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Microplastic and Nanoplastic Contamination in Coastal Sediments: Sources, Ecological Risks, and Mitigation Strategies

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Abstract

Plastic pollution has become a defining environmental challenge of recent decades, with increasing attention now directed toward microplastics (<5 mm) and nanoplastics (<1 µm) as pervasive and biologically active contaminants in coastal systems. These particles are particularly prone to accumulation in sediments, where they interact with biotic and abiotic components over extended periods. This study synthesizes current knowledge on the occurrence, sources, analytical detection, ecological implications, and mitigation of microplastics and nanoplastics in coastal sediments. Evidence indicates that estuarine and mangrove environments function as major retention zones, particularly under conditions of reduced hydrodynamic flushing and high organic matter content. Advances in analytical methods, including Fourier Transform Infrared spectroscopy, dynamic light scattering, and electron microscopy, have improved detection, although nanoplastics remain difficult to quantify consistently. Ecological impacts are increasingly linked to trophic transfer, chemical toxicity, and disruptions in benthic ecosystem functioning. Integrated ecological risk approaches highlight the importance of polymer type, contaminant load, and habitat sensitivity in shaping environmental outcomes. The study further discusses emerging mitigation strategies, emphasizing upstream waste reduction, sediment management, and the integration of real-time monitoring technologies. These findings underscore the need for standardized methodologies and interdisciplinary frameworks to better understand and manage plastic pollution in coastal sediments.

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1. INTRODUCTION

The proliferation of synthetic polymers has reshaped contemporary material cycles by creating highly persistent anthropogenic particles that move across environmental compartments but do not readily re-enter closed biogeochemical loops. Recent syntheses conceptualize this pattern as largely unidirectional ("irreversible") plastic transport, in which production and release are followed by dispersal and long-term retention in receiving environments—especially sediments—thereby generating durable ecological legacies rather than transient pollution pulses (Napper and Thompson, 2020; Moon et al., 2025). Plastic debris is now understood to contaminate both marine and freshwater systems globally, motivating scientific and regulatory attention that extends beyond

the historically visible problem of macro-debris at the sea surface to include smaller size fractions and less conspicuous sinks (Rochman et al., 2016).

Once released, plastic is progressively transformed by a combination of physical abrasion, photo-oxidative weathering driven by solar ultraviolet radiation, and biologically mediated surface alteration, which together promote cracking, embrittlement, and fragmentation into increasingly small particles (Wayman and Niemann, 2021; Jansen et al., 2023; Zhang et al., 2024). These processes generate secondary microplastics and nanoplastics from larger debris, complementing emissions of primary micro-/nano-sized plastics that enter the environment already in particulate form (e.g., from industrial and consumer sources) (Boyle and Örmeci, 2020; Belioka and Achilias, 2024; Sharma et al., 2024). Definitions of the smallest fractions remain heterogeneous across scientific and governance contexts: microplastics are commonly treated as particles <5 mm, whereas nanoplastics are variously defined by upper size cutoffs ranging from <1 μm (environmental exposure framing) to the nanoscale ~1–100 nm (aligned with nanomaterial definitions) (Hoogenboom, 2016; Provencher et al., 2022; Sharma et al., 2024). This definitional variability is not merely semantic; it contributes to inconsistencies in measurement, comparability, and risk assessment, particularly at the nanoscale where particle behaviour becomes strongly colloidal and analytically challenging (Reynaud et al., 2022).

Although early monitoring and public narratives emphasized floating litter, multiple lines of evidence now indicate that sediments constitute a dominant long-term sink for many plastic particles, including polymers initially buoyant in seawater (Brander et al., 2020; Lamichhane et al., 2022). Key mechanisms that transfer plastics from the water column to benthic environments include biofouling-driven increases in particle density, aggregation with organic matter and natural colloids, and incorporation into faecal pellets and marine snow, all of which can accelerate settling and promote burial (Galloway et al., 2017; Casabianca et al., 2021; Jansen et al., 2023). Estuaries and river plumes are repeatedly highlighted as dynamic transition zones where changes in salinity, ionic strength, and organic matter favour aggregation and deposition, making them likely hotspots for the retention of small plastics and their aggregates (Wayman and Niemann, 2021; Pinheiro et al., 2021; Lins et al., 2022). In parallel, sediment-focused studies emphasize that monitoring programs centred on surface waters can systematically understate environmental burdens by overlooking sedimentary entrapment and the long residence times associated with benthic storage (Brander et al., 2020).

The accumulation of microplastics and nanoplastics in coastal and estuarine sediments is ecologically consequential because benthic habitats host diverse communities and regulate key ecosystem processes (e.g., carbon burial, nutrient cycling, and bioturbation). Microplastics that settle into sediments become bioavailable to deposit feeders, suspension feeders, and other benthic fauna, creating exposure pathways distinct from those in the pelagic zone (Casabianca et al., 2021; Nawaz et al., 2025). Experimental and conceptual syntheses further indicate that ingestion can propagate plastics through food webs via egestion and predation, while changes to feeding, energy allocation, and organismal performance may scale to altered bioturbation and ecosystem functioning under some conditions (Galloway et al., 2017; Horton et al., 2017; Krause et al., 2021). Evidence for trophic transfer and biomagnification remains context-dependent and is often stronger in controlled laboratory studies than in field settings, underscoring the need for ecologically realistic exposure scenarios in sedimentary systems (Koelmans et al., 2017).

Microplastics and nanoplastics are also not chemically inert. Their surfaces can sorb and transport co-occurring contaminants—including heavy metals and hydrophobic organic pollutants (e.g., PAHs, POPs)—with sorption behaviour shaped by polymer chemistry, surface ageing, and

interactions with natural organic matter (Lins et al., 2022; Cássio et al., 2022; Watson et al., 2023). The formation of an environmentally derived surface layer (often discussed as an eco-corona) can modify surface charge, density, and contaminant affinity, thereby changing both particle fate (e.g., settling) and biological interactions (e.g., bioavailability and toxicity) (Reynaud et al., 2022). Modelling work suggests that nanoscale plastics may, under some conditions, carry disproportionately high chemical "payloads" relative to larger particles because of their higher surface-area-to-volume ratios and their propensity to aggregate with natural colloids that settle into sediments (Wayman and Niemann, 2021). At the organismal level, "Trojan horse" mechanisms—where pollutant-sorbed nanoplastics alter contaminant uptake pathways or tissue distribution—have been demonstrated in experimental models, although the magnitude and direction of combined effects can vary with particle properties and exposure conditions (Trevisan et al., 2020; Corsi et al., 2020).

Despite rapid advances, several uncertainties constrain robust synthesis and cross-study comparison for coastal sediments. First, methodological heterogeneity—spanning sampling design, density separation choices, contamination control, reporting units, and polymer identification—can substantially influence measured concentrations and inferred distributions (Costa et al., 2019; Brander et al., 2020; Pinheiro et al., 2021). Second, nanoplastic detection and quantification remain a central bottleneck: multiple reviews note that routine monitoring approaches are often not sensitive to the smallest particles, that validated reference materials are limited, and that nanoscale measurements in complex matrices (including organic-rich sediments and biota) remain difficult (Hoogenboom, 2016; Boakye et al., 2025; Cunningham et al., 2023; Reynaud et al., 2022). Third, risk assessment frameworks developed for dissolved chemicals do not transfer straightforwardly to particulate pollutants, and several authors stress that environmentally realistic effect thresholds, harmonized exposure metrics, and fate-informed assessments are still emerging for micro-/nanoplastics—particularly in sediments and estuarine gradients (Koelmans et al., 2017; Galgani et al., 2019; Brander et al., 2020).

The present paper synthesizes current understanding of microplastic and nanoplastic contamination in coastal sediments, emphasizing (i) dominant sources and delivery pathways to nearshore and estuarine sinks, (ii) spatial patterns and depositional controls that structure sedimentary burdens, (iii) ecological risks to benthic organisms and sediment-linked food webs, including interactions with co-contaminants, and (iv) emerging mitigation directions—from upstream waste-management interventions and governance strategies to improved monitoring and treatment technologies capable of addressing smaller size fractions (Sanjeev and Manjunath, 2025). In doing so, it responds to repeated calls for sediment-inclusive assessments and standardized analytical approaches that can better capture long-term ecological legacies of plastic pollution in coastal environments.

2. MATERIAL AND METHOD

This study applied a structured narrative synthesis approach, compiling relevant peer-reviewed literature through targeted searches of major bibliographic databases (including Web of Science and Scopus) consistent with practices used in prior plastics-focused evidence syntheses. Inclusion prioritized foundational and recent work addressing microplastic and nanoplastic occurrence and analysis in aquatic systems, with emphasis on coastal and estuarine sediment contexts where methodological choices strongly influence reported burdens.

Methods reported across studies were extracted and compared for (i) sediment sampling and handling, (ii) isolation steps (e.g., sieving/filtration, digestion, and density separation), and (iii) quality assurance/quality control procedures designed to minimize contamination and analytical bias. Polymer identification approaches were evaluated with particular attention to vibrational

spectroscopy (FTIR and Raman), given their widespread use but size-dependent constraints and interpretive limitations in complex matrices.

For nanoplastic characterization, the review emphasized techniques frequently proposed or applied for sub-micron particles (e.g., DLS, nanoparticle tracking analysis, and electron microscopy) and noted the common need for complementary or hyphenated methods to improve confidence in detection and identification. Studies incorporating environmental fate/exposure and ecological risk assessment frameworks were examined to summarize commonly used exposure metrics, experimental design considerations, and evaluation criteria for particulate pollutants.

3. RESULTS AND DISCUSSION

Sources and Pathways to Coastal Sediment Contamination

Microplastics and nanoplastics enter coastal environments through a combination of primary emissions (particles intentionally produced at micro-/nanoscales) and secondary formation (fragmentation of larger debris into smaller particles during use and environmental weathering) (Rochman et al., 2016; Napper and Thompson, 2020). These inputs are strongly coupled to land-based human activities and infrastructure, with plastics originating from mismanaged waste and urban/industrial sources subsequently redistributed through hydrological and coastal transport processes (Wayman and Niemann, 2021; Jansen et al., 2023). In this framing, river catchments and nearshore zones function as connected components of a broader source-to-sea continuum in which particle properties (size, density, shape, surface chemistry) and environmental forcing jointly determine delivery to coastal compartments (Zhang et al., 2024).

Within the category of primary particles, direct releases of manufactured microplastics (e.g., pellets and particles associated with consumer and industrial products) are relevant contributors to environmental burdens, while also noting that many particles observed in the environment are ultimately derived from fragmentation of larger items (secondary microplastics). Field evidence further supports wastewater effluent as a major point-source pathway for microplastics (including pellets, fibres, and fragments) to receiving waters, with concentrations often elevated downstream of outfalls (Wayman and Niemann, 2021). Broader syntheses similarly highlight that wastewater treatment systems can remove substantial fractions of microplastics, but—because of large, treated volumes and incomplete retention—effluent and associated sludge management can still sustain environmental loading, including to coastal waters via river networks (Jansen et al., 2023).

For coastal systems specifically, estuarine and nearshore contamination patterns are frequently attributed to the convergence of riverine transport, stormwater and urban runoff, and coastal/maritime activities (including fishing- and aquaculture-associated plastic use such as ropes and nets). In urbanized coastal wetlands, polymer compositions dominated by commonly used packaging and fishery-related plastics (e.g., PE and PP) have been interpreted as consistent with multiple local inputs, including wastewater and coastal economic activities. In estuarine ecosystems, transboundary transport and multi-source inputs make it difficult to assign dominant sources without sampling designs that explicitly resolve estuarine gradients and multiple environmental compartments (water, sediment, biota) (Zhang et al., 2024).

Fate in Coastal Waters: From Buoyant Particles to Sedimentary Sinks

Although many widely used polymers are initially buoyant or near-neutrally buoyant, sediments are a major long-term reservoir for microplastics in aquatic systems, consistent with the broader "missing plastic" problem in surface waters (Boyle and Örmeci, 2020). Mechanistically, the vertical

redistribution of plastics is governed by coupled physical–chemical–biological processes, including biofouling, heteroaggregation with suspended mineral and organic matter, and incorporation into rapidly sinking organic matrices (e.g., marine snow and faecal material) (Sharma et al., 2024; Provencher et al., 2022). Buoyancy alone is therefore an unreliable predictor of ultimate fate, because surface properties evolve through weathering and colonization, and particles interact dynamically with natural colloids and biogenic particles (Hoogenboom, 2016).

Biofilm development on plastic surfaces is repeatedly identified as a key transformation because it can (i) increase effective density and promote sinking, and (ii) increase "stickiness" via extracellular polymeric substances (EPS), facilitating aggregation with detritus and suspended sediment (Lamichhane et al., 2022). Experimental incubations demonstrate that biofouling can measurably change sinking behaviour for both higher-density and lower-density polymers, thereby enhancing deposition potential and complicating steady-state transport assumptions (Reynaud et al., 2022). Microbial colonization, phytoplankton, and suspended sediments can substantially alter aggregation states, and that more aggregated particles tend to settle and accumulate in bed sediments (Lamichhane et al., 2022). In situ flux measurements in the North Atlantic further show that microplastics can be exported downward by embedding in rapidly sinking biogenic particles, reinforcing biological pumping as a plausible mechanism linking surface inputs to deep and benthic sinks (Brander et al., 2020; Boyle and Örmeci, 2020).

At freshwater–marine transitions, estuarine gradients (including salinity-driven changes in aggregation and water density) can shift residence times in the water column and alter deposition–resuspension dynamics, producing strong spatial contrasts in exposure across adjacent habitats (Casabianca et al., 2021). More broadly, coastal particle-transport studies highlight that aggregation, and subsequent sedimentation may dominate microplastic fate in nearshore waters because coastal zones often contain high concentrations of suspended sediments and particulate organic matter that increase collision/attachment opportunities (Galloway et al., 2017). Microplastics should often be treated as particulate/colloidal entities whose transport depends on aggregation, wetting, and interfacial interactions—not only polymer density—thereby motivating cross-disciplinary approaches borrowed from sediment and colloid transport theory (Lins et al., 2022).

Spatial Heterogeneity in Sediments: Role of Hydrodynamics and Sediment Properties

Observed distributions of microplastics in coastal and estuarine sediments are consistently described as heterogeneous, reflecting the coupling of (i) spatially variable inputs and (ii) depositional environments with different retention capacities (Belioka and Achilias, 2024). Estuarine assessments emphasize that low-energy depositional zones and compartments with high retention capacity can accumulate high particle loads relative to more energetic reaches, while also noting that methodological limitations and under-sampling of gradients have historically constrained generalization. Hydrodynamic field studies in urban coastal rivers further show that turbulence, cross-sectional mixing, and advective transport vary with flow conditions and interact with particle size/shape/composition, implying that exposure and eventual deposition can shift substantially in time (e.g., across calm versus turbulent periods) (Sharma et al., 2024).

Sediment characteristics—particularly grain-size distributions and organic matter—are frequently proposed as additional controls on accumulation and retention. For example, lagoon sediment surveys attribute higher microplastic counts in fine-grained sediments to textural controls that favour particle retention and reduce remobilization relative to coarser substrates (Pinheiro et al., 2021). Urban wetland studies likewise report that depositional contexts and local hydrodynamics can influence whether buoyant polymers (e.g., PE/PP) are retained in surface sediments, with

biofouling, weathering, and heteroaggregation invoked as plausible mechanisms enabling deposition of otherwise buoyant plastics (Belioka and Achilias, 2024). Natural drivers of microplastic migration indicate that coarse beds can be more prone to resuspension, while organic-rich and more cohesive matrices can enhance retention—linking substrate properties to both accumulation and remobilization potential (Provencher et al., 2022).

Process-based river studies offer additional mechanistic insight relevant to coastal sediment sinks because they demonstrate how plastics can be transferred into bed sediments by exchange flows and retention in interstitial spaces and biofilms. In particular, hyporheic exchange has been shown to be important for delivery and accumulation of small microplastics in streambed sediments, implying that models focusing only on gravitational settling may underestimate deposition and longer-term burial in bed sediments (Krause et al., 2021; Nawaz et al., 2025). While these studies focus on fluvial settings, they reinforce a broader conclusion across aquatic environments: fine particles can be immobilized via interactions with porous beds and biofilm matrices and can later be remobilized during higher-energy events, complicating "static sink" assumptions for sediments (Krause et al., 2021; Provencher et al., 2022).

Analytical Identification: Progress for Microplastics, Persistent Bottlenecks for Nanoplastics

Advances in vibrational spectroscopy and automated imaging have substantially improved the identification and quantification of microplastics in complex environmental matrices, especially sediments. Automated μFTIR imaging has enabled high-throughput polymer identification in riverbed sediments while reducing visual selection bias and has highlighted that very small size fractions can dominate numerically in bed sediments (Horton et al., 2017). Extended, cross-sectional and longer-term river monitoring likewise demonstrates that concentrations in the water column fluctuate greatly over time and space, reinforcing the need for sampling strategies that capture variability rather than relying on single-timepoint measurements (Koelmans et al., 2017; Sharma et al., 2024). Method-comparison studies for marine sediments, however, show that recovery can vary strongly with sediment matrix, polymer density, particle size/shape, and extraction method—supporting the conclusion that analytical variability can meaningfully influence reported concentration patterns and inter-study comparability (Cássio et al., 2022; Watson et al., 2023; Trevisan et al., 2020).

Accordingly, multiple methodological studies emphasize that harmonization of sampling, QA/QC, and extraction protocols remains essential for robust cross-site comparisons. Meta-analytic work in river systems identifies persistent issues including selective sampling depth, inconsistent reporting, and limited capture of vertical variability within beds—factors that directly affect inferred storage and exposure in sediments (Corsi et al., 2020; Trevisan et al., 2020). Experimental evaluations of extraction and control-matrix preparation for beach sediments further demonstrate that matrix pretreatment and organic matter removal can change recovery efficiency, illustrating how procedural choices can bias estimates of sedimentary loads (Costa et al., 2019; Cássio et al., 2022). Collectively, these studies support the conclusion that improving comparability requires explicit performance characterization (e.g., recovery testing) and careful protocol selection tuned to sediment type and particle properties (Cássio et al., 2022; Corsi et al., 2020).

Nanoscale plastics emphasize that environmental nanoplastics are difficult to isolate, identify, and quantify because of their very small sizes, tendency to aggregate, and transformation into diverse physicochemical forms during degradation (Boakye et al., 2025). Overviews of nanoplastic sample processing stress that aggregation with organic matter and inorganic colloids can change mobility and settling behaviour, while simultaneously complicating analytical workflows that seek to

preserve environmentally realistic states (Cunningham et al., 2023). Spectroscopic-method studies similarly indicate that traditional μFTIR/μRaman approaches face diffraction-limited spatial resolution at the nanoscale, motivating interest in higher-resolution or hybrid methods (e.g., AFM-IR, TERS, advanced photothermal IR approaches), while recognizing that applications to environmental nanoplastics remain emergent (Galgani et al., 2019; Rochman et al., 2016). Work comparing nanoplastics and microplastics in urban waters reinforces that nanoscale particles can remain highly dispersed yet also heteroaggregate (e.g., with clay and natural organic matter), implying that both fate and detectability depend strongly on water chemistry and surrounding colloids (Boakye et al., 2025).

Ecological Implications: Benthic Exposure, Trophic Interactions, and Co-Contaminant Dynamics

Because sediments can store large quantities of microplastics, the benthos is repeatedly identified as a major exposure interface for deposit feeders, suspension feeders, and other sediment-associated organisms (Sanjeev and Manjunath, 2025). Microplastic ingestion is widespread across taxa and trophic modes, in part because particle sizes overlap with natural prey/food size ranges. Chronic exposures can alter feeding and energy allocation even when lethality is uncommon (Arp et al., 2021). Exposures can occur at multiple trophic levels, including via sediment-associated pathways, and that understanding uptake routes requires coupling particle fate (settling/retention/resuspension) with habitat-specific feeding ecology (Molazadeh et al., 2023). Microplastics are persistent and widely distributed, reinforcing that interactions with organisms extend from surface waters to benthic environments and can include both physical and chemical stressors (Hoellein et al., 2019; Drummond et al., 2020).

Chemical interactions represent a second major dimension of risk. Sorption/desorption kinetics vary by polymer type and contaminant properties, and microplastics can act as vectors for metals and hydrophobic organic contaminants under some conditions (Stead and Bond, 2023). Adsorption and aggregation processes are fundamental to predicting when microplastics act as contaminant carriers versus when natural particles dominate contaminant partitioning (Lins et al., 2022; Lamichhane et al., 2022). Importantly, the net contribution of plastics to organismal uptake of some hydrophobic contaminants may be small relative to direct uptake from water and diet in many contexts; nevertheless, plastics may still create distinct exposure routes depending on how chemicals are presented to tissues and receptors (Stead and Bond, 2023). This nuanced position reinforces the need for risk frameworks that are explicit about exposure pathways, comparative baselines (natural particulates), and site-specific context (Sanjeev and Manjunath, 2025).

For nanoplastics, toxicology-oriented studies raise additional concerns because smaller particles may cross biological barriers more readily and trigger cellular responses (e.g., oxidative stress and inflammation), although they also emphasize that mechanistic understanding and environmentally representative exposure characterization remain incomplete (Krause et al., 2021). Broader assessments of weathering plastics as a potentially poorly reversible, planetary-scale exposure problem similarly argue that hazard characterization must account for continuously evolving particle properties and mixtures of particles and leachates across sensitive environments (Linders et al., 2018). These converging views motivate greater attention to nanoscale detection, transformation, and realistic exposure metrics—particularly for sediment-associated communities where long residence times may elevate cumulative exposure potential (Krause et al., 2021).

Risk Assessment and Uncertainty: Toward Comparable, Fate-Informed Evaluations

Work on weathering plastics frames plastic pollution as increasingly widespread and not readily reversible, stressing that thresholds for disruptive impacts remain difficult to parameterize because

fate processes, transformations, and ecotoxicological hazards vary across environments and particle types (Linders et al., 2018). Marine ecosystem analyses similarly propose that adverse outcome pathways (AOP) can help organize mechanistic evidence across biological levels but also highlight that many studies remain focused on simplified particles and laboratory settings, limiting direct extrapolation to heterogeneous field exposures (Moon et al., 2025).

Methodological variability is repeatedly identified as a key barrier to comparability. Sediment extraction studies show that recovery efficiencies can vary widely across methods and sediment matrices, affecting apparent spatial patterns (Cássio et al., 2022; Trevisan et al., 2020). Meta-analyses and long-term monitoring demonstrate that concentrations can fluctuate strongly over time, and that single-compartment or surface-focused sampling can misrepresent system-level burdens, reinforcing the need for integrated designs that include sediments and resolve variability in time and space (Corsi et al., 2020). Estuarine overview work adds that limited sample sizes and incomplete gradient coverage impede robust inference about hotspots and transport processes and calls for multivariate analyses and modelling approaches that explicitly incorporate estuarine compartmentalization (Zhang et al., 2024; Boyle and Örmeci, 2020; Casabianca et al., 2021).

In heavily urbanized coastal regions and river mouths, multiple studies and syntheses report elevated contamination consistent with high local inputs and concentrated transport pathways (e.g., wastewater, runoff, industrial and coastal activities) (Belioka and Achilias, 2024). Empirical evidence of downstream increases in microplastics near wastewater outfalls supports this conclusion at local scales, while lagoon and wetland sediment studies in urbanized settings similarly show measurable sedimentary burdens with compositions consistent with common consumer and industrial polymers (Pinheiro et al., 2021). Hence, there is heightened risk in high-input coastal zones, while emphasizing that quantifying risk robustly requires standardized measurement, fate-informed interpretation, and explicit uncertainty accounting (Linders et al., 2018).

Mitigation and Monitoring: Upstream Prevention, Treatment, and Sediment-Focused Strategies

Mitigation syntheses consistently prioritize source reduction and upstream prevention because weathering plastic pollution is described as increasing in exposure and difficult to reverse once distributed across aquatic compartments (Padmakumar and Joseph, 2022). Conventional and advanced wastewater and water-treatment processes (e.g., sedimentation, filtration, coagulation/flocculation, membrane-based approaches, and hybrid trains) can remove substantial fractions of microplastics, but performance depends on particle size, density, and shape, and small particles remain especially challenging (Miller and Miller, 2020; Gao et al., 2023; Zhang et al., 2023). Modelling of settling-based removal in wastewater further suggests that capture efficiency increases with larger size and greater density contrast (and with more sphere-like shapes), reinforcing the need to match treatment mechanisms to particle properties (Joo et al., 2021). Because treatment systems can also generate or concentrate microplastics in sludges, these reviews collectively imply that end-to-end management (including residual handling) is required to avoid shifting burdens across compartments (Napper and Thompson, 2020).

Sediment- and ecology-focused mitigation options are also emerging. Studies on microplastics–biofilm relationships highlight the dual role of biofilms: they can promote sinking/retention (thereby increasing sediment exposure) while also potentially contributing to biodegradation and offering bioremediation opportunities under some conditions (Shamskhany et al., 2021; Stride et al., 2023). At the same time, work on microbial mediation of sediment stability emphasizes that biofilm–EPS effects on sediments can range from stabilization to destabilization depending on disturbance state and bio-sediment development, implying that sediment-focused interventions must consider

site hydrodynamics and ecological feedback rather than assuming uniformly beneficial outcomes (Zhang, 2017; Provencher et al., 2022). Consequently, emerging remediation concepts increasingly emphasize integrated strategies that combine prevention, improved treatment, and targeted site management, rather than relying on any single "downstream" fix (Stride et al., 2023).

Multiple coastal-particle studies call for improved monitoring capacity, including better characterization tools and novel in situ sensors capable of tracking particle dynamics across nanometre-to-millimetre scales, as well as sampling designs that resolve vertical and horizontal variability (Galloway et al., 2017). Hydrodynamic field studies further reinforce that multipoint, cross-sectional sampling and concurrent flow characterization can reduce uncertainty in transport estimates, strengthening the evidence base for targeted interventions. In combination, these directions align with broader calls to reduce uncertainty through coordinated monitoring and discovery-oriented research that can detect unanticipated effects of weathering plastics and their evolving mixtures in coastal environments (Linders et al., 2018).

4. CONCLUSION

Microplastic and nanoplastic contamination in coastal sediments has emerged as a multi-dimensional environmental challenge in which particle inputs, transport, and transformation are inseparable from ecological exposure and risk. As plastics move through coastal systems, a substantial share becomes retained in benthic environments, where persistence over long timeframes increases the likelihood of interaction with sediment biota and with co-occurring chemical stressors. The ecological relevance of this problem therefore extends beyond the physical presence of particles, encompassing their evolving surfaces, their capacity to associate with pollutants, and the cumulative consequences of long-term residence within biologically active sediments.

At the same time, the scientific basis for evaluating impacts is advancing unevenly across size classes. Methodological progress has strengthened microplastic identification and polymer attribution in sediments, yet robust, environmentally representative characterization of nanoplastics remains comparatively underdeveloped. This imbalance constrains both exposure assessment and the interpretation of chronic and sublethal effects, particularly where nanoscale behaviour (aggregation, colloidal stability, and biological interactions) may depart from expectations derived from larger particles. Addressing these limitations will require coordinated, cross-disciplinary efforts that integrate harmonized monitoring designs, standardized QA/QC and reporting practices, and fate-informed risk assessment frameworks capable of linking laboratory evidence to realistic field scenarios.

Protecting coastal ecosystem integrity will depend on coupling improved environmental diagnostics with upstream prevention. Reducing plastic emissions at source—through strengthened waste management systems and policy instruments—remains foundational, because once plastics fragment and become distributed across sedimentary habitats, remediation becomes technically challenging and uncertain. Nonetheless, complementary mitigation strategies, including innovations in treatment and monitoring technologies and targeted approaches for high-retention environments, can support risk reduction when they are embedded within a lifecycle-oriented management strategy.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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