, though particles below 10 μm remain difficult to capture consistently [86,87]. This size-dependent performance reflects the inherent limitations of granular filtration processes, as smaller and lighter particles possess lower settling velocities and reduced interception probabilities.

Membrane filtration technologies offer the most reliable microplastic removal capabilities, with efficiency closely linked to membrane pore size. Microfiltration (MF; 0.1–10 μm) generally removes >90% of microplastics larger than its nominal pore size, although operational constraints such as membrane fouling, cleaning frequency, and energy demands (~0.2–1.0 kWh m^{-3}) can affect sustainability [92,93,]. Ultrafiltration (UF; 0.01–0.1 μm) and nanofiltration (NF; 0.001–0.01 μm) systems can achieve >95–99% removal, including most particles in the 1–10 μm range that bypass conventional treatment, but high capital and operational costs, often equivalent to £700–2,000 per m^3 day^{-1} capacity, limit their widespread deployment, particularly in low-resource regions [94,95].

A critical analytical limitation must be acknowledged: current detection methods struggle to accurately identify and quantify microplastics below 5 μm, with even advanced spectroscopic techniques such as micro-FTIR and Raman imaging showing diminished detection reliability in the 1–5 μm range [96,97]. This analytical gap implies that reported removal efficiencies for sub-5 μm particles are uncertain and likely overestimated. Furthermore, nanoplastics (<1 μm) present an emerging concern; early findings indicate that their abundance may exceed that of microplastics by one to two orders of magnitude, yet analytical constraints currently hinder comprehensive quantification and treatment performance assessment for this fraction [98,99].

3.2. Emerging treatment technologies

3.2.1. Photocatalytic degradation

Photocatalytic degradation utilising semiconductor catalysts has emerged as a promising advanced oxidation process for microplastic degradation. Titanium dioxide (TiO_2)-based photocatalysts under UV irradiation demonstrate the capacity to degrade polyethylene and polypropylene microplastics through the generation of reactive oxygen species (hydroxyl radicals and superoxide anions) that cleave polymer chains. Laboratory studies have confirmed significant structural and chemical alterations in polymer matrices after extended UV-TiO_2 exposure, indicating potential pathways for microplastic mineralisation in controlled environments [100,101].

However, critical scalability and practical implementation challenges temper enthusiasm for widespread deployment. Energy requirements remain high, while catalyst recovery and recycling introduce additional operational complexity. Moreover, incomplete degradation raises concerns about the formation of potentially more toxic low-molecular-weight intermediates, oligomers, and oxidised polymer fragments, which may exhibit enhanced bioavailability and cellular uptake compared to parent microplastics. Comprehensive toxicity assessments of degradation products are still limited [102,103].

Recent advances in visible-light-activated photocatalysts (such as doped TiO_2 and graphitic carbon nitride) aim to reduce energy demands by harnessing solar radiation. These materials offer promise for lowering operational costs and improving sustainability. Nonetheless, pilot-scale demonstrations remain necessary to validate performance under real-world conditions, including variable water quality, organic matter interference, and particle loading. Environmental risk assessments of photocatalyst release and long-term fate are warranted before large-scale implementation [104].

3.2.2. Bioremediation and microbial degradation

Bioremediation approaches leveraging microbial communities capable of plastic biodegradation offer environmentally benign alternatives to chemical and physical treatment methods.

Microbial biofilm formation on microplastic surfaces initiates biodegradation through enzymatic polymer chain cleavage, principally mediated by hydrolases, oxidoreductases, and esterases produced by bacteria (*Pseudomonas, Bacillus, Rhodococcus*) and fungi (*Aspergillus, Penicillium*) [105]. Laboratory studies demonstrate 20–65% mass reduction of polyethylene and polystyrene microplastics following 30–90 days incubation with selected microbial consortia under optimised conditions (temperature 25–35°C, pH 6.5–8.0, adequate oxygen supply) [106].

Biofilm-mediated microplastic aggregation facilitates removal through enhanced settling and flotation, achieving reported removal efficiencies of 40–75% in experimental bioreactors [107]. Cost projections for biological treatment systems range from £0.15–0.45/m^3, substantially lower than advanced oxidation or membrane technologies, attributed to minimal energy and chemical inputs. However, several limitations constrain practical application: (1) biodegradation rates are slow, requiring extended hydraulic retention times (weeks to months) incompatible with high-throughput water treatment plants; (2) efficacy varies considerably across polymer types, with recalcitrant plastics (PVC, PET) showing minimal biodegradation; (3) environmental conditions (temperature, pH, nutrient availability) critically influence performance, potentially limiting applicability in temperate climates or

Table 2
Data on the occurrence of MPs in various freshwater sources across the world.

Location	Period/ Water source	Sampling	Characterization	Concentration	Size	Type of MP	Refs.
Rize, Turkey	Apr to May 2019 Ponds, ditches and puddles	2 L glass bottles	Stereomicroscope & ATR technique	1 to 13 items/L	-	Nylon, PET, polyester, PP, PVA derivaties, PAN and PMM	[59]
China	Jan. 2018 Yulin River	Teflon pump	Green fluorescence, micro-RS, XPS and SEM	0.013 to 0.7 items/L	Majorly 64 to 100 μm	PE, PP and PS	[60]
Dhaka, Bangladesh (Dhanmondi, Gulshan, Hatir Jheel lakes)	September 2021 Surface water, sediment, fish	Eijkelkamp agrisearch equipment analysis	Visual observation, FTIR analysis	36 items/L (water), 67 items/kg (sediment), 17 items/individual (fish), 4.88 items/gm (gastrointestinal tract)	<100 μm, transparent	High-density polyethylene, low-density polyethylene, ethylene vinyl acetate, polyvinyl chloride, polycarbonate, cellulose acetate, polypropylene (films, pellets, foams)	[61]
China	Jul 2018 & Mar 2019 Yellow River	Stainless steel bucket	Optical electron microscope & ATR-FTIR	Dry season: 930 items/L Wet season: 497 items/L	Majorly less than 200 μm	PE, PP and PS	[51]
Skane, Sweden	May 2019 DWTP linked to Lake Vombsjon	Stainless steel filters	Focal Plane Array based FTIR and Py-GCMS	0 to 1219 MPs/m^3 (Mean: 174±405 MPs/m^3)	8 μm to 316 μm	PA, Polyester, acrylic, PVC, PS	[62]
Lake Michigan and Lake Erie, USA	September 2013 & 2014 Sediment from Lake Michigan and Lake Erie	Stainless-steel standard ponar	Visual and FTIR analysis	65.2 p kg–1 (Lake Michigan, particles > 0.355 mm), 431 p kg–1 (Lake Erie, particles > 0.355 mm), 631 p kg–1 (Lake Erie, particles 0.1250–0.3549 mm)	>0.355 mm and 0.1250–0.3549 mm	PET, HDPE, semisynthetic cellulose, PP, PVC	[63]
Tamil Nadu, India	Jan 2019 GW	Teflon pump	Stereomicroscope & ATR FTIR	0 to 4.3 particles/L	0.12 to 2.50 mm	Nylon, PP, Polyester	[64]
Rewalsar Lake, Northwest Himalaya	Surface water, sediments	Microplastic and phthalate esters extraction	FTIR, analysis of phthalate esters	13–238 particles/L (water), 750–3020 particles/kg dw (sediments), 1.69–4.03 μg/g dw (PAEs)	-	Polystyrene, polyethylene, polypropylene (pellets, fragments)	[65]
Victoria, Australia	Apr to Jul 2018 Goulburn River	5 L food-grade blue polypropylene jars	Stereomicroscope & ART FT-IR microscopy	0.11±0.11 to 0.72 ±0.29 items/L (0.40±0.27 items/L)	0.036 to 4.668 mm (Mean-0.942 ±0.835 mm)	Polyester, PA, rayon	[66]
Queensland, Australia	Dec 2017 & Mar, Jun, Sep 2018 Brisbane River	Stainless steel Grab sampler	FTIR	0 to 55 mg/kg- Dec 0 to 130 mg/kg- Mar 0 to 19 mg/kg- June 0 to 60 mg/kg- Sept	-	PE, PA and PP	[67]
Russelsheim, Germany	Oct 2019 to Mar 2020 Drinking water from GW source	Stainless steel membrane	micro- RS	0 particles	-	-	[68]
London, United Kingdom	Jun to Oct, 2017 River Thames	250 μm mesh ichthyoplankton net	Stereomicroscope & FTIR	24.8 particles/m^3 upstream 14.2 particles/m^3 downstream	32 μm to 5 mm	PE and PP	[69]
Southwestern Nigeria	Dry and wet seasons / Major rivers (sediments and surface water)	Density separation, FTIR-ATR	12.82 to 22.90 particles/kg dw (sediment), 6.71 to 17.12 particles/L (water) during dry season; 5.69 to 14.38 particles/kg dw (sediment), 12.41 to 22.73 particles/L (water) during wet season	<1 mm (≥55% of MPs)	Predominantly fibers (71% in sediment, 67% in water), PP, PE, foam (lowest at 0.6% and 1.7%)	PE and PP	[70]
Mexico City, Mexico	Jul to Aug 2019 Drinking water fountains	Pre-cleaned glass bottles	Epifluorescence microscope & SEM coupled with energy-dispersive spectroscopy & Micro-RS	5±2 to 91±14 MP/L (Mean: 18±7 MP/L	0.1 mm to 5 mm	Poly-trimethylene terephthalate and epoxy resin	[71]
Lake Superior, USA/Canada (Apostle Islands and Western Shores)	May and July 2018 Beach sand and surface water	Melt test, Py-GCMS, SEM/EDS	Low abundance: 0 to 55 particles/kg (sand), 9000 to 40,000 particles/km^2 (water)	<4 mm	Mainly fibers, with polyethylene identified by Py-GCMS	PE	[72]
Finland	Autumn 2016 Lake Kallavesi	Manta trawl sampling	Stereomicroscope & FTIR	0.037 MP/m^3 to 0.66 MP/m^3 (0.27±0.18 MP/m^3)		PP, PE, propylene, PET, PAN	[73]

(*continued on next page*)

Table 2 (*continued*)

Location	Period/ Water source	Sampling	Characterization	Concentration	Size	Type of MP	Refs.
Finland	Spring 2017 Lake Kallavesi	Pump with filter	Stereomicroscope & FTIR	1.8±2.3 MP/m^3: over 300 μm 12±17 MP/m^3: 100 to 300 μm 155±73 MP/m^3: 20 to 100 μm	20 μm to over 300 μm	PP, PE, propylene, PET, PAN	[73]
France	Oct 2015 to Oct 2016 Rhône River	Manta trawl	Stereomicroscope & FTIR	0.3 to 58.9 items/m^3 (Mean: 11.6±17.7 items/m^3)	-	PE, PP, Polyester, Acrylic	[74]
Roussillon, France	Dec 2015 to Oct 2016 Têt River	Manta trawl	Stereomicroscope & FTIR	0.8 to 618 items/m^3 (42±18 items/m^3)	-	PE, PP, PS, Polyester, Acrylic	[74]
Uganda	Jul to Nov 2019 Lake Victoria	Manta trawl	Stereomicroscope & ATR-FTIR	0.02 to 2.19 MP/m^3(0.73 MP/m^3)	0.3 to 4.9 mm	Low density PE, High density PE, PP, PS and Polyester	[75]
Western Lake Superior and adjacent harbor, USA	August and September 2021 Surface water	R/V Kingfisher and R/V Blue Heron	Size fraction, morphology, color, polymer composition analysis, Power law size distribution modeling, Nile Red staining, Flow Cytometry (FCM)	0.62 to 3.32 microplastics/L (harbor), 0.83 to 1.4 microplastics/L (lake)	5–45 μm, larger size fractions	Various polymers, greater diversity in harbor samples due to urban activity	[76]
Kaohsiung City, China	Sep 2018 Fengshan River	Grab water sample via 50L stainless steel bucket, sieved through diff-sized mesh	Stereomicroscope & ART-FTIR spectrometer	334-1058 items/m^3	50 to 5000 μm	PE, PE terephthalate, PA and polyester	[77]
Bayannaoer City, China	May 2019 Wuliangsuhai Lake	Stainless steel buckets, filtered through a sieve	Metallographic microscope & ATR-FTIR & SEM	3.2 to 11.25 n/L	Majority less than 2 mm	PS and PE	[78]
Czech Republic	winter 2019/ 2020 DWTP Milence from Nýrsko Dam	2 L water in borosilicate glass bottles	Scanning electron microscope & micro-Raman	Raw water: 23±2 MP/L Treated: 14±1 MP/L	-	CA, PET, PVC, PE, PP	[53]
Czech Republic	winter 2019/ 2020 DWTP Plzeň from Úhlava River	2 L water in borosilicate glass bottles	SEM & micro-RS	Raw: 1296±35 MP/L Treated: 151±4 MP/L	-	CA, PET, PVC, PE, PP	[53]
China	Tap water from different DWTP	1L HDPE bottle	Florescence microscope using Nile Red & micro-RS	0 to 1247 particles/L (Mean: 440 ± 275 particles/L)	3 to 4453 μm	PE and PP	[79]
Xinjiang, China	Oct 2018 Manas River Basin	grab sampling 2.5 L stainless steel drum	fluorescent inverted microscope, SEM & Energy disperse spectroscopy & μ-FTIR	21 ± 3 – 49±3 items/L	0.1 to 5 mm	PP and PET	[80]
Xinjiang, China	Apr to Jul 2019 Manas River Basin	stainless-steel sampler (2.5 L)	fluorescence inverted microscope, SEM & μ-FTIR	Wet: April 22 ± 5–14 ± 3 items/L (17 ± 4 items/L) Dry: July 19 ± 2–10 ± 1 items/L (14 ± 2 items/L)	Majorly between 0.1 mm to 0.3 mm	PP, PET, PS, PE	[81]
Fujian Province, China	May 2019 Zhangjiang River	bulk sampling method (water from steel bucket passed through a manta net with mesh size 330 um	stereomicroscopy and micro-RS	50 to 725 items/m^3 (Mean: 246 items/m^3)	Majorly 0.5 mm to 1 mm	PP and PE	[82]
Vietnam	July 2016 to January 2018 Saigon River	bulk surface water via bucket	stereomicroscope	22 to 251 items/L	Majorly 40 to 300 μm	-	[83]
Vietnam	Dec 2018 Thi Tinh River & Sunrise River	bulk surface water	stereomicroscope	30 to 242 item/L 30 to 166 item/L	-	-	[83]
Shanghai, China	Summer & Winter, 2018 Huangpu River & Suzhou Creek & Jinze Reservoir	stainless-steel net (80 μm mesh size) & large flow automatic samplers for real time wet weather	High-Speed Stereomicroscope & ART-μFT-IR	Jinze reservoir- 28.3 ±4.1 p/L Huangpu river- 26.2 ±9.6 p/L Suzhou creek: 14.4 ±5.1 p/L	Majorly 80 to 500 μm	Majorly PET	[84]
Johannesburg, South Africa	Jun 2019 Braamfontein Spruit urban stream	100L of water filtered through series of stainless	stereomicroscope microscope	160 p/m^3 to 2080 p/m^3 (705 particles/m^3)		-	[52]

(*continued on next page*)

Table 2 (*continued*)

Location	Period/ Water source	Sampling	Characterization	Concentration	Size	Type of MP	Refs.
		steel sieves with diff sizes					
China	Dec 2018 to Jan 2019 DWTP linked to Yangtze River	1 L brown glass bottles	SEM & micro-RM	Raw: 6614± 1132 particles/L Effluent: 930±72 particles/L	Raw: Majorly 1-5 μm and 5 to 10 μm Effluent: Majorly 1-5 μm	Majorly PET, PAM, PP, & PE	[85]

**Polypropylene (PP), polyvinylacetate (PVA), Polyethylene (PE), polystyrene (PS), Polyvinyl chloride (PVC), polyamide (PA), polyacrylonitrile (PAN), polymethylmethacrylate (PMM), polyethylene terephthalate (PET), cellulose acetate (CA), Raman spectroscopy (RS), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), Attenuated total reflectance (ATR), Fourier transform infrared spectrometers (FTIR), Pyrolysis gas chromatography mass spectrometry (Py-GCMS), Drinking water treatment plant (DWTP), Microplastic (MP), Groundwater (GW)

nutrient-poor waters [108].

Moreover, fundamental knowledge gaps persist regarding the long-term environmental fate of biotransformation products, potential selection for antibiotic-resistant bacterial strains in biofilm communities exposed to plastic-associated contaminants, and ecological implications of releasing genetically modified or bioaugmented microbial strains into natural water systems [109]. Large-scale field trials assessing performance, stability, and environmental safety under operational conditions are necessary before widespread adoption. Life cycle assessments comparing environmental footprints of biological versus conventional treatment approaches would inform evidence-based decision-making. Table 3 demonstrates that while advanced treatment technologies such as granular activated carbon filtration achieve removal efficiencies exceeding 85% for microplastics, conventional coagulation-flocculation-sedimentation processes show limited effectiveness (40–65%), and particles below 10 μm consistently persist across most treatment systems, highlighting the technological challenges in eliminating smaller microplastic fractions from water sources [90].

4. Groundwater microplastic contamination

Groundwater systems, historically presumed protected from microplastic contamination by soil filtration and aquifer isolation, have recently been documented to harbour microplastic particles, albeit at significantly lower concentrations compared to surface waters. Surveys across multiple groundwater sites in Europe, Asia, and North America reveal microplastic detection in over 50% of samples, with mean concentrations generally below 1 particle/L, approximately one to two orders of magnitude lower than typical surface water levels [122,123].

Transport mechanisms facilitating microplastic infiltration into aquifers include: (1) preferential flow pathways through macropores, fractures, and karst conduits bypassing soil filtration, (2) leachate migration from unlined landfills and waste disposal sites, (3) agricultural irrigation using microplastic-contaminated surface water or treated wastewater, and (4) direct injection through improperly sealed boreholes or abandoned wells [86,124]. Particle size distributions in groundwater are strongly skewed towards smaller fractions (<100 μm), reflecting size-selective filtration during percolation through porous media. Fibres constitute a majority of groundwater microplastics, likely due to their elongated morphology facilitating transport through narrow pore throats [125].

Polymer composition mirrors surface water signatures, with polyethylene, polypropylene, and polyester predominating, suggesting surface-derived sources rather than in-situ generation. Contamination levels correlate positively with proximate anthropogenic activities, including urban development intensity, agricultural land use, and waste management infrastructure. Remote aquifers and deep confined systems demonstrate substantially lower detection frequencies and concentrations, supporting the hypothesis that microplastic infiltration requires relatively short residence times and shallow depths [36]. Hydrogeological properties modulate microplastic mobility and retention. Coarse-grained aquifers (sand, gravel) permit greater particle transport compared to fine-grained formations (silt, clay) exhibiting enhanced filtration capacity. Groundwater velocity, influenced by hydraulic gradient and permeability, governs particle travel distances. Modelling studies suggest microplastic transport ranges from metres to kilometres depending on particle characteristics and aquifer properties, with residence times spanning years to decades in low-permeability systems.

The presence of microplastics in groundwater raises concerns for drinking water supply security, as many regions rely predominantly on groundwater resources. Conventional groundwater treatment often comprises minimal processing (disinfection only), lacking the filtration stages employed in surface water treatment that provide partial microplastic removal. This vulnerability underscores the need for source protection measures, improved waste management, and consideration of advanced treatment technologies for high-risk supply systems [90,123].

5. Wastewater treatment plants as sources and sinks

Wastewater treatment plants (WWTPs) occupy a dual role as both microplastic sinks, removing particles from influent wastewater, and sources, discharging residual microplastics in treated effluent into receiving waters. Comprehensive mass balance assessments reveal WWTPs capture 90–98% of influent microplastics through sequential treatment processes, yet the remaining 2–10% fraction discharged in effluent represents a significant continuous point-source input to freshwater systems given the enormous volumetric flows processed daily (typically 50,000–500,000 m^3/day for municipal facilities serving 100,000–1,000,000 population equivalents) [126,127].

Influent microplastic concentrations vary widely, ranging from 100 to 700 particles/L depending on catchment characteristics, industrial contributions, and rainfall-induced stormwater dilution. Textile fibres dominate influent loading, constituting 60–85% of particles, primarily polyester and polyamide released during laundry washing cycles. Fragments from packaging waste, personal care product microbeads (though increasingly regulated), and tyre wear particles comprise the remainder [128,129].

Treatment process efficiency varies by stage: preliminary screening and grit removal capture minimal microplastics (<5%), primary sedimentation removes 10–40% (predominantly denser particles and aggregates), secondary biological treatment (activated sludge, trickling filters) achieves 50–80% removal through bioflocculation and settling, and tertiary treatments (sand filtration, membrane bioreactors) provide additional 20–40% removal. Overall, conventional WWTPs achieve 85–95% total microplastic removal, with advanced facilities incorporating membrane bioreactors reaching 97–99% [122,130].

However, captured microplastics partition predominantly to sewage sludge (biosolids), which undergoes subsequent processing (digestion, dewatering, drying) prior to disposal. Sludge microplastic concentrations reach 1,500–10,000 particles/kg dry weight, raising concerns about land application as agricultural fertiliser, a common disposal route in many jurisdictions. This practice potentially transfers microplastics from the wastewater stream to terrestrial ecosystems and

Table 3
Available MP treatment techniques and removal efficiency.

Study method	Facility/Efficiency	MP Sizes	Refs.
DWTP	CFS- 40%	Raw- Majorly ≥ 100 μm and 50 to < 100 μm MP fibres & Majorly ≥ 1 to < 5 μm MP fragments present Treated water- Majorly < 100 μm fibres & Majorly ≥ 1 to < 5 μm fragments persisted	[95]
DWTP Plzen	CFS- 62% Deep-bed infiltration- 20% Granular activated carbon filtration- 6% Total- 88%	Raw- Majorly ≥ 50 to < 100 μm and ≥ 10 to < 50 μm MP fibres & Majorly ≥ 1 to < 5 μm and ≥ 5 to < 10 μm MP fragments present Treated- Majorly ≥ 10 to < 50 μm fibres & Majorly ≥ 1 to < 10 μm fragments persisted	[95]
Advanced DWTP	CFS- 40.5 to 54.5% Sand filtration- 29.0 to 44.4% Ozonation + GAC filtration- 17.2 to 22.2% Total- 82.1 to 88.6%	Raw: 1 μm to > 100 μm present Treated: > 10 μm almost totally removed. 1 to 5 μm and 5 to 10 μm least removed	[85]
Bench-scale water treatment	CFS via $Al_2(SO_4)_3$ at 20 ppm- < 2.0% CFS with PolyDADMAC 0.5 ppm- - < 0.1% to 13.6% GAC- 86.9% to 99.9%	Raw- 180 nm to 125 μm present Treated 1- Majorly 10 to 20 μm and 106 to 125 μm removed Treated 2- Majorly 45 to 53 μm removed Treated 3- All sizes removed by over 95% except 1 μm & 10 to 20 μm	[86]
Bench-scale water treatment (biofilm plastics)	CFS via $Al_2(SO_4)_3$ at 20 ppm- 16.5% GAC- 99.7%	Raw- 45–53 μm present Treated- 45–53 μm removed	[86]
Wastewater Treatment	Biofilm Formation - Highest on polyethylene particles, UV and chlorine treatment effective in inactivating biofilms within 30 and 10 min, respectively	Biofilm formation observed after 3 weeks, with the highest biofilm on MPs exposed to dark, mesophilic temperature (25°C), and aerobic conditions. Dominant MP Sizes: Not explicitly mentioned in the abstract.	[110]
Coagulation in Wastewater Treatment	Removal efficiency for PA, PS, and PE was 65%, 22%, and 12% respectively. Coagulant efficiency: $Al(OH)^3$ was the most suitable with the lowest dose	Polyamide (PA), Polystyrene (PS), Polyethylene (PE)	[111]
Bench-scale water treatment	Ferric chloride (1.2mmol/L)- 99.4% polyaluminum chloride (1.2mmol/L)- 98.2%	Raw: MPs less than 10 μm After coagulation: 95% removal for 1 μm and 76% removal for 6.3 μm	[112]
Bench-scale water treatment	Alum at 30 mg/L- 70.7% Alum at 20 mg/L- 65.7% Alum at 40 mg/L- 48.8% PC sand (500 mg/L) + 20 mg/L alum- 92.7% PC sand (500 mg/L) + 30 mg/L alum- 90.2%	Raw - 10-100 μm After coagulation: 10 to 30 μm least removed	[113]
WWTP	The MBR process (W3) showed the highest MP concentration in sludge ($81.1 \pm 4.2 \times 10^3$ particles/kg dry sludge). The CAS plants (W1, W2) had lower concentrations ($46.0 \pm 14.8 \times 10^3$ and $36.0 \pm 5.2 \times 10^3$ particles/kg, respectively). MBR sludge had a more diverse MP composition, with fibers being the most abundant.	-	[114]
Drinking Water Treatment Plant (DWTP)	Alum-CFS bench tests showed that an alum dose of 30 mg/L achieved 75.6% removal of 6-μm PS microspheres from Grand River water and 85.2% removal from Lake Erie water. Higher alum doses improved removal of MPs smaller than 90 μm.	Carboxylated polystyrene (PS) microspheres: 3, 6, 25, 45, 90 μm	[115]
WWTP	Anaerobic/anoxic/aerobic membrane bioreactor- 82.1% based on number and 99.5% based on mass Aerated grit chamber, oxidation ditch, secondary settling tank and UV- 53.6% based on number and 97% based on mass	Inlet- Majorly over 500 μm and 62.5 to 125 μm	[116]
WWTP	Membrane bioreactor technology- 79.01% Rapid sand infiltration- 75.49%	Inlet- 210 μm to over 5 mm Majorly between 210 μm to 2 mm not removed	[117]
Photocatalytic degradation	Photocatalytic degradation of PP by visible light irradiation of zinc oxide nanorods on glass fibers- 65% after 456 hours	Initial Average size: 154.8 ± 1.4 μm Average size after 456 hours: 108.2 ± 2.5 μm	[118]
Photocatalytic degradation	Triton based titanium oxide nanoparticle film with UV- 98.4% degradation in 12 hours	400 nm PS particles	[119]
Hydrothermal Coupled Fenton System	95.9% weight loss in 16 hours; 75.6% mineralization efficiency in 12 hours	Ultrahigh-molecular-weight polyethylene (UHMWPE)	[120]
Trap and release bio-aggregation	P. aeruginosa trapped almost all MPs within 24 hours	Less than 106 to 300 μm Particles less than 106 μm	[121]

agricultural soils, from which they may subsequently re-enter freshwater through runoff and leaching, establishing a secondary contamination pathway. Alternative sludge disposal methods (incineration, landfilling) eliminate microplastics but entail higher costs and energy consumption (incineration) or long-term containment challenges (landfilling) [131].

Effluent microplastic discharges, while representing a small fraction of influent loads, accumulate to substantial absolute quantities. A typical 100,000-population-equivalent WWTP discharging 20,000 m^3/day at 95% removal efficiency with influent concentration of 300 particles/L releases approximately 3×10^8 microplastic particles annually into receiving waters. This continuous input can locally elevate river microplastic concentrations by 0.5–2 particles/L immediately downstream of discharge points, with effects detectable tens of kilometres downstream depending on dilution and transport dynamics [126,132].

6. Regulatory frameworks and policy effectiveness

Legislative responses to plastic pollution have proliferated globally, targeting both macro-plastic waste reduction and, increasingly, micro-plastic sources. The European Union's Single-Use Plastics Directive (2019) mandates restrictions on specific single-use plastic items (straws, cutlery, stirrers, balloon sticks, cotton bud sticks) and establishes extended producer responsibility schemes [133]. Early assessments indicate measurable reductions in targeted item abundance in aquatic environments, with 20–40% decreases in beach litter surveys (2019–2023), though comprehensive freshwater monitoring data remain limited [122].

National and regional plastic bag levies and bans implemented across over 100 jurisdictions demonstrate variable effectiveness. Jurisdictions with outright bans (Kenya, Rwanda, Bangladesh) report substantial reductions in polyethylene bag contamination (60–80% declines in waterway surveys), whilejurisdictions employing modest levies (5–10 pence per bag) show smaller but significant effects (20–40% reductions) [36]. However, substitution effects complicate interpretation, as increased use of alternative materials (paper, heavier-gauge reusable plastics) may offset environmental benefits.

Microplastic-specific regulations remain nascent but expanding. The EU restriction on intentionally added microplastics in cosmetics and detergents (implemented 2023–2027 in phases) targets an estimated 500,000 tonnes of deliberate microplastic releases annually [134]. Early data from cosmetic product surveys indicate compliance, with detection rates of microbeads declining from 15–20% of products pre-regulation to <2% post-implementation. However, unintentional microplastic sources (textile fibre shedding, tyre wear, plastic film fragmentation) dwarf intentional additions in magnitude, limiting overall impact [86, 125].

Enforcement challenges constrain regulatory efficacy, particularly in developing economies with limited monitoring and compliance infrastructure. Informal waste management sectors, prevalent in many regions, operate largely outside regulatory frameworks, perpetuating improper plastic disposal. International plastic pollution conventions, while establishing aspirational goals and norms, lack binding enforcement mechanisms and face collective action dilemmas characteristic of transboundary environmental challenges [36].

Furthermore, regulatory gaps persist regarding microplastic concentration limits in drinking water, analogous to standards established for chemical contaminants. The absence of such limits reflects ongoing debates about health risk thresholds, analytical method standardisation, and treatment technology feasibility. The World Health Organization's (2019) report on microplastics in drinking water concluded available evidence does not indicate health risks at currently detected concentrations but acknowledged substantial uncertainty and called for further research, declining to establish guideline values [135]. Several jurisdictions (California, European Union) are developing monitoring frameworks and considering regulatory standards, likely to emerge within the next 3–5 years as scientific understanding advances.

Critical evaluation reveals that while regulations have demonstrably reduced targeted plastic pollution sources, comprehensive microplastic contamination control requires integrated approaches addressing both primary prevention (reducing plastic production and consumption, enhancing waste management infrastructure, promoting circular economy models) and secondary mitigation (improving treatment technology deployment, implementing source control measures at industrial and municipal effluent discharge points). Current regulatory frameworks, though expanding, remain insufficient to reverse accumulating environmental burdens, necessitating accelerated policy development aligned with emerging scientific evidence [90,122].

7. International analytical standards

The establishment of standardised analytical protocols represents a critical priority for advancing microplastic research comparability and regulatory implementation. Variability in sampling methods, sample processing, particle identification criteria, and quality control measures has historically constrained inter-study comparisons and hindered development of coherent contamination baselines [36,122].

ISO Technical Report 21960:2020 provides comprehensive guidance on sampling and analysing microplastics in environmental media, addressing critical methodological dimensions: (1) sampling design considerations including representative site selection, replication requirements, and blank controls; (2) sample collection techniques for water (surface trawls, grab samples, filtration volumes), sediment (coring, grab sampling), and biota (tissue digestion protocols); (3) density separation methods for extracting microplastics from complex matrices; (4) purification procedures minimising organic matter interference; (5) particle identification and characterisation using stereomicroscopy and spectroscopic confirmation (ATR-FTIR, Raman microspectroscopy); and (6) quality assurance/quality control (QA/QC) requirements including procedural blanks, contamination prevention protocols (lab coats, filtered air, glass/metal equipment), and recovery efficiency assessments using spiked controls [136].

The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has similarly developed methodological guidelines emphasising spectroscopic verification of all particles suspected to be plastic, recognising that visual identification alone yields false positive rates of 20–70% depending on particle characteristics and analyst experience [137]. Advanced techniques including Raman microspectroscopy enable high-resolution chemical mapping and can identify polymer composition of particles down to 1 μm, though analysis is time-intensive. Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) provides quantitative mass-based assessments including polymer additives, advantageous for particles too small or numerous for individual spectroscopic analysis, but requires extensive method development and standardisation [96].

Adoption of these standards across the research community remains incomplete, with recent literature reviews indicating only 40–60% of published studies implement full spectroscopic confirmation and adequate blank controls [36]. Progressive journal policies mandating compliance with ISO and GESAMP guidelines for manuscript acceptance will likely accelerate standardisation. International inter-laboratory comparison exercises assessing method performance and result comparability are ongoing, identifying sources of variability and refining best practices. Harmonised analytical protocols will facilitate robust regulatory standard development, enable accurate temporal trend assessment, and support evidence-based policy interventions [122].

8. Conclusion and future research directions

The pervasive occurrence of microplastics in freshwater ecosystems across all continents underscores the global scale and urgency of plastic pollution. This review reveals several critical findings:

1. Spatial distribution patterns demonstrate marked contamination gradients, with riverine systems generally exhibiting higher microplastic loads than lakes, and groundwater systems showing relatively lower levels. Surface waters in proximity to urban centres and wastewater discharge points display elevated contamination, while remote and deeper groundwater systems demonstrate relative protection.
2. Polyethylene and polypropylene dominate polymer composition in most freshwater systems, reflecting their prevalence in packaging and consumer products. These primarily represent secondary microplastics arising from fragmentation of larger items. Textile fibres such as polyester and polyamide constitute a significant fraction, particularly in systems receiving wastewater effluents, highlighting the importance of distinguishing primary versus secondary sources for effective pollution control strategies.

3. Conventional water treatment plants achieve moderate to high microplastic removal, with performance declining substantially for smaller particles. Advanced filtration technologies, including membrane systems, provide enhanced removal including smaller size fractions but entail higher costs and energy demands. Emerging treatment approaches, such as photocatalysis and bioremediation, show promise in laboratory settings but face scalability challenges, uncertain environmental implications, and limited techno-economic assessment. Critical analytical limitations persist for the smallest particles, and current removal efficiency claims in this size range carry substantial uncertainty.
4. Wastewater treatment plants function as major microplastic sinks, effectively removing a substantial proportion of influent particles, yet simultaneously represent significant point sources discharging residual microplastics in treated effluents. The fate of captured microplastics in sewage sludge, particularly when applied to agricultural land, establishes secondary contamination pathways that require comprehensive assessment.
5. Nanoplastics represent an emerging concern, with potential environmental prevalence exceeding that of microplastics, yet analytical methods remain inadequate for robust quantification and characterisation. Health implications, particularly regarding endocrine disruption and systemic exposure risks, necessitate urgent toxicological research and the establishment of protective drinking water standards aligned with precautionary principles.
6. Legislative interventions targeting single-use plastics and intentionally added microplastics demonstrate measurable pollution reductions for specific polymer types and pathways, yet comprehensive contamination control requires broader systemic changes. These include reduced plastic production, enhanced circular economy implementation, improved global waste management infrastructure, and deployment of advanced treatment technologies.
7. International analytical standardisation, particularly alignment with ISO/TR 21960 and GESAMP protocols, is essential for ensuring data comparability, supporting regulatory standard development, and enabling accurate temporal trend assessment to evaluate policy effectiveness.

Priority research needs include: (1) development of reliable analytical methods for sub-micrometer microplastics and nanoplastics, enabling comprehensive size distribution characterisation and treatment evaluation; (2) comprehensive human health risk assessment establishing exposure thresholds, bioaccumulation potential, and toxicological endpoints; (3) large-scale pilot demonstrations of emerging treatment technologies under real-world operational conditions with full techno-economic and environmental impact assessments; (4) mechanistic understanding of microplastic transport dynamics in groundwater systems to inform source protection strategies; (5) long-term monitoring programmes assessing temporal trends in microplastic contamination and evaluating policy intervention effectiveness; and (6) interdisciplinary research integrating physical science, ecology, toxicology, engineering, economics, and policy analysis to develop holistic solutions addressing this multifaceted environmental challenge.

With the continued expansion of global plastic production projected to double by 2050 under current trajectories, proactive interventions combining source reduction, enhanced waste management, advanced treatment deployment, and evidence-based regulation are imperative to mitigate mounting environmental and health burdens. The transition towards circular economy models, sustainable material alternatives, and responsible consumption patterns offers pathways towards substantive long-term solutions, while interim measures prioritising vulnerable populations, critical water supplies, and sensitive ecosystems must be implemented urgently.

CRediT authorship contribution statement

Ojima Z. Wada: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **James O. Ijiwade:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Abimbola O. Ige:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **David B. Olawade:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation.

Declaration of competing interest

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

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