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Plastic Pollution in the Anthropocene: A Systematic Review of Ecological and Public Health Risks

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ABSTRACT

Plastic pollution has become a cross-cutting environmental and public health concern because persistent plastic materials fragment into microplastics and nanoplastics, interact with chemicals and microorganisms, and move across ecological compartments. This systematic review synthesised contemporary evidence on ecological effects, plastisphere microbial dynamics, chemical leaching, toxicological outcomes, human exposure, and public health implications. Three parallel searches were conducted for literature published from 2007 to 2026, yielding approximately 4.9 million aggregated search results; 135 records were retained for eligibility assessment and 50 studies were included in the evidence synthesis. The literature indicates that plastic pollution affects marine, freshwater, terrestrial, and urban systems through physical contamination, habitat modification, chemical exchange, and altered microbial communities. Plastics can provide persistent surfaces for biofilm development and may facilitate the transport of potentially pathogenic and antibiotic-resistant microorganisms, although evidence linking plastic-associated microbial carriage directly to human infection remains limited. Chemical evidence indicates that additives and sorbed contaminants can migrate from plastic materials, with weathering, ultraviolet radiation, temperature, polymer properties, and biofilm formation influencing release. Human health literature identifies plausible pathways involving ingestion, inhalation, and dermal exposure and reports associations with oxidative stress, inflammation, endocrine disruption, reproductive effects, immune dysregulation, and other biological responses. However, population-level causal evidence remains less developed than mechanistic and experimental evidence. The findings support lifecycle plastic governance, stronger waste infrastructure, controls on chemicals of concern, standardised monitoring, and interdisciplinary epidemiological and environmental research.

INTRODUCTION

Plastic materials have transformed food systems, healthcare, manufacturing, construction, transport, and consumer markets because they combine low cost, durability, lightweight design, and functional versatility (Abahussain et al., 2025; Ibrahim et al., 2025). These same properties create profound environmental persistence when plastics are discarded or inadequately managed

(Hossain & Engelhardt, 2025). The physical fragmentation of larger items generates microplastics, while further degradation produces nanoplastics capable of crossing biological barriers and interacting with environmental matrices at microscopic spatial scales (Ghosh et al., 2023; Hossain & Engelhardt, 2025; Li & Meng, 2025).

The environmental distribution of plastic particles is no longer confined to marine debris. Contemporary evidence documents microplastics in marine waters and sediments, freshwater systems, agricultural soils, atmospheric pathways, drinking water, and biological tissues (Bhardwaj et al., 2024; Jiang et al., 2025; Kang et al., 2025; Mokgalaka-Fleischmann et al., 2024). This distribution reflects multiple sources and transport processes, including wastewater, stormwater, agricultural films, textiles, road-derived particles, macroplastic fragmentation, atmospheric deposition, and riverine transport (Bhardwaj et al., 2024; Jiang et al., 2025; Kang et al., 2025; Mokgalaka-Fleischmann et al., 2024).

Plastic pollution is also chemically and biologically active. Plastic materials contain chemical additives introduced to alter flexibility, stability, colour, flame resistance, and other properties (Wang et al., 2022). Environmental weathering modifies polymer surfaces, influencing the partitioning and release of associated contaminants (Henkel et al., 2024). Furthermore, microplastic surfaces simultaneously accumulate environmental pollutants and support biofilm formation, producing a dynamic exposure interface where particles, chemicals, and microorganisms interact (Alijagic et al., 2024; Henkel et al., 2024; Wang et al., 2022; Zhang et al., 2022).

The public health significance of these processes requires careful interpretation. The detection of microplastics in human samples establishes exposure but does not, by itself, establish disease causation (Feng et al., 2023; Zuri et al., 2023). Current evidence is substantially stronger for biological plausibility and mechanistic toxicity than for long-term population-level outcomes. Recent systematic reviews emphasise uncertainty arising from heterogeneous particle characteristics, variable exposure conditions, analytical inconsistencies, and limited longitudinal epidemiology (Chartres et al., 2024; Feng et al., 2023; Zuri et al., 2023).

Rationale and Review Objective

A synthesis that treats ecological contamination, microbial transport, chemical exposure, and human health as separate but interacting dimensions is necessary because the risks associated with plastics cannot be adequately represented by litter counts alone (Morrison et al., 2022). The objective of this review was therefore to synthesise contemporary evidence regarding the ecological and public health risks of plastic pollution, with particular attention to microbial colonisation and transport, chemical leaching, human exposure, toxicological effects, and policy implications.

Scope and Analytical Framework

The review considered evidence addressing plastic litter, microplastics, nanoplastics, plastisphere communities, plastic-associated chemicals, environmental exposure, toxicological outcomes, and public health implications. The synthesis was structured thematically rather than chronologically. Evidence was interpreted according to environmental relevance, methodological approach, consistency of findings, and the critical distinction between exposure, hazard, association, and demonstrated causation. This aligns with the requirement that an academic review critically analyses literature rather than merely cataloguing sources.

METHODS

Review Design

A systematic literature review design was used to identify and synthesise evidence relevant to the ecological and public health dimensions of plastic pollution. Reporting adhered to the principles of PRISMA 2020, ensuring transparent documentation of the rationale, information sources, eligibility criteria, selection process, synthesis methods, and study limitations (Page et al., 2021).

Search Strategy and Information Sources

Three parallel searches were conducted using topic clusters covering:

1. marine plastic litter, bacterial transfer, microorganisms, and pollution;
2. chemical leaching, plastic-derived chemicals, endocrine disruption, and environmental contamination; and

3. plastic pollution, public health impacts, toxicology, and biological effects.

The search period spanned from 2007 to 2026. The aggregated search yield across the three parallel searches was approximately 4.9 million results. Following screening and eligibility assessment, 135 records were retained for detailed eligibility consideration, and 50 studies were included in the final synthesis **(Figure 1)**.

Eligibility Criteria

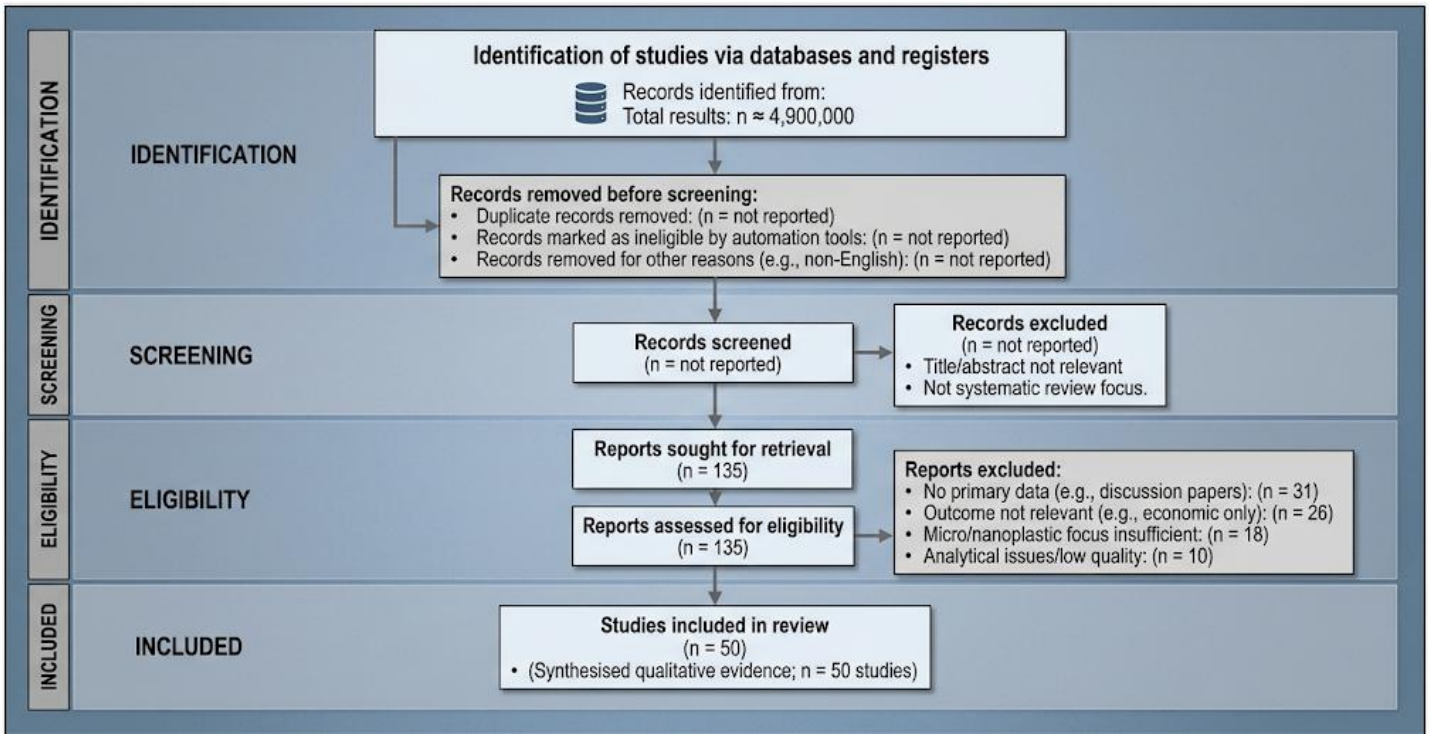
Studies were eligible if they addressed at least one of the following domains:

- ecological effects of plastic pollution;
- microbial colonisation or bacterial transport associated with plastics;
- chemical migration, leaching, or contamination associated with plastics;
- human exposure or toxicological effects of microplastics or nanoplastics; or
- public health and environmental health implications.

Priority was given to peer-reviewed scholarly literature and contemporary evidence relevant to the review objectives. Duplicate records and material without substantive relevance were excluded.

Study Selection and PRISMA Flow

Figure 1:
PRISMA Flow Diagram of the Systematic Review Process



The flow of records through the identification, screening, eligibility, and inclusion stages is summarised below:

- **Aggregated search results:** ≈ 4.9 million
- **Records retained for eligibility assessment:** 135
- **Studies included in synthesis:** 50

Note. The aggregated search-result figure represents the combined yield reported for the parallel search queries and should not be interpreted as 4.9 million unique records. The analytically relevant selection pathway is therefore reported as the number retained for eligibility assessment and the final number included (Page et al., 2021).

Data Extraction and Thematic Synthesis

Data were organised according to study purpose, environmental compartment, plastic type or particle context, exposure pathway, biological or ecological endpoint, principal findings, and evidence limitations. The synthesis was structured around five core themes:

1. ecological degradation;
2. microbial colonisation and bacterial transfer;
3. chemical contamination and leaching;
4. human health and toxicological effects; and
5. policy, public health, and research implications.

Quality and Risk-of-Bias Assessment

Because the evidence base comprises heterogeneous designs, quality appraisal was undertaken using a design-sensitive framework. ROBIS principles were used to evaluate review-level risk of bias across study eligibility, identification, selection, data collection, appraisal, synthesis, and interpretation. SANRA principles were used to strengthen the assessment of scholarly quality, relevance, justification, and transparency. For primary empirical studies, appraisal focused on methodological appropriateness, exposure characterisation, outcome measurement, control of confounding, reproducibility, environmental realism, and the strength of causal inference.

The appraisal informed the evidentiary weight assigned to different findings. Laboratory studies were considered informative for mechanisms of toxicity but were interpreted cautiously where experimental doses or conditions differed from environmental realities. Field studies were given greater weight for environmental occurrence and ecological relevance. Human studies were assessed with particular attention to exposure measurement, outcome ascertainment, sample characteristics, longitudinal follow-up, and dose-response evidence.

Table 1 outlines the quality and risk-of-bias appraisal framework applied to the included evidence.

Table 1:
Quality and Risk-of-Bias Appraisal Framework Applied to Included Evidence

Evidence category	Principal contribution	Principal appraisal concern	Interpretive weight
Systematic/review literature	Cross-study synthesis and contextualisation	Heterogeneous underlying evidence; primary-study overlap	Contextual/triangulating
Environmental field studies	Occurrence and ecological relevance	Observational designs; limited causal inference	Moderate–high for occurrence
Laboratory mechanistic studies	Chemical release and biological mechanisms	Experimental conditions may differ from field exposure	High for mechanism
Toxicological studies	Cellular, reproductive, endocrine, and inflammatory responses	Dose and particle characteristics vary	High for mechanism; cautious for human risk
Plastisphere/microbial studies	Microbial colonisation and potential transport	Presence does not establish transmission or disease	Moderate–high for microbial ecology
Human exposure/biomonitoring	Exposure and internal body burden	Analytical and longitudinal limitations	Moderate for exposure
Human epidemiology	Potential exposure–outcome associations	Limited cohorts, confounding, and dose-response evidence	Limited for causality

RESULTS

Characteristics of the Evidence Base

The 50 included studies encompassed diverse methodological designs, including environmental surveillance, laboratory toxicology, materials science evaluations, microbiological metagenomics, and public health reviews. The literature reflects a significant geographical and scientific expansion between 2007 and 2026, shifting from early documentation of marine debris to comprehensive multi-compartment assessments of micro- and nanoplastics.

Ecological Distribution and Environmental Effects

Plastic pollution occurs across marine, freshwater, and terrestrial systems, with transport determined by polymer properties, particle size, density, hydrodynamics, sediment interactions, atmospheric deposition, and land-use practices (Kang et al., 2025; Li & Meng, 2025; Meng & Zhang, 2025). Marine systems remain a major research focus, but freshwater and soil environments increasingly demonstrate that plastics alter ecological processes outside oceanic basins (Kang et al., 2025; Li & Meng, 2025; Meng & Zhang, 2025).

In aquatic environments, microplastics interact with sediments, plankton, benthic organisms, and complex food webs (Kumar et al., 2024; Liza et al., 2024). Their ecological significance depends on abundance, particle characteristics, weathering state, chemical composition, and biological colonisation (Fernandes et al., 2025; Kumar et al., 2024). Terrestrial evidence is similarly concerning; agricultural plastics introduce particles into soils, where microplastics modify soil structure, microbial communities, nutrient cycling, and plant responses, establishing soil as a major exposure reservoir (Kang et al., 2025; Meng & Zhang, 2025).

Plastisphere and Microbial Transfer

Plastic surfaces provide persistent substrates for microbial attachment and biofilm formation (Du Toit, 2022; Zhang et al., 2022). The resulting "plastisphere" differs from surrounding environmental communities, demonstrating selective colonisation rather than passive accumulation (Bai et al., 2024). Research across aquatic and terrestrial settings confirms that community composition is influenced by environmental conditions, plastic polymer properties, residence time, and microbial succession (Chen et al., 2023; Delacuvellerie et al., 2022; Miao et al., 2023; Meng et al., 2024).

The primary public health concern involves the potential carriage of opportunistic pathogens and antimicrobial resistance (AMR) determinants (Bai et al., 2024; Woodford et al., 2025). Metagenomic analyses have identified the enrichment of pathogenic and antibiotic-resistant bacteria within plastisphere communities (Bao et al., 2025; Woodford et al., 2025). Nevertheless, microbial carriage must not be equated with clinical disease transmission; evidence demonstrating a complete causal chain from plastic colonisation to human exposure and subsequent infection remains insufficient.

Chemical Leaching and Contaminant Transfer

Plastic-associated chemicals represent a secondary exposure pathway. Additives such as plasticizers, flame retardants, and antioxidants migrate from polymer matrices, while environmental contaminants partition onto weathered plastic surfaces (Henkel et al., 2024; Wang et al., 2022). Leaching dynamics are governed by diffusion, desorption, polymer characteristics, surface modification, temperature, ultraviolet radiation, and biofilm development (Henkel et al., 2024; Li et al., 2024).

Photoaging of polymer matrices (such as polyvinyl chloride microplastics) accelerates the release of toxic compounds like di(2-ethylhexyl) phthalate and associated transformation products into aquatic environments (Henkel et al., 2024). Monitoring studies further confirm that plastic-associated endocrine-disrupting chemicals (EDCs) are widely distributed across freshwater systems, sediments, biota, and plastic litter (Balaraman et al., 2023; Gil-Solsona et al., 2022; Ologundudu et al., 2025).

3.5 Human Exposure and Toxicological Effects

Human exposure occurs primarily via ingestion, inhalation, and dermal contact (Li et al., 2024; Zuri et al., 2023). Drinking water, food supplies, household dust, and occupational environments serve as major exposure pathways, with biomonitoring studies confirming the presence of plastic particles in human tissues and biological fluids (Li et al., 2024; Xu et al., 2024; Yee et al., 2021).

Toxicological evaluations identify oxidative stress, inflammation, immune disturbance, endocrine disruption, reproductive toxicity, and cellular barrier dysfunction as recurring biological endpoints (Feng et al., 2023; Ullah et al., 2023; Yang et al., 2023). Particle size, surface charge, polymer composition, and leached chemicals heavily influence these toxicological outcomes (Boháčková & Cajthaml, 2024; Yang et al., 2023).

However, evidence for direct human clinical outcomes requires caution. Systematic reviews of reproductive health note that while microplastics have been detected in human reproductive tissues, epidemiological evidence linking exposure directly to adverse reproductive outcomes remains insufficient for definitive causal conclusions (Hunt et al., 2024). Distinguishing between laboratory-demonstrated hazard and population-level risk remains essential for evidence-based risk assessment (Chartres et al., 2024; Feng et al., 2023).

Public Health and Socio-Economic Implications

Plastic pollution generates extensive socio-economic burdens. Waste accumulation disrupts municipal sanitation, stormwater drainage, recreation, and tourism, while inadequate disposal intensifies community exposure

risks (Ninduwezuor-Ehiobu et al., 2024). In low- and middle-income regions, deficient waste management infrastructure accelerates the persistence and redistribution of plastic waste (Mokgalaka-Fleischmann et al., 2024). Data from South Africa demonstrate extensive microplastic contamination across regional environmental matrices, highlighting the necessity for locally tailored monitoring frameworks (Mokgalaka-Fleischmann et al., 2024).

3.7 Evidence Gaps

Three critical gaps persist across the literature:

1. Long-term human epidemiological data linking chronic exposure to clinical disease endpoints remain scarce (Chartres et al., 2024; Zuri et al., 2023).
2. Analytical methods for detecting nanoplastics and complex low-concentration chemical mixtures require standardisation (Fernandes et al., 2025; Jiang et al., 2025).
3. Evidence connecting plastisphere colonisation directly to human infection pathways remains insufficient (Woodford et al., 2025).

Additional gaps include understanding cumulative mixture toxicity, vulnerable population susceptibilities, and chronic low-dose exposure scenarios (Alijagic et al., 2024; Yang et al., 2023; Zuri et al., 2023).

Table 2 details the study-level appraisal domains used to determine evidentiary weight.

Table 2:
Study-Level Appraisal Domains Used to Determine Evidentiary Weight

Appraisal domain	Assessment focus	Key concern identified	Implication for synthesis
Study design and appropriateness	Alignment of design with research question	Heterogeneous designs across disciplines	Evidence weighted by design rigor
Exposure characterisation	Polymer, particle size, additives, dose, duration	Variable environmental realism	Limits direct cross-study comparison
Outcome measurement	Validity of ecological or health endpoints	Diverse endpoints and analytical methods	Prevents simple quantitative pooling
Confounding and bias	Control of confounding and selection bias	Observational limitations in human studies	Causal claims interpreted cautiously
Reproducibility	Analytical transparency and reporting	Variable methodological reporting	Affects confidence in individual findings
Causal inference	Temporal relationship and dose-response	Long-term human causal data remain limited	Mechanistic plausibility separated from causation

DISCUSSION

Integrated Interpretation

The synthesis supports conceptualising plastic pollution as a multi-pathway environmental health challenge rather than a single-contaminant issue. A plastic particle acts simultaneously as a physical stressor, a microbial habitat, a chemical vector, and a source of toxic additives (Alijagic et al., 2024; Morrison et al., 2022). While chemical leaching and environmental occurrence are well documented, and toxicological responses are increasingly characterised, direct population-level disease attribution remains uncertain (Feng et al., 2023; Zuri et al., 2023). This hierarchy is crucial for policy formulation: the presence of EDCs and biological hazards provides a sound rationale for preventative regulation, but should not be translated into exaggerated disease burden estimates.

Ecological and Microbial Dimensions

The plastisphere literature demonstrates that plastic debris creates distinct ecological niches that alter microbial community structure and biogeochemical cycling (Meng et al., 2024). From a public health perspective, plastics serve as mobile vectors for microorganisms, including potential pathogens (Perdigão et al., 2025; Póvoa et al., 2026; Woodford et al., 2025). River-to-sea and wastewater studies confirm that environmental conditions heavily dictate microbial colonisation patterns (Philip et al., 2025). Consequently, risk assessment should focus on high-risk aquatic conditions, such as wastewater effluent discharge zones, warm water bodies, and high-residence-time debris (Woodford et al., 2025).

Chemical and Human Health Dimensions

Polymer aging fundamentally alters chemical exposure dynamics. Leaching cannot be predicted solely from virgin product composition, as weathering, ultraviolet exposure, and biofilm formation modify release kinetics (Henkel et al., 2024). This reinforces the need for comprehensive lifecycle regulation governing chemical additives from manufacturing to end-of-life disposal (Abahussain et al.,

2025). For public health surveillance, future research must prioritise prospective human cohorts, validated biomonitoring protocols, and repeated exposure assessments linked to clinically meaningful endpoints (Li et al., 2024; Zuri et al., 2023).

Policy Implications

The evidence supports a prevention-oriented policy framework encompassing source reduction, safer material design, improved waste collection infrastructure, and stringent environmental monitoring (Abahussain et al., 2025; Ibrahim et al., 2025). Policies focused exclusively on downstream cleanup fail to address upstream manufacturing and additive leakage. International cooperation is vital, given the transboundary nature of plastic trade and marine transport. Public health systems should integrate environmental exposure tracking (such as drinking water and wastewater surveillance) alongside conventional epidemiological indicators.

CONCLUSION

Plastic pollution represents an interconnected environmental and public health challenge involving persistent particles, microbial colonisation, chemical exchange, and human exposure. The evidence is strongest for widespread environmental occurrence, plastisphere formation, and the release of plastic-associated chemicals. Experimental and biomonitoring data confirm biological plausibility for adverse effects including inflammation, oxidative stress, endocrine disruption, and reproductive toxicity. However, direct causal evidence for long-term human disease remains underdeveloped.

Addressing this crisis requires a robust prevention framework focused on reducing unnecessary plastic production, strengthening waste infrastructure, enforcing chemical transparency, and advancing standardised environmental and human monitoring. Future research must prioritise prospective human cohorts, validated nanoplastic detection, environmentally realistic mixture studies, and interdisciplinary integration across environmental science, microbiology, toxicology, and epidemiology.

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