Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 14 May 2026
Revised 18 June 2026
Accepted 02 July 2026

Natural Resources for Human Health 2026, Vol. 6 (4s): 864–872

KEYWORDS: Microplastics, Aquatic Pollution, Spectroscopic Detection, Ecotoxicology, Wastewater Treatment, Plastic Debris, Nanoplastics, Sustainable Mitigation.

Microplastic Pollution in Aquatic Environments: Advanced Detection Technologies, Ecological Impacts, and Sustainable Mitigation Strategies

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ABSTRACT: Microplastic contamination of aquatic environments has progressed from a niche observation in marine debris research to a globally documented contamination class spanning oceans, freshwater systems, and wastewater infrastructure, driven by the sheer scale of global plastic production and the fragmentation, rather than degradation, that characterizes plastic's environmental fate. This paper reviews the analytical, ecological, and mitigation literature on microplastic pollution, tracing the field's development from early marine-debris quantification through the standardization of spectroscopic identification methods, the accumulated ecotoxicological evidence on ingestion, physical harm, and chemical vector effects in aquatic organisms, and the wastewater-treatment and source-reduction literature addressing mitigation. The review synthesizes foundational abundance and sourcing studies, the methodological literature comparing visual, spectroscopic, and thermoanalytical detection techniques, and the ecological effects literature spanning invertebrates, fish, and trophic transfer. Distinct comparative tables map detection technologies onto their particle-size resolution and polymer-identification capability, cross-reference documented ecological impact mechanisms against the aquatic taxa and evidence type supporting each, and set specific mitigation strategies against the point in the plastic lifecycle each targets. The paper concludes that microplastic detection methodology has matured considerably faster than either a mechanistic consensus on ecological risk thresholds or the deployment of source-level mitigation infrastructure, and identifies standardized, cross-laboratory detection

protocols as the central precondition for resolving the field's remaining ecological and regulatory uncertainty.

1. INTRODUCTION

Plastic production has grown from approximately 2 million metric tons globally in 1950 to a cumulative total exceeding 8 billion metric tons by the mid-2010s, and Geyer, Jambeck, and Law's comprehensive life-cycle accounting of this production found that of this cumulative total, a substantial majority had already become waste, with the large majority of that waste never having been recycled or incinerated but instead accumulated in landfills or released directly into the natural environment [13]. Jambeck et al.'s widely cited quantitative estimate of land-based plastic waste inputs into the ocean found that several million metric tons of plastic debris entered the marine environment annually from coastal populations alone, establishing the first rigorous, model-based global estimate of the scale of ocean plastic loading and providing the quantitative foundation for the subsequent microplastic-specific research this paper reviews [14]. Thompson et al.'s early identification of microscopic plastic fragments accumulating in marine sediments and the water column, published in *Science*, was among the first studies to explicitly document and name "microplastics" as a distinct contamination category, distinguishing these small fragments from the larger, more visually conspicuous macroplastic debris that had previously dominated marine litter research [1].

Andrady's foundational review of microplastics in the marine environment formalized the field's now-standard distinction between primary microplastics, manufactured directly at microscopic scale for applications such as cosmetic exfoliants and industrial abrasives, and secondary microplastics, formed through the fragmentation of larger plastic debris via photodegradation, mechanical abrasion, and biological degradation processes operating over years to decades, a distinction with direct implications for the mitigation strategies reviewed later in this paper, since primary and secondary microplastics originate from and respond to different intervention points [2]. Cole et al.'s comprehensive review of microplastics as marine contaminants catalogued the diversity of documented environmental sources and pathways, including wastewater effluent, atmospheric deposition, and riverine transport, and argued that microplastics' combination of small particle size, high surface-area-to-volume ratio, and chemical persistence together create a distinctive contamination profile requiring dedicated analytical and ecotoxicological methodology rather than a straightforward extension of methods developed for larger marine debris [3].

This methodological requirement motivated a substantial body of subsequent research addressing microplastic detection and quantification specifically. Hidalgo-Ruz et al.'s widely cited methodological review found considerable inconsistency across early microplastic studies in sampling protocol, size classification threshold, and identification method, a methodological heterogeneity the authors argued directly undermined efforts to compare reported abundance figures across studies or establish reliable global or regional contamination trends [8]. Shim, Hong, and Eo's subsequent review of identification methods specifically catalogued the field's progression from simple visual sorting under microscopy, a method prone to substantial false-positive and false-negative error for particles below approximately 100 micrometers, toward spectroscopic techniques, Fourier-transform infrared (FTIR) and Raman spectroscopy specifically, capable of confirming a particle's polymer identity rather than relying on visual appearance alone [9]. Primpke et al.'s development of an automated, reference-database-driven FTIR analysis workflow addressed a further practical limitation this methodological transition introduced, the substantial analyst time required to manually classify the very large numbers of particles a single environmental sample can contain, demonstrating that automated spectral library matching could process environmental samples at a throughput conventional manual FTIR analysis could not achieve [10]. Käppler et al.'s comparative evaluation of Raman microspectroscopy specifically found that Raman analysis could resolve substantially smaller microplastic particles than FTIR, extending reliable polymer identification down toward the micrometer scale and into the size range increasingly recognized as ecologically important for ingestion by smaller aquatic organisms [11].

The ecological significance of this detection capability is substantiated by an accumulating body of ecotoxicological evidence. Wright, Thompson, and Galloway's review of microplastics' physical impacts on marine organisms catalogued documented effects spanning gastrointestinal blockage, reduced feeding activity, and tissue abrasion across taxa ranging from zooplankton to larger marine vertebrates, establishing physical harm as a distinct ecological impact mechanism separate from any chemical toxicity microplastics might additionally introduce [4]. Rochman et al.'s experimental study extended this physical-harm literature into the chemical domain directly, finding that plastic debris pre-exposed to marine environmental conditions had adsorbed environmental pollutants onto its surface, and that fish fed this chemically contaminated plastic exhibited measurable liver toxicity and altered gene expression relative to control fish, providing direct experimental evidence for microplastics' function as a vector transporting adsorbed environmental contaminants into aquatic food webs [6]. Galloway, Cole, and Lewis's broader synthesis of microplastic interactions across the marine ecosystem situated these individual physical and chemical impact mechanisms within a wider ecosystem-level framework, arguing that microplastic pollution's full ecological significance depends on interactions across trophic levels and ecosystem processes that single-species toxicological studies cannot fully capture [16].

This paper reviews the sourcing and abundance literature, the detection-methodology literature, and the ecotoxicological literature within a single comparative framework, before examining the wastewater-treatment and source-reduction evidence addressing mitigation specifically.

Research Objectives

- To review the foundational literature on microplastic sourcing, classification, and global abundance estimation in aquatic environments.
- To synthesize the analytical and spectroscopic detection methodology literature, from visual sorting through automated FTIR and Raman analysis.
- To examine the ecotoxicological evidence on microplastics' physical and chemical impact mechanisms across aquatic taxa.
- To evaluate wastewater treatment and source-reduction mitigation strategies addressing microplastic pollution at different points in the plastic lifecycle.
- To identify future research priorities for standardizing detection protocols and resolving ecological risk uncertainty.

2. LITERATURE REVIEW

2.1 Sourcing, Classification, and Global Abundance

Andrady's primary-versus-secondary microplastic classification remains the field's standard organizing distinction, with primary microplastics entering aquatic environments directly through manufactured microbead products and industrial pellet loss, and secondary microplastics forming through the progressive fragmentation of macroplastic debris, fishing gear, packaging, and textiles among the most commonly documented sources, via UV photodegradation and mechanical weathering [2]. Napper and Thompson's experimental quantification of synthetic microfiber release from domestic washing machines found that a single wash load of synthetic clothing could release several hundred thousand to over a million individual microfibers into wastewater, identifying textile laundering as a substantial and previously underappreciated primary source of secondary microplastic fiber pollution entering municipal wastewater systems specifically [12]. Eriksen et al.'s global ocean-surface survey, combining an extensive multi-ocean sampling campaign with an oceanographic transport model, produced one of the first comprehensive global estimates of total floating plastic debris mass and particle count, finding that microplastic particles vastly outnumbered larger debris items numerically even though they constituted a comparatively small fraction of total floating plastic mass, a size-distribution finding with direct implications for why particle-count-based abundance metrics and mass-based metrics can produce divergent characterizations of the same underlying contamination [5].

2.2 Detection and Identification Methodology

Hidalgo-Ruz et al.'s methodological review formalized the specific technical challenges microplastic identification confronts, including the difficulty of visually distinguishing small plastic particles from natural organic and mineral material under standard microscopy, and the resulting risk of both false-positive misidentification of non-plastic material and false-negative failure to detect genuine microplastic particles, particularly at smaller size fractions [8]. Shim, Hong, and Eo's subsequent review traced the field's methodological progression in response to this challenge, from visual identification, adequate for larger, more morphologically distinctive particles but unreliable below approximately 100 micrometers, through density separation and chemical digestion sample-preparation techniques, toward spectroscopic confirmation methods capable of definitively establishing a particle's polymer composition [9]. Primpke et al.'s automated FTIR imaging and reference-database matching approach directly addressed the throughput limitation that had constrained spectroscopic methods' practical application to large environmental sample sets, demonstrating that automated spectral classification against a curated polymer reference library could process substantially more particles per sample than manual spectral interpretation while maintaining high classification accuracy [10]. Käppler et al.'s comparative Raman microspectroscopy evaluation found that Raman analysis's shorter excitation wavelength and higher spatial resolution allowed reliable polymer identification for particles smaller than FTIR's practical resolution limit, at the cost of longer per-particle acquisition time and greater susceptibility to fluorescence interference from adsorbed organic material, establishing a specific resolution-versus-throughput trade-off between the field's two dominant spectroscopic methods [11]. Prata et al.'s more recent critical review of sampling and detection methods synthesized this accumulated methodological literature, concluding that no single detection technique currently provides simultaneously high throughput, high size-resolution, and definitive polymer identification, and recommending that method selection be made explicit and justified relative to a given study's specific size range and throughput requirements rather than treated as methodologically interchangeable across studies [17].

2.3 Physical Ecological Impacts

Wright, Thompson, and Galloway's review catalogued physical impact mechanisms documented across a wide range of aquatic taxa, including gut blockage and false satiation in filter-feeding invertebrates, reduced energy reserves attributable to reduced feeding following ingestion, and physical abrasion of gill and digestive tissue in fish and larger organisms, establishing that microplastic ingestion carries direct physical consequences independent of any chemical toxicity the ingested material might additionally introduce [4]. De Sá et al.'s broader synthesis of aquatic organism studies extended this physical-impact evidence base considerably, reviewing accumulated experimental studies across fish, crustaceans, and mollusks and finding generally consistent evidence for reduced feeding, altered behavior, and measurable physiological stress responses following microplastic exposure, while specifically noting that the environmental realism of many laboratory exposure concentrations, frequently far exceeding field-measured environmental concentrations, remains a significant limitation constraining how directly laboratory findings can be extrapolated to real-world ecological risk [18].

2.4 Chemical Vector Effects and Trophic Transfer

Rochman et al.'s experimental demonstration that environmentally weathered plastic debris adsorbs hydrophobic organic pollutants and subsequently transfers measurable toxicological effects to fish that ingest it established microplastics' function as a chemical contaminant vector, distinct from and additive to the physical harm mechanisms reviewed in Section 2.3 [6]. Galloway, Cole, and Lewis's ecosystem-level synthesis argued that this vector function, combined with documented evidence of microplastic ingestion across multiple trophic levels from zooplankton through fish and seabirds, raises the possibility of trophic transfer, in which microplastic particles and their adsorbed contaminant load move progressively up a food web through predator-prey ingestion, though the authors specifically cautioned that direct empirical evidence for biomagnification of microplastic particle number, as opposed to biomagnification of specific adsorbed chemical contaminants, remains considerably more limited than the physical-ingestion evidence reviewed in Section 2.3 [16].

2.5 Nanoplastics as an Emerging Sub-Category

Koelmans, Besseling, and Shim's critical review of nanoplastics in the aquatic environment identified a size-based sub-category, plastic particles below approximately one micrometer, that current standard detection methodology reviewed in Section 2.2 struggles to reliably identify and quantify, since both FTIR and Raman spectroscopy face fundamental spatial-resolution limits as particle size approaches and falls below the wavelength of the excitation light used, meaning that documented microplastic abundance figures likely substantially undercount the true particle count once the nanoplastic size fraction is considered [19]. This detection limitation carries direct relevance for the ecotoxicological evidence reviewed in Sections 2.3 and 2.4, since Koelmans, Besseling, and Shim's review notes that smaller particles are generally expected to cross biological membranes and accumulate in tissue more readily than larger microplastic particles, suggesting that the ecological risk profile of the nanoplastic size fraction may differ qualitatively from the risk profile established for the more readily detected and studied microplastic size range [19].

2.6 Wastewater Treatment as a Mitigation Point

Sun et al.'s review of microplastics in wastewater treatment plants found that conventional wastewater treatment processes, while not specifically designed to target microplastic removal, nonetheless remove a substantial majority of influent microplastic particles through a combination of primary sedimentation, secondary biological treatment, and tertiary filtration stages, though the authors noted that even a small percentage of uncaptured particles translates into a very large absolute particle count released to receiving waters given the very large volumes of wastewater municipal treatment plants process [20]. Talvitie et al.'s direct comparative evaluation of advanced tertiary treatment technologies, including membrane bioreactors, rapid sand filtration, and dissolved air flotation, specifically for microplastic removal found that membrane bioreactor technology achieved the highest documented removal efficiency among the technologies tested, approaching complete removal of influent microplastic particles, while more conventional tertiary technologies achieved somewhat lower, though still substantial, removal efficiencies, providing direct comparative evidence relevant to wastewater infrastructure investment decisions specifically targeting microplastic mitigation [15].

2.7 Source Reduction and Upstream Mitigation

Napper and Thompson's washing-machine microfiber study, beyond documenting the scale of textile-sourced microplastic release, specifically evaluated candidate mitigation interventions including in-drum capture devices and external washing-machine filters, finding that these devices could capture a meaningful proportion of released microfibers before they entered wastewater, providing an evidence base for source-level, point-of-release mitigation as a complement to downstream wastewater-treatment interventions [12]. Geyer, Jambeck, and Law's lifecycle-accounting framework, while not focused on microplastics specifically, provides the broader upstream context within which source-reduction mitigation operates, since the very large share of historical plastic production that the authors found had never been recycled or incinerated indicates that end-of-pipe wastewater treatment alone cannot address the accumulated and ongoing macroplastic debris stock that continues to fragment into secondary microplastics over long timescales independent of any wastewater-treatment intervention [13].

2.8 Research Gap

While the detection-methodology literature reviewed in Section 2.2 has matured considerably, progressing from inconsistent visual sorting toward standardized, automated spectroscopic identification, and the ecotoxicological literature reviewed in Sections 2.3 through 2.5 has established a substantial, if methodologically heterogeneous, physical and chemical impact evidence base, comparatively few studies directly connect the specific detection method's size-resolution limitations, particularly the nanoplastic detection gap Koelmans, Besseling, and Shim identify, to the interpretation of ecotoxicological dose-response evidence, since laboratory exposure studies frequently use manufactured, uniformly sized microplastic particles that may not represent the actual particle-size distribution, including the undercounted nanoplastic fraction, present in real environmental exposures [4], [8], [19]. This review addresses this gap by organizing the reviewed evidence within a comparative framework spanning detection technology, ecological impact mechanism, and mitigation strategy.

3. METHODOLOGY

This study adopts a qualitative, descriptive, and comparative research design synthesizing peer-reviewed environmental science, analytical chemistry, and ecotoxicology literature addressing microplastic pollution in aquatic environments. Reviewed studies were compared along four axes: research focus (sourcing/abundance, detection methodology, ecological impact, or mitigation); detection or exposure method employed, where applicable; aquatic environment and taxa examined; and whether the study's evidence is observational/field-based, experimental/laboratory-based, or technology-evaluative.

4. RESULTS AND DISCUSSION

4.1 Detection Technologies Mapped to Size Resolution and Identification Capability

Table 1 maps the detection technologies reviewed in Section 2.2 onto their particle-size resolution and polymer-identification capability, a structure emphasizing method selection rather than a chronological summary of technique development.

Table 1. Microplastic Detection Technologies: Size Resolution and Identification Capability

Detection Technology	Approximate Size Resolution Limit	Polymer Identification Capability	Throughput	Key Reference
Visual sorting (microscopy)	~500 micrometers (unreliable below ~100 μm)	None (morphology-based, high misidentification risk)	High (fast per sample)	Hidalgo-Ruz et al. [8]

Manual FTIR spectroscopy	~20 micrometers	Definitive (spectral matching to polymer library)	Low (labor-intensive per particle)	Shim, Hong & Eo [9]
Automated FTIR imaging	~20 micrometers	Definitive (automated database matching)	Moderate-to-high (automated classification)	Primpke et al. [10]
Raman microspectroscopy	~1 micrometer	Definitive (higher spatial resolution than FTIR)	Low (longer acquisition; fluorescence interference)	Käppler et al. [11]
Standard spectroscopic methods (nanoplastic range)	Below ~1 micrometer: largely unresolved	Not reliably achievable with current standard methods	N/A (detection gap)	Koelmans, Besseling & Shim [19]

4.2 Ecological Impact Mechanisms Cross-Referenced Against Taxa and Evidence Type

Table 2 cross-references the ecological impact mechanisms reviewed in Sections 2.3 and 2.4 against the aquatic taxa and evidence type supporting each, a structure distinct from Table 1 in that it addresses biological effect rather than analytical method.

Table 2. Ecological Impact Mechanisms, Affected Taxa, and Evidence Type

Impact Mechanism	**Affected Taxa (Documented)**	**Evidence Type**	**Key Reference**
Gut blockage / false satiation	Filter-feeding invertebrates, zooplankton	Laboratory exposure studies	Wright, Thompson & Galloway [4]
Reduced feeding / energy reserves	Fish, crustaceans, mollusks	Laboratory exposure studies (varied concentrations)	de Sá et al. [18]
Tissue abrasion (gill/digestive)	Fish and larger aquatic organisms	Laboratory and field-observational studies	Wright, Thompson & Galloway [4]
Chemical contaminant vector effect (adsorbed pollutants)	Fish (liver toxicity, altered gene expression)	Controlled laboratory experiment	Rochman et al. [6]
Trophic transfer (particle + adsorbed chemical)	Cross-trophic-level (zooplankton to seabirds, inferred)	Ecosystem-level synthesis; limited direct biomagnification evidence	Galloway, Cole & Lewis [16]
Enhanced tissue/membrane penetration (size-dependent)	Broadly inferred across taxa (nanoplastic size fraction)	Theoretical/review synthesis; limited direct field evidence	Koelmans, Besseling & Shim [19]

4.3 Mitigation Strategies Mapped to Plastic Lifecycle Stage

Table 3 sets the mitigation strategies reviewed in Sections 2.6 and 2.7 against the specific point in the plastic lifecycle each target, a structure distinct from Tables 1 and 2 in that it addresses intervention rather than detection or impact.

Table 3. Mitigation Strategies Mapped to Plastic Lifecycle Stage

Lifecycle Stage Targeted	Mitigation Strategy	Documented Effectiveness	Key Reference
Point-of-release (textile laundering)	In-drum capture devices / external washing-machine filters	Captures a meaningful proportion of released microfibers before wastewater entry	Napper & Thompson [12]
Municipal wastewater treatment (conventional)	Standard primary/secondary/tertiary treatment train	Removes a substantial majority of influent particles (not purpose-designed)	Sun et al. [20]
Municipal wastewater treatment (advanced tertiary)	Membrane bioreactors, rapid sand filtration, dissolved air flotation	Membrane bioreactors achieve near-complete removal; other technologies moderately effective	Talvitie et al. [15]
Upstream production/waste management	Reduced virgin production; improved recycling/incineration capture	Addresses accumulated macroplastic stock that fragments into secondary microplastics over time	Geyer, Jambeck & Law [13]
Coastal/riverine input reduction	Land-based waste management improvement (source of ocean input)	Targets the dominant modeled pathway of land-to-ocean plastic transport	Jambeck et al. [14]

DISCUSSION

Read together, Tables 1 through 3 support the paper's central claim that microplastic pollution's detection methodology has matured considerably faster than either the mechanistic ecological risk evidence or mitigation infrastructure deployment needed to fully act on it. Table 1 establishes that no single detection technology simultaneously achieves high throughput, fine size resolution, and definitive polymer identification, with Raman microspectroscopy's superior size resolution coming at a direct cost to throughput relative to automated FTIR imaging, and with the nanoplastic size fraction remaining largely outside the resolution of either standard technique, a gap Koelmans, Besseling, and Shim identify as a fundamental rather than merely practical limitation of current spectroscopic methods [9], [10], [11], [19]. Table 2's impact-mechanism mapping indicates that the strongest ecotoxicological evidence, physical harm from gut blockage and reduced feeding, and chemical vector effects demonstrated experimentally by Rochman et al., is concentrated in the microplastic size range current detection technology resolves well, while the trophic-transfer and enhanced-penetration mechanisms most relevant to the nanoplastic fraction remain considerably less directly evidenced, a pattern that plausibly reflects a detection-driven rather than purely biological explanation for where the evidence base is strongest [4], [6], [16], [19]. Table 3's lifecycle mapping indicates that effective mitigation requires intervention at multiple, structurally distinct points, point-of-release textile capture, wastewater treatment upgrade, and upstream production and waste-management reform, since Geyer, Jambeck, and Law's lifecycle accounting demonstrates that the very large existing stock of already-released macroplastic debris will continue generating secondary microplastics through ongoing fragmentation regardless of how effectively downstream wastewater treatment or point-of-release capture technologies perform going forward [12], [13], [15], [20]. This multi-point mitigation requirement, read against Table 1's detection-technology limitations, suggests that resolving the field's remaining uncertainty, particularly regarding nanoplastic-scale ecological risk, depends on parallel progress in detection technology and mitigation deployment rather than either alone.

CONCLUSION

This paper has reviewed the analytical, ecological, and mitigation literature on microplastic pollution in aquatic environments, synthesizing foundational sourcing and abundance studies, the spectroscopic detection methodology literature, the ecotoxicological evidence on physical and chemical impact mechanisms, and the wastewater-treatment and source-reduction mitigation literature. The evidence indicates that detection methodology has progressed substantially from inconsistent visual sorting toward automated, spectroscopically confirmed identification, but that this progress has not eliminated a persistent size-resolution gap at the nanoplastic scale, a gap with direct implications for how confidently the field can characterize ecological risk across the full particle-size distribution actually present in aquatic environments. The ecotoxicological evidence establishes both physical harm and chemical vector effects across multiple aquatic taxa with reasonable consistency, though this evidence base remains concentrated in the size range current detection technology resolves well. Mitigation strategies spanning point-of-release capture, wastewater treatment upgrades, and upstream production and waste-management reform each address a structurally distinct stage of the plastic lifecycle, and the evidence indicates that no single intervention point is sufficient given the very large existing stock of macroplastic debris that will continue fragmenting into secondary microplastics independent of any single mitigation strategy's effectiveness.

FUTURE WORK

Future research should prioritize the development of detection methods capable of reliably resolving the nanoplastic size fraction, extending the spatial-resolution improvements Raman microspectroscopy has achieved relative to FTIR toward the sub-micrometer range that current standard methods cannot reliably address. Further work is needed to directly link detection-method size resolution to ecotoxicological study design, ensuring that laboratory exposure studies use particle-size distributions representative of actual environmental exposure, including the currently undercounted nanoplastic fraction, rather than relying predominantly on uniformly sized manufactured test particles. Continued research should also extend Talvitie et al.'s comparative wastewater-treatment-technology evaluation to a broader range of treatment plant scales and configurations, to establish cost-effective advanced-treatment retrofit pathways applicable beyond the specific facilities examined in existing comparative studies. Finally, future work should pursue standardized, internationally harmonized detection and reporting protocols, directly addressing the methodological inconsistency Hidalgo-Ruz et al. identified over a decade ago, so that abundance and trend data collected across different research groups and monitoring programs can be meaningfully compared and aggregated into the kind of global contamination trend analysis current methodological heterogeneity continues to constrain.

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