A Hybrid Narrative-Systematic Review of the Global Implications and Remediation of Environmental Microplastics

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ABSTRACT

Microplastics (MPs) have emerged as a pervasive, transboundary pollutant driven by exponential plastic production (473 Mt in 2020; projected 1,150 Mt by 2060) and low global recycling (9-13%). This hybrid narrative-systematic review synthesises 252 open-access studies (2015-2025) from PubMed and ScienceDirect to assess the generation, fate, detection, ecological and human health implications, and remediation of environmental microplastics. Dominant polymers (PE, PP, PET) and morphologies (fibres, fragments) are ubiquitous across matrices, with abundances ranging from 1-12 items/L (rivers) to 15-17 MPs/mollusc. Detection methods (FTIR, Raman, Pyrolysis-GC/MS) reliably identify MPs ≥1-20 µm but underestimate nanoplastics, skewing risk assessment. Ecological impacts include impaired feeding, reproduction, and trophic transfer, while human exposure via ingestion (4.22-22.01 MPs/day), inhalation, and medical pathways results in systemic accumulation (20.81 µg/g blood; 3.5 particles/g stool), linked to inflammation and neurotoxicity. Remediation achieves 90-99.98% removal in WWTPs, but scalability, sludge reintroduction, and nanoplastic persistence remain barriers. Geographic biases (sparse data from Africa, South Asia), methodological inconsistencies, and small-cohort health studies limit generalizability. Policy must prioritise source reduction through extended producer responsibility, virgin plastic caps, and the UNEA treaty. Research requires standardised detection, longitudinal biomonitoring, and field-scale remediation trials. This review emphasises the need for integrated governance and innovation to mitigate the global microplastic crisis.

Keywords: Microplastics, Hybrid Review, Environmental Fate, Human Health, Remediation, Policy

Abbreviation

Abbreviation	Full Form
MP	Microplastic
NPs	Nanoplastics
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
PA	Polyamide
ABS	Acrylonitrile Butadiene Styrene
PU	Polyurethane
FTIR	Fourier-Transform Infrared Spectroscopy
µ-FTIR	Micro-Fourier-Transform Infrared Spectroscopy
Raman	Raman Spectroscopy
µ-Raman	Micro-Raman Spectroscopy
Pyrolysis-GC/MS	Pyrolysis–Gas Chromatography/Mass Spectrometry

SEM-EDS	Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy
TGA	Thermogravimetric Analysis
DSC	Differential Scanning Calorimetry
WWTP	Wastewater Treatment Plant
MBR	Membrane Bioreactor
UF	Ultrafiltration
NF	Nanofiltration
RO	Reverse Osmosis
DAF	Dissolved Air Flotation
EPR	Extended Producer Responsibility
UNEA	United Nations Environment Assembly
QA/QC	Quality Assurance/Quality Control
JBI	Joanna Briggs Institute
OECD	Organisation for Economic Co-operation and Development
GHG	Greenhouse Gas
PETase	PET-degrading enzyme (polyethylene terephthalate hydrolase)
MHETase	Mono(2-hydroxyethyl) terephthalate hydrolase
R^2	Coefficient of Determination
t/y	Tons per year
Mt	Million metric tons
L	Liter
m^3	Cubic meter
µg/g	Micrograms per gram
ng/g	Nanograms per gram
items/L	Items per litre
particles/m^3	Particles per cubic meter
MPs/g	Microplastics per gram
MPs/ind	Microplastics per individual
MPs/day	Microplastics per day
LOD	Limit of Detection
LOQ	Limit of Quantification
BAF	Bioaccumulation Factor
BCF	Bioconcentration Factor
TF	Transfer Factor (trophic transfer)
ROS	Reactive Oxygen Species
NOAEL	No Observed Adverse Effect Level
ADME	Absorption, Distribution, Metabolism, Excretion
HOC	Hydrophobic Organic Contaminant
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PBDE	Polybrominated Diphenyl Ether
ADD	Additives (e.g., plasticisers, flame retardants)

INTRODUCTION

Background and Problem Statement

Plastic production has increased over the past half-century due to its lightweight, durable, and cost-effective properties [258-260]. This leads to fragmentation into microplastics (MPs),synthetic polymeric particles ≤5 mm, detected in environmental, food, and biological matrices [261-263]. Microplastic prevalence reflects the high volumes of environmental plastic and the complex physicochemical processes that drive fragmentation and global transport [264, 265]. Their occurrence varies by size, abundance, and residence

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time, creating a multidimensional pollution challenge for human and environmental health [266-268]. Microplastics arise from primary sources (e.g., pellets, microbeads, tyre wear, textile fibres) and secondary fragmentation [269-272]. They act as vectors for hydrophobic contaminants and additives, forming a "plastisphere" that alters microbial colonisation and ecosystem interactions [273-277]. Microplastic ubiquity, physicochemical heterogeneity, and biological uptake raise scientific and policy concerns, yet uncertainties persist regarding exposure pathways, dose-response relationships, and long-term risks [278-280].

Study Justification

The literature on microplastics spans diverse disciplines, complicating traditional systematic reviews that require narrowly defined questions [281]. Narrative reviews provide synthesis but lack reproducible methods [282]. A hybrid narrative-systematic approach combines methodical search, screening, and quality evaluation for evidence-based results with narrative synthesis to integrate mechanistic, procedural, and policy insights [283, 284]. This suits microplastics research, where heterogeneous sampling, size thresholds, and endpoints preclude meta-analysis but demand transparent methods to ensure credibility and identify knowledge gaps.

This review is guided by the premise that increasing plastic production, inadequate waste management, and diverse environmental transport pathways have resulted in the widespread distribution of microplastics across terrestrial, aquatic, atmospheric, and biological systems. It further assumes that synthesising evidence through a structured hybrid narrative-systematic review provides a comprehensive framework for evaluating current knowledge, identifying methodological gaps, and informing future research and policy directions

Definition and Key Terms

This review defines microplastics as synthetic polymeric particles $\leq$5 mm, encompassing various polymer types (e.g., polyethylene, polypropylene, polystyrene), morphologies (e.g., fibres, fragments, films), and additives [285, 286]. Environmental media include marine/freshwater, sediments, soils, air, biota, and human exposure pathways (e.g., food, aerosols, and drinking water) [287, 288]. Media sampling, digestion, and detection limits influence microplastic abundance and size distributions, with consistent reporting critical for cross-study comparisons. On the other hand, inconsistent operational thresholds often drive variable findings, not environmental differences.

Research Objectives

This study aims to synthesise and critically evaluate the current body of evidence on the occurrence, environmental fate, human health implications, and remediation of microplastics. Specifically, the objectives of this review are to:

1. Examine global trends in plastic production, waste generation, and the formation of environmental microplastics.
2. Evaluate the classification, characteristics, sources, and environmental transport pathways of microplastics.
3. Assess the analytical methods currently used for the detection and characterisation of microplastics in different environmental and biological matrices.
4. Synthesise available evidence on the ecological and human health impacts associated with microplastic exposure.
5. Review existing remediation technologies, management strategies, and policy interventions for mitigating microplastic pollution.

6. Identify current knowledge gaps and propose future research directions to improve global understanding and management of microplastics.

Research questions

(1) What are the dominant production patterns, recycling efficiencies, and waste streams driving microplastic generation? (2) How are microplastics categorised by type, size, morphology, and composition? (3) Which sources and vectors control their mobilisation across terrestrial, aquatic, and atmospheric systems? (4) How do sampling and analytical methods affect detection limits and data comparability? (5) What organism- and ecosystem-level impacts result from microplastic exposure? (6) What pathways enable human microplastic exposure, and what evidence links to health outcomes? (7) Which technologies effectively remove or degrade microplastics, and what barriers persist? These questions frame an integrated understanding of the microplastic continuum, identifying needs for standardisation, monitoring, and solutions.

Structure of the Review

Section 2 details the methodology, including search strategy, inclusion criteria, and quality appraisal. Section 3 presents results on microplastics production, classification, sources, detection, ecotoxicological and health effects, and remediation. Section 4 integrates findings with policy implications. Section 5 outlines research and policy priorities, and Section 6 provides evidence-based conclusions. Supplementary materials include search documentation and appraisal matrices.

METHODOLOGY

Protocol Registration

This review adopted a structured, resource-conscious approach to ensure methodological transparency despite financial constraints. Without institutional access to platforms like PROSPERO, the review protocol detailing research questions, eligibility criteria, and analysis methods was documented in a dated logbook for accountability.

Search Strategy

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA), as described by Page et al. [290] and shown in Figure 1, a literature search was conducted on August 25, 2025, using PubMed and ScienceDirect for their coverage of biomedical, environmental, and engineering sciences relevant to microplastics [13]. PubMed was chosen for toxicology and health studies, and ScienceDirect for environmental and remediation research [205, 209]. The search spanned January 2015 to August 2025, focusing on contemporary evidence in microplastic detection, toxicity, and remediation. Only full-text, open-access articles were included to ensure feasibility. Only original research and systematic reviews addressing microplastic production, classification, sources, detection, ecotoxicological effects, human exposure, or remediation were eligible.

The ScienceDirect search string was: *microplastic OR nanoplastic AND (Global production OR classification OR sources OR detection OR toxicity OR exposure OR remediation) since 2015.* For PubMed: *(("microplastics"[MeSH Terms] OR microplastic OR nanoplastic) AND (production OR manufacturing OR classification OR sources OR detection OR toxicity OR exposure OR remediation) AND ("2015/01/01"[Date - Publication]: "3000"[Date - Publication])).* Boolean operators and MeSH terms (PubMed) or proximity functions (ScienceDirect) were tailored to database specifications [223, 234]. Citation chasing from reviews and highly cited studies supplemented searches, with periodic updates to capture new articles [240, 289].

Screening and Data Extraction

The search yielded 5,641 records (PubMed: 1,025, ScienceDirect: 4,616). After removing 1,389 duplicates, 4,252 records were screened by title and abstract using eligibility criteria. A total of 3,540 articles were excluded (e.g., macroplastics, non-empirical), leaving 712 for full-text review. Of these, 468 were excluded (inaccessible, or not relevant enough to warrant inclusion). Citation chasing added 8 eligible studies. The final dataset included 252 studies (Figure 1), as shown in the attached spreadsheet for transparency (See the **attached Excel File**). Data were extracted manually in Excel, with fields for study characteristics, matrix, microplastic/nanoplastic properties, detection methods, findings, limitations, and thematic relevance. Each article was read fully, with entries double-checked for accuracy.

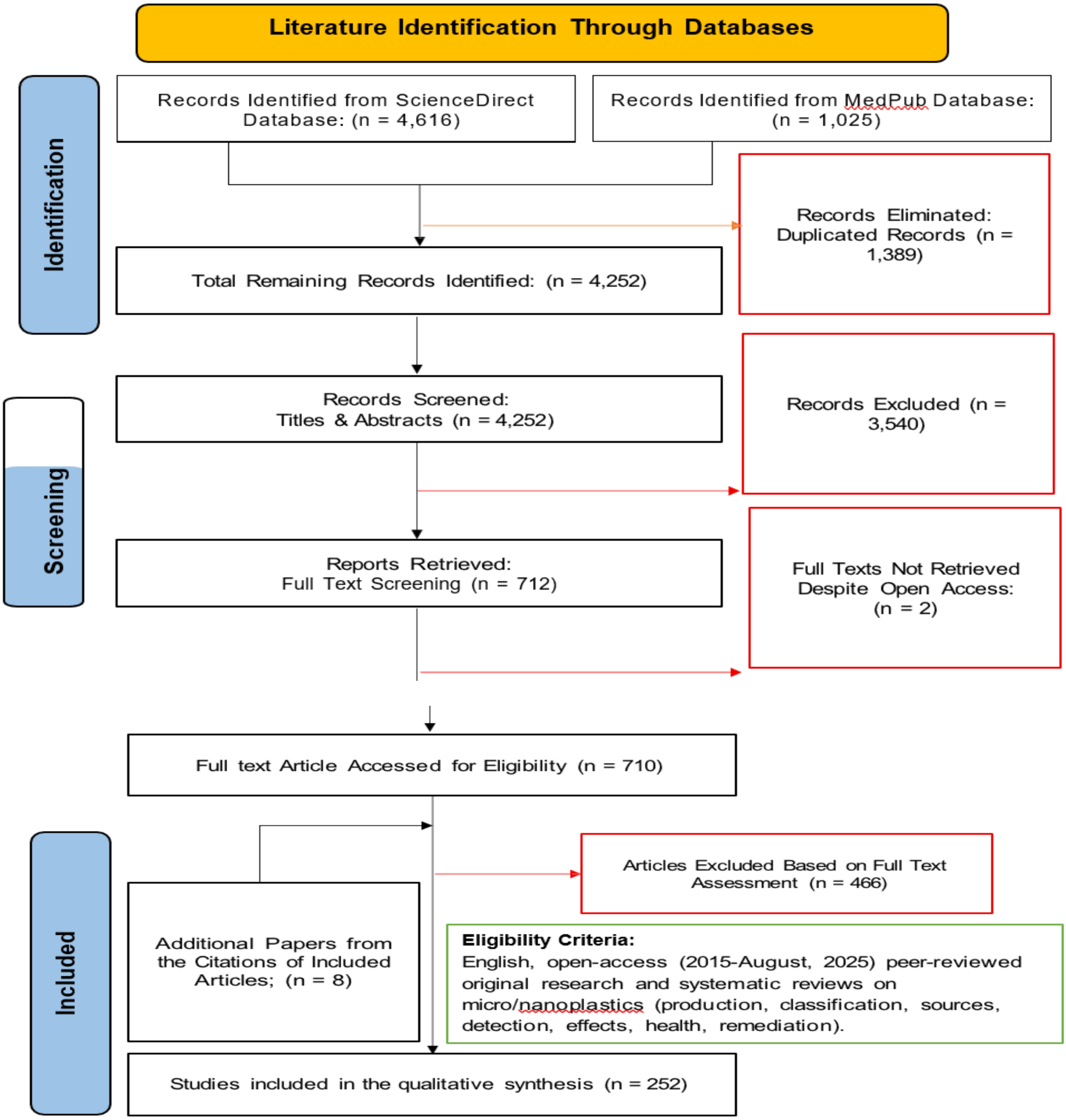

Figure 1: A flow chart summarising how the hybrid narrative-systematic review was conducted

between 2015 & August 2025, following PRISMA guideline (adapted from adapted from Page et al. [290]).

Eligibility Criteria

The criteria used for screening, selecting, and including studies identified via databases and citation chasing are presented in Table 1.

Table 1. Inclusion and Exclusion Criteria

Domain	Inclusion Criteria	Exclusion Criteria
Publication type	Peer-reviewed original research articles and systematic review papers	Conference abstracts, editorials, commentaries, letters without primary data; unsystematic reviews
Access status	Full-text, open access (to ensure feasibility and transparency)	Paywalled or inaccessible articles
Language	English	Non-English publications
Timeframe	Published between January 2015 and August 2025	Published before 2015
Study focus	Studies explicitly investigating microplastics or nanoplastics, including: -Global production and waste -Classification and characteristics -Sources and environmental pathways -Detection and analytical methods -Ecotoxicological effects -Human exposure and health impacts -Remediation strategies	Studies focused exclusively on - Macroplastics (>5 mm) - Plastic policy without empirical evidence - Unrelated polymer/material science without environmental or biological relevance
Study setting	Environmental, biomedical, toxicological, engineering, or ecological contexts	Purely theoretical modelling with no empirical or methodological component
Population/Matrix	Aquatic, terrestrial, atmospheric, and biological compartments, including human health	Studies unrelated to microplastic presence, fate, or effects
Study design	Experimental, observational, monitoring surveys, toxicological assays, epidemiological studies, and remediation trials	Studies lacking original data or systematic evidence (e.g., opinion pieces and other reviews that aren't systematic)

Quality Assessment and Data Synthesis

A tailored checklist, adapted from the Joanna Briggs Institute (JBI Evidence Synthesis), assessed study quality across objectives, design, measurement validity, reporting transparency, and limitation acknowledgement [291]. Studies were classified as high (rigorous methods, validated techniques), moderate (sound methods, limited reporting), or low quality (poor objectives, weak methods). This qualitative approach ensured consistent evaluation despite resource constraints. Due to study heterogeneity, a narrative synthesis [292, 293] was conducted, organised by thematic domains [294]: classification, production, sources, detection, ecotoxicological effects, human exposure, and remediation. Findings were collated to identify patterns, consensus, and contradictions. Cross-domain comparisons were also conducted to provide additional structure.

Limitations of the Methods

This review has several methodological, measurement, analytical, and evidence-related limitations that should be considered when interpreting the findings. First, the included studies employed diverse sampling designs, environmental matrices, particle-size thresholds, extraction procedures, and analytical techniques, resulting in substantial methodological heterogeneity. Consequently, direct comparison of results across studies was challenging and precluded the use of formal meta-analysis or pooled effect estimates. The heterogeneity also limited the ability to establish quantitative dose–response relationships or generate unified global estimates of microplastic exposure with narrow uncertainty.

Second, considerable variation existed in measurement approaches. Detection methods such as Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, Pyrolysis–Gas Chromatography/Mass Spectrometry (Pyrolysis-GC/MS), and microscopic techniques differed in their sensitivity and minimum detectable particle size. Many studies were unable to detect nanoplastics or particles below their analytical limits of detection, which may have resulted in systematic underestimation of small-particle abundance and associated exposure.

Third, the available evidence showed important geographical and epidemiological imbalances. Most studies originated from high-income countries, while relatively few investigations were conducted in low- and middle-income regions, particularly Africa and parts of South Asia. Furthermore, much of the human health evidence was based on small cohort studies or cross-sectional biomonitoring investigations, limiting causal inference and reducing the generalisability of reported health outcomes.

Finally, this review was restricted to English-language, open-access publications retrieved from PubMed and ScienceDirect. Although citation tracking was performed to identify additional relevant studies, this approach may have excluded important paywalled publications, grey literature, and studies published in other languages, thereby introducing publication and selection bias. Despite these limitations, the application of transparent eligibility criteria, structured quality appraisal, and systematic data extraction enhanced the credibility, reproducibility, and overall reliability of the review findings.

Ethical considerations: This review synthesised evidence from previously published studies and did not involve the collection of primary data from human participants or animals. Therefore, ethical approval and informed consent were not required.

LITERATURE REVIEW AND RESULTS

Global Plastics Production and Waste Statistics

Historical and Recent Production Volumes and Projections

Global plastics production surged from 2 Mt in 1950 to 380 Mt in 2015 and 473 Mt by 2020, with cumulative output at ~10 Gt [244, 245]. Estimates report 460 Mt in 2019, projected to reach 800 Mt by 2050 under BAU [255], or 1,150 Mt by 2060 without interventions [246]. Production was 348 Mt in 2017, potentially doubling by 2100 without recycling and stock limits [29]. Cumulative production may hit 40 Gt by 2050, though with moderate confidence [83]. Despite per capita declines in Switzerland post-2010 [27], global demand, driven by GDP and urbanisation, rises, especially in emerging economies [246, 250]. Plastic accumulation could reach 2.15-5.3 Gt by 2050 [16], nearly doubling 2017 levels [33]. Circular economy scenarios with 55% packaging recycling by 2030 could limit production to 735-884 Mt by 2050 [33, 252], with OECD policies reducing leakage by 74% and GHG emissions by 30% [246]. Non-OECD countries will drive 80% of demand growth by 2060 [246]. Without change, production may double in 30-40 years.

Recycling, Recovery, and Waste Management Effectiveness

Recycling remains low: only 9% of 8.3 Gt was recycled from 1950-2015, with 79% landfilled or released [245]; by 2020, recycling was below 13% [244]. The EU projects 41-46% mechanical and 15-38% chemical recycling by 2030 [257], while the U.S. landfills over half its municipal waste [44]. Developing regions lag: UAE recycles 7% (2021), projected to reach 11-15% by 2050, with 90% landfilled [28]; South and Southeast Asia have <30% recycling, with 50-70% open dumping or burning [254]. China’s 2018 import ban, after handling >50% of global plastic waste, increased intra-regional trade, exposing weak recycling capacity [26]. Circular economy models could raise recycling to 30% by 2060 and cut mismanaged waste by 80% by 2040 [246, 250]. Policies like recycled-content mandates could reduce leakage by 91% and GHG emissions by 33% [251], but weak infrastructure limits global recovery.

Sources of Microplastics Linked to Production and Use

Mismanaged plastic waste (MPW) fuels macro- and microplastic emissions, reaching ~100 Mt in 2019, projected to double by 2040 and triple to 228 Mt by 2060 under BAU [246, 250]. Over 90% of MPW reaches oceans via rivers [249]. Switzerland reports 31 kg/capita release, mostly macroplastic [27], and 222 ± 50 g/capita/year, with 82% macroplastics [14]. South and Southeast Asia have 50-75% leakage from burning and dumping [254]. Packaging accounts for

~40% of consumption [44], with industrial processes contributing minimally due to >99% removal in advanced systems [215]. Ocean emissions may hit 90 Mt/yr by 2030 but could stabilise by 2050 with a 32% cut by 2035 [253]. Cumulative mismanaged plastics may reach 12,000 Mt by 2050 [245], with 75-199 Mt in oceans, including 233,400 t macroplastics and 35,540 t microplastics [256]. Waste mismanagement and packaging drive microplastic generation.

Synthesis and Evidence Quality

Global plastic production (>460 Mt/yr), low recycling (<13%), and rising mismanaged waste drive leakage, supported by robust, multi-regional data [248]. Stringent lifecycle policies and global cooperation are vital, as partial measures fail [247]. In Bali, remote sensing and machine learning estimated 132.6 tons/day of household waste (R^2=0.882), showing potential to address data gaps in low-income regions [42]. However, inconsistencies and gaps in informal sector data persist, especially in low- and middle-income nations. These trends inform environmental transport and impact analyses.

Table 1: Summary of Global Plastics Production and Waste Statistics

Paper	Authors & Year	Region	Years Covered	Production (Mt)	Recycling (%)	Mismanaged Waste	Key Findings	Quality
14	Jiang & Nowack, 2025	Switzerland	2022	-	-	222 ± 50 g/cap/yr	82% macroplastics; total releases below earlier estimates	High
16	Schwarz et al., 2023	Global	2017-2050	-	-	9.5 Mt/yr (2017)	Plastic stock 2.15-5.3 Gt by 2050; land dominates	High
26	Xu et al., 2024	Global	1988-2022	460 (2019)	9	79% landfill; 255 Mt exports	China >50% imports; trade rising; exports 8.1 Mt by 2030; minor COVID effect	High
27	Liu & Nowack, 2025	Switzerland	1950-2022	- (per capita)	0→↑	31±1 kg/cap cumul.	Peak 2010 (120→107 kg/cap); EF: 0.76% total	High
28	Razaviarani et al., 2025	UAE	2021-2050	3.2→5.4	7→15	0.1 Mt→↑	~90% landfilled;	High

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							emissions to rise	
29	Gao & Serrenho, 2025	Global	1950-2100	348 (2017)	6	-	Demand doubles by 2100; avoid via recycling/stock limits	High
33	Dokl et al., 2024	Global	1980-2050	464→735-884	↑ (55% by 2030)	↓ share, high absolute	Plastic use/waste nearly doubles; bioplastics need large land	High
42	Agustina et al., 2025	Bali, Indonesia	2023-2025	132.6 t/d	-	-	ML model $R^2 = 0.882$; income strongest predictor	High
44	Narancic & O'Connor, 2019	Global (EU/USA)	2016	335	6	EU: 70% landfill/incin.; US: 53%	40% single-use; low recovery; circularity needed	High
83	Nhu Da Le et al., 2022	Global	2015-2050	5→40	-	-	Global output 40 Bt by 2050	Mod.
215	Steinfeld et al., 2025	Germany	2022-2024	18.6 Mg paper/yr	83	-	WWTP MPs comparable to municipal; >99% removal	High
244	Liu et al., 2024	Global (regional)	1950-2020	473 (2020); 10 Gt cum.	13 cum.; 21 (2020)	60 Mt/yr; 71% cum.	Growth outpaced systems; mismanagement may double by 2050	High
245	Geyer et al., 2017	Global	1950-2015	380 (2015); 8300 cum.	9 cum.	79% discarded	2→380 Mt; waste 6300 Mt; 12% incin.; 12,000 Mt by 2050	High
246	OECD, 2022	Global	2019-2060	460→1150	9→30	76→228→58 Mt/yr	Output/waste triple; policies cut leakage 74%, CO_2 30%	High
247	OECD, 2024	Global	2020-2040	-	-	-	BAU unsustainable;	High

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							full lifecycle action needed	
248	OECD, 2022	Global	2020+	-	-	↑	Rising waste; lifecycle/global policy essential	High
249	Lebreton & Andrady, 2019	Global	2015-2060	-	-	60–99→155-265 Mt/yr	MPW triples by 2060; 91% riverborne; infra cuts growth	High
250	World Bank, 2024	Global	2019-2040	400→800	9→40	100→200 Mt/yr	Baseline doubles; circularity cuts waste 80%	High
251	Pottinger et al., 2024	Global	2020-2050	547→749	14	68→121 Mt/yr	Policies cut waste 91%, GHG 33%	High
252	Dokl et al., 2024	Global	2018-2050	594–1018	>75 (packaging)	-	15% packaging cut → 27% less use; bioplastics need land	High
253	Higuchi & Isobe, 2024	Global	1961-2060	-	-	20→90 Mt/yr ocean	32% cut by 2035 halts growth; BAU +250% by 2060	High
254	Goh et al., 2025	S/SE Asia	2017-2030	-	9-41	54–75% open burn/dump	Recycling 19-100% lowers GWP 5–611%; open burn key issue	High
255	Saxena, 2025	Global	1950-2050	460→800	9	~79% land/env.	Pyrolysis treats 50%; 75% cut needed for 1.5 °C goal	High
256	Harris et al., 2023	Global	1950-2015	-	-	-	75-199 Mt ocean; 233 kt float; MPs 40-90 Mt suspended	High
257	Lase et al., 2023	Europe (global)	2018-2030	460 (2019)	6→73–80 (EU 2030)	-	Europe recycling ↑; plastic-to-plastic 61% (MR/CR)	High

↑ = increasing trend; ↓ = decreasing trend; → = leads to / contributes to

Microplastic Classification and Characteristics

Classification

Primary microplastics, intentionally made for industrial or consumer use (e.g., microbeads, pellets, fibres), vary in environmental impact. Coastal sediments contain 2.5-4 mm polyethylene pellets (87-90%), with 50% non-degraded, indicating recent spills [47]. Seabird regurgitates show ~20% primary pellets (5 mm) alongside fragments, suggesting bioaccumulation risks [23]. In soils, sewage sludge contributes primarily high-density polymers [54]. Tyre wear particles (TWPs) add primary inputs in sediments [57]. Though secondary microplastics dominate, primary sources like pellets and TWPs remain locally significant.

Secondary microplastics, from fragmented larger plastics, dominate globally. Marine waters show particles 1-53 μm (80% <6 μm), with concentrations up to 750 × 10^3 particles/L, far exceeding net-tow estimates [2]. Riverine and estuarine waters contain fibres and fragments (tens of micrometres to millimetres) [5, 9, 19, 32, 35, 37, 46, 49, 51, 59, 131, 133]. Sediments

have abundant fragments, foams, and fibres, with fragments often >50% [7, 40, 50, 77, 119]. Lab studies confirm fragmentation: 250 μm polystyrene degrades to <100 nm nanoplastics under shear [56], with polyethylene and polystyrene yielding 54-348 nm particles via crack propagation [59, 66]. UV degradation of PET and PA fibres produces fragments and leaches additives, while PAN resists [165]. Small particles (<100 μm) dominate sediment and soil counts [40, 67, 72], confirming secondary microplastics' prevalence.

Characteristics

In terms of **Origins**, microplastics stem from urban runoff, wastewater, and atmospheric deposition. Sewage sludge and wastewater effluents contribute fibres and fragments [31, 122, 133], with sludge-amended soils showing persistent polyester, polyurethane, and polyethylene [54]. Airborne PET, PP, and PE fibres reach 238 ng/m^3 in urban air [79, 100]. Bird faeces and regurgitates reflect local polymer sources [22, 23]. These pathways tie human activity to widespread contamination.

In terms of **Size Categories**, microplastics <100 μm dominate sediments (38.5% in estuaries)

[40] and soils (≥50 μm) [54]. Aquatic systems show 10–1000 μm particles [10, 32, 37, 46, 49,

51, 122, 133], with sediment abundance decreasing exponentially with grain size [166]. Marine size distributions follow a power law [131]. Lab studies show abrasion and photodegradation reduce particles to <100 nm, posing unique risks [56, 59, 74]. Small fractions dominate, but nanoplastics are underreported due to detection limits.

In terms of **Shape and Morphology,** fibres dominate globally (42-80% in sediments, water, and soil) [5, 8, 9, 19, 22, 31, 40, 50, 77, 97, 133, 176], with sediment fibre abundance influenced

by drift [48]. Fragments follow (30–50% in sediments, wastewater) [7, 40, 119, 122]. Films and foams are less common [5, 7, 22, 54]. Primary pellets persist in sediments and biota [23, 47]. Lab-degraded microplastics show irregular, cracked surfaces [56, 59, 66]. Fibres prevail in textile- and sewage-influenced areas, fragments in weathering zones.

In terms of **Polymer Types**, Polyethylene (PE) and polypropylene (PP) dominate aquatic, sediment, and soil systems, often >60-70% [5, 8, 9, 19, 22, 23, 31, 37, 40, 49, 50, 77, 78, 97,

119, 131, 133, 176]. Polyester (PET) comprises up to 50% of fibres in sediments, sludge, and drift-influenced areas [17, 22, 31, 40, 48, 100]. Polyamide is common in sediments and soils [8, 40, 77]. PVC, PS, and PU appear less frequently [32, 37, 46, 49, 122, 133]. PP: PE ratios rise in marine biota and shorelines, reflecting waste trends [23].

In terms of **Colouration**, colour data, though inconsistent, suggest ecological implications. Pellets in sediments are mostly white/transparent, with 48% tied to spills [47]. Soil fibres lose dye, indicating additive leaching [54]. Blue rayon and polyester fibres dominate atmospheric and aquatic samples [97]. Sparse reporting limits broader conclusions.

Concerning **Environmental Matrices**, microplastics pervade all compartments. Sediments range from 20–740 particles/kg [77] to >11,000 counts/kg [57], with mangrove ecosystems at

1122.98 ± 150.17 MPs kg^{-1} [1]. Seawater varies from 1-12 items/L [49] to 750 × 10^3 items/L for sub-10 µm particles [2]. Soils with sludge show >1,000% contamination increase, with species-specific bioaccumulation [54, 166]. Airborne PET and rayon fibres are widespread [79, 97, 100]. Biota, including fish, shrimp, and birds, show pervasive fibre ingestion [1, 22, 176]. Multi-compartmental pollution links aquatic, terrestrial, atmospheric, and biological systems.

Synthesis Summary and Quality of Evidence

Secondary microplastics, mainly fibres and fragments, dominate global environmental matrices, with PE, PP, and PET as key polymers and small fractions (<100 µm) most abundant. Evidence strength is strong, based on a high number of studies across multiple matrices and consistent methodological findings, supported by both field surveys and mechanistic experiments. However, key gaps remain in standardised reporting of colouration, nanoplastic detection, and region-specific polymer signatures, which limit comparability across studies. These insights provide a foundation for linking classification and characteristics with sources, environmental transport, and ecological impacts in subsequent sections

Paper	Authors & Year	Matrix	Classification	Size Range	Shape	Polymers	Key Findings	Quality
1	Deakin et al., 2025	Sediment, water, biota	Secondary	<1000 µm	Sheets, bags, ropes	Not consistent	Sed: 1123 MPs/kg; Water: 16/L; Biota: 149 MPs/indiv; MPs lower in MPAs	High
2	Medina Faull et al., 2024	Water	Secondary	1-53 µm (<6 µm 80%)	Fragments	PS, PP, PET, PE, PTFE	Tiny MPs dominate; up to 7.5×10^5 part/L; 10^5-10^6× > net tows	High
5	Gonçalves et al., 2025	Water, sediment	Secondary	0.04-5 mm	Fibres (67%), frags	PES, PE, PP	Fibres prevail; PES from textiles; urban hotspots	High

7	Botterell et al., 2025	Sediment	Secondary	<5 mm	Frags>foam>threads	Various	MPs on 45% beaches; frags >50%; remote hotspots	High
8	de Lena et al., 2025	Sediment	Both	<0.3-5 mm	Fibres, frags	PE, PA	Small MPs >99%; PE/PA dominant	High
9	Bermúdez et al., 2025	Water	Secondary	<5 mm	Fibres, frags	PE, PP	Fibres doubled (2008-18); ×9.7 by 2100	High
10	Risku et al., 2025	Soil	Secondary	>20 µm	–	PET	Up to 944 ± 586/g compost; smaller with composting	High
17	Ruiz-Fernández et al., 2024	Sediment	Both	–	Fibres (66–89%), frags	PET, cellulosic	None pre-1950; PET/fibres rise post-1990s	High
19	Morici et al., 2025	Water	Both	<5 mm	Fibres, frags	–	Fibres dominant; 230-3320 MPs/L; coastal max	High
22	Sarlin et al., 2025	Bird feces	Both	<250 µm-5 mm	Fibres, pellets	PE, PP, PS, Nylon, Cellulose	Fibres dominant; polymer mix mirrors local plastics	High
23	Perold et al., 2025	Biota & shoreline	Both	~2-7 mm	Frags, pellets	PE, PP	Frags 78%, pellets 20%; PP rising over time	High

31	Styszko et al., 2025	Sludge, fertiliser	Both	Not classed	Frags, fibres	LDPE	2429/100 g sludge, 720/100g fert.; colour persists	High
32	Wang et al., 2025	Water	Secondary	1 µm-5 mm	–	PI, PVC, PU, 29 types	MPs abundant, low risk; poor removal	High
35	Buhhalko et al., 2025	Water	Secondary	10 µm-5 mm	Frags	PES, PP, PE	80% <300 µm; estuary hotspots	High
37	Kadir et al., 2025	Water	Secondary	>20 µm-5 mm	Frags	CPE	3-12 part/L; uniform ponds	High
40	Kesavan et al., 2025	Sediment	Secondary	<5 mm	Fibres	PE, PES, PA	6730/kg; <100 µm 38.5%; translucent common	High
46	Hansen et al., 2023	Water	Secondary	20 µm->300 µm	Particles, fibres	20 types; PET 20%	PET most frequent; <100 µm dominant	High

Table 2: Summary of Microplastics Classification and Characteristics Data

47	Cocozza et al., 2025	Beach sediment	Primary	1-5 mm	Cylindrical/disk	PE	7263 pellets; 50% fresh, 48% from Toconao	High
48	Lo Bue et al., 2025	Sediment	Secondary	0.002-5 mm	Fibres	PET	West side richer; PET fibres dominate	High
49	Vetter et al., 2025	Water	Secondary	20-500 µm	–	PET (96%)	1-12/L; high near settlements	High
50	Morgana et al., 2025	Sediment	Secondary	0.002-5 mm	Fibres	–	33.7/kg; west side & depth linked	High
51	Kumar et al., 2024	Groundwater	Secondary	10-1000 µm	Frags, fibres	PP, PE,	MPs 0.14-0.92/L;	High

						PET, PVC, PS	sewage key source	
54	Ramage et al., 2025	Soil, sludge	Both	≥50 µm-2 mm	Fibres, films, frags	PES, PU, PMMA, PE, PET	Sludge ↑ MPs 7-14×; persist >22 y; weathered fibres	High
56	Monira et al., 2023	Water	Secondary	106–250 µm→72-120 nm	Irregular	PS	Shear fragmented PS→NPs; 28× NP rise	High
57	Molazadeh et al., 2023	Sediment	Sec. + TWP	≥10 µm	–	PP, PVC, PES, PE, TWP	11k/kg; 6.9% TWP; random spread	High
59	Monira et al., 2025	Water	Secondary	106–250 µm→54-348 nm	Irregular	PE, PS	120d weathering → 54 nm NPs	High
66	Jarosz et al., 2024	Synthetic polymers	Secondary	10 nm-10 mm	Irregular	PVC, PET, PP, PS, LDPE	Weathering polymer-specific; nano formation	High
67	Klemmensen et al., 2024	Soil	Secondary	<5 mm	–	PES, acrylic	2.4k–48.8k/kg; half-life 2.5–4 y	High
72	Morioka et al., 2023	Road dust	Secondary	1.1-850 µm	–	PE, PP, PVC, PS, SBR, ABS, PC	MPs rise as size ↓; PE/PVC dominate fine	High
74	Ducoli et al., 2024	Synthetic (NPs)	Secondary	10-1000 nm	Irregular	PET, PA66	T2LNPs 10-1000 nm; corona varies	High
77	Hailu et al., 2025	Sediment	Secondary	–	Fibres, frags	PA, PE, PP	20-740/kg; fibres dominate	High
78	Erni-Cassola et al., 2019	Water, sediment	Secondary	–	–	PP, PE, PES,	PP/PE surface;	High

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						acrylics	PES/acrylic deep	
79	Kirchsteiger et al., 2023	Air	–	<2.5 µm	–	PET, PP, PE	238 ng/m³; PET dominant	High
119	Al-Fares & Al-Zaidan, 2025	Sediment	Secondary	≤5 mm	Frags, fibres	–	Frags/fibres 95%; supratidal > others	Mod.
97	Napper et al., 2023	Air, water, sediment	Secondary	<5 mm	Fibres	Rayon, acrylic, PES	Rayon 54-82%; fibres 95–99%	High
100	Illuminati et al., 2024	Air	Secondary	5-100 µm	Frags	PP, PE, PC, PS	53% 5-10 µm; PP 31%, PE 19%	High
122	Wang et al., 2025	Wastewater	Secondary	20-500 µm	Frags, spheres	PI, PVC, PU	Small frags (72% <50 µm); farm-specific mix	High

131	Bermúdez et al., 2025	Water	Secondary	~30 µm->5 mm	Fibres, films, frags	PE, PP, PVC, PA, PS, etc.	Fibres dominate; ×9.7 by 2100	High
133	Negrete Velasco et al., 2025	Water	Secondary	20-5000 µm	Fibres, frags	PE, PP, PVC, PET, PA	DWTP removes 97%; recontam. in DWSN	High
165	Sait et al., 2021	Water	Secondary	1-5 mm	Fibres	PET, PA, PAN	PET/PA degrade under UV; PAN stable	High
166	Vermeiren et al., 2021	Sediment	Both	5 mm-66 µm	Fibres, irregular	Polyolefins, PES, PVC	MPs ↑ at impact sites; species-specific loads	High
176	Li et al., 2021	Water, sediment, biota	Both	<5 mm	Fibres	Cellulose, PP, PE	MPs 6.6–263k/m³ (water), 566-2500/kg (sed.); fibres dominate	High

↑ = increasing trend; ↓ = decreasing trend; → = leads to / contributes to

Sources and Environmental Transport Pathways

Microplastics (MPs) enter ecosystems via primary (manufactured) and secondary (fragmented) sources, transported by runoff, wastewater, atmospheric processes, and long-range mechanisms, creating spatial hotspots.

Primary and Secondary Sources

Primary MPs, from tyre wear, textiles, and agriculture, are significant. Tyre wear particles (TWPs) release 94,000 t/y in EU waters, with high per capita inputs in Luxembourg and the US [20]. Snowmelt runoff near highways mobilises TWPs up to 1300 mg/L, with 48% fine fraction [146]. Urban air resuspension adds TWPs to particulate matter [142]. Textile abrasion releases 5-30× more fibres indoors, with urban air MPs at 0.1-6.6 particles/m³ [195, 199]. Agricultural sludge, mulch, and fertiliser introduce MPs, with sheep redistributing ~10^6 particles/ha/y [18, 155]. Mountain bike tyre abrasion adds ~3.62 g/100 km [135].

Secondary MPs dominate, with Taihu Basin rivers showing 1,200-11,000 items/m³ (PE, PP, PET), peaking in summer [3]. Irrigation canals transport fragments to rice soils [15]. Urban/industrial sites have higher loads, with winter floods remobilising MPs [4]. UK waste facilities mobilise ~5 Mt/day during 50-year floods, tripling risks [38]. Ageing PE/PVC pipes in water networks release MPs/nanoplastics [80], highlighting pervasive secondary sources.

Surface Runoff and Stormwater Transport

Runoff drives MP transport, contributing 80% of emissions (269.1 t/y) in Kyoto [113]. Stormflow increases MPs by up to 5 orders of magnitude, with TWPs dominant [90]. Industrial runoff carries large PVC particles [94], and road dust enters wetlands [116]. Urban rivers show 1.52-5.13 MP/L, peaking in spring [71]. Road runoff has >50% MPs <75 μm, with winter TWP spikes [102, 103]. Rainfall, fishing, and fertilisers drive riverine variation [24]. Biofilters retain

>90% MPs, but freeze-thaw cycles enable deeper migration [124]. Rainfall intensity mediates MP loads (3.1-11.9 particles/L), with no consistent first-flush [98, 109, 125].

Wastewater Treatment, Effluent, and Sludge Reuse

WWTPs remove 36-40% of MPs but release significant loads via effluents and sludge. CSOs emit 0.8–16 kg/event [114]. In Vietnam, WWTPs discharge ~1.7M MPs/day [123], and Colombia’s Cispata MPA sees ~1.38M MPs/day [121]. Sludge raises soil MPs by >1400%,persisting >25 years [54]. WWTPs and runoff are key fibre sources in Argentina [127], with stormwater dominating in Kyoto [113] and Danish Straits [95].

Atmospheric Deposition and Long-Range Transport

Atmospheric transport creates oceanic hotspots, with MP density doubling per decade in gyres [6]. Urban emissions from combustion and transport peak in winter [21]. Deposition is higher in urban Ontario than rural Dorset [118], and seabird guano redistributes MPs near colonies [156]. High-altitude lakes [85] and the Southern Ocean (0.14% particulate mass) show deposition [76]. WWTPs add downstream loads in Italy [87]. Together, these findings reveal atmosphere–ocean–land linkages that sustain global-scale circulation of MPs.

Spatial Patterns and Hotspots

Spatial patterns of MPs reflect combined source and transport dynamics. Urban rivers such as the Taihu Basin [3] and the Kamo River catchment [113], and coastal outlets [86, 121] are hotspots, with summer/wet season peaks [111]. Agricultural soils show high MPs from sludge, mulch, and livestock [18, 54, 155].

Remote areas are not immune: high-altitude lakes in the Indian Himalayas [85] and the Southern Ocean [76] both reveal deposition-driven contamination, demonstrating the planetary reach of atmospheric transport.

Synthesis and Evidence Quality

Primary (e.g., TWPs, textiles) and secondary (e.g., runoff, sludge) sources feed runoff, wastewater, and atmospheric pathways, creating urban, coastal, and agricultural hotspots. High-quality studies confirm these patterns, but gaps remain in quantifying atmospheric fluxes, flood remobilisation, and agricultural sources. These insights provide a foundation for understanding how environmental transport not only redistributes MPs but also shapes exposure risks across ecosystems, linking source identification with ecological and human health impacts addressed in subsequent sections.

Paper	Authors & Year	Source Type	Pathway	Spatial Hotspots	Key Findings	Quality Tier
3	Zhou et al., 2025	Secondary	Runoff, WWTP, agriculture	Urban rivers, Taihu Basin	1,200-11,000 items/m³; higher in summer; PE, PP, PET dominate; moderate risk	High
4	Skalska et al., 2024	Both	Runoff, WWTP, floods	Urban/industrial zones	Land use shapes MPs; floods redistribute; winter flushing lowers counts	High
6	Goddijn-Murphy et al., 2025	Both	Runoff, WWTP, air, currents, ice melt	Global gyres, Amazon, Arctic	MP density doubles/decade; climate & rain drive peaks	High
15	Muñoz Yustres et al., 2025	Secondary	Irrigation	Near cities	Irrigation transfers MPs to rice soils; fibres/fragments dominate	High
18	Wrigley et al., 2024	Both	Sludge, mulch	Rural soils	Sludge/mulch main rural inputs	High
20	Sun et al., 2025	Primary	Runoff, wastewater, air	Europe (DE, FR, IT)	TWP 94,000 t/y to EU waters; LU & US lead per capita	High
21	Zhou et al., 2025	Secondary	Atmosphere	Urban, winter	Combustion, waste, and transport emit MPs	High
24	Qian et al., 2023	Both	Runoff	South riverbank	Rain, fishing, fertilisers drive MPs; PAM from additives	High
38	Ponti et al., 2022	Secondary	Flooding	UK waste sites	Floods mobilise 5 Mt/day MPs; 3× risk	High
54	Ramage et al., 2025	Secondary	WWTP sludge → soil	UK farmlands	Sludge raised soil MPs 1445%; fibres persist >25 yrs	High

71	Apetogbor et al., 2023	Secondary	WWTP, runoff, wind	Urban rivers	1.5-5.1 MP/L water; 1,587 MP/kg sediment; PE/fibres dominant	High
76	Rindelaub et al., 2025	Secondary	Atmosphere (sea spray)	S. Ocean, NZ coast	MPs 65 ng/m³; sea spray source; undercounted	High
80	Świetlik & Magnucka, 2024	Secondary	DWSN degradation	Pipes	PE/PVC ageing releases MPs; small pipes worst	High
113	Imbulana et al., 2024	Secondary	WWTP, runoff, air	Kyoto City	269 t/y; 80% runoff, 20% WWTP; stormwater key	High
114	Todeschini et al., 2025	Secondary	CSOs, WWTP, runoff	Lake Como/Lugano	CSOs emit up to 16 kg/event; WWTPs 40% removal; tourism adds load	High
111	Hailu et al., 2025	Secondary	Runoff, air	Lakes Ziway, Hawassa, Koka	Wet season > dry; fibres/fragments; Koka highest risk	High
110	Beaurepaire et al., 2025	Secondary	Road runoff, air	Road bio-swales	TRWP > MPs; swales retain 90%; fragmentation key	High
116	Kabir et al., 2025	Secondary	Stormwater runoff	Urban wetlands	MPs from road dust; transport size/density-dependent	High
118	Yao et al., 2025	Secondary	Atmosphere	UK/Canada sites	Urban > rural deposition; air key transport	High

Table 3: Summary of Sources and Transport Pathways of Microplastics

85	Kumar et al., 2025	Both	Atmosphere	Mountain lakes	MPs 1-81/L; PE dominant; wind transport	Moderate
86	Ariefdien et al., 2024	Both	Runoff	Cape Town coast	Stormwater main source; winter > summer	Moderate
87	Sandil et al., 2025	Both	Atmosphere, WWTP	Rome sites	Air dominates upstream; WWTP downstream	Moderate
90	Murphy-Hagan et al., 2025	Both	Runoff	S. California	Stormflow ↑ MPs 10^5×; TRWP dominant	High
94	Liu et al., 2019	Secondary	Runoff	Industrial ponds	Industrial runoff ↑ PVC MPs	Moderate

95	Liu et al., 2023	Secondary	Runoff, WWTP	Copenhagen–Malmö	Urban discharges, a major MP source	High
98	Ochoa et al., 2024	Secondary	Runoff	Urban outfalls	MPs ↑ with rain; no first-flush	High
102	Lindfors et al., 2025	Secondary	Runoff	Roads, roofs	Road runoff highest; >50% <75 µm	High
103	Järlskog et al., 2022	Secondary	Runoff, air	Roads	38% TWP; winter ↑ BiWP; traffic major source	High
109	Lofty et al., 2025	Secondary	Runoff	Coal mine	MPs 0.27-28.9/m³; rainfall-linked	High
121	Arregocés-Garcés et al., 2024	Secondary	WWTP effluent/sludge	Colombian MPA	1.38M MPs/day; fibres in effluent; fragments in sludge	Moderate
123	Kieu-Le et al., 2025	Secondary	WWTP, sludge reuse	Saigon basin	1.7M MPs/day effluent; sludge reintroduces MPs	Moderate
124	Koutnik et al., 2022	Secondary	Stormwater → biofilters	Los Angeles	90% MPs retained top 5 cm; remobilised by freeze–thaw	High
125	Kadir et al., 2025	Secondary	Runoff, air	Sydney ponds	3–12 MPs/L; fragments; rain dilution >40 mm	High
127	Kittner et al., 2022	Secondary	WWTP, runoff	Argentina	WWTPs' main fibre source; sediments trap MPs	High
135	Sommer et al., 2025	Secondary	Direct soil deposition	MTB trails	Tire wear ~3.6 g/100 km; <1% total MPs	High
142	Yoo et al., 2025	Secondary	Atmosphere	Urban/industrial	Tyre wear main TRWP source; phthalates confirm origin	High
146	Gaggini et al., 2025	Secondary	Snowmelt, air	Highway ditches	TWP 7.8-1300 mg/L; 48% fine; emission risk high	High
155	Beriot et al., 2021	Secondary	Livestock, mulch	Farms	Soil 2×10³/kg; sheep faeces 10³/kg; 10⁶ MPs/ha/y	High
156	Hamilton et al., 2021	N/A	Air, water, guano	Seabird colony	MPs in all media; no clear gradient	High

195	Cai et al., 2021	Secondary	Atmosphere	Indoor	Textile abrasion releases 5-30× more fibres	High
199	Zhu et al., 2021	Both	Atmosphere	Urban megacities	0.1-6.6 MPs/m³; textile fibres dominant	High

↑ = increasing trend; ↓ = decreasing trend; → = leads to / contributes to

Microplastics Detection and Analytical Methods

Sampling Strategies

Sampling is critical for microplastics (MP) detection, influencing detection limits and data comparability. Aquatic sampling includes manta trawls (300 µm mesh, 15 min at 2-3 knots) for surface waters, capturing millimetre-scale MPs but missing smaller particles [61]. Large-volume filtration (20 µm stainless-steel sieves, up to 2000 L) [133] and 24-h autosampler composites (1-5 L) [134] improve size range but risk clogging and contamination. Cascade sieving (500/100/10 µm) achieves 10 µm resolution in surface water [152]. Wastewater studies use volume-reduced filtration (10–1000 µm, 2-2000 L) [55, 115, 132], but high suspended solids and contamination are challenges. Atmospheric sampling employs monthly open collectors (Palmex, NILU) [126], PM2.5 samplers [203], and high-flow filters (25 mm, 10 L/min, 1.5-3 h) [186], risking particle loss during transfer. Sediment sampling involves grid-based high-tide mark collection [129] or random intertidal sampling [130]. Biota sampling includes necropsy of turtle chyme [162] and oysters [130], while human milk [138] and tissue[197] require direct or chemical extraction. Diverse strategies highlight the need for standardised protocols.

Analytical Techniques

Visual and Microscopic Identification

Visual microscopy is common but limited. Brown and Williams [130] used NaCl density separation and microscopy for sediments and oysters (5 µm limit), lacking polymer confirmation. Torres-Agullo et al. [186] paired stereomicroscopy with µFTIR, but particle transfer was time-intensive. SEM, used with µFTIR and Raman for air MPs (<2.5 µm) [203], or with deep learning (U-Net, Mask R-CNN) [141], identifies small particles but faces matrix interference and low-resolution dataset constraints.

Fourier Transform Infrared (FTIR) Spectroscopy and Imaging

FTIR is widely used for polymer identification. Ochoa et al. [93] applied ATR/transmission FTIR for water/sediment MPs (≥500 µm), noting weathering-induced spectral discrepancies. Kim et al. [115] confirmed eight polymers (e.g., PE, PP, PET) in wastewater (≥20 µm), limited by small-size capture. De Lena et al. [129] used FTIR microscopy with a focal plane array (25 µm resolution) in sediments, despite cellulose interference. IR spectroscopy identified MPs in water down to 10 µm, though seasonal and microbial effects posed challenges [152]. FTIR mapping in human milk [138] and turtle chyme [162] faced eco-corona and fat/sediment interference. FTIR is robust but struggles with <20 µm particles and complex matrices.

Raman Spectroscopy and Micro-Raman Mapping

Raman spectroscopy detects MPs down to 1-2 µm. Ripken et al. [61] used optical tweezers Raman (OTRS) for surface water (1.4 µm), limited by manual trapping and organic overlays. Barkmann-Metaj et al. [55] paired µ-Raman with DSC in wastewater (10 µm), facing high suspended solids interference. Allen et al.

[126] used μ-Raman (>10 μm) with TD-PTR-MS for atmospheric NPs, requiring assumptions for mass-to-count conversion. Raman with oil extraction in wastewater [132] faced oil residue issues. Raman offers precision but is constrained by throughput and interference.

Pyrolysis-GC/MS and Thermal-Desorption Methods

Thermal methods complement particle-based approaches. Materić et al. [64] used TD-PTR-MS for seawater (<1 μm), detecting NPs but not particle counts, with organic interference. Allen et al. [126] applied TD-PTR-MS for atmospheric NP mass, facing count conversion challenges. Rauert et al. [197] used Py-GC-MS on human tissue, confirming polymers but with low recovery due to matrix complexity. These methods provide chemical precision but cannot quantify particle abundance.

Emerging Technologies

Emerging methods enhance sensitivity. Pagliaccia et al. [134] used Laser Direct Infrared (LDIR) spectroscopy to identify MPs in water samples down to 10 μm, though sample volumes were small and cellulose misidentification occurred. Cheng et al. [136] optimised digestion protocols (2 μm detection), highlighting standardisation needs. Chen et al. [147] applied SWIR hyperspectral imaging with machine learning for soil MPs (≤50 μm PA, ≤300 μm PE), with reduced accuracy at low concentrations. Papavasiliou et al. [52] used a model-based Enalos Cloud platform for PP, PET, and LDPE, lacking empirical validation. These methods show promise but need broader testing.

Methodological Challenges

Contamination is a major issue in atmospheric [126, 186, 203] and wastewater [55, 115] studies. Organic matter interferes in seawater [64] and sediments [129], while oil residues and iron precipitates affect Raman and digestion [132, 136]. FTIR struggles with <20 μm MPs, and Raman faces throughput limits. Nanoplastic detection relies on indirect TD-PTR-MS [64, 126], missing particle counts. Non-standardised digestion and separation protocols hinder comparability [136].

Synthesis and Evidence Quality

Microplastic detection spans millimetre to submicrometer scales, with robust polymer identification across water, sediment, air, and biota. High-quality studies using spectroscopy, thermal methods, and imaging support these findings. However, key gaps remain in standardising sampling strategies, digestion protocols, and size thresholds, particularly for particles <10 μm and nanoplastics, where particle counts remain elusive. These insights provide a foundation for linking analytical innovations with improved monitoring frameworks and for advancing cross-study comparability in future.

Table 4: Summary of Analytical Methods Used for the Detection of Microplastics

Paper	Authors & Year	Matrix	Sampling Strategy	Method	Size Limit	Polymer ID	Key Challenges	Quality
52	Papavasiliou et al., 2025	Air, soil, water, sediment	Model-based	Enalos Cloud (SB4P GUI/API)	<5 mm	Yes (PP, PET, LDPE)	Limited scope, no dataset validation	High
55	Barkmann-Metaj et al., 2023	Wastewater	Filtration (10-1000 μm)	μ-Raman, DSC	10 μm	Yes	High variability, contamination, TSS interference	High

61	Ripken et al., 2021	Surface water	Manta trawl (300 μm)	OTRS	1.4 μm	Yes	Organic overlay, low throughput	High
64	Materić et al., 2022	Seawater	Aliquots + filtration	TD-PTR-MS	<1 μm	Yes	OM interference, low mass sensitivity	High
115	Kim et al., 2022	WWTP influent/effluent	Grab & filtration	Fenton, density sep., FTIR	≥20 μm	Yes (8 polymers)	<20 μm missed, incomplete data	High
93	Ochoa et al., 2025	Water/Sediment	Surface tows	FTIR (ATR/trans.)	500 μm	Yes	Weathering, mode differences	High
126	Allen et al., 2022	Air (wet/dry)	Monthly collectors	μ-Raman, TD-PTR-MS	1–0.45 μm	Yes	Conversion limits, blanks, short series	High
129	de Lena et al., 2025	Beach sediment	Grid at high tide	NaI sep., H_2O_2, FTIR	32 μm	Yes	Incomplete digestion, variability	High
130	Brown & Williams, 2025	Sediment/Biota	Random intertidal	H_2O_2, NaCl, microscopy	5 μm	No	Foaming, loss, visual errors	Moderate
132	Austin et al., 2025	Wastewater	Grab + spiking	Fenton + Oil Extraction	0.8 μm	Yes (Raman)	Iron, oil residues, limited tests	High
133	Negrete Velasco et al., 2025	Water	Filtration (20 μm)	Sieving, μFTIR	20 μm	Yes	Clogging, contamination	High
134	Pagliaccia et al., 2025	Water	24-h composites	LDIR spectroscopy	10 μm	Yes	Small volume, contamination	High
136	Cheng et al., 2025	Water	Filtration (0.45 μm)	Fenton + enzymes	2 μm	Yes	Iron precipitates, matrix effects	High
138	Dąbrowska et al., 2025	Human milk	Direct drops	FTIR/Raman	N/A	Yes	Complex matrix, qualitative only	High
141	Cabaneros et al., 2025	Air	Filter sampling	SEM + ML (U-Net, Mask R-CNN)	<5 mm	No	Low res, small dataset	High

147	Chen et al., 2025	Soil	Spiked (0.01-12%)	SWIR imaging + ML	≤50-300 µm	Yes	Low conc. accuracy, sensor limits	High
152	Mughini-Gras et al., 2021	Water	Sieving (500-10 µm)	IR, 16S rRNA, qPCR	10 µm	Yes	Seasonal, microbial bias	High
162	Caron et al., 2018	Biota	Necropsy	Acid, NaCl, ATR-FTIR	>100 µm	Yes	Fat/sediment interference	High
186	Torres-Agullo et al., 2022	Air	Filters (10 L/min)	Microscopy, µFTIR	<100 µm	Yes	Time, small particle loss	High
197	Rauert et al., 2025	Human	Extraction	Py-GC-MS	Up to 20× nominal	Yes	Matrix interference, low recovery	High
203	Rahman et al., 2021	Air	PM2.5 filters	SEM, µFTIR, Raman	<2.5 µm	Yes	Low conc., interferences	High

Ecotoxicological Effects of Microplastics

Organismal Impacts

Microplastics (MPs) cause physical, physiological, and behavioural effects across taxa. Vertebrates (mammals, birds, reptiles) show higher MP bioaccumulation than fish, with trophic transfer evident [11]. Terrestrial salamanders accumulate more MPs (86% sites, 48 MPs) than aquatic ones (78% sites, 31 MPs), with juveniles most affected (0.39 MPs/indiv.) [12]. Arctic amphipods ingest 1-1.8 MPs/individual, mainly <50 µm fragments, reducing feeding, growth, and fecundity [62]. *Daphnia magna/pulex* ingest more MPs at low food/high temperature [167], with PS/PE exposure (1.25-2.8 mg/L) decreasing body size, reproduction, and inducing antioxidant activity [65]. Multiple species show concentration-dependent ingestion [168].

Zebrafish larvae exposed to PS MPs/NPs (3-60 µg/mL, 50 nm/2 µm) exhibit developmental delays, hepatic inflammation, and lipid disruption, with NPs penetrating brain/vessels [70, 139]. European sea bass (65% individuals, 0.6-2.7 MPs/fish) show blockage, inflammation, and mortality [149]. *Rutilus rutilus* (32.8%) [163], *Neogobius melanostomus* (19 MPs/fish)

[169], and wild *Mugil cephalus* (60%, 4.3 items/fish) [175] ingest microplastics, linked to size/distance. Rabbitfish ingest low MPs (0.05 items/indiv.), suggesting selective feeding [150]. *Paracyclopina nana* shows growth retardation and oxidative stress from small MPs (0.05/0.5 µm) [183].

Marine molluscs ingest 15-17 MPs/organism, causing digestive damage and immunotoxicity [145]. Ribbed mussels accumulate 11,000-50,000 MPs/m², altering faecal buoyancy [148]. Corals exhibit polyp retraction, reduced calcification, and prefer microplastics over food, co-ingesting E. coli [170, 178, 182]. *Gammarus fossarum* shows reduced assimilation/weight gain [172], while *Lymnaea stagnalis* ingests/excretes MPs without chronic toxicity [153]. Fish and brachyuran larvae show rising microplastic ingestion (cellophane/PET dominant) [73]. Aquatic species suffer organ damage, growth delays, and oxidative stress [84]. *Drosophila melanogaster* faces gut damage, reduced lifespan, and ovary size from dietary microplastics [185]. Rats show maternal–fetal NP transfer, reducing fetal/placental weights by 7-

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8% [190].

Chemical Interactions

Microplastics (MP) act as chemical vectors, leaching additives or sorbing pollutants. Zebrafish larvae show lipid disruption and inflammation from MP-associated chemicals [70, 139]. Molluscs exhibit immunotoxicity from MPs with organic contaminants [145]. PPCP-sorbed

MPs amplify toxicity, causing oxidative stress, reproductive failure, and antibiotic resistance gene spread in aquatic biota [161]. PS/PE MPs with progestogens in Daphnia magna show antagonistic/synergistic effects [65]. PA MPs reduce BPA toxicity via sorption [173]. Sea cucumbers experience immune suppression and oxidative stress [158], while PS MPs adsorb Cu/Cd in wheat, reducing phytotoxicity [159]. MPs with PAHs reduce biodegradation in bacterial communities, altering sediment microbial assemblages [174]. Polyethylene MPs slightly increase PCB uptake in lugworms [171]. Chemical interactions vary by pollutant, matrix, and organism.

Ecosystem-level Consequences

microplastics (MPs) disrupt food webs, microbial communities, and biogeochemical cycles. Species sensitivities vary, with high ecological risks in Morocco, Bangladesh, Turkey, and China [43]. Benthic sediments (500-8900 items/kg) pose moderate risks near aquaculture/sewage [25], with tyre and road wear particles exceeding predicted no-effect concentrations sediment (1,000 mg/kg) [104]. MPs impair feeding, reproduction, and immunity, causing ecological imbalances [105]. Trophic transfer occurs in grey seals and mackerel [164], Arctic/deep-sea amphipods (1-8 MPs/indiv.) [181], and krill/salps (1.38–2.13 MPs/indiv.) [180]. Macroinvertebrates accumulate ~0.14 MP/mg tissue [154]. Cyanobacteria show suppressed growth, oxidative stress, and increased toxin production (PVC > PS > PE) [157]. Plants absorb MPs, reducing productivity and altering soil–microbe interactions [151]. MPs reduce PAH biodegradation, disrupting nutrient cycling [174].

Synthesis and Evidence Quality

Microplastic (MPs) cause organismal (blockage, inflammation, developmental delays), chemical (pollutant vector), and ecosystem-level (trophic transfer, microbial shifts) effects across diverse taxa. High-quality studies support these findings, with consistent laboratory and field data. However, key gaps remain in long-term exposure data, nanoplastic-specific impacts, and standardised metrics that connect laboratory endpoints to real-world population and ecosystem outcomes. These insights provide a foundation for understanding how MP exposure cascades across biological scales, linking mechanistic toxicology with broader ecological risk assessments in subsequent sections.

Table 5: Summary of Ecotoxicological Effects of Microplastics Data

Paper	Authors & Year	Organism(s)	Exposure Route	Effects	Key Findings	Quality
11	Parolini et al., 2023	Zooplankton–vertebrates	Ingestion	Physical, chemical, ecological	Bioaccumulation highest in vertebrates; no spatial/temporal trend	High
12	Altunışık et al., 2024	Salamanders	Ingestion	Physical, ecological	Terrestrial > aquatic; juveniles most affected	High

25	Fok et al., 2023	Benthic fauna	Ingestion (sediment)	Ecological	500-8900 MPs/kg; fibres dominate; moderate risk	High
43	Hossain et al., 2025	Aquatic spp.	Water	Chemical, ecological	Variable sensitivities; high RQs in some regions	High
62	Botterell et al., 2022	Arctic zooplankton	Ingestion	Physical, ecological	Amphipods > copepods; PU dominant; 75% <50 µm	High
65	Svigruha et al., 2023	*Daphnia magna*	Ingestion	Physical, chemical, ecological	↓growth/reproduction; ↑enzymes; joint effects variable	High
70	Xin et al., 2024	Zebrafish larvae	Ingestion, microinjection	Physical, chemical, ecological	50 nm NPs in brain; liver inflammation; lipid disruption	High
73	Carrillo-Barragán et al., 2024	Fish/larvae	Ingestion	Ecological	Rising MP intake; cellophane/PET common; additives present	High
84	Venkatesh et al., 2024	Aquatic spp.	Ingestion	Physical, chemical	MPs impair organs, growth, and induce stress	High
104	Iannuzzi et al., 2025	—	Sediment	Ecological	TRWP > PNEC (1000 mg/kg); all basins contaminated	High
105	Yang et al., 2025	Aquatic spp.	Water/sediment	Physical, ecological	MPs disrupt feeding, reproduction, and immunity	High
139	Xin et al., 2024	Zebrafish larvae	Ingestion	Physical, chemical, ecological	MPs in gut/liver; NPs reach brain; ↑ inflammation	High
145	Polidoro et al., 2022	Molluscs	Ingestion	Physical, chemical, ecological	15-17 MPs/org.; low human risk; site variability	High
148	Khan & Prezant, 2018	Mussels	Ingestion	Physical, ecological	MPs 11k-50k/m²; affects buoyancy, transfer	High
149	Reinold et al., 2021	Sea bass	Ingestion	Physical, chemical, ecological	65% fish ingest MPs; fibres dominate; health impact	High
150	Paler et al., 2021	Rabbit fish	Ingestion	—	0.05 items/ind.; fibres dominant; selective feeding	High

151	Mateos-Cárdenas et al., 2021	Plants/macrophytes	Adsorption, uptake	Physical, chemical, ecological	MPs internalised; ↓productivity; alter microbes	High
153	Weber et al., 2021	*L. stagnalis*	Ingestion	Physical, chemical	Ingestion size/time-dependent; no chronic effect	High
154	Windsor et al., 2019	Macroinvertebrates	Ingestion	Ecological	MPs in ~50%; taxa/biomass linked	High
157	Zheng et al., 2021	*M. aeruginosa*	Contact	Physical, chemical	MPs inhibit growth, ↑oxidative stress/toxins	High
158	Mohsen et al., 2021	Sea cucumber	Ingestion	Chemical	Altered immunity, ↑stress, no growth effect	High
159	Zong et al., 2021	Wheat	Hydroponic	Chemical	MPs adsorb Cu/Cd, reduce toxicity	High
160	Bai et al., 2021	Copepods	Ingestion	Physical, chemical, ecological	↓feeding/growth; ↑stress; species-dependent	High
161	Atugoda et al., 2021	Aquatic biota	Ingestion/trophic	Physical, chemical	MPs+PPCPs → synergistic toxicity, ARG spread	High
163	Horton et al., 2018	*Rutilus rutilus*	Ingestion	Physical	32.8% ingested MPs; size/location linked	High
164	Nelms et al., 2018	Seals/mackerel	Trophic, ingestion	Physical, chemical	32-48% MPs; trophic transfer evident	High
167	Hoffschröer et al., 2021	*Daphnia spp.*	Ingestion	Physiological	↑MP load at low food/high temp; no glycogen effect	High

168	Scherer et al., 2017	Aquatic inverts	Ingestion	Physical	Size/species-dependent ingestion; reduced by particles	High
169	McNeish et al., 2018	Fish (round goby etc.)	Ingestion	Physical, chemical, ecological	19 MPs/fish; linked to size, feeding type	High
170	Bejarano et al., 2022	Coral (S. pistillata)	Deposition/ingestion	Physical	MPs cause polyp retraction; no sediment effect	High
171	Besseling et al., 2017	*A. marina*	Ingestion	Chemical	Minor PCB vector effect	High

172	Straub et al., 2017	*G. fossarum*	Ingestion	Physical	PMMA ↓assimilation/weight gain	High
173	Rehse et al., 2018	*D. magna*	Ingestion	Chemical	MPs reduce BPA toxicity via sorption	High
174	Kleinteich et al., 2018	Bacteria	Sediment exposure	Ecological, chemical	MPs alter communities; ↓PAH degradation	High
175	Cheung et al., 2018	*M. cephalus*	Ingestion	Physical	60% wild vs 16.7% captive; wild > load	High
178	Hankins et al., 2021	Corals	Ingestion	Physical	↓growth, calcification; MPs egested in 48 h	High
180	Wilkie Johnston et al., 2023	Krill, salps	Ingestion	Ecological	MPs 1-2 items/ind.; fibres dominate	High
181	Jamieson et al., 2019	Amphipods	Ingestion	Ecological	72% ingested MPs; deepest sites highest	High
182	Rotjan et al., 2019	*A. poculata*	Ingestion	Physical, ecological	>100 MPs/polyp; corals prefer MPs; E. coli transfer	High
183	Jeong et al., 2017	*P. nana*	Ingestion	Physical, chemical, ecological	Small MPs → ↓growth, fecundity; ↑stress	High
185	Yan et al., 2024	*D. melanogaster*	Dietary	Physical, chemical, ecological	Gut damage, ↓lifespan, disrupted sleep	High
190	Fournier et al., 2020	Rats (maternal/fetal)	Inhalation	Physical	NPs in placenta; ↓fetal/placental weight	High

↑ = increasing trend; ↓ = decreasing trend; → = leads to / contributes to

Human Exposure and Health Risks

Exposure Pathways

Microplastics (MPs) enter humans via ingestion, inhalation, and dermal contact, with ingestion dominant. Seafood yields 4.22-6.0 MPs/day for adults and 15.48-22.01 MPs/day for children, a threefold higher burden [41, 128]. Clams contribute ~1,489 MPs/person/year [45], canned fish 16,500 MPs/capita/year [143], beverages 1.65 MPs/kg BW/day [137], and dietary supplements 0.1-4.08 MPs/day [75]. Polystyrene containers release up to 56 mg MPs at 120

°C [81], and cookware adds 2,409-4,964 MPs/year [68]. Broad estimates range from 0.0002-1,531,524 MPs/day [188]. Wastewater effluents discharge up to 77 million MPs/day, contributing to ingestion risks [120].

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Inhalation is significant, with indoor air at 1.7-16.2 particles/m³ [191], surgical theatres at 1,924 MPs/m²/day [69], and waste segregation workers exposed to 3,964-5,460 particles/8h [201]. Children inhale 1.57 ng/kg bw/d, higher indoors with additive co-exposure [140]. N95 masks reduce spherical microplastic risk by 25.5×, but reuse increases shedding [187]. Intravenous medical exposure yields MPs in 77% of blood samples (10.32 items/person/year) [58], with surgical procedures doubling MP blood levels in children [82, 144]. Dermal exposure via period products introduces cytotoxic polyethylene particles [202].

Toxicological Evidence

Microplastics (MPs) translocate across barriers, accumulating in placenta, cord blood, and pediatric myocardium (38.4-92.4 μg/g) [82, 144]. Maternal Nanoplastics (NPs) inhalation reduces fetal/placental weights by 7-8% [190]. Phagocytosis induces glycolysis, inflammation, and reduced respiration [177]. MPs cause oxidative stress, lipid disruption, and hepatic toxicity [204, 207], inhibit fibrin clot formation [194], and alter saliva/mucus viscosity [200]. Neurotoxicity is evident, with MPs in olfactory bulbs [193] and seizure exacerbation via ferroptosis [212]. Smaller MPs (<100 nm) cross barriers more readily, amplifying toxicity [204].

Microplastics (MPs) sorb pharmaceuticals, BPA, and phthalates, enhancing oxidative stress and reproductive toxicity [161, 184]. They reduce heavy metal bioaccessibility [189], promote antibiotic resistance gene transfer [161], and facilitate pathogen adhesion in seafood [192]. MPs alter gut microbiome, increasing indirect health risks [161]. Toxicity depends on size, polymer, and co-contaminants.

Epidemiological Findings

Microplastics (MPs) are detected in stool (3.5 particles/g) [211], blood (20.81 μg/g) [58, 208],

urine (5.06 μg/g) [208], and lungs (0.69-1.42 MP/g) [63, 210]. Lifetime intake reaches 553-

883 particles/day, accumulating to 5.01×10^4 by age 70 [196]. Food deposition adds 0.46-3.1 particles/cm²/h [198]. Elevated NT-proBNP in children indicates cardiovascular stress [82, 144]. Occupational exposure in recycling workers is high [201, 206]. MPs correlate with inflammation, oxidative stress, and microbiome changes [143, 211], but studies are limited by small, cross-sectional designs.

Knowledge Gaps

Methodological heterogeneity hinders comparisons, with non-standardised digestion and detection protocols [45, 143]. Dietary exposure studies focus on seafood, underestimating beverages, cookware, and inhalation [68, 137, 188]. Toxicological data rely on animal/in vitro models, limiting human relevance due to interspecies differences and acute dosing [204, 207, 212]. Epidemiological studies lack large, longitudinal cohorts [208, 211]. Microplastic (MP) interactions with co-contaminants (metals, pathogens, additives) need systematic study [161, 184, 192]. Placental transfer mechanisms and chronic effects remain unclear [82, 144].

Synthesis and Evidence Quality

Ingestion dominates microplastic (MP) exposure, followed by inhalation and medical routes, with MPs detected in human tissues (e.g., 20.81 μg/g serum, 3.5 particles/g stool). Toxicological studies show inflammation, oxidative stress, and neuro/cardiovascular effects, amplified by co-contaminants. Epidemiological data confirm tissue accumulation and health correlations, but are limited. Evidence is moderate to strong, supported by diverse studies, yet gaps in standardisation, chronic toxicology, and large-scale epidemiology persist. Mechanisms of placental transfer, additive effects with co-contaminants, and chronic health outcomes are particularly underexplored. These insights underscore the need for unified methods and longitudinal research to assess MP health risks.

Table 6: Summary of Human Exposure and Health Risks of Microplastics Data

Paper	Authors & Year	Exposure Pathway	Health Endpoint	Key Findings	Knowledge Gaps	Quality
41	Islam et al., 2025	Seafood ingestion	Exposure (MP intake)	Children 3× higher intake (15-22 MPs/day)	Long-term impacts	High
45	de Guzman et al., 2022	Seafood (Manila clams)	Exposure/toxic risk	~1489 MPs/year; PS dominant	Standard methods; dose–response data	High
58	Li et al., 2025	IV injection (medical devices)	Tissue damage, leaching	77% blood +MPs; ~10/year; ↑ with reuse	Long-term, size effects	High
63	Jenner et al., 2022	Inhalation	ROS, inflammation	MPs in 11/13 lungs; PP/PET fibres dominant	Long-term, NPs detection	High
68	Cole et al., 2024	Cookware food contact	Toxic potential	2.4-5k MPs/year; PTFE/PE/PP	NP quantification; chronic data	High
69	Field et al., 2022	Surgical air	Lung/tissue exposure	541-1924 MPs m^{-2}/day; PET/PP	Long-term impacts	High
75	Panneerselvan et al., 2024	Supplements	Potential toxicity	0.1-5.9 MPs/day; polyamide dominant	Size effects	High
81	Kelishadi et al., 2024	Disposable PS containers	Toxic persistence	Up to 56 mg MPs at 120°C; nano-sized	No in vivo or real-food data	High
82	Lv et al., 2025	Placental/surgical	Cardiac stress	MPs in heart, blood, placenta; neonates highest	Mechanisms, long-term effects	High
120	Le et al., 2023	Wastewater	Indirect chemical risk	69-99% removal; 77M MPs/day	No direct health data	High
128	Islam et al., 2025	Seafood	Toxic risk	15-20 MPs/day	No cooking/other foods	High

				(children), 3.7× adults		
137	Al-Mansoori et al., 2025	Beverages	Adverse potential	1.65 MPs/kg BW/day	Long-term, small MPs	High
140	Torres-Agullo et al., 2025	Inhalation	Respiratory risk	1.57 ng/kg bw/d (children); indoor ↑	Additive toxicity; long-term	High
143	Süssmann et al., 2025	Seafood	CV/microbiome risk	16.5k MPs/year; higher in canned fish	Long-term, standardisation	High
144	Lv et al., 2025	Maternal-fetal, surgery	Cardiac contamination	MPs in myocardium; neonates highest	Mechanisms, long-term	High
177	Merkley et al., 2022	Ingestion (phagocytosis)	Immunometabolic change	↑ Glycolysis, inflammation	Human relevance	High
184	Hu et al., 2021	Ingestion/inhalation	Mutagenesis, cancer	BPA/SO cause DNA mutations, cancers	Synergistic exposure	High
187	Li et al., 2021	Mask use	Inhalation risk	N95 ↓MPs by 25×; reuse ↑risk	Long-term exposure	High
188	Heo et al., 2025	Food	Toxicity potential	0.0002-1.5M MPs/day detected	Chronic effects, methods	High
189	Chen et al., 2022	Ingestion	Metal toxicity	MPs lower Pb bioaccessibility	Long-term effects	High
191	Vianello et al., 2019	Inhalation	Lung inflammation	1.7-16.2 MPs/m³ indoor	Mechanisms, chronic risk	High
192	Zhang et al., 2022	Seafood	Pathogen risk	MPs aid parasite adhesion	Long-term effects	High
193	Amato-Lourenço et al., 2024	Inhalation (olfactory)	Neurotoxicity	MPs in 8/15 olfactory bulbs	Sources, effects	High
194	Tran et al., 2022	Multi-route	Thrombosis	MPs inhibit fibrin clots; nPS strongest	Long-term data	High
196	Mohamed Nor et al., 2021	Multi-route	Inflammation, stress	553-883 MPs/day; 50k lifetime	Chemical toxicity	High

198	Fang et al., 2022	Food/drinks	Ingestion risk	0.46-3.1 MPs/cm²/h deposition	Chronic exposure	High
200	Przekop et al., 2023	Multi-route	Mucus viscosity	MPs ↑saliva, ↓mucus viscosity	In vivo data	High

201	Limsiriwong & Winijkul, 2023	Inhalation	Respiratory exposure	Up to 5.4k MPs/8h (waste workers)	Health outcomes	High
202	Pontocorvi et al., 2023	Dermal (period products)	Cytotoxicity, inflammation	PE NPs alter genes, cause inflammation	In vivo, long-term	High
204	Tan et al., 2025	Ingestion	Oxidative stress	MPs/NPs disrupt GI barrier	Chronic, low-dose data	High
206	Hasan et al., 2024	Inhalation, ingestion	Multi-organ risk	Worker exposure protocol developed	Health outcomes, seasons	High
207	Guraka et al., 2024	Ingestion	Hepatic toxicity	1 µm PS causes liver inflammation	In vivo relevance	High
208	Song et al., 2024	Ingestion/inhalation	Systemic exposure	MPs in serum, faeces, urine; diet main source	Larger cohorts needed	High
210	Jenner et al., 2022	Inhalation	Respiratory accumulation	1.42 MP/g in lungs	Long-term effects	High
211	Hartmann et al., 2024	Ingestion (diet)	Internal burden	MPs in stool (3.5/g); diet ↑exposure	Health risk data	High
212	Xie et al., 2025	Ingestion	Neurotoxicity/seizures	PS MPs ↑seizures; melatonin mitigates	Human validation	High

↑ = *increasing trend;* ↓ = *decreasing trend;* → = *leads to / contributes to*

Remediation Strategies

Physical Removal Methods

Physical methods dominate microplastics (MPs) remediation, particularly in wastewater treatment plants (WWTPs) and stormwater systems. Conventional WWTPs achieve 90-99% MP removal [237], with activated sludge and tertiary treatments reaching 96.8% in centralised systems [53, 60, 88, 92, 101, 117]. Membrane bioreactors (MBR) and moving bed biofilmreactors (MBBR) exceed 97-99% [117, 236, 238], and mechanical/rapid sand filtration

achieves 99.98% [219]. However, decentralised systems (14.2-53.6%) face fragmentation issues [60, 92], and high costs, fouling, and secondary MP release limit advanced systems [117, 238]. Stormwater solutions include horizontal sand filters (>98% retention) [112], permeable pavements (89-99.6%) [99], retention ponds (1,511-127,986 MPs/kg) [106], and gully pots

(>125 µm, 709-10,600 items/100 g) [107]. Bioretention filters retain 91.8% MPs [89], but gross pollutant traps fail for 20-100 µm MPs [89]. Wash water filtration (>50 µm) removes coarse MPs but misses <5 µm particles, discharging 59-1184 tonnes/year [39, 242]. Bark/biochar filters achieve >97% retention but face channelling [108]. Smaller MPs (<63 µm) reduce efficiency in sand/biofilm filters [243].

Classification of Health Implications According to Health-Care Determinants

To provide a clearer public health perspective, the health implications of microplastic exposure can be classified according to the four major health determinants: preventive, promotive, palliative, and rehabilitative care. This classification complements the evidence presented throughout this review and demonstrates how scientific findings can inform practical health interventions.

Preventive care focuses on reducing exposure before adverse health effects occur. Preventive measures include reducing plastic pollution at its source, improving waste management systems, strengthening environmental regulations, monitoring microplastic contamination in food and water, and increasing public awareness of exposure pathways.

Promotive care emphasizes improving health and creating environments that reduce long-term risks. This includes promoting sustainable consumption practices, encouraging the use of environmentally friendly materials, supporting environmental education, and implementing policies that encourage industries and communities to reduce plastic waste generation.

Palliative care becomes relevant when individuals experience chronic conditions that may be associated with prolonged exposure to environmental contaminants. Although direct clinical evidence linking microplastics to specific diseases is still emerging, supportive management of symptoms and measures that improve patients' quality of life remain important components of healthcare.

Rehabilitative care focuses on restoring health and function following illness or environmental exposure. Continued medical follow-up, rehabilitation services where appropriate, multidisciplinary healthcare support, and ongoing research into the long-term effects of microplastic exposure can contribute to improved recovery and health outcomes for affected populations.

Overall, classifying the health implications of microplastics according to these four health determinants highlights that addressing microplastic pollution requires not only environmental remediation but also integrated public health strategies that combine prevention, health promotion, clinical care, and rehabilitation.

Chemical Degradation Techniques

Chemical methods target microplastic (MP) breakdown. Photocatalysis with TiO_2/SiO_2 (9-16% PET loss) [213] and ZnO nanorods (65% volume reduction) [233] shows promise. UV-humic acid systems yield 42.6% oxygen incorporation [220], and solar-driven processes enhance PLA degradation [221]. Hydrothermal processing degrades >95% polyamide at 300 °C [218], NaOCl digestion recovers 92-100% MPs [224], and coagulation with SDBS achieves 95.92-98.9% removal [239]. Alkaline-thermal pretreatment with anaerobic digestion reduces PET but not PA66 [225]. Nanomaterial-based methods near 100% MP removal [238]. These approaches are energy-intensive, polymer-specific, and lack field validation.

Biological and Biotechnological Approaches

Biological methods degrade specific polymers. Bacteria/fungi degrade PLA/BHET, with *Planococcus sp*. achieving high hydrolysis [179]. Fungal-bacterial co-cultures reduce LDPE half-life (26.3% loss) [241], and sequential consortia achieve 28% degradation [228]. Bacterial mixtures [227] and bacterial-charged biochar [214] enhance soil MP removal and crop growth. Anaerobic digestion degrades <1 mm plastics minimally [217, 225]. Phytoremediationtranslocates MPs [232], and plankton uptake enhances PLGA degradation [230]. Constructed wetlands remove 40-77% MPs [222], but surface flow wetlands increase outflow (-92% to - 43%) due to atmospheric deposition [96]. Scalability, polymer range, and field testing limit these methods.

Innovative Technologies

Innovative solutions address microplastics (MPs). Fe_2O_3 microparticles with NIR remove 100% MPs in 80 min [216]. Polysaccharide aerogels achieve 93.68% MP and 96.98% nanoplastics (NP) removal but face pH/temperature instability [226]. Chitosan-modified mycelium adsorbs 68.8% MPs (412.42 mg/g) [235], and modified PES membranes remove 100% MPs and 99.7% PCBs [231]. Bioelectric fields reduce PLA by 8.94% [229]. Policy frameworks advocate land-sea integration [30], but reverse logistics and waste plans suffer low recycling (<30%) due to weak enforcement and infrastructure [34, 36]. Scalability and cost remain barriers.

Implementation Barriers

Despite technical progress, multiple barriers hinder real-world deployment. Physical methods miss <10 µm MPs [39, 242, 243], and WWTPs concentrate MPs in sludge, risking reintroduction [53, 60, 101]. Chemical methods are energy-intensive and polymer-specific [218, 220, 225]. Biological approaches are promising but lack field validation and polymer versatility [179, 217, 228]. Innovative technologies such as aerogels, nanomaterials, and magnetic extraction systems, face scalability and cost issues [226, 231, 235, 238]. Policy frameworks are hindered by poor coordination and infrastructure [30, 34, 36]. Addressing these barriers will require integration of technology with regulatory, financial, and socio-political mechanisms to ensure both technical and systemic feasibility.

Synthesis and Evidence Quality

Studies consistently show that remediation strategies for microplastics are advancing rapidly. Physical methods (90-99.98% removal) [88, 219, 237], chemical degradation (65-100%) [233, 238], and biological approaches (e.g., 26.3% LDPE loss) [241] show strong microplastic (MP) remediation potential. Innovative technologies target micro-/nano-plastics (MPs/NPs) effectively [226, 235]. High-quality studies support these findings, with robust lab and field data. Gaps in scalability, nanoplastic removal, and sludge management persist, alongside policy integration challenges. These insights link remediation to ecological and health outcomes.

Table 7: Summary of Data on Microplastics Remediation Strategies

Paper	Authors & Year	Approach	Method Tested	Matrix	Efficiency/Outcome	Barriers	Quality
30	Yang et al., 2021	Innovative	Land-sea integration; lifecycle management	Marine	Pollution reversal potential	Coordination gaps	High
34	Andrade & Araujo, 2025	Policy/Legal	NSWP, logistics, litter plan	Plastic waste	>70% landfilled	Poor infra; weak laws	High
36	Abdullah & Abedin, 2024	Phys/Chem	Sorting, recycling	Waste	10% recycled	Informal sector; poor infra	High
39	Brown et al., 2023	Physical	Wash-water filter >5 µm	Water	Good >40 µm; poor <5 µm	Fine MPs persist	High
53	Monira et al., 2023	Physical	WWTP + DAF	Water	~95% removed; sludge-bound	NPs persist; sludge issue	High
60	Maw et al., 2024	Phys/Bio	Activated sludge types	WW/Sludge	50–96% central; 14–53% decen.	Long HRT; sludge buildup	High
112	Rullander et al., 2023	Physical	Sand filters (25-100 cm)	Stormwater	>98% retention	Lab-only; high MP load	High
117	Cavazzoli et al., 2025	Phys/Innov	CAS, MBBR, MBR, filters	WW	97-99% removal	Filter release; cost	High
88	Steinfeld et al., 2025	Phys/Bio	Mech + sludge	Water	>99% removal	Not noted	High
89	Lange et al., 2022	Phys/Bio	GPT, bioretention, sand	Water	Bioret. 91.8%; GPT low	Size limits; few tests	High
91	Lange et al., 2023	Phys/Bio	Bioretention	Sediment	MPs in top layers	Local, polymer gaps	Mod
92	Maw et al., 2024	Phys/Bio	Activated sludge	Water/Sludge	50-96% (centralised)	Fragmentation; regional	Mod
96	Büngener et al., 2023	Bio/Phys	Surface wetland	Water	-92% to -43% (↑MPs)	Air deposition	High

99	García-Haba et al., 2024	Phys/Innov	Permeable pavements	Water/Sed	89-99.6% retained	<0.1 mm MPs	High
101	Prada et al., 2024	Phys/Bio	WWTP	Water/Sed	Lower MP effluent	Biosolids reuse	High
106	Liu et al., 2019	Physical	Retention ponds	Sediment	1.5–128k MPs/kg trapped	Flow-dependent	High
107	Öborn et al., 2024	Physical	Gully pots	Sediment	709-10,600 MPs/100g	Large MPs only	High
108	Rullander et al., 2024	Phys/Innov	Bark/biochar filters	Water/Sed	>97% retained	Short filter channelling	High
179	Chaimusik et al., 2024	Biological	Microbial degradation	Sed/Biota	27 spp.; PLA degraded	Lab-only; limited polymers	High
241	Alidoosti et al., 2025	Biological	Fungal-bacterial coculture	LDPE	26.3% loss (60d)	Lab-only; untested	High
242	Brown et al., 2023	Physical	50 μm sieve + skimming	Wash water	Removed >5 μm; <5 μm remain	Clogging; cost; policy gap	High
243	Martín-García et al., 2024	Phys/Bio	Sand/coke filters	Freshwater/WWTP	>80% (>63 μm); coke best	Small MPs low removal	High
213	Ariza-Tarazona et al., 2023	Innovative	C,N-TiO_2/SiO_2 photocatalyst	Water	9-16% PET loss	Not detailed	High
214	Afzal et al., 2025	Bio/Innov	Bacterial biochar	Soil	↑Growth, P, nitrif.; ↓stress	Short-term; cost	High
216	Sanchez et al., 2024	Innovative	Fe_2O_3 + NIR	Water	100% in 80 min	Lab-only	High
217	Lessa Belone et al., 2024	Biological	AD (meso/thermo)	Sludge	Minimal degradation	Slow rate	High
218	Vo et al., 2023	Innovative	Hydrothermal + metal ions	Water	>95% PA degraded	Polymer-specific	High
219	Chand et al., 2024	Multi	Mech + sand filter	Water	99.98% MPs removed	Design-specific	High
220	Wang et al., 2023	Chemical	UV + humic acid	Water	4.3% loss; ↑oxidation	Lab-only	High

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221	Russo et al., 2024	Innovative	UVA/solar + MeOx NPs	Water	↑PLA oxidation	Controlled setup	High
222	Sarti et al., 2024	Phys/Bio	Wetland (multi-stage)	Water	40-77% VF removal	Variable retention	High
224	Faikhaw et al., 2025	Chemical	NaOCl digestion	Water	92–100% recovery	Debris interference	High
225	Zoccali et al., 2025	Chem/Bio	Alkaline + AD	Sludge	PET ↓; PA resist	Competing organics	High
226	Liu et al., 2025	Innovative	Polysaccharide aerogel	Water	94% MP; 97% NP removed	pH/temp sensitive	High
227	Chen et al., 2025	Biological	Bacterial mix	Soil	↓Toxicity; ↑growth	Low degradation	High
228	Giyahchi & Moghimi, 2025	Biological	Microbial consortia	-	28% degraded; ↓toxicity	Scale limits	High
229	Wang et al., 2023	Innovative	Bioelectric field	Soil	8.9% PLA loss (120d)	Low scalability	High
230	Schenone et al., 2025	Biological	Plankton uptake	Water	↑PLGA degradation	Narrow scope	High
231	Babalar et al., 2025	Innovative	PES membrane	Water	100% MP; 99.7% PCB rem.	Synthetic setup	High
232	Marzi et al., 2025	Biological	Phytoremediation	Soil	Plant uptake/translocation	Species-limited	High
233	Uheida et al., 2021	Chemical	ZnO photocatalysis	Water	65% vol. reduction	Scale issue	High
235	Dong et al., 2025	Innovative	Chitosan–mycelium	Water	69% MP removal	Lab-only	High
236	Cavazzoli et al., 2025	Physical	CAS, MBR, filtration	Water	>99% removed	Residual MPs	High
237	Cavazzoli et al., 2025	Physical	WWTP processes	Water	90-99% removed	Residual MPs	High
238	Bodzek & Pohl, 2023	Physical	Membrane (UF, NF, RO)	Water	≤99.9% removed	Fouling; scale	High
239	Ziembowicz et al., 2023	Chemical	Coagulation (SDBS)	Water	96-99% removed	Lab-limited	High
238	Bodzek, 2023	Innovative	Nanomaterial-based	Water	High MP/NP removal	Cost; scale	High

↑ = *increasing trend;* ↓ = *decreasing trend;* → = *leads to / contributes to*

DISCUSSION

Synthesis Across Thematic Results

The trajectory of plastic production and waste directly underpins the ubiquity of microplastics (MPs) across ecosystems. Global plastic production rose from 2 Mt (1950) to 473 Mt (2020), projected to reach 1,150 Mt by 2060 under business-as-usual [1-15, 244-246, 255]. Low

recycling (9-13%) and mismanaged waste (100 Mt in 2019, potentially 228 Mt by 2060) in low/middle-income countries drive microplastic (MP) inputs from packaging, textiles, and tyres [14, 16-29, 40-52, 244, 245, 250, 254]. Microplastics are now recognised as pervasive contaminants across environmental matrices. Fibres, polyethylene/polypropylene fragments, and tyre particles dominate rivers (1-12 items/L), soils (>1,000% increase with sludge), and Arctic snow [2, 5, 7-9, 19, 22, 23, 31, 37, 40, 44, 46-50, 54, 57, 76, 77, 79, 97, 100, 119, 131,133, 176]. Transport via wastewater (1.7M–77M MPs/day), runoff (269.1 t/y), atmospheric deposition (0.1-6.6 particles/m^3), and trophic transfer creates transboundary pollution, amplified by floods or storm surges [3, 4, 6, 21, 24, 38, 40-52, 71, 85-87, 90, 94, 95, 98, 109,113, 114, 118, 120, 121, 123, 125, 127].

Detection and quantification methods provide the technical bridge between sources and impacts. Methods such as Microscopy, FTIR, Raman spectroscopy, and Pyrolysis-GC/MS identify microplastics (MPs) ≥1–20 μm but miss nanoplastics [52, 55, 61, 64, 66-87, 93, 115,126, 129, 130, 132-134, 136, 138, 141, 147, 152, 162, 186, 197, 203]. The biological andecological effects of microplastics (MPs) are now well documented across taxa. MPs cause ecological harm, such as reducing feeding efficiency, growth, and reproduction (for aquatic organisms) and gut damage, reduced lifespans, and altered nutrient cycles (for terrestrial organisms), with neuro/immunotoxicity and co-contaminant sorption that amplifies toxicity [11, 12, 25, 43, 62, 65, 70, 73, 84, 104, 105, 124-153, 157-161, 163-175, 178, 180-183]. Theseimpacts cascade to ecosystem-level disruptions, including altered food webs, shifts in microbial communities, and impaired biogeochemical processes.

Human exposure represents a final nexus in the cycle. Human exposure via seafood (4.22-22.01 MPs/day), inhalation (1.7-16.2 particles/m^3), and medical devices (10.32 items/year) leads to MPs in blood (20.81 μg/g), lungs (0.69-1.42 MP/g), and myocardium (38.4-92.4 μg/g), causing inflammation and neurotoxicity [41, 45, 58, 63, 68, 69, 75, 81, 82, 120, 128, 137, 140,143, 144, 154-178, 184, 187-196, 198, 200-202, 204, 206-208, 210-212]. Remediationstrategies close the cycle by addressing how societies may mitigate Microplastic (MP) burdens.

Remediation achieves 90-99.98% MP removal via WWTPs, filtration, membrane bioreactors, photocatalysis, and enzymatic degradation, but nanoplastics and sludge reintroduction persist [30, 34, 36, 39, 53, 60, 88–92, 96, 99, 101, 106–108, 112, 117, 179, 213–243].

Cross-Cutting Methodological Challenges

Detection methods like FTIR and Raman fail to capture nanoplastics (<1-20 μm), likely underestimating their high toxicity [52, 55, 61, 64, 66-87, 93, 115, 126, 129, 130, 132-134,

136, 138, 141, 147, 152, 162, 186, 197, 203]. Sampling inconsistencies, such as manta trawls (≥300 μm) versus sieves (0.2-1000 μm), miss patchy or storm-driven microplastics, particularly in atmospheric and sediment studies [40-52, 66-87, 113, 126]. Polymer biases favour buoyant PE/PP over denser PET/PVC, skewing water-column data [16-29, 40-52]. Organic matter interference and non-standardised digestion (e.g., nitric acid degrading PET) obscure spectra, while contamination in air and wastewater sampling reduces reliability [55, 64, 115, 126, 129,

132, 136, 186, 203]. These issues suggest conservative microplastics estimates, underrepresenting ecological and health risks [124-178].

Contradictions vs. Consensus

Consensus affirms the ubiquity of microplastics, with PE/PP fibres and fragments prevalent across matrices [2, 5, 7-9, 16-29, 40-52]. Ecological impacts include impaired feeding, growth,

and reproduction (0.05-19 MPs/fish), with trophic transfer to vertebrates [11, 12, 25, 43, 62,

65, 70, 73, 84, 104, 105, 124-153, 157-175, 178, 180-183]. Human exposure (3.5 particles/g

stool, 553-883 particles/day) is confirmed via ingestion and inhalation [41, 45, 58, 63, 68, 69,

75, 81, 82, 120, 128, 137, 140, 143, 144, 154-178, 184, 187-196, 198, 200-202, 204, 206-208,

210-212]. Contradictions emerge in exposure thresholds, with some species showing resilience due to lab-to-field mismatches or compensatory mechanisms [124-153]. Human health studies vary, with some linking microplastics to oxidative stress and others finding weak correlations due to small cohorts [154-178, 196, 208, 211]. WWTPs remove 90-99.98% MPs, yet effluents release 1.7M-77M MPs/day, questioning the efficiency of conventional methods [30, 34, 36, 39, 53, 60, 88-92, 96, 99, 101, 106-108, 112, 117, 120, 179, 213-243].

Policy and Governance Implications

Source reduction through extended producer responsibility (EPR) and bans on high-risk polymers (e.g., microbeads) is critical to curb production (473 Mt in 2020, projected 1,150 Mt by 2060) and mismanaged waste (100 Mt in 2019) [1-15, 27, 28, 30, 34, 36, 39, 244-247, 250-

254]. The UNEA plastics treaty can set legally binding targets to address transboundary microplastic transport through atmospheric and oceanic currents [40-52, 76, 85]. National policies must enhance wastewater treatment (36-99% MP removal), stormwater management, and agricultural runoff controls, especially in high-leakage regions like South Asia (<30% recycling, 50-70% open dumping) [18, 53, 60, 88-92, 96, 99, 101, 106-108, 112-114, 117, 121,

123, 127, 254]. Circular economy models with recycled-content mandates could reduce leakage by 91% and GHG emissions by 33%, but weak infrastructure and enforcement, particularly in non-OECD countries, are driving 80% demand growth, limiting progress [246, 250-252].

Translational Research Opportunities

Standardising detection protocols (e.g., sampling, digestion, QA/QC) can unify datasets for global MP surveillance [41, 45, 58, 63, 68, 69, 75, 81, 82, 120, 128, 137, 140, 143, 144, 154-

178, 184, 187-196, 198, 200-202, 204, 206-208, 210-212]. Longitudinal epidemiology using biomarkers (e.g., 3.5 particles/g stool, 20.81 µg/g blood) can assess chronic human health risks [58, 63, 82, 144, 196, 208, 211]. Scaling enzymatic (e.g., PETase, 28% degradation) and filtration technologies (90-99.98% removal) require pilot testing in WWTPs and stormwater systems [179, 213-243]. Integrating MPs into climate policies, such as reducing fossil fuel-based plastics, aligns with carbon reduction goals [1-15, 30, 34, 36, 246, 250-252]. Remote sensing and machine learning (e.g., 132.6 tons/day waste in Bali, $R^2=0.882$) can bridge data gaps in low-income regions [42].

Limitations of the current evidence base and of this review

Rising plastic production (473 Mt in 2020, projected 1,150 Mt by 2060) drives microplastic (MP) contamination across ecosystems, with ecological impacts (15-17 MPs/mollusc, 0.05-19 MPs/fish) and human health risks (20.81 μg/g blood, 3.5 particles/g stool) [1-15, 16-29, 40-52,

124-178, 196, 244-246, 255]. However, geographic biases, with sparse data from Africa, South

America, and South Asia, limit global insights [16-29, 40-52, 54, 154-178, 254]. Nanoplastic detection is constrained by FTIR/Raman limits (<1-20 μm) and indirect thermal methods, missing particle counts and underestimating risks [52, 55, 61, 64, 66-87, 93, 115, 126, 129,130, 132-134, 136, 138, 141, 147, 152, 162, 186, 197, 203].

Methodological inconsistencies in sampling, digestion, and QA/QC hinder comparability, while human epidemiological studies rely on small, cross-sectional cohorts, lacking standardised exposure metrics [66-87, 124-178, 196, 208, 211]. This review's hybrid approachrisks interpretative bias, and exclusion of grey literature may skew regional estimates. Remediation achieves 90-99.98% MP removal but faces challenges with nanoplastics, sludge reintroduction, and scalability [30, 34, 36, 39, 53, 60, 88-92, 96, 99, 101, 106-108, 112, 117, 179, 213-243]. Policy must prioritise source reduction via EPR, bans, and global treaties, while research should standardise detection and scale solutions to address this transboundary crisis [1-15, 30, 34, 36, 39, 42, 244-247, 250-254]. These insights provide a foundation for advancing global governance and research agendas on microplastic pollution.

Future Directions And Research Needs

First, methodological harmonisation must be standardised. Harmonised protocols for microplastic (MP) sampling, analysis, and reporting are critical to improve comparability and reduce uncertainty [66-87, 126, 129, 132-134, 136]. Current methods, from manta trawls (≥300

μm) to FTIR/Raman (≥1-20 μm), lack consistency, hindering meta-analyses [52, 55, 61, 64,

93, 115, 126, 129, 130, 132-134, 136, 138, 141, 147, 152]. Future efforts should prioritise inter-laboratory calibration, shared QA/QC standards (e.g., field blanks), and size-inclusive detection for nanoplastics (<1 μm) [64, 126, 197, 203]. A centralised framework reporting polymer type, size, morphology, and concentration (e.g., 1-12 items/L in rivers) would enhance transparency and synthesis [2, 5, 49].

Secondly, remediation tools must be developed and scaled. Promising technologies, such as membrane bioreactors (97-99% removal), photocatalysis (65-100% degradation), and enzymatic PETase (28% loss), require optimisation for scalability, energy efficiency, and affordability, especially in low-income regions [30, 34, 36, 39, 53, 60, 88-92, 96, 99, 101, 106-

108, 112, 117, 179, 213-243]. Field trials in high-turbidity wastewaters and mixed-polymer matrices are essential [117, 238]. Integrating MP-specific controls into existing wastewater and stormwater systems (e.g., >90% retention by biofilters) offers near-term solutions, while advanced membranes and bio-chemical hybrids promise long-term impact [89, 99, 226, 231].

Thirdly, longitudinal human health studies and biomonitoring are important. Longitudinal cohort studies are needed to clarify chronic microplastic exposure risks, particularly in children, workers, and medical patients [41, 45, 58, 63, 68, 69, 75, 81, 82, 120, 128, 137, 140,

143, 144, 154-178, 184, 187-196, 198, 200-202, 204, 206-208, 210-212]. Standardisedbiomarkers (e.g., 3.5 particles/g stool, 20.81 μg/g blood) and non-invasive sampling (stool, urine) can track burdens and link to outcomes such as inflammation and neurotoxicity [58, 63,82, 144, 196, 208, 211]. Biomonitoring frameworks should integrate exposure metrics (4.22-22.01 MPs/day via seafood) with clinical data to inform health guidelines [41, 128].

Fourth, policy interventions for pollution control are vital. Lifecycle management requires upstream interventions, such as caps on virgin plastic production (473 Mt in 2020), eco-friendly alternative materials, and design for recyclability [1-15, 27, 28, 30, 34, 36, 39, 244-247, 250-254]. Local solutions, like improved waste collection and stormwater systems, must address high-leakage regions (e.g., South Asia's <30% recycling) [18, 53, 60, 88-92, 96, 99, 101, 106-108, 112-114, 117, 121, 123, 127, 254]. The UNEA plastics treaty can enforce global targets,integrating science with stakeholder-driven policies [40-52, 76, 85].

Finally, data sharing and capacity building are critical because open-access databases and harmonised metadata can unify global MP datasets [42]. Capacity building in low-resource regions, where data gaps persist (e.g., Africa, South Asia), requires investment in laboratories, training, and low-cost detection methods (e.g., remote sensing, R^2 = 0.882 in Bali) [16-29, 40-52, 54, 154-178, 254]. South-South collaborations and citizen science can enhance monitoringequity [42].

CONCLUSION

Increasing plastic production (473 Mt in 2020, projected to reach 1,150 Mt by 2060) and low recycling rates (9-13%) drive microplastic pollution across ecosystems [1-15, 244-246, 255]. MPs (15-17 MPs/mollusc, 0.05-19 MPs/fish) disrupt feeding, growth, and ecosystems, while human exposure (20.81 µg/g blood) causes inflammation and neurotoxicity [11, 12, 25, 43, 62,65, 70, 73, 84, 104, 105, 124-153, 157-175, 178, 180-183, 196]. Detection underestimatesnanoplastics, and remediation (90-99.98%) faces scalability issues [30, 34, 36, 39, 53, 60, 66-87, 88-92, 96, 99, 101, 106-108, 112, 117, 179, 213-243]. Upstream interventions, such as production caps and the circular economy, are critical [1-15, 244-247, 250-254]. The microplastic crisis demands urgent action. Researchers must standardise detection, quantify nanoplastics, and conduct longitudinal health studies [66-87, 154-178]. Funders should support interdisciplinary work and capacity building in underrepresented regions [42, 254]. Policymakers must advance the UNEA treaty, enforce EPR, and scale remediation to align science, technology, and governance [1-15, 30, 34, 36, 39, 244-247, 250-254].

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Supplementary data

Supplementary data to this article can be found in the attached Excel file.

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