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Living in a Microplastic World: An Analytical Review of an Insidious Global Contaminant

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Abstract: This structured analytical narrative review consolidates current knowledge on plastic pollution across its life cycle, from production and waste generation to the formation, environmental distribution, human exposure, and toxicity of microplastics (MPs). The review was based on thematic searches in Web of Science, Scopus, ScienceDirect, and PubMed/MEDLINE, complemented by citation chaining from key reviews and source articles. Evidence was selected and critically organized according to relevance to plastic production, environmental monitoring, human biomonitoring, in vitro and in vivo toxicology, mitigation technologies, and policy responses. Because the literature uses heterogeneous matrices, particle-size thresholds, analytical methods, reporting units, and toxicological endpoints, the synthesis was presented narratively and in tabular form, and no meta-analysis was performed. The specific contribution of this review is the integration of environmental occurrence, human biomonitoring, mechanistic toxicology, and mitigation evidence in a single environmental-health framework. Findings confirm the widespread presence of MPs, with contamination documented from Mount Everest to the Mariana Trench. Human exposure is supported by the detection of plastic particles in blood, placenta, breast milk, urine, and lung tissue, indicating potential passage across biological barriers. Ingestion and inhalation are the main exposure routes: particle-count estimates indicate tens of thousands to more than 100000 particles per person per year, whereas a separate mass-based modeling study estimated 0.1-5 g per week under conservative assumptions and substantial uncertainty (Cox et al., 2019; Senathirajah et al., 2021). Toxicological evidence links MPs and NPs to oxidative stress, inflammation, epithelial barrier disruption, and cellular dysfunction. Additives such as dicyclohexyl phthalate (DCHP) can activate the pregnane X receptor (PXR), connecting plastic-associated chemicals with lipid-metabolism dysregulation and cardiovascular risk. Overall, MPs and NPs represent a growing environmental and public health concern that requires standardized methods, exposure metrics, and coordinated regulatory action.

Keywords: Microplastics; Plastic pollution; Human exposure; Toxicological Mechanisms; Bioaccumulation.

1. Introduction

The advent of the plastic age has transformed modern society. Synthetic polymers have provided substantial societal benefits because of their versatility, durability, low cost, mouldability, and chemical resistance. Plastics are now integral to packaging, construction, agriculture, medicine, textiles, electronics, and countless consumer products (Andrady, 2011; Wright et al., 2017; Weithmann et al., 2018). However, the same properties that make these materials technically useful also explain their persistence, progressive fragmentation, and accumulation in environmental and biological systems (Thompson et al., 2004; Avio et al., 2017).

Plastic pollution became a global scientific concern when plastic fragments smaller than 5 mm were recognized as an emerging class of contaminants. Microplastics (MPs) are commonly defined as particles smaller than 5 mm, whereas nanoplastics (NPs) are smaller and may exhibit enhanced colloidal mobility, surface reactivity, and biological translocation. As larger debris fragments through mechanical abrasion, ultraviolet radiation, thermal oxidation, and biological action, plastics are transformed from macroscopic waste into particles that can circulate through air, water, soil, food webs, and human tissues (Ragusa et al., 2022; Lamichhane et al., 2023).

The scientific recognition of this threat has expanded from marine litter to planetary contamination. Early reports documented plastic debris in coastal sediments and marine waters, but later studies detected particles in remote mountains, polar snow, atmospheric fallout, and the Mariana Trench (Barnes et al., 2009; Schlining et al., 2013; Karbalaei et al., 2018; Napper et al., 2020; Peng et al., 2018). This spatial expansion indicates that MPs and NPs should no longer be interpreted solely as local waste-management residues; rather, they behave as a class of distributed environmental contaminants with atmospheric, hydrological, and biological transport pathways.

The public-health dimension is equally important. MPs have been detected in human-consumed products, including seafood, table salt, drinking water, beer, honey, and milk (Yang et al., 2015; Kosuth et al., 2018; Zhang et al., 2020). Human biomonitoring studies have reported particles in blood, feces, breast milk, urine, sputum, placental tissue, lung tissue, and other biological matrices, supporting the premise that exposure is not merely external but potentially systemic (Vethaak & Legler, 2021; Ragusa et al., 2021; Pironti et al., 2022; Nihart et al., 2025). Nevertheless, the field still faces severe methodological limitations, especially in recovering, identifying, and quantifying particles below the micrometer range.

This review frames microplastic pollution as an integrated environmental-health problem, connecting sources, environmental distribution, human exposure, toxicological mechanisms, and mitigation strategies. Its added value is not limited to compiling occurrence data; rather, it organizes fragmented evidence from environmental monitoring, human biomonitoring, mechanistic toxicology, and policy studies into a single life-cycle framework that distinguishes established findings from unresolved uncertainties. By doing so, the article identifies where quantitative estimates are robust, where they remain model-dependent, and where methodological standardization is still required for risk assessment

Thus, the general objective of this review is to synthesize and critically organize the scientific evidence on microplastic pollution as a connected environmental, toxicological, and policy challenge.

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The review is explicitly positioned as a structured analytical narrative review, supported by evidence mapping and tabular synthesis, rather

than as an experimental study or a registered systematic review. Its contribution

lies in integrating production, environmental fate, human exposure, toxicity mechanisms, and mitigation into a coherent framework for academic interpretation and the design of future risk assessment.

- To describe the scale of plastic production, plastic waste generation, and the formation routes of MPs and NPs.
- To organize the evidence on aquatic, atmospheric, and terrestrial distribution of microplastics and nanoplastics.
- To summarize human exposure routes, including ingestion, inhalation, dermal contact, and emerging medical routes.
- To synthesize toxicological mechanisms, with emphasis on oxidative stress, inflammation, epithelial barrier disruption, endocrine/metabolic pathways, and particle-mediated transport of co-contaminants.
- To identify contradictions and methodological limitations that currently restrict risk assessment, including analytical detection limits, heterogeneous reporting units and limited environmental realism in some experimental designs.
- To discuss mitigation strategies and policy responses, especially circular-economy approaches, wastewater treatment, adsorption technologies and international regulatory coordination.

2. Methodology

2.1 Review design and rationale

This study was designed as a structured analytical narrative review with an integrative evidence-mapping component. The available evidence covers heterogeneous matrices, particle sizes, polymer types, analytical methods, biological endpoints and reporting units; therefore, a broad environmental-health synthesis was more appropriate than a narrowly framed intervention-style systematic review. The methodological organization was informed by transparent review principles used in PRISMA-type and rapid-review workflows, but the article was not registered as a systematic review protocol and does not claim to follow a full PRISMA systematic review design (Moher et al., 2009; Shamseer et al., 2015; Garritty et al., 2021; Hamel et al., 2021; Higgins et al., 2021).

The review followed an integrative evidence-mapping strategy. Evidence was classified by source domain, environmental or biological matrix, particle type, particle size, analytical method, exposure metric, toxicological endpoint and mitigation or policy relevance. This structure was adopted to make the narrative synthesis transparent and reproducible while preserving the broad interdisciplinary scope required by the topic.

2.2 Search strategy and information sources

The literature search was conducted on the Web of Science, Scopus, ScienceDirect, and PubMed/MEDLINE, supplemented by citation chaining from highly relevant reviews, systematic reviews, and primary studies. Searches covered literature with no initial year restriction but were limited to English-language peer-reviewed articles, review papers, methodological papers, and authoritative technical or policy reports when they provided essential quantitative or regulatory information. Comparable database combinations have been used in microplastic toxicology and oxidative-stress reviews, including Web of Science and MEDLINE for human cell studies, and PubMed, ScienceDirect, and Scopus for oxidative-stress syntheses (Danopoulos et al., 2022; Kadac-Czapska et al., 2024).

The main search strings combined controlled thematic blocks using Boolean operators, for example: ('microplastic*' OR 'nanoplastic*' OR 'plastic particle*' OR 'polymer particle*') AND ('human exposure' OR 'ingestion' OR 'inhalation' OR 'drinking water' OR 'seafood' OR 'salt' OR 'airborne' OR 'soil' OR 'wastewater') AND ('toxicity' OR 'oxidative stress' OR 'inflammation' OR 'barrier disruption' OR 'bioaccumulation' OR 'blood' OR 'placenta' OR 'breast milk' OR 'urine' OR 'lung'). Additional targeted searches were framed around specific mechanisms, technologies, and policy topics, including 'DCHP', 'pregnane X receptor', 'intravenous fluids', 'wastewater treatment', 'adsorption', 'FAST-PETase', 'PET depolymerization', 'circular economy,' and 'plastic pollution treaty'.

Records were first screened by title and abstract for thematic relevance. Full texts were then assessed when they provided quantitative estimates, methodological detail, polymer identification, particle-size information, biological matrices, toxicological endpoints, mitigation performance or policy relevance. Citation chaining was

used to identify the primary sources behind frequently repeated quantitative claims, especially mass-based estimates of human intake and cumulative projections of plastic waste.

2.3 Eligibility criteria

Studies were considered eligible when they addressed at least one of the following domains: plastic production and waste generation; environmental occurrence of MPs; particle formation mechanisms; human exposure through food, water, air or medical routes; biomonitoring in human biological matrices; in vitro or in vivo toxicological mechanisms; particle interactions with co-contaminants; wastewater treatment or remediation; enzymatic or chemical recycling; or policy and circular-economy responses. Preference was given to sources that reported the sample matrix, analytical method, particle-size range, polymer identification procedure, concentration or exposure metric, biological endpoint, or mitigation outcome.

Exclusion criteria included records focused only on macroplastic debris without a clear link to MP/NP formation or exposure; works lacking identifiable methods, matrix, endpoint, or polymer/particle information; opinion pieces without traceable evidence; duplicated records; and studies whose quantitative claims could not be connected to a primary or methodologically transparent source. Because the review integrates environmental, toxicological, and policy studies rather than a single clinical intervention question, eligibility was not restricted to one experimental design; nevertheless, evidence with transparent methods and explicit quantitative reporting was prioritized.

2.4 Screening, extraction and organization of evidence

Screening was conducted in two stages: title/abstract screening followed by full-text evaluation. During extraction, evidence was grouped into six domains: (I) production and waste scale; (II) sources and formation of MPs/NPs; (III) environmental distribution; (IV) human exposure and biomonitoring; (V) toxicological mechanisms; and (VI) mitigation and policy. Data items extracted included study type, database/source pathway, environmental or biological matrix, polymer or particle type, size range, concentration or exposure estimate, analytical method, toxicological endpoint, mitigation metric, and principal limitation, as summarized in Table 1.

The synthesis was narrative and tabular. Quantitative values were preserved only when they could be traced to the cited evidence base and the interpretation distinguished between measured concentrations, modeled estimates, and scenario-based projections. No meta-analysis was performed, and no pooled effect size was calculated. This decision was methodologically necessary because the reviewed studies used incompatible units, different sampling matrices, different recovery and contamination-control procedures, different minimum size thresholds and highly variable toxicological endpoints. Consequently, heterogeneity and limited standardization were treated as substantive findings rather than as obstacles to statistical averaging.

2.5 Quality appraisal and critical assessment

The methodological quality and scientific robustness of the included literature were evaluated using a pragmatic evidence-mapping framework specifically adapted for the multidisciplinary nature of microplastic and nanoplastic research. Because the review integrates evidence from environmental monitoring, human biomonitoring, experimental toxicology, engineering, and policy studies, a domain-specific quality appraisal was adopted instead of a numerical scoring system. The objective was to assess the reliability, transparency, reproducibility, and interpretability of the available evidence and to identify methodological strengths, limitations, and knowledge gaps.

Environmental monitoring and human biomonitoring studies were critically appraised according to the implementation of contamination prevention measures, use of procedural and field blanks, correction for laboratory contamination, analytical confirmation of polymer identity (e.g., FTIR, Raman spectroscopy or pyrolysis-GC/MS), characterization of particle size and morphology, reporting of detection and quantification limits, sample digestion and recovery efficiency, replicate analyses, quality assurance and quality control (QA/QC) procedures, and consistency in reporting particle abundance and concentration units.

Experimental toxicological studies were evaluated based on the physicochemical characterization of the tested particles (polymer composition, particle size, morphology and surface properties), exposure concentration and duration, biological model, environmental relevance of exposure scenarios, dose realism relative to measured environmental concentrations, selection of biological endpoints, statistical robustness, and

whether pristine, weathered, or environmentally aged microplastics were employed. Particular attention was given to the ecological and human-health relevance of experimental designs.

Review articles, regulatory documents, and policy reports were assessed according to the clarity of their objectives, methodological transparency, comprehensiveness of the evidence synthesis, traceability of information sources, consistency of interpretation, and applicability to environmental risk assessment, public health evaluation, and policy development.

The outcomes of the quality appraisal were incorporated into the narrative synthesis to support the critical interpretation of findings, evaluate the strength of the available evidence, identify potential sources of uncertainty and bias, and highlight methodological priorities for future research, harmonization of analytical protocols, and development of standardized monitoring frameworks (Table 1).

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Table 1. Review protocol and evidence-organization framework

Component	Operational definition in this review	Role in the synthesis
Review design	Structured analytical narrative review integrating evidence mapping from environmental sciences, toxicology, engineering, and policy. This review was not conducted as a registered systematic review.	Defines the methodological framework while avoiding inappropriate characterization as a PRISMA systematic review or meta-analysis
Information sources	Literature retrieved from Web of Science, Scopus, ScienceDirect, and PubMed/MEDLINE, complemented by backward and forward citation tracking of influential reviews and primary studies.	Ensures comprehensive coverage of multidisciplinary scientific evidence and minimizes omission of highly cited publications
Search date	Search covered literature available up to May 2026, with no initial year restriction.	Makes the temporal coverage of the review explicit and updateable.
Search concepts	microplastic*, nanoplastic*, plastic particles*, exposure, ingestion, inhalation, drinking water, air, soil, biomonitoring, oxidative stress, DCHP, PXR, FAST-PETase, wastewater treatment and policy.	Allows reproducibility and future updating of the search strategy.
Inclusion criteria	Peer-reviewed and technical evidence on sources, environmental distribution, exposure, mitigation, enzymatic recycling or policy.	Defines the conceptual boundaries of the broad environmental-health synthesis.
Exclusion criteria	Macroplastic-only studies without MP/NP relevance; records lacking identifiable methods, matrix or endpoint; duplicated records; and claims without traceable primary or methodological support.	Prevents indiscriminate compilation and strengthens bibliographic integrity.
Quality appraisal	Assessment of QA/QC, blank correction, polymer identification, size range, detection limits, matrix recovery, dose realism, endpoint relevance and reporting quality.	Supports critical analysis rather than simple compilation.
Synthesis approach	Narrative synthesis is supported by summary tables; no meta-analysis or pooled effect size.	Meta-analysis was not appropriate because of heterogeneous matrices, units and endpoints.

2.6 Limitations of the review method.

This study should be interpreted as a structured analytical narrative review rather than as a registered systematic review. The corpus was assembled through database-guided thematic searches, citation chaining and evidence mapping, and the final synthesis prioritized scientific coherence, critical interpretation and comparability across environmental and biological matrices. The main methodological limitation is that the search did not generate a PRISMA flow diagram with a fixed denominator of screened and excluded records. To mitigate this limitation, the review explicitly reports databases, search date, search concepts, eligibility criteria, exclusion criteria, quality-appraisal domains and the reason why statistical pooling was not performed.

3. Results and Discussion

3.1 Plastic production, waste generation and the persistence of the plastic burden

The evidence confirms that microplastic pollution is inseparable from the large and accelerating scale of plastic production. Global plastic production rose from approximately 2 million metric tonnes in 1950 to hundreds of millions of tonnes per year in recent decades, with estimates including 380 Mt in 2015, 368 Mt in 2019 and more than 390 Mt in 2021 (Geyer et al., 2017; Europe, 2022; Lamichhane et al., 2023). Figure 1 contextualizes this growth and the long-term fate of plastic waste.

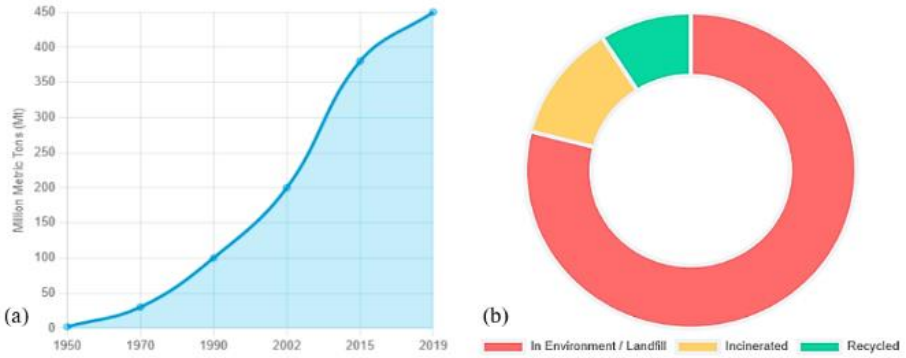


Figure 1. (a) Great acceleration of plastic production; (b) fate of 6300 Mt of plastic waste. Source: authors' elaboration based on Geyer et al. (2017), Jambeck et al. (2015), UNEP (2016) and the data compiled in this review.

Global production of polymer resins and synthetic fibers has soared from 2 million metric tonnes (Mt) in 1950 to 380 Mt in 2015, with other analyses documenting outputs surpassing 300 million tonnes annually, reaching 368 Mt in 2019 and over 390 million tonnes in 2021 (Geyer et al., 2017; Karbalaei et al., 2018; Goodman et al., 2022; Europe, 2022; Çağlayan et al., 2024; Lamichhane et al., 2023). This reflects an annual compound growth rate of over 8.4% (Geyer et al. 2017). The cumulative production from 1950 to 2015 was estimated at 8300 Mt (Geyer et al., 2017). Geographically, Asia accounts for nearly half of all plastics produced in 2019, with China emerging as the dominant producer, responsible for 28% of global resin and 68% of fiber production (Geyer et al., 2017; Lamichhane et al., 2023). Figure 2 illustrates the scale and distribution of this challenge, presenting a heat map of plastic waste generation by region and polymer type in 2019. This visual representation reinforces the geographical concentration of production and disposal,

while detailing the contribution of various polymers, such as polyethylene (HDPE, LLDPE), polypropylene (PP), PVC, Polystyrene (PS) and many others.

Figure 2 shows substantial differences in the regional distribution of the main polymeric materials. The most significant quantitative highlight is the high PVC percentage in Europe (28.49%), indicating an atypical concentration of this polymer compared with other regions, likely due to its intensive use in the construction and infrastructure sectors. Similarly, there is a peak for elastomers (tires) in Asia (excluding China and India), at 23.58%, reflecting the strong presence of the rubber and pneumatic industries in this region. In contrast, the regions of the Middle and Northeast of Africa, India, and Sub-Saharan Africa have globally low and homogeneous percentages across allmaterials, suggesting less diversification and a smaller productive scale in the polymer chain.

Materials such as PET, LDPE/LLDPE and PP show relatively balanced distribution between Europe, China and Asia, which indicates industrial maturity and consolidated insertion in global chains, especially in packaging areas and consumer products. On the other hand, the predominance of high values of PUR and ABS, ASA, SAN in Europe reinforces the specialization of this continent in segments of higher added value.

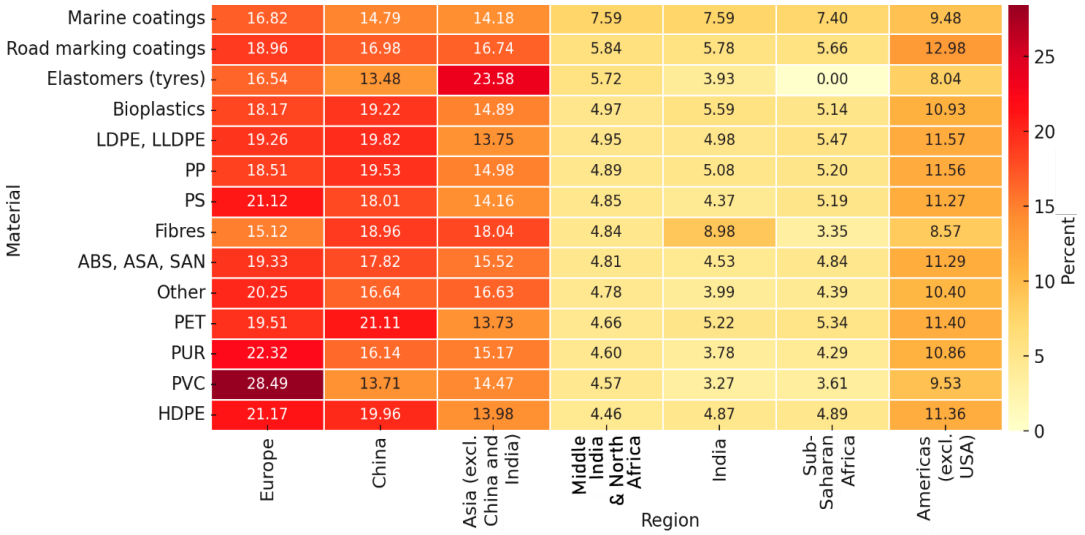


Figure 2. Heatmap of plastic waste generation by region and polymer in 2019. Polymer types are as follows: High-Density Polyethylene (HDPE), Linear Low-Density Polyethylene (LLDPE), Acrylonitrile Styrene Acrylate (ASA), Polyurethane (PUR), Polyvinyl Chloride (PVC), Acrylonitrile Butadiene Styrene (ABS), Styrene Acrylonitrile (SAN), Polystyrene (PS), Polypropylene (PP), Polyethylene Terephthalate (PET). Source: authors' own elaboration based on Geyer et al. (2017), Europe (2022), Lamichhane et al. (2023), Sofield et al. (2024) and the polymer-distribution evidence compiled in this review.

These results show that the regional industrial structure and productive vocations determine the concentration and consumption profiles of each polymer, revealing opportunities for industrial policies and innovation strategies aimed at sustainability and technological diversification in less-developed regions. This global problem manifests significant geographic disparities in waste generation and environmental emissions. For instance, a ranking by Chandra et al., (2024) of per capita plastic waste generation places Kuwait at the top with nearly 700 grams per person daily, while the 20th highest nation, Vanuatu, still generates a substantial 300 grams daily. Similarly, oceanic emissions of plastic waste are led by the Philippines at 3.3 kg/person/year, while Cameroon, ranked 20th, emits just under 0.5 kg/person/year (Chandra et al., 2024).

This staggering production, particularly of disposable and single-use items, has resulted in a waste management crisis of planetary scale (Sofield et al., 2024). A significant fraction of this output is used for short-lived applications, especially packaging, which constitutes over 40-50% of non-fiber plastic use and dominates waste streams (Geyer et al., 2017; Ragusa et al., 2022; Goodman et al., 2022). As of 2015, approximately 6300 Mt of plastic waste had been generated globally (Geyer et al., 2017). Global waste management systems have failed to cope; research suggests that only 9% of all post-consumer plastics have ever been recycled and 12% incinerated, leaving 79% to accumulate in landfills or the natural environment (Geyer et al., 2017). Inadequate waste management has resulted in a significant proportion of these plastics entering the environment; alarmingly, less than 14% of plastics in municipal solid waste streams are recycled (Goodman et al., 2022), with the rate in Europe being 32.5% as of 2018 (Ragusa et al., 2022). Furthermore, only about 10% of recycled plastic undergoes more than a single recycling cycle (Jambeck et al., 2015).

Consequently, millions of tonnes of plastic waste are released each year (Karbalaei et al., 2018). It is estimated that 4.8 to 12.7 million metric tonnes of plastic enter the oceans annually, contributing significantly to marine plastic pollution (Jambeck et al., 2015; Hirt et al., 2020). The frequently cited projection of approximately 12 billion metric tonnes by 2050 should be interpreted as a cumulative stock of discarded plastic waste expected to be in landfills or in the natural environment, not as annual waste generation. In the material-flow analysis by Geyer et al. (2017), continued production and waste-management trends would lead to roughly 12000 Mt of discarded plastic waste in landfills or the natural environment by 2050. The COVID-19 pandemic amplified this crisis, with the demand for disposable face masks surging to an estimated 89 million units globally each month (WHO, 2020). The mismanagement of even 1% of these masks could result in approximately 10 million masks, equivalent to 30-40 thousand kg of plastic waste, being released into the environment daily (Benson et al., 2021; Uddin et al., 2022; Idowu et al., 2023).

3.2 Formation and main sources of microplastics

Microplastics (MPs), typically defined as plastic particles smaller than 5 mm in diameter, are formed via two principal mechanisms (Karbalaei et al., 2018; Lamichhane et al., 2023). Primary microplastics are polymers intentionally manufactured to be of microscopic size for use in products such as microbeads in cosmetics, personal care and cleaning products, industrial abrasives and plastic pellets (nurdles) for transport and processing (Napper et al., 2016; Cai et al., 2017; Goodman et al., 2022; Lamichhane et al., 2023). The industrial path for these particles often leads directly to their release into wastewater streams and waterways (Cole et al., 2011; Sui et al., 2021).

Secondary microplastics, however, are the more prevalent and significant source of environmental contamination (Karbalaei et al., 2018; Ragusa et al., 2022; Lamichhane et al., 2023). Figure 3 details the primary sources of this diffuse contamination, revealing as daily activities, notably washing synthetic tissue and vehicle tires wear, have become the largest contributors to ocean pollution by microplastics. Microplastics are not confined to urban waste sites. Driven by environmental forces, they have reached every corner of the globe, contaminating our oceans, air, and soil. These particles are generated from the breakdown and fragmentation of larger plastic debris into MPs and NPs (<100 nm) through a combination of environmental degradation mechanisms (Andrady, 2011; Cole et al., 2011; Geyer et al., 2017). This breakdown is mediated by physical, chemical and biological processes, including weathering, abrasion, mechanical stress, hydrolysis, photodegradation from UV radiation and thermal decomposition (Karbalaei et al., 2018; Goodman et al., 2022; Pironti et al., 2022; Lamichhane et al., 2023).

Key sources include the abrasion of synthetic textiles during laundering (which can shed 700 thousand fibers per 6 kg load), wear from vehicle tires and the breakdown of agricultural films and other plastic products (Kole et al., 2017; De Falco et al., 2019

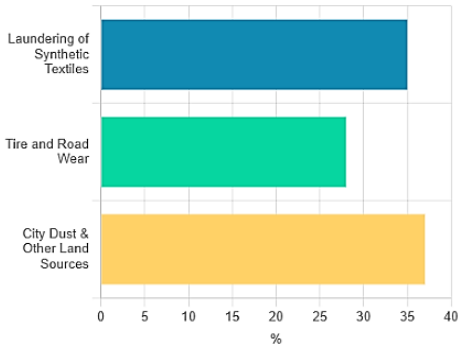


Figure 3. Primary sources of ocean microplastics. Source: authors' own elaboration based on GESAMP (2015), Kole et al. (2017), De Falco et al. (2019), Napper and Thompson (2016) and related source-attribution studies cited in this review.

In a different context, but illustrating the importance of nanoscale engineering, very small superparamagnetic iron oxide particles (VSOPs) are synthesized with a specific core and coating to achieve a tailored interaction with cellular membranes, reflecting the importance of understanding how materials are engineered at the nanoscale for specific biological interactions (Stroh et al., 2004; Bucci-Sabattini et al., 2010).

3.3 Global distribution and environmental fate

The small size and persistence of microplastics facilitate transport over vast distances, making them truly global pollutants that invade even ostensibly pristine locales (Wright et al., 2017; Horton et al., 2017). They are now recognized as pervasive contaminants of global concern, distributed throughout aquatic, terrestrial and atmospheric systems (Karbalaei et al., 2018; Pironti et al., 2022; Lamichhane et al., 2023). Their occurrence in urban atmospheres, remote mountain regions and Antarctic snow demonstrates that MPs should be evaluated as mobile contaminants with long-range transport potential (Allen et al., 2019; Bergmann et al., 2019; Brahney et al., 2020; Aves et al., 2022). In this context, the projection of approximately 12 billion metric tonnes by 2050 refers specifically to cumulative discarded plastic waste in landfills or the natural environment under continued historical trends, thereby contextualizing the long-term reservoir from which secondary MPs can continue to form (Geyer et al., 2017).

A crucial aspect of their environmental fate is their role as vectors for other contaminants. The environmental fate of MPs is shaped by their ability to adsorb pollutants, which facilitates transport across ecosystems and accumulation in organisms, including humans (Lamichhane et al., 2023). The physicochemical diversity of MPs, including high surface-area-to-volume ratios and hydrophobic surfaces, facilitates the adsorption of hazardous chemicals, such as persistent organic pollutants (POPs) and heavy metals (Teuten et al., 2007; GESAMP, 2015).

When ingested, these toxins can desorb and concentrations up the food web (Jamieson et al., 2017). The detection of high levels of POPs, such as PCBs, in hadal amphipods from deep-sea trenches, exceeding those on heavily industrialized coasts, confirms that these plastic-associated contaminants have reached the most isolated food webs (Kallenborn et al., 2012; Wang et al., 2016; Jamieson et al., 2017).

3.3.1 Contamination of aquatic and marine systems

Aquatic ecosystems are the primary repository for plastic pollution, receiving an estimated 15 million metric tonnes annually via urban runoff, wastewater effluents, atmospheric deposition and direct ocean dumping (Jambeck et al., 2015; GESAMP, 2015). Riverine inputs are estimated to carry 1.15–2.41 million metric tonnes into the oceans annually (Lebreton et al., 2017). Studies have confirmed their widespread distribution from surface waters to deep-sea sediments (Ng et al., 2006; Desforges et al., 2014; Eriksen et al., 2014; Cai et al., 2017). The fate of this debris is largely determined by polymer density; lower-density plastics such as PE and PP remain buoyant and accumulate in oceanic gyres, whereas denser polymers such as PVC and PET sink to the seabed (Eriksen et al., 2014; UNEP, 2019).

A global inventory estimated that as of 2014, between 15 and 51 trillion microplastic particles were present at the ocean surface (Van Sebille et al., 2015). To size the magnitude of this estimate, Figure 4(a) illustrates the concentrations of microplastics on the marine surface on a global scale. The map highlights the most heavily accumulated areas, such as oceanic gyres, which act as vast repositories for trillions of particles and show how pollution is distributed and persists in marine ecosystems. In a comprehensive review of 50 studies, Koelmans et al. (2015) and Mattsson et al. (2019) highlighted the frequent detection of microplastics across freshwater systems, reporting concentrations spanning 10 orders of magnitude, from 1×10−2 to 108 particles per cubic meter, depending on the water type

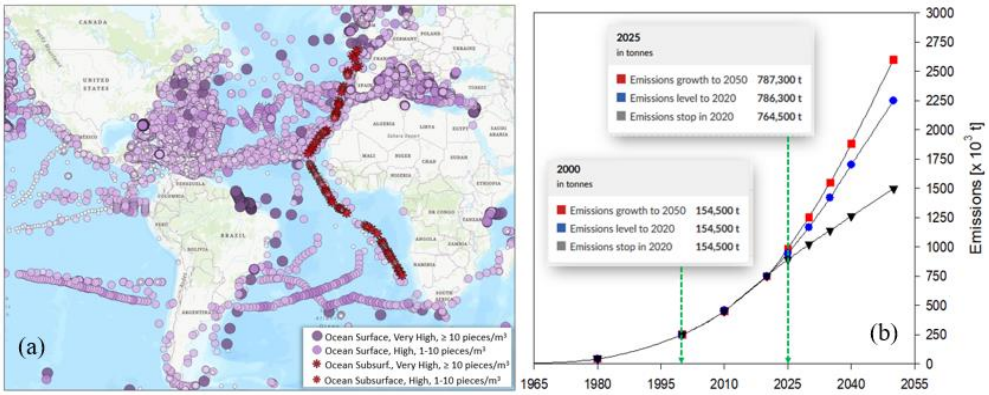


Figure 4. (a) Mapping of the distribution of microplastics, highlighting accumulation on the surface and subsurface along the Mid-Atlantic Ridge from 1972 to 2025. Adapted from NCEI (2025); (b) projected microplastic accumulation on the ocean surface from 1965 to 2050 under contrasting policy scenarios. Source: authors' own elaboration based on NCEI (2025), Jambeck et al. (2015), Van Sebille et al. (2015), Geyer et al. (2017), Lebreton et al. (2019) and related scenario evidence cited in the manuscript.

Figure 4(b) models the accumulation of microplastics on the ocean surface, using historical data and projects three distinct future scenarios to 2050. The historical period is characterized by

exponential growth in microplastic pollution, directly reflecting the global increase in plastic production and disposal. Projections from 2020 onward illustrate divergent outcomes based on the level of policy intervention. A "business-as-usual" scenario (Growth) indicates a continued exponential increase, with total accumulation reaching approximately 2.6 million tons by 2050. A second scenario, which caps the annual rate of new emissions at 2020 levels, still results in a substantial linear accumulation to 2.25 million tons, demonstrating that such a measure is insufficient to halt the problem. The most optimistic model (Stop), representing an aggressive and immediate mitigation plan, significantly slows the rate of pollution. However, even in this prognosis, the total accumulated mass continues to increase, reaching approximately 1.5 million tons by 2050 due to the persistence of existing plastic and residual emissions. While aggressive environmental policies can substantially curb future pollution, as shown by the significant difference between the "business-as-usual" and "aggressive mitigation" scenarios, the total accumulated mass of microplastics will remain a severe, long-term environmental challenge under all modeled conditions.

More profoundly, investigations have confirmed microplastic contamination in the deepest parts of the ocean. In the Mariana Trench, water-column concentrations of microplastics range from 2.06 to 13.51 pieces per liter, with sediments showing even higher concentrations, up to 2200 pieces per liter (Peng et al., 2018; Cox et al., 2019). In the deep sea, protected from UV radiation, biodegradation is the main, although extremely slow, breach mechanism, with estimated degradation deadlines in centuries or millennia (Chamas et al., 2020; Vizentin et al., 2020; Zeng et al., 2026).

The ecological impacts are severe, with ingestion or entanglement recorded in over 690 marine species (Laist, 1997; Halsband et al., 2026; Cusba et al., 2026). Aquatic organisms, ranging from zooplankton and mollusks to fish and seabirds, ingest microplastics, leading to adverse effects such as gastrointestinal toxicity, inflammation, altered feeding behaviors, physical injury and bioaccumulation through trophic levels (Karbalaei et al., 2018; Lamichhane et al., 2023). Specific impacts documented include aneurysms in fish and cognitive impairment in crustaceans (Watts et al., 2015; Karbalaei et al., 2018). Experiments with European perch larvae exposed to environmentally relevant polystyrene microplastics concentrations (10 to 80 thousand particles/m³) found significantly reduced hatching rates, altered activity patterns and a four-fold higher mortality rate when exposed to predators (Lönnstedt et al., 2016). Accumulation of MPs in aquatic organisms has also been associated with oxidative stress and impaired growth and fertility (Rochman et al., 2013; Goodman et al., 2022;). The ingestion of microplastics by fish and shellfish has led to their detection in seafood intended for human consumption and in drinking water (Barboza et al., 2018; Schymanski et al., 2018; Lamichhane et al., 2023).

This translates into a significant annual burden for consumers. Cox et al. (2019) reported an average concentration of 1.48 microplastics per gram in seafood samples, which can result in an ingestion of approximately 7–9 thousand microplastics per year for an adult in the U.S. following recommended seafood intake. According to Cox et al. (2019), this risk varies globally with dietary habits; in countries with much higher seafood consumption, such as Japan (104.2 g/day), the daily microplastic intake from this route could reach as high as 154 particles.

3.3.2 Atmospheric contamination

Atmospheric transport is now recognized as a primary pathway for the global distribution of microplastics, particularly windborne synthetic fibers from textiles, carpets, tire wear and associated chemicals like phthalates (Gasperi et al., 2018; Liu et al., 2019; Sui et al., 2021). Wind-driven transport, resuspension and sea-spray aerosolization

allow these lightweight particles to travel long distances from their sources (Wright et al., 2020). Atmospheric dispersion models, such as NOAA's HYSPLIT, show that particles can have residence times of weeks, enabling intercontinental dispersal before deposition via wet or dry fallout (Tatsii et al., 2023).

This mechanism explains the detection of microplastics in highly remote locations. Studies have confirmed the presence of polyester, acrylic and polyamide fibers in snow samples from Mount Everest at altitudes over 8000 meters and in protected mountain catchments (Allen et al., 2019; Napper et al., 2020; Brahney et al., 2020). A study in the French Pyrenees demonstrated an average daily MP deposition of 365 particles/m², comprised of 249 fragments, 73 films and 44 fibres per square meter per day (Allen et al., 2019). Atmospheric fallout has been documented in rural, urban and remote environments, including Dongguan, China, with concentrations ranging from 31 to 43 particles/m²/day (Cai et al., 2017). Back-trajectory analyses in Antarctica revealed air masses that could transport microplastics over distances of up to 6000 km (Aves et al., 2022).

This atmospheric fallout serves as a source of contamination for ecosystems and poses a direct inhalation risk to animals and humans (Wright et al., 2017; Reche et al., 2018). Indoor air concentrations of microplastic fibers can be significantly higher (1.0–60.0 fibers/m³) than those outdoors (0.3–1.5 fibers/m³) (Dris et al., 2015). The sources of this indoor pollution are closely linked to modern lifestyles such as Torres-Agullo et al. (2022) and Chandra et al. (2024) identified synthetic textiles as the largest contributor, responsible for up to 60% of indoor microplastic particles, while plastic bottles and food packaging account for an additional 30% and 10%, respectively. Once inhaled, MPs may penetrate the lower respiratory tract and enter the bloodstream (Ragusa et al., 2022; Prata et al., 2020; Ragusa et al., 2022), with studies associating exposure to airborne particles with negative respiratory and cardiovascular outcomes (Madl et al., 2009; Srivastava et al., 2015; Turner et al., 2017).

3.3.3 Terrestrial contamination

Terrestrial ecosystems are heavily contaminated with microplastics, mainly through the application of sewage sludge as fertilizer, degradation of agricultural plastics, littering and atmospheric fallout (Wright et al., 2017; Karbalaei et al., 2018; Lamichhane et al., 2023). A direct and significant pathway for microplastic entry into soil is the application of organic fertilizers produced from biowaste (Weithmann et al., 2018).

Soils, particularly in agricultural fields, act as sinks for microplastics, where they can alter soil structure, impact plant growth by reducing germination rates and biomass and affect soil fauna such as earthworms and microarthropods (Huerta Lwanga et al., 2017; Boots et al., 2019; Ding et al., 2022; Lamichhane et al., 2023). Studies on invertebrates, such as the earthworm Lumbricus terrestris, have shown that exposure to polyethylene microplastics leads to increased mortality and reduced growth rates (Huerta Lwanga et al., 2017).

3.4 Human exposure, biomonitoring and health-related pathways

Human exposure occurs through multiple routes, primarily ingestion and inhalation, with dermal contact considered a minor route for most larger MPs (Karbalaei et al., 2018; Danopoulos et al., 2022). Figures 5(a,b) connect the environmental scale with human exposure by contrasting drinking-water sources and summarizing modeled annual intake. Based on food, water, and air samples compiled by exposure-modeling studies, an average person may ingest and inhale tens of thousands of microplastic particles each year, although these estimates remain sensitive to particle-size detection limits and the incomplete coverage of food categories (Cox et al., 2019; Zhang et al., 2020).

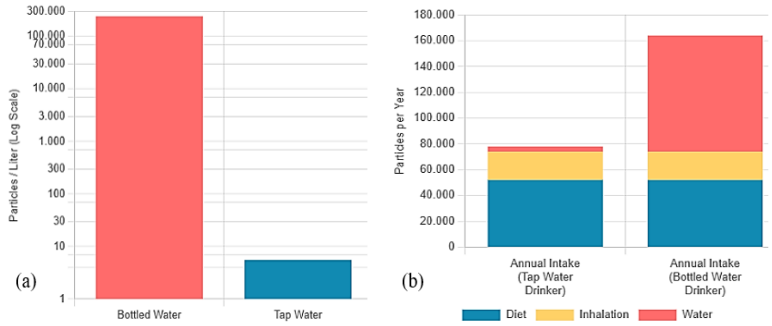


Figure 5. (a) The bottled-water exposure paradox; (b) estimated annual human intake of microplastic particles. Source: authors' own elaboration based on Cox et al. (2019), Kosuth et al. (2018), Schymanski et al. (2018), Zhang et al. (2020) and related exposure estimates cited in the manuscript.

Ingestion is a major pathway, with estimated annual intakes ranging from approximately 39 thousand to more than 100 thousand particles, depending on age, sex, diet and drinking-water source (Kosuth et al., 2018; Cox et al., 2019). Specific estimates include exposure through table salt, drinking water, seafood and airborne deposition onto food (Schymanski et al., 2018; Zhang et al., 2020). Figure 6 illustrates the widespread detection of plastic fibers in tap water samples, while bottled water remains a particularly important source of exposure. Cox et al. (2019) estimated that individuals who exclusively drink bottled water may invest approximately 90 thousand microplastic particles per year, compared with approximately 4000 particles per year for those who drink only tap water. This difference reflects measured concentrations of approximately 94.37 MPs/L in bottled water versus 4.23 MPs/L in tap water (Cox et al., 2019), although direct comparisons depend on analytical methods, minimum particle-size thresholds and contamination-control procedures (Koelmans et al., 2019; Gambino et al., 2022; Hart & Lenhart, 2026).

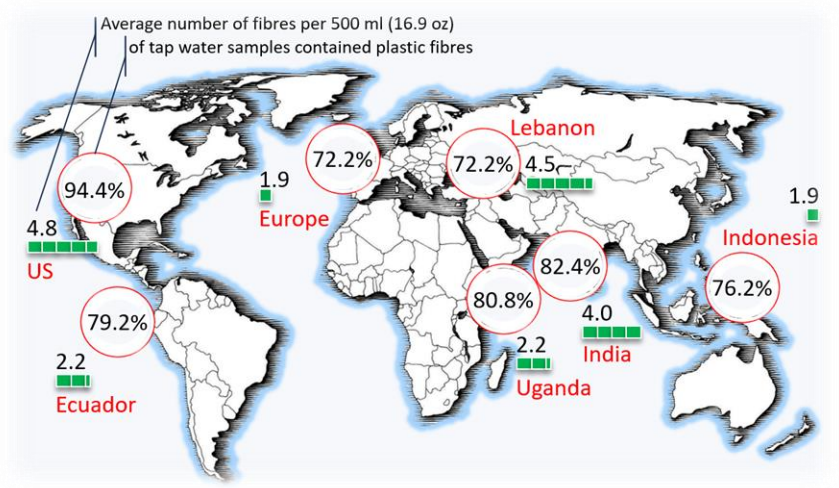


Figure 6. Presence of microplastics in drinking water and contamination hotspots, with summarized detection rates. Source: authors' own elaboration based on Kosuth et al. (2018), Koelmans et al. (2019), Gambino et al. (2022), Zhang et al. (2020), Hart and Lenhart (2026) and related drinking-water studies cited in the manuscript.

Inhalation of airborne MPs is another critical route. Urban air and indoor environments can contain measurable microplastic fibers and fragments, and modeling estimates suggest that daily inhalation may substantially contribute to total annual particle intake (Dris et al., 2015; Cox et al., 2019; Zhang et al., 2020). The inhalation of particles in the fine and nanoscale range is especially relevant because smaller particles can penetrate deeper into the respiratory tract, interact with epithelial cells and potentially contribute to inflammatory or genotoxic responses (Forte et al., 2016; Prata et al., 2020; Wright et al., 2020).

Once inside the body, smaller micro- and nanoplastics may translocate into the bloodstream, allowing systemic distribution (Stock et al., 2019). Microplastics have been detected in several human biological matrices, including blood, feces, placenta, breast milk, sputum and urine, raising concerns about bioaccumulation and long-term health effects (Karbalaei et al., 2018; Yan et al., 2021; Leslie et al., 2022; Pironti et al., 2022; Lamichhane et al., 2023). Of particular concern is exposure during pregnancy. An ex vivo human placental perfusion model demonstrated that polystyrene nanoparticles up to 240 nm can cross from maternal to fetal circulation (Wick et al., 2009).

Pregnant rat models also provide evidence of nanoplastic translocation frommaternal lungs to fetal organs, including the liver, lungs, heart and brain. Chemical toxicity arises partly from additives such as BPA and phthalates, which can leach and act as endocrine disruptors (Rubio et al., 2020). Recent studies identified dicyclohexyl phthalate (DCHP) as a potent agonist of the pregnane X receptor (PXR), altering lipid metabolism and elevating plasma cholesterol in mouse models (Sui et al., 2021; Lin et al., 2025). PXR is a nuclear receptor that acts as a

transcription factor and xenobiotic sensor, especially in liver and intestinal tissues. Its activation by agonist ligands upregulates genes encoding phase I and II metabolizing enzymes, including members of the cytochrome P450 family, and efflux transporters. Because PXR also participates in endogenous pathways, including lipid and cholesterol homeostasis, chronic activation by exogenous agonists such as DCHP can dysregulate metabolic pathways and contribute to dyslipidemia, a risk factor for cardiometabolic disease (Sui et al., 2021).

Representative values compiled from the reviewed evidence are synthesized in Table 2, preserving the key numerical details needed to interpret the scale of the problem.

Table 2. Key quantitative findings linking production, exposure, biomonitoring and treatment performance

Evidence domain	Representative finding and interpretation
Production scale	Plastic production rose from 2 Mt in 1950 to 380 Mt in 2015, 368 Mt in 2019 and >390 Mt in 2021, with cumulative production of ~8300 Mt from 1950 to 2015. This trajectory explains the long-term reservoir from which MPs and NPs are generated (Geyer et al., 2017; Europe, 2022; Lamichhane et al., 2023).
Waste fate and recycling	~6300 Mt of plastic waste had been generated by 2015; only 9% had been recycled, 12% incinerated and 79% accumulated in landfills or the environment. The recycling rate in Europe was 32.5% in 2018, indicating that management capacity has lagged behind production growth (Geyer et al., 2017; Ragusa et al., 2022; Goodman et al., 2022).
Ocean leakage	An estimated 4.8–12.7 million metric tonnes of plastic enter oceans annually, with riverine inputs of 1.15–2.41 million tonnes per year. Aquatic systems therefore remain major sinks and transport corridors (Jambeck et al., 2015; Lebreton et al., 2017; Hirt and Body-Malapel, 2020).
Human intake	Particle-count estimates commonly range from approximately 39000 to more than 100000 particles per person per year, and exclusive consumption of bottled water may contribute to approximately 90000 particles/year. A separate mass-based model estimated 0.1-5 g/week, but this value is scenario-dependent and relies on particle-size distribution and density assumptions; it should therefore be interpreted as a modeled exposure estimate rather than a direct biomonitoring measurement (Cox et al., 2019; Senathirajah et al., 2021; Zhang et al., 2020).
Atmospheric deposition	A remote mountain catchment showed 365 particles m^{-2} day^{-1}, while indoor air often ranges from 1.0–60.0 fibres m^{-3}. Airborne transport links local sources to remote deposition and inhalation exposure (Allen et al., 2019; Dris et al., 2015; Gasperi et al., 2018).
Treatment transfer	Some MBR systems can remove >99% of MPs from effluent, but ~94% of incoming MPs may be retained in sludge. Removal from water can therefore transfer particles to agricultural soils if sludge is reused (Chandra and Walsh, 2024; Weithmann et al., 2018).

3.5 Polymer size, type, chemistry and morphology

The physical and chemical characteristics of micro and nanoparticles; including size, polymer type, chemistry and morphology, are critical determinants of their environmental fate and biological effects (Johnston et al., 2010; Karbalaei et al., 2018). They occur in diverse morphologies, including fragments, fibers, beads, films and foams (Cai et al., 2017; Lamichhane et al., 2023). The most frequently detected polymers in environmental and biological samples are (PE), (PP), (PVC), (PS), (PUR), (PET), (PA) and Styrene-Butadiene Rubber (SBR) (He et al., 2022; Lamichhane et al., 2023; Damaj et al., 2024; Nihart et al., 2025). Confirming this, a meta-analysis by Koelmans et al. (2019) established that the order of global detection frequency for polymers in water was PE > PP > PS > PVC > PET, which mirrors global plastic demand and the physical properties of these materials.

Size is a critical determinant of bioavailability and toxicity. In human breastmilk, only irregular fragments and spheres were identified, with sizes ranging from 2 to 12 μm, whereas in human urine, particles ranged from 4 to 15 μm (Ragusa et al., 2022; Pironti et al., 2022). In Antarctic snow, particles ranged from 50 to 3510 μm, with fibers accounting for 61% (Aves et al., 2022). Studies using polystyrene particles demonstrated that 1 μm particles are internalized by human kidney and liver cells (Goodman et al., 2022), whereas 20 nm nanoparticles are rapidly internalized by hepatocytes, while 200 nm particles remain mainly at the cell surface (Johnston et al., 2010).

The ability to cross biological barriers is a key concern. An ex vivo human placental perfusion study using polystyrene nanoparticles of 50, 80, 240 and 500 nm demonstrated that not only size but also surface chemistry and particle composition likely influence transplacental passage (Wick et al., 2009). The toxicity of microplastics is mediated by both physical mechanisms (tissue abrasion, digestive blockage, induction of chronic inflammation and oxidative stress) and chemical risks (Wright et al., 2017). Chemically, the risks derive from the leaching of additives like BPA and phthalates, which are known endocrine disruptors and the "Trojan Horse" effect, where the hydrophobic surface of plastic particles attracts and concentrates POPs and heavy metals from the environment (Teuten et al., 2009; Melzer et al., 2010; Hartmann et al., 2019). However, this same feature can be explored for removal: hydrophobic interactions are the dominant mechanism that drives 'spontaneous and instantaneous' adsorption of non-polar microplastics in hydrophobic bio-substrates such as cattail fibers, Typha Latifolia, which are efficient, sustainable, and low-cost for this purpose (Bhagwat et al., 2024). Environmental exposure also leads to weathering, evidenced by grooves, pits, fractures and the presence of carbonyl and hydroxyl groups on the surface of atmospheric microplastics (Cai et al., 2017).

The main toxicological mechanisms identified in the reviewed literature are consolidated in Table 3, which separates biological signals from interpretive limitations.

Table 3. Toxicological mechanisms and interpretive limitations are reported across the reviewed evidence.

Mechanism	Main signal and interpretive limitation
Oxidative stress	ROS generation, mitochondrial dysfunction, antioxidant imbalance and cellular damage. Relevant evidence exists in human cells and animal models, but many assays use pristine particles or concentrations that exceed typical environmental exposure levels.
Inflammation and immune response	Cytokine induction, immune-cell activation and inflammatory signaling. Chronic low-dose inflammatory effects remain difficult to quantify.
Barrier disruption and translocation	Placental, intestinal and pulmonary passage, with possible systemic distribution. Detection in tissues does not by itself define dose-response causality.
Endocrine and metabolic disturbance	DCHP-mediated PXR activation, altered lipid metabolism and elevated cholesterol/ceramide signals. Particle effects and additive effects must be interpreted together.
Vector effect	Sorption and transport of POPs, metals and additives. Real exposure involves polymer–chemical mixtures rather than isolated particles.
Particle-specific toxicity	Size-, shape-, surface-chemistry- and polymer-dependent cellular outcomes. Lack of standardized reporting hinders cross-study comparability.

3.6 Mitigation strategies and policy responses

3.6.1 Waste management, recycling and a circular economy

A primary cause of microplastic pollution is the inadequacy of traditional recycling and waste management approaches to contain the vast and persistent flow of plastic waste (Damaj et al., 2024; Tang et al., 2024). Ineffective plastic waste management, low recycling rates and the lack of a truly circular economy exacerbate the environmental

release of plastics, which then fragment into MPs (Amato-Lourenço et al., 2021;

Tang et al., 2024). Conventional mechanical recycling often results in the degradation of polymer quality ("downcycling") and can itself generate secondary microplastics, though life cycle assessments confirm it offers significant environmental benefits over virgin materials, saving up to 50% in carbon emissions (Hopewell et al., 2009; Voelp et al., 2025).

Addressing the root of the problem requires a fundamental transition to a circular economy, a model that prioritizes the reduction of single-use plastics, improves end-of-life product management and promotes the reuse and retention of plastic materials within the economy for as long as possible (Zheng et al., 2019; Damaj et al., 2024; Li et al., 2024). This includes improving collection systems, enhancing recycling technologies and developing truly biodegradable alternatives, although even some 'biodegradable' plastics may fragment into persistent micro-sized residues under certain environmental conditions (He et al., 2022). Emerging technologies such as chemical recycling and enzymatic depolymerization may help produce higher-quality recycled polymers, but their scalability, energy demand and environmental footprint still require careful evaluation (Austin et al., 2018; Danso et al., 2018). A notable laboratory advance is FAST-PETase, a machine-learning-engineered PET hydrolase that

was reported to almost completely degrade untreated post-consumer PET from 51 different thermoformed products within one week, under the experimental conditions described by Lu et al. (2022). Enhancing sewage treatment with advanced filtration could also significantly reduce the discharge of microplastic fibers from wastewater (Fent, 1996; Browne et al., 2011).

3.6.2 Regulatory frameworks and global cooperation

The complexity and global, transboundary scale of microplastic pollution necessitate coordinated policy responses and harmonized international regulatory frameworks (Li et al., 2024; Kadac-Czapska et al., 2024). Current legislative efforts are often fragmented and insufficient, with many guidelines focusing on macroplastic waste rather than microplastic-specific risks (Tang et al., 2024). Regulatory measures have included national bans on microbeads in personal care products (e.g., U.S. Microbead-Free Waters Act of 2015) and prohibitions on certain single-use plastic items (European Parliament., 2018). Market-based instruments such as Extended Producer Responsibility (EPR) policies are also being implemented to hold manufacturers accountable for the life cycle of their products (UNEP, 2016).

Given that plastic pollution is a transboundary problem, global cooperation is essential (Wilcox et al., 2015; Van Sebille et al., 2015). The Basel Convention's amendments now regulate the transboundary movement of plastic waste and there is a growing consensus on the need for a legally binding global treaty to harmonize policies, promote technology sharing and establish common targets for reducing plastic waste. A critical element of any global framework is the development of standardized scientific methodologies for sampling, identifying and quantifying microplastics to enable accurate risk assessment and policy evaluation (Hidalgo-Ruz et al., 2012; Directive, 2013).

Taken together, the evidence confirms the omnipresence of MPs, with documented contamination extending from Mount Everest to the Mariana Trench. Human bioaccumulation is supported by the detection of plastic particles in blood, placenta, breast milk, urine and lung tissue, indicating potential translocation through biological barriers. The main exposure routes are ingestion and inhalation, whilecontamination of intravenous fluids represents an emerging direct route. Quantitative intake should be interpreted with care: Cox et al. (2019) estimated exposure mainly as particle counts, whereas Senathirajah et al. (2021) converted selected exposure pathways into mass and estimated 0.1-5 g/week under conservative assumptions. Thus, the widely repeated "up to 5 g/week" value is a modeled upper-bound estimate, not a directly measured universal intake. Toxicological results indicate that MPs can induce oxidative stress and cellular dysfunction and that specific additives, such as DCHP, act as pregnane X receptor (PXR) agonists, providing a mechanistic link with lipid-metabolism dysregulation and cardiovascular risk.

The quantitative exposure assessment by Cox et al. (2019) advanced the understanding of human exposure by stratifying estimates according to age, sex and exposure pathway. The findings indicate that Americans may be exposed to tens of thousands of microplastic particles per year, with totals exceeding 120 thousand particles annually for some individuals when both ingestion and inhalation are considered. Bottled water emerges as a major contributor, resulting in a 22-fold increase in ingestion for individuals who drink exclusively bottled water compared with those who drink tap water. Nevertheless, particle-count estimates and mass-based estimates answer different questions and should not be conflated: the former estimates the number of particles encountered, whereas the latter depends strongly

on assumed particle geometry, density and size distribution. Despite this detail, the authors recognized limitations suggesting that the true scale of exposure is probably underestimated:

- Food groups analyzed in that estimate covered only about 15% of the caloric intake of a typical American diet.
- Important food groups such as meat, dairy, grains and vegetables had not yet been systematically studied.
- A crucial technical limitation is that most analytical methods are unable to detect particles smaller than 6.5 micrometers, contributing to probable underestimation.
- Estimates did not account for microplastics ingested through atmospheric deposition onto food, which could add tens of thousands of particles to the annual total.

Notwithstanding, advances in detecting MPs in food, water, air and human tissues, substantial knowledge gaps remain concerning human exposure levels, toxicological effects and overall risk assessment (Damaj et al., 2024). A primary hurdle is the lack of standardized methodologies for MP detection and quantification in biological samples, which hinders the comparability of research outcomes and the establishment of clear dose-response relationships (He et al., 2022; Damaj et al., 2024). This methodological weakness is a significant barrier; a systematic review by Koelmans et al. (2019) revealed that only 8% of the fifty

studies analyzed met all quality assurance criteria, indicating a pressing need for standardized protocols before a robust human health risk assessment can be made. Table 4 organizes the main evidence tensions that constrain the interpretation of microplastic and nanoplastic risk.

Table 4. Critical evidence tensions and implications for risk assessment.

Evidence tension	Interpretive implication
Removal efficiency versus environmental transfer	Particles removed from water may accumulate in sludge and return to soil. Treatment performance should be evaluated across the full water–sludge–soil pathway.
Mass-based versus particle-number exposure	Small particles contribute little mass but dominate particle counts and may have higher bioavailability. Risk assessment should report mass, number concentration and size distribution together.
Laboratory dose realism	Many experiments use high concentration and pristine particles. Chronic, low-dose studies with environmentally aged particles are needed.
Particle effects versus additive effects	Toxicity may arise from polymer particles, sorbed contaminants or additives such as phthalates. Real-world mixtures should be considered rather than particle-only models.
Detection versus causality	Particles are detected in human tissues, but the causal relationship to disease remains unresolved. Biomonitoring must be linked to exposure histories, dose metrics, and biomarkers of effect.
Comprehensiveness versus reproducibility	Broad reviews integrate many domains but can become difficult to reproduce. Transparent search logic, eligibility criteria and quality appraisal are essential.

Many experimental studies use concentrations of pristine MPs that exceed real-world exposures, limiting their direct relevance to human health (Zurub et al., 2024). A critical point is the fate of microplastics in current mitigation infrastructure, especially at wastewater treatment plants (WWTPs). Although technologies such as membrane bioreactors (MBR) can remove more than 99% of MPs from water

effluents, this does not necessarily mean elimination. Instead, WWTPs often function as transfer points, moving MPs from wastewater to sewage

sludge. Approximately 94% of MPs entering a treatment facility may be retained in sludge, which is frequently applied to agricultural land as fertilizer, creating a pathway for extensive terrestrial

contamination. The chemical properties of plastics also have a dual role. The hydrophobic surface of plastic particles can promote the "Trojan Horse" effect by concentrating organic pollutants, but this property can also be exploited for remediation. Recent evidence indicates that hydrophobic interactions drive the spontaneous and rapid adsorption of non-polar MPs onto natural, low-cost biosubstrates. Cattail fibers (Typha latifolia), for example, have been proposed as efficient, sustainable and biodegradable adsorbents for MP removal from wastewater.

However, recent mechanistic studies are beginning to provide clarity. The study by Weithmann et al. (2018) demonstrates that biowaste-derived fertilizers are a major yet overlooked pathway for the introduction of microplastics into terrestrial ecosystems. At the cellular level, the research of Xu et al. (2019) provides a clear mechanism for the toxicity of inhaled nanoplastics. They demonstrated that polystyrene nanoparticles are promptly internalized by human alveolar epithelial cells (A549), leading to dose-dependent decreases in cell viability, S phase cell cycle arrest and significantly induced apoptosis, as evidenced by upregulation of pro-apoptotic proteins (e.g., BAX, caspase-3, cytochrome c), activating both

mitochondrial and death receptor pathways. The study also showed increased transcription of pro-inflammatory cytokines (IL-6, IL-8, TNF-α), indicating a robust inflammatory response.

In the field of chemical toxicity, the work of Sui et al. (2021) provides a clear molecular mechanism that connects a specific plastic additive to a disease-relevant pathway, showing that the Plasticizer Dicyclohexyl Phthalate (DCHP) acts as a potent agonist for the pregnane X receptor (PXR), altering lipid metabolism and elevating cholesterol and ceramide levels in mouse models.

The experimental data from Wick et al. (2009) provide human-relevant evidence that the placental barrier can be permeable to selected nanoparticles, with passage depending on particle size, surface chemistry and experimental conditions. Clinical and biomonitoring evidence has also reported MPs in placenta and mechanism, including the clinical setting described by Braun et al. (2021). Recent findings of significantly higher MNP concentrations in the brains of individuals with dementia, while not establishing causality, suggest a possible association between neuro-pathological conditions and impaired clearance or increased uptake of microplastics (Nihart et al., 2025). The confirmed presence of MPs in human organs such as kidneys, lungs and brain, together with reports of placental passage, highlights the potential vulnerability of infants and pregnant women and the need for exposure histories, dose metrics and biomarkers of effect (Ragusa et al., 2021; Braun et al., 2021; Damaj et al., 2024).

To consolidate the information discussed, Figure 7 presents a visual summary of human exposure routes, bioaccumulation sites and potential health risks associated with microplastics. This integrating scheme connects particle input through ingestion and inhalation with its subsequent systemic distribution and accumulation in vital organs, highlighting the mechanisms of physical and chemical toxicity that underlies human health concerns.

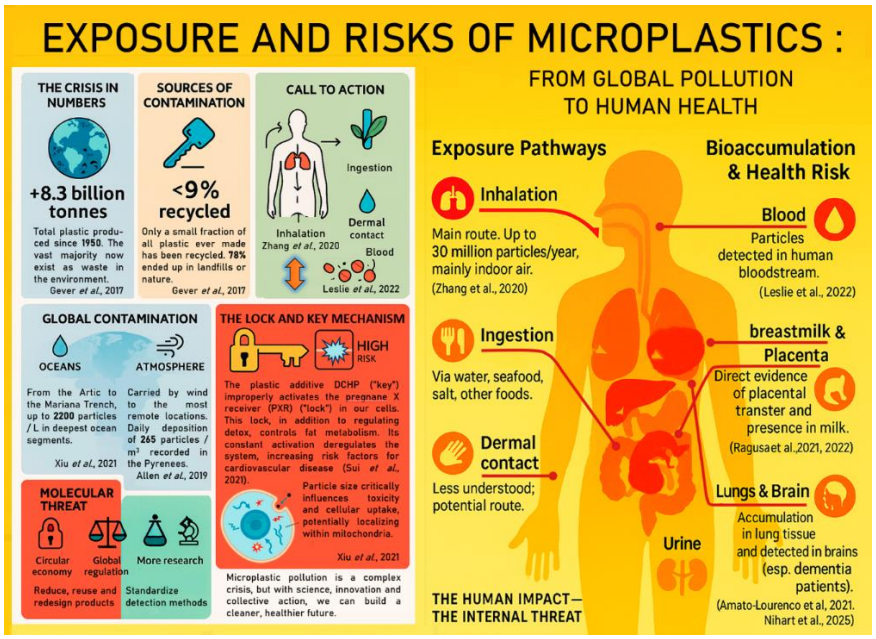


Figure 7. The anatomy of contamination by a silent intruder in the human body. Integrative schematic based on the synthesis of exposure routes, bioaccumulation sites and health-relevant mechanisms reported in the literature. Source: authors' own elaboration based on Wright and Kelly (2017), Zhang et al. (2020), Sui et al. (2021), Amato-Lourenço et al. (2021), Ragusa et al. (2021, 2022), Leslie et al. (2022), Pironti et al. (2022), Danopoulos et al. (2022), Çağlayan et al. (2024), Nihart et al. (2025) and some other related references cited in the manuscript.

4. Conclusion

This synthesized research conclusively demonstrates that micro and nanoparticle pollution represent a pervasive and persistent threat to both environmental integrity and public health (Karbalaei et al., 2018). The detection of microplastics in human urine, breastmilk and placenta provides unequivocal evidence of their ability to traverse biological barriers, supporting the hypothesis of systemic distribution in humans (Ragusa et al., 2021, 2022; Pironti et al., 2022). However, significant challenges remain at all stages of the problem. The removal of microplastics during water treatment is variable and often incomplete, particularly for smaller, more numerous particles. At the same time, while human exposure is now quantified in tens of thousands of particles per year, the direct toxicological meaning of this chronic intake remains largely unresolved, creating a pressing gap. This combination of known high exposure and unknown lasting risk requires that political interventions, technological innovation and integrated waste management strategies are prioritized.

The findings also indicate that biological outcomes are particle specific. For example, 1 µm polystyrene MPs can provoke significant morphological, proliferative, and metabolic disturbances in human cells, including increased oxidative stress and impaired antioxidant defenses (Goodman et al., 2022). Conversely, other materials, such as very small superparamagnetic iron oxide particles (VSOPs), have been reported to induce transient and reversible oxidative stress without long-term impairment of cell viability, reinforcing that size, chemistry, surface coating and exposure context are decisive determinants of toxicity (Stroh et al., 2004).

Given the ubiquity of microplastics and the escalating production of nanomaterials, continued investigation and comprehensive policy responses are urgently needed (Karbalaei et al., 2018; Goodman et al., 2022). Future research should prioritize the chronic health impacts of

long-term exposure, standardization of analytical methodologies for biomonitoring and in vivo validation of mechanistic findings (Stroh et al., 2004; Johnston et al., 2010). A promising direction is the combination of degradation technologies, in which abiotic degradation,

such as photocatalysis, is used as a pre-treatment to reduce particle size and molecular weight and increase surface roughness, thereby facilitating subsequent biodegradation by plastic-degrading bacteria.

In such two-step strategies, the initial abiotic stage may make polymer fragments more accessible to specialized microbial communities, improving attachment to the particle surface and increasing the efficiency of mineralization. This combined approach is particularly relevant because not single technology is likely to address the full diversity of polymer types, particle sizes and environmental matrices involved in microplastic pollution.

With extended follow-up, toxicological and epidemiological studies are required to establish causal links between defined nanoparticle exposure and human diseases, including research on placental transfer mechanisms and the effects of fetal exposure (Wick et al., 2009). Ultimately, multidisciplinary collaboration and coordinated global action are essential for developing sustainable solutions, promoting circular economic models, and implementing effective regulations to mitigate human exposure and associated health risks from this complex and growing challenge (Lamichhane et al., 2023; Barros et al., 2025).

Finally, to realize the call for sustainable, circular-economy-based solutions, future work should focus on the potential of effective, low-cost, and biodegradable natural adsorbents. The successful use of native cattail fibers, which demonstrated removal efficiencies of 89% to 100% for key plastics such as PVC, PP, and HDPE in contaminated water, serves as a powerful proof of concept. Investing in the research and development of readily available natural materials offers a practical, environmentally sound strategy to mitigate microplastic pollution, aligning technological innovation with ecological sustainability.

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