Journal of Hazardous Materials 508 (2026) 141908

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Review

Plastic pollution interception by vegetation: A mechanistic review across diverse habitats

Corinne Corbau [a,*], M. Skalny [b], T. Bajda [b], P. Le Coustumer [c], Vlatka Filipović Marijić [d], A. Lazarou [e], W. Nardin [f], M. Coltorti [a], U. Simeoni [g]

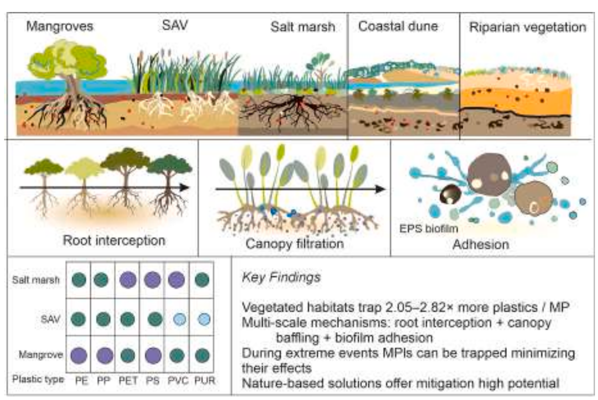
[a] University of Ferrara, Ferrara, Italy
[b] AGH University of Krakow, Krakow, Poland
[c] University of Bordeaux, Bordeaux, France
[d] Ruđer Bošković Institute, Zagreb, Croatia
[e] Zanasi and Partners, Modena, Italy
[f] HPL-UMCES, Cambridge, MD, USA
[g] CURSA, Roma, Italy

HIGHLIGHTS

- Vegetation traps 2.0–2.9 times more microplastics, creating toxic hotspots.
- Weathered plastics release flame retardants, phthalates, and POPs into rhizospheres.
- Biofilm eco-coronas improve the adsorption of hazardous pollutants on plant surfaces.
- The sink-hazard paradox poses a threat to carbon storage and microbial communities.
- Nature-based solutions necessitate hazard threshold monitoring and eco-engineering.

GRAPHICAL ABSTRACT

Caption: Mechanisms of plastic trapping in vegetated coastal and riparian zones. Top panels: interfaces between habitats across five ecosystem types. Middle panels: main trapping mechanisms, such as eco-corona coatings and subsequent biofilm/EPS formation that promotes adsorption/attachment. Bottom panels: important results indicating differences in polymer retention and the formation of accumulation hotspots (~2.05–2.82 × higher loads), emphasizing the balance between pollution reduction and hazard concentration.



ARTICLE INFO

Keywords:
Microplastic pollution

ABSTRACT

Plastic pollution is intensifying across freshwater–coastal continua and impacts terrestrial, freshwater, and marine habitats. While vegetated areas are vital sinks, they are approaching a critical tipping point at which

* Corresponding author.
E-mail addresses: cbc@unife.it (C. Corbau), mskalny@agh.edu.pl (M. Skalny), bajda@agh.edu.pl (T. Bajda), philippe.le-coustumer@u-bordeaux.fr (P. Le Coustumer), vfilip@irb.hr (V. Filipović Marijić), alexandros.lazarou@gmail.com (A. Lazarou), wnardin@umces.edu (W. Nardin), clt@unife.it (M. Coltorti), g23@unife.it (U. Simeoni).

https://doi.org/10.1016/j.jhazmat.2026.141908
Received 11 January 2026; Received in revised form 21 March 2026; Accepted 27 March 2026
Available online 28 March 2026

Vegetation interception
Sink-hazard paradox
Ecotoxicity
Biofilm eco-corona
Nature-based solutions

accumulation transforms these habitats from natural filters into toxic hotspots. This review synthesizes data from nearly 199 peer-reviewed studies to understand how vegetation traps macro- and microplastics in ecosystems such as mangroves, salt marshes, seagrass meadows, coastal dunes, and riparian zones, and explains the implications for exposure, fate, and risk management. We examine how the main factors affecting retention, such as plastic physicochemical properties (size, shape, density, weathering), vegetation structural characteristics (root and stem complexity, canopy architecture), and environmental conditions (water flow, geomorphology, climate), jointly influence retention dynamics. Results show vegetated ecosystems capture ~2.05–2.82 times more microplastics than non-vegetated areas. Plastic retention occurs mainly through two pathways: (1) physical interception and flow reduction at large scales, and (2) micro-scale adhesion via eco-corona formation, and subsequent biofilm/EPS development that promote particle sticking and persistence and limit resuspension. However, significant uncertainties remain about nanoplastic–plant interactions, long-term accumulation and remobilization, and climate impacts on exposure and fate, particularly under shifting hydrodynamic and geomorphic regimes. A crucial sink–hazard paradox exists: although vegetation effectively traps plastics, this accumulation transforms sediments into dangerous hotspots by concentrating toxic additives (e.g., flame retardants), co-transporting persistent organic pollutants, and promoting potentially harmful biofilms. We recommend a research roadmap that includes standardized protocols and reporting units, advanced process-based modeling frameworks, climate-resilience scenarios, and nature-based solutions for shifting vegetation from passive pollution sinks to active, managed mitigation tools. Implementing these recommendations is crucial for developing effective, evidence-based strategies that balance pollution control with hazard containment in vegetated ecosystems.

1. Introduction

Global plastic production continues to accelerate, reaching approximately 430 million metric tons in 2024 and projected to exceed one billion tons annually by 2050 [1,2]. Each year, approximately 4.8–12.7 million metric tons of mismanaged plastic waste enter the ocean from coastal areas [3,4]. Microplastics (MPs)(<5 mm) are also released from persistent point sources; for instance, treated wastewater from a large municipal plant is estimated to discharge around 65 million microplastic particles daily [4–6].

The prevalence of MPs exhibits considerable variability across different environments, attributable to local factors such as retention potential, proximity to urban or industrial areas, and disparities in sampling and analytical methods [7–9]. Systematic analyses reveal surface freshwater concentrations ranging from 1.2×10^{-3} to 5.42×10^{5} items/m^3 , while sediments contain between 18.3 and 30,000 particles/kg [8]. Oceanic waters generally exhibit lower levels, from 1.2×10^{-3} to 62.5 items/m^3 [9]. There is significant spatial variability independent of urbanization: urban lakes in Hanoi, Vietnam, show 3.4–589 items/m^3 [10], canals in Amsterdam range from 16 to 1707 items/m^3 , and remote lakes in Muskoka-Haliburton, Ontario, hold 910–2090 items/m^3 [11]. Daily levels fluctuate with weather and local activities, with extreme weather events causing sharp increases—for instance, a storm in Australia increased MPs from 400 to 17,383 particles/m^3 , and a flood in India raised levels from 28.3 ± 12.3–95.1 ± 21.1 items/L [12,13].

The widespread presence of plastic pollution now impacts nearly all ecosystems, from alpine soils to deep-sea sediments [14,15]. While initial studies primarily focused on marine and pelagic environments, emerging research highlights the important role of vegetated habitats, including mangroves, salt marshes, seagrass meadows, coastal dunes, and riparian zones as both natural reservoirs and vulnerable interfaces within the global plastic cycle [16–18]. For instance, the Sundarbans mangroves (Bangladesh–India) show how large vegetated areas can serve as plastic accumulation zones, driven by river inputs from the Ganges–Brahmaputra–Meghna basin and the Bay of Bengal [19]. Similarly, saltmarshes with vegetation have higher mean total NMP mass concentrations (13–19 mg kg^{-1}) than bare mudflats (~5 mg kg^{-1}). Additionally, the estimated burial rates were greater in vegetated zones (approximately 0.63–0.91 g m^{-2}) than in non-vegetated areas (0.40 g m^{-2}yr^{-1}) [20] Consistent with this "vegetation-enhanced trapping" aspect, sediment cores from the River Thames estuary (UK) reveal increased microplastic in vegetated high-marsh zones (mean 267.1 ± 10.2 particles/100 g dwt in 0–10 cm) and urban tributary hotspots linked to sewer overflows (up to 360.0 ± 12.0 particles/100 g dwt) [21]. These ecosystems trap plastics through various mechanisms, including physical entanglement by roots, stems, and leaves, as well as adhesion facilitated by biofilms on plant surfaces. Dense canopies reduce water flow, thereby facilitating plastic deposition and retention. Recent research shows that the complexity of vegetation structure, measured using 3D Vegetation Indices (3DVI), strongly correlates with entrapment efficiency, with denser and more morphologically diverse plant communities trapping more macroplastics [18]. Likewise, canopy arrangement, shoot density, and hydrodynamic conditions influence the retention of microplastics (MPs) in seagrass beds and riparian plants [16, 22]. In riparian soils, MPs and tire-wear particles affect soil aggregation, organic matter, and contaminant adsorption, impacting sediment stability and nutrient cycling [23–25].

Vegetation–plastic interactions extend beyond physical entrapment and have significant ecological and functional impacts, influencing trophic levels and biogeochemical cycles. Plastics accumulated in vegetated environments can impact key ecosystem roles, including carbon storage, sediment stabilization, and habitat creation [26,27]. For example, degraded seagrass meadows experience a decline in regulating and supporting services valued at around USD 18,800 per hectare annually, highlighting the economic importance of ecosystem preservation [28]. On the other hand, the ability of vegetated habitats to capture and immobilize plastics provides a natural mitigation strategy, supporting restoration efforts and blue-carbon initiatives that integrate pollution control with climate adaptation [1]. However, this retention can also create hazards: trapped litter can blanket branches and pneumatophores, limiting light, disrupting photosynthesis, and potentially causing localized anoxia [22]. This creates a sink–hazard paradox: while mangrove roots trap plastics, continuous coverage and burial can harm the very structures that provide the service [23]. Raising risks of localized chemical and physical damage. [25]Despite progress, significant gaps remain in our understanding of environmental factors, spatial and species-specific differences, and the effectiveness of plastic trapping across different habitats and environmental gradients. Understanding these mechanisms is crucial for predicting plastic exchange between terrestrial and aquatic systems and for developing effective mitigation and restoration strategies [17,18,29–31].

This study reviews existing knowledge concerning (i) the physical and chemical properties of plastics that influence their capture and persistence, such as size, density, shape, and surface conditioning resulting from weathering and biofilm development; (ii) the role of various vegetated habitats—including mangroves, salt marshes, seagrass beds, coastal dunes, and riparian zones—as trapping pathways;

and (iii) the hydrodynamic, geomorphic, and structural factors that determine whether these habitats function as net sinks or temporary sources, particularly during storms and floods. By conceptualizing vegetation as a natural yet dynamic biotic filter that intercepts debris and simultaneously concentrates exposure, this review provides a mechanistic foundation to improve measurement consistency, parameterize the fate and transport processes in ecological and hydrodynamic models, and support management strategies to identify retention hotspots, event-driven remobilization periods, and targeted monitoring within vegetated environments.

2. Literature search and methodology

2.1. State of knowledge and analytical limitations

The scientific study of plastic debris in the environment is not recent, with key reports dating back to 1972 [32]. However, it wasn't until more than thirty years later that the term "microplastic" became common in academic circles [33]. Over the past decade, research has grown rapidly; recent surveys show an 800% increase in publications from 2016 to 2021 alone [34], and current metadata searches reveal over 11,000 articles on plastic transport and vegetation.

Despite the increase in volume, the field faces significant discrepancies in terminology and methodological rigor [35]. A fundamental issue is the absence of standardized sampling strategies. Methods for particle collection, size-class definitions, and extraction-purification protocols vary widely across the different studies compiled herein. Additionally, reporting units remain highly inconsistent across environmental matrices, ranging from particles per liter (p/L) in aquatic environments to particles per gram (p/g) in sediments or items per square meter (items/m2) on strandlines. To handle this complexity and guide our literature review, Fig. 1 shows various land-based sources and transport routes that bring plastics to the vegetated sinks examined in this study.

Historically, the absence of procedural blanks and rigorous calibration methods was common, particularly in studies published before 2021, raising concerns about the reliability of results at low concentrations [36]. Although the International Organization for Standardization (ISO) has recently established standards to standardize these procedures, such as ISO/TR 21960 (methodologies) and ISO 24187 (analysis principles) [37,38], most existing publications rarely cite these non-mandatory guidelines.

In this review, we have adopted a comprehensive approach that incorporates data irrespective of the particular units or sampling methodologies employed. This strategy enables us to encompass a broad spectrum of cases and habitats. However, we explicitly recognize that this decision limits direct representativeness, owing to the inherent heterogeneity and the absence of standardization across the global literature.

2.2. Literature search and selection

We conducted a systematic review of peer-reviewed literature on the retention and trapping of plastic particles, both microplastics and macroplastics, by aquatic and coastal vegetation. The primary search was conducted in Scopus using the Advanced Search function, focusing on titles, abstracts, and keywords. Supplementary searches were conducted in PubMed (titles and abstracts) and the Web of Science Core Collection during the preliminary scoping, which returned results similar to those from Scopus. The search spanned publications from 1990 to 16 June 2025, the date of the most recent search.

To better align with the review goal of plastic retention in aquatic vegetated environments and to minimize unrelated terrestrial, agricultural, and molecular biology studies, we refined the search through an iterative process (Table SM1).

- Scopus (TITLE-ABS-KEY) scoping query (broad; not used for screening): TITLE-ABS-KEY("Plastic") AND TITLE-ABS-KEY ("vegetation") AND TITLE-ABS-KEY("entrapment" OR "accumulation"), n = 7323
- Scopus (TITLE-ABS-KEY) refinement (not used for screening): TITLE-ABS-KEY("Plastic" OR "microplastic") AND TITLE-ABS-KEY ("vegetation") AND TITLE-ABS-KEY("entrapment" OR "accumulation"), n = 2385
- Final Scopus query used for PRISMA screening (TITLE-ABS-KEY): TITLE-ABS-KEY("Plastic" OR "microplastic") AND TITLE-ABS-KEY ("aquatic") AND TITLE-ABS-KEY("vegetation") AND TITLE-ABS-KEY ("entrapment" OR "accumulation"), n = 1363

PubMed checks using the same concepts in Title/Abstract were performed during the initial scoping/refinement and for the final query (see Table SM1).

The records from the final Scopus search were exported and systematically compiled for screening. Microsoft Excel was used to record inclusion or exclusion decisions, and Zotero (version 7.0) was used for final reference management. Duplicate removal was performed in Zotero using DOI and title matching, with manual verification as needed.

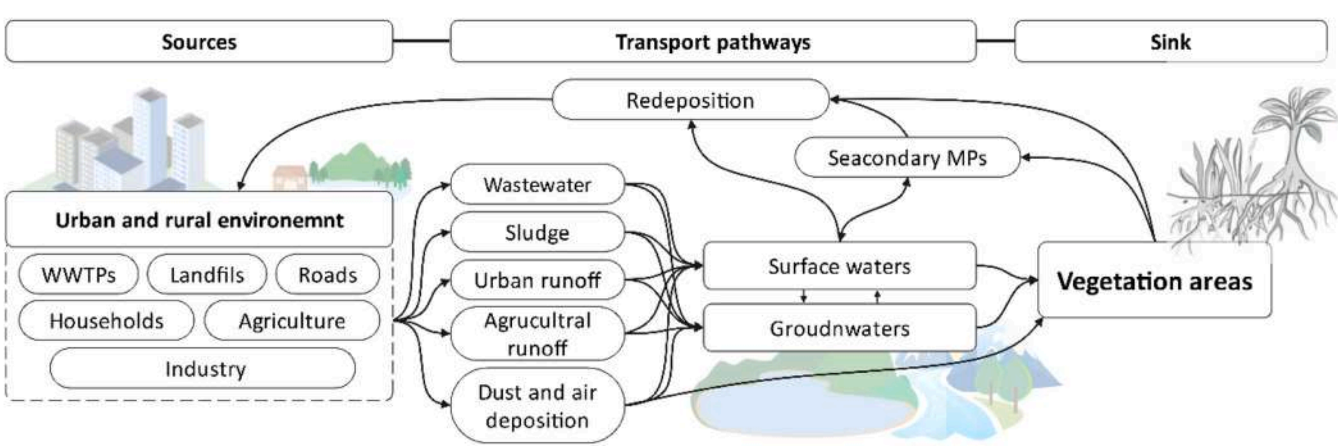


Fig. 1. Conceptual framework of microplastic sources, transport pathways, and sinks. This schematic shows plastics' journey from origin to the environment. Sources include industrial, domestic, and agricultural activities in urban and rural areas. Transport pathways involve wastewater, runoff, and atmospheric deposition. The diagram shows macroplastics degrading into secondary microplastics (MPs) and redepositing via wind and water. These deliver plastics to vegetation areas, the primary sinks of this review.

The screening process occurred in two phases: first, title/abstract screening, and then full-text review based on specific eligibility criteria. Studies were included if they investigated plastics (micro- and/or macroplastics) in aquatic or coastal vegetated habitats like mangroves, salt marshes, seagrass meadows, or vegetated dunes, with a focus on vegetation-assisted trapping or retention. Additionally, two other factors were considered, which are:

1. Reported quantitative abundance or concentration data with specified matrix and units (e.g., items/kg dry sediment; items/m^2; items/L), or
2. Presented mechanistic evidence of retention related to vegetation structure or habitat processes, such as canopy baffling, root interception, strandline or wrack retention, or wind interception.

In contrast, studies were excluded if they:

- Were outside vegetated aquatic or coastal habitats (e.g., terrestrial agriculture lacking a relevant aquatic context);
- Focused solely on ingestion outcomes without relating to vegetation-mediated retention;
- Emphasized molecular or biological endpoints (e.g., DNA/genetic responses, biomarker-only studies) without relevance to habitat-scale trapping or retention;
- Did not present extractable quantitative data or usable mechanistic evidence; or reported incompatible matrices or units without adequate metadata for interpretation (e.g., missing information on dry vs. wet basis, sampling depth, or size-class definition).

From the final Scopus search (n = 1363), 1128 records were excluded during title/abstract screening. 235 full texts were assessed for eligibility; 36 were excluded. 199 studies were included in the final synthesis. The screening process and reasons for exclusion are summarized in the PRISMA flow diagram (Fig. 2).

The reviewed papers covered multiple ecosystems (unique assignment; n = 199):

- Marine (including Seagrass meadows/tidal): 42 articles (21.1%)
- Coastal: 24 articles (12.1%) 12.06
- Freshwater: 28 articles (14.1%) 14.07
- Mixed studies (≥2 environments): 76 articles (38.2%)
- Terrestrial/other: 20 articles (10.1%)
- Unclassified/broad: 9 articles (4.4%)

Each study is counted once; "multi-ecosystem", defined as mixed, includes studies spanning more than one ecosystem. Additionally, 36 further studies were reviewed, focusing on MPs generation, degradation, transport, and emission pathways, to provide a comprehensive overview of plastic sources relevant to vegetated ecosystems.

2.3. Data extraction and synthesis

From selected studies, data were systematically extracted on:

- Ecosystem type and dominant vegetation species
- Plastic size classes and polymer types studied
- Polymers and shapes,
- QA/QC (when reported),

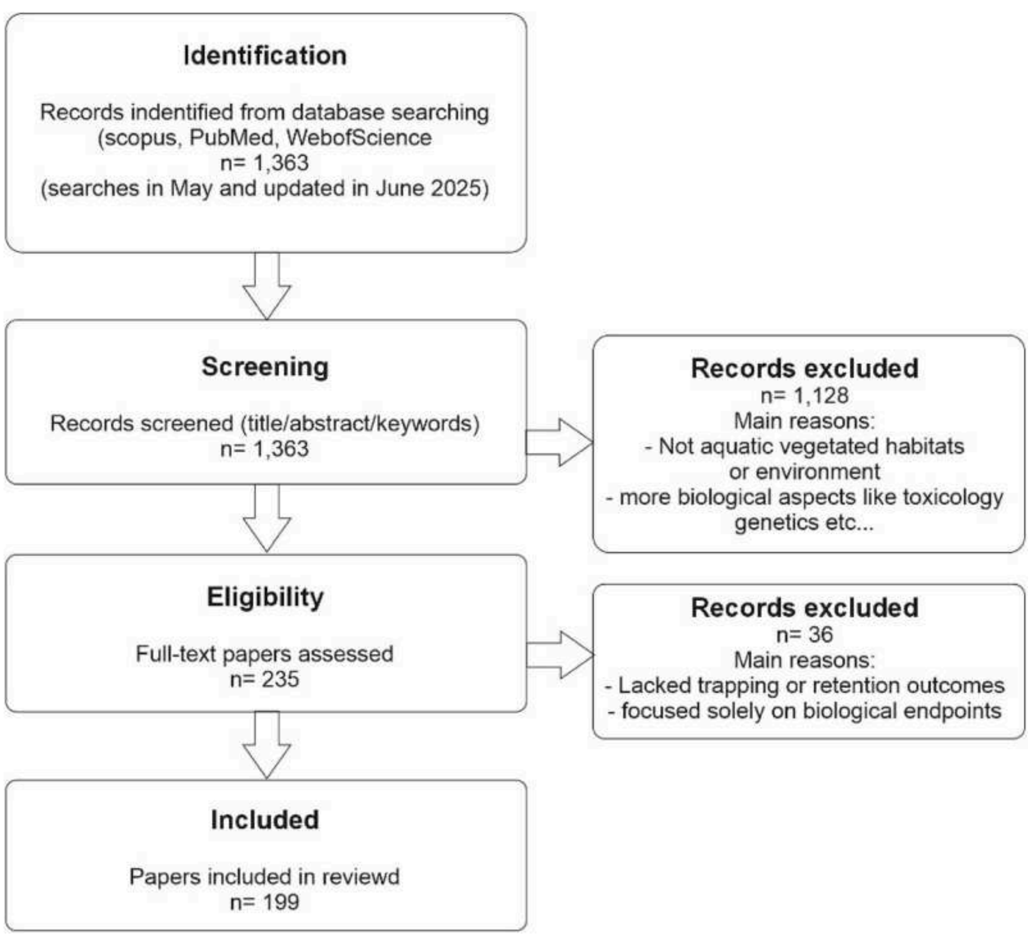


Fig. 2. PRISMA flow diagram illustrating the study selection process for this review.

- Abundance values (as originally reported),
- Mechanistic details of plastic trapping (physical, chemical, and biological processes)
- Environmental and structural factors influencing trapping efficiency
- Methodologies employed (sampling, analytical techniques, modeling approaches)

Data were qualitatively synthesized thematically to describe mechanistic processes across habitats, highlighting comparative trends and knowledge gaps. Quantitative data on plastic concentrations and trapping efficiencies were organized and analyzed where applicable.

2.4. Scope and limitations

This review mainly focuses on how vegetation physically traps plastics by examining the interactions between plastic properties and plant structures across different habitats. In particular, it highlights physical trapping and retention mechanisms resulting from interactions among vegetation structure, hydrodynamics, and plastic traits. It does not provide detailed discussions of downstream ecological effects, such as influences on plant physiology, soil and microbial communities, biogeochemical cycles, or ecosystem services. These broader ecological and ecosystem-service implications will be addressed in a forthcoming publication.

A key challenge in synthesizing this literature is the persistent lack of methodological consistency. Despite standards for plastic analysis and reporting, articles rarely mention them, and sampling strategies and methods vary widely [36]. This inconsistency, combined with different units in matrices and the absence of analytical blanks in previous studies, undermines data comparability and raises concerns regarding the reliability of the results, particularly at low concentrations.

Because the reviewed studies measure plastic abundance in different environmental matrices and report units (like items per kg of dry sediment, items per liter of water, or items per square meter of surface), this review does not directly compare quantities across these matrices. Instead, it provides matrix-specific summaries along with key methodological metadata to avoid any misleading comparisons. By recognizing these limitations, the authors support the need for more standardized methods and definitions to make future research more rigorous and comparable.

Having established a thorough, systematic approach to literature selection, the subsequent sections delve into the mechanisms by which vegetation traps plastics. We begin by examining the physicochemical properties of plastics that influence their behavior in vegetated environments, followed by an analysis of habitat-specific trapping mechanisms. Additionally, insights into environmental and structural factors that affect trapping efficiency are presented, providing a basis for understanding plastic accumulation across various ecosystems.

2.5. Terminology

This review uses standardized terminology to distinguish external surface binding from internal uptake and to avoid confusion between eco-corona formation and microbial biofilms. The definitions are summarized in Table 1.

3. Types of plastics and physicochemical properties

Macroplastic pollution, defined as plastic debris larger than 5 mm, has become a widespread threat to freshwater, marine, and terrestrial ecosystems worldwide. These large plastic items are common across rivers, lakes, and coastal regions, with rivers acting as primary transport pathways and accumulation zones that carry plastics from land into the oceans. Key factors driving macroplastic accumulation include urbanization, population density, and inadequate waste management, especially in urban areas and along riverbanks. Typical macroplastic debris includes bags, bottles, food wrappers, and packaging materials, mainly originating from households and consumer sources [39–41].

Importantly, the fragmentation of macroplastics serves as a primary source of MPs, plastic particles smaller than 5 mm that interact closely with vegetation surfaces and sediments. Understanding this size continuum is essential to comprehensively assess the impacts of plastic pollution, which we explore next with a detailed focus on MPs.

3.1. Origin of microplastics

Microplastics (MPs) originate from numerous sources, primarily driven by the widespread use of plastics in everyday human activities and industry. They are classified into two types: primary MPs and secondary MPs. Primary MPs are released into the environment as micro- or nanoparticulate matter, whereas secondary MPs originate from the fragmentation of larger plastic pieces or other microplastic fragments [42]. The main sources of primary MPs include tire dust, artificial turf, synthetic fibers, and coatings [43,44]. In addition, exfoliants in personal care products and scrubs [45], oil drilling fluids, abrasive agents [46], glitters [47], and improperly handled plastic raw materials [15].

The formation of secondary MPs occurs when already deposited plastics are affected by chemical, physical, biological, or combined processes [48]. Main types of plastic degradation reactions include photodegradation, oxidation, thermal degradation, hydrolysis [49], enzymatic degradation, bacteria-driven degradation [50], or even direct ingestion by animals or insects [51], as well as abrasive forces and physical wear [52]. The degradation and aging of already deposited MPs can significantly change their properties. Aged MPs are usually smaller,

Table 1
Standardized terminology used in this review.

Term	Definition	Typical relevance	Notes
Adsorption / attachment	Particles bind externally to surfaces such as leaf cuticles, root epidermis, sediment organic matter, or EPS/biofilm matrices without penetrating the plant tissues.	Macro/MP/NP; leaf/canopy, root/rhizosphere, sediment/soil	For adhesion or retention on surfaces; avoid using 'absorption' for this purpose.
Absorption / uptake	Entry of particles into plant tissues or cells (apoplast and symplast) and their potential translocation.	Mostly, NP (and the smallest MPs) are observed under controlled conditions, focusing on roots and leaves.	Only when internalization is confirmed, such as through imaging or tracer evidence.
EPS	Extracellular polymeric substances: sticky polymeric matrix secreted mainly by microbes that promotes adhesion and aggregation.	MP/NP; plant surfaces and plastic surfaces	EPS is a matrix, and a biofilm is a microbial community embedded in EPS.
Biofilm	Structured microbial community embedded in EPS attached to a surface (plant or plastic).	MP/NP; leaf/canopy, roots, sediment interface	Biofilm can form on plants and on plastics; do not equate biofilm with eco-corona.
Eco-corona	Environmentally acquired molecular coating (e.g., natural organic matter) that modifies particle surface properties (charge, hydrophobicity) and can precede/enhance biofilm formation.	Mostly NP/MP; water and sediment interfaces	Eco-corona ≠ biofilm; eco-corona is a molecular coating, and biofilm is a living community.
Plastisphere	Plastic-associated biofilm community colonizing plastic surfaces.	MP/NP; plastic surfaces in any environment	Plastisphere refers to the community on plastics (a specific biofilm type).

have an irregular shape, and increased roughness compared to pristine MPs. This results in higher reactivity, such as improved adsorption of heavy metals [53], organic pollutants, or potentially greater bacterial uptake [54].

Primary MPs are mainly released through everyday human activities and industrial processes. In contrast, secondary MPs are reemitted from environmental matrices and redeposited. Both types of MPs mainly enter the environment via pathways closely linked to urbanization, population density, and local industry. Municipal and industrial wastewaters are key sources of MPs, as large amounts are directed to wastewater treatment plants through activities such as washing, urban runoff, and manufacturing [55]. In wastewater treatment plants, MPs are effectively captured in the activated sludge; however, their removal during treatment is incomplete, leading to their release into the environment with the treated effluent. This poses a significant challenge to aquatic environments due to the large volume of treated wastewater discharged [5]. Furthermore, the presence of MPs in sewage sludge limits its use on agricultural land because this practice can directly transfer MPs to plants and crops [56]. Landfill leachates are also a significant source of MPs. Rainwater can mobilize primary MPs, such as those from residual personal care products. At the same time, landfills can release significant amounts of secondary MPs as plastic waste accumulates and undergoes weathering and degradation [57]. Another important source of MPs is surface and urban runoff. This media is known to contain various types of MPs; however, the dominant types are tire-wear-related and road-marking-related particles. Due to high friction between road surfaces and tires, polymer abrasion occurs, and subsequent rainfall results in runoff enriched with MPs [58].

A wide variety of MPs sources and their high transfer potential contribute to the global dissemination across almost all Earth biomes and environments. MPs have been detected throughout surface waters [59,60], coastal zones [61], marine waters [62], and soils [63]. MPs are even present in remote areas, such as the Tibetan Plateau, indicating substantial potential for their long-range atmospheric and environmental transport [49].

3.2. *Physicochemical properties of MPs*

While the environmental context of polluted habitats affects the fate and behavior of MPs, interactions within specific environmental matrices are influenced by MPs' physicochemical properties.

The physicochemical characteristics of plastics, such as size, shape, density, buoyancy, and surface chemistry, are crucial in shaping their environmental fate and interactions with vegetated ecosystems. Polymer composition mainly determines properties like density and buoyancy, which in turn affect sedimentation, transport pathways, and accumulation patterns [63,64]. Main polymer types of MPs include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyester (PES), polyvinyl chloride (PVC), and polyurethane (PUR). For example, PP and PE have specific gravities of approximately 0.83–0.85 and 0.91–0.94 g/cm^3 , respectively, allowing them to float on water surfaces. Conversely, PET and PS have higher specific gravities than water and tend to sink [65]. Table 2 summarizes the density, buoyancy, and typical environmental behavior of these common plastic polymers. Additionally, the chemical composition influences surface properties, such as roughness and charge, which, in turn, affect interactions with sediment or soil minerals [66], organic matter [67], or plant roots [68]. Researchers classify MPs into various shapes, including particles, pellets, microbeads, fibers, films, nets, spheres, foams, flakes, or irregular fragments [64]. The shape of primary MPs derives from their source materials, while secondary MPs are shaped by degradation and weathering processes. For instance, MPs from cosmetic products are typically spherical, while fibers mainly come from clothing-related sources. Irregular fragments are common among secondary MPs exposed to environmental conditions [69]. The size of MPs varies widely, from macro-sized particles up to 5 mm to nanoplastics smaller than 1 µm [70,71].

Table 2
Influence of physicochemical properties on vegetation trapping efficiency. The weathering and biodegradation of MPs particles typically reduce their size and alter their shape, affecting their mobility and reactivity in the environment [61, 64]. For instance, the degradation of MPs often leads to oxidation of their surfaces, increasing the presence of oxygen-containing functional groups such as carbonyl, carboxyl, or hydroxyl [74]. Additionally, during degradation, MPs can release additives used in their production, potentially emitting toxic chemicals such as flame retardants, plasticizers, and stabilizers [75]. This also includes the release of specific oligomers during MPs degradation, which could have harmful effects on plants and microbiota.

Plastic characteristic	Description - Key classifications & metrics	Effect on trapping mechanism	Typical trapping mechanisms and ecosystems
Density	Low: PE, PP (0.83–0.94 g/cm^3) High: PET, PVC (1.16–1.56 g/cm^3)	Buoyancy: Low-density polymers float and transport easily; high-density polymers settle rapidly.	Floating: Trapped by surface vegetation (e.g., riparian mats). Sinking: Burial in sediments (mangroves, salt marshes). Water-surface canopies, sediments
Size	Macro (>5 mm), micro (<5 mm), nano (<1 µm)	Mobility: Larger items are governed by inertia/drag; colloidal forces influence smaller particles.	Smaller particles adhere to biofilms and electrostatic attraction (leaves/root hairs). larger ones physically trapped, entanglement (roots/branches) Mangroves, seagrass, riparian, dunes
Shape	Fibers, fragments, beads, films	Settling Velocity: Spheres settle fastest; fibers have high drag and stay suspended longer.	Fibers entangle easily; fragments settle differently based on shape All habitats
Surface Roughness	Pristine: Smooth Weathered plastics have higher adhesion due to biofilm formation	Biofouling: Weathering increases surface area (30–50%) and hydrophilicity.	Adhesion: Rough surfaces support the formation of "eco-corona" (biofilm), enhancing stickiness to plant surfaces. Mangrove roots, seagrass leaves
Aging	UV Degradation Oxidation	Reactivity: Increases oxygen-containing functional groups (C=O, C-OH).	Interaction: Aged plastics interact more strongly with mineral sediments and plant roots via heteroaggregation.

The shape and size of MPs strongly influence their reactivity and behavior in environmental matrices. Some studies suggest that spherical MPs settle faster in water than other types [72], potentially improving their confinement in sediments. Conversely, fibrous MPs show lower settling velocities and can be transported over greater distances by air [73]. The effect of shape on MPs' bioavailability remains unclear, as different species efficiently ingest various types of MPs, including microbeads, fibers, and irregular fragments [69]. Regarding size, larger MPs generally settle faster in the water column than smaller particles, affecting the transport and accumulation of MPs in environmental matrices. Additionally, smaller MPs have a higher surface area-to-volume ratio than larger particles, resulting in increased reactivity [67]. This is evidenced by smaller MP fractions adsorbing more effectively on mineral surfaces or adhering to natural organic matter than larger ones. Table 2 summarizes how these key characteristics affect trapping mechanisms.

Building on this understanding, the following section examines how these properties affect the physical trapping and retention of plastics across habitats by different vegetation types.

4. Vegetation trapping mechanisms

Coastal and riverbank plant communities play a crucial, though passive, role in the plastic pollution cycle by acting as natural filters for human-made debris (Fig. 3). This section examines the primary mechanisms by which various vegetated ecosystems capture plastics, highlighting how the structural complexity of these plants creates conditions that slow water and wind flow, allowing plastics to settle and remain in place instead of being carried further into marine or terrestrial environments.

4.1. Habitat-specific trapping

A review of existing research shows that coastal habitats with vegetation tend to accumulate more plastic debris than nearby areas without vegetation (Table 3, SM2). Methodological heterogeneity (sampling depths, polymer ID, QA/QC) is addressed through Table 3 Quality Tiers (1−5) and SM2 Y/N standardization flags. Ecosystems with high complexity, such as mangroves and salt marshes, exhibit the most significant retention, with sediment MP levels ~2.05–2.82 times higher than in nearby unvegetated areas [76,77]. This phenomenon results from the presence of roots, pneumatophores, and dense canopies, which slow water flow and promote sedimentation, thereby creating low-energy environments in which plastics accumulate (Table 3a), while water column concentrations remain consistently low (0.1–3.2 items/L) across vegetated zones, reflecting effective flow attenuation (Table 3c).

While seagrass meadows trap fewer plastics, they actively remove them via Posidonia seagrass balls [78]. Field evidence also shows seagrass canopies act as local sinks: in an Orkney Zostera marina bed, microplastic loads were higher (2.7 x higher) in sediments than in nearby bare sand, and microplastics adhered to blades, with fibres making up over 50% of particles [79]. This has been observed directly for Z. marina, where microplastics occurred on every blade sample examined (mean ~4.25 items per blade) [79].

Saltmarsh strandlines show extreme accumulation (20,060 + items/m^2) (Table 3b). Riparian and dune systems serve as intermittent sinks, especially during floods or wind surges [80,81]. All these ecosystems shift from acting as filters to becoming hotspots, where trapped plastics become persistent pollution that affects microbes, enzymes, and the carbon cycle [82–84].

Beyond physical presence, trapped plastics act as chemical sources, with macro- and microplastics leaching additives. Seed impacts are mainly due to leachates, which can reduce germination, such as PBAT mulch leachates inhibiting Arabidopsis, and many leached compounds are unregulated [85]. These insights reveal the dual role of vegetation as both a mitigator and a victim of plastic pollution, emphasizing the importance of integrated management and standardized monitoring across coastal and terrestrial interfaces.

4.1.1. Mangrove and salt marsh ecosystems: complex traps at the land-sea interface

Mangrove forests and salt marshes are often regarded as highly effective in trapping plastic debris due to their unique location at the land-sea interface and their intricate physical structures [77,113,114]. The dense network of aerial roots in mangroves, such as the stilt and prop roots of *Rhizophora* species, the finger-like pneumatophores of

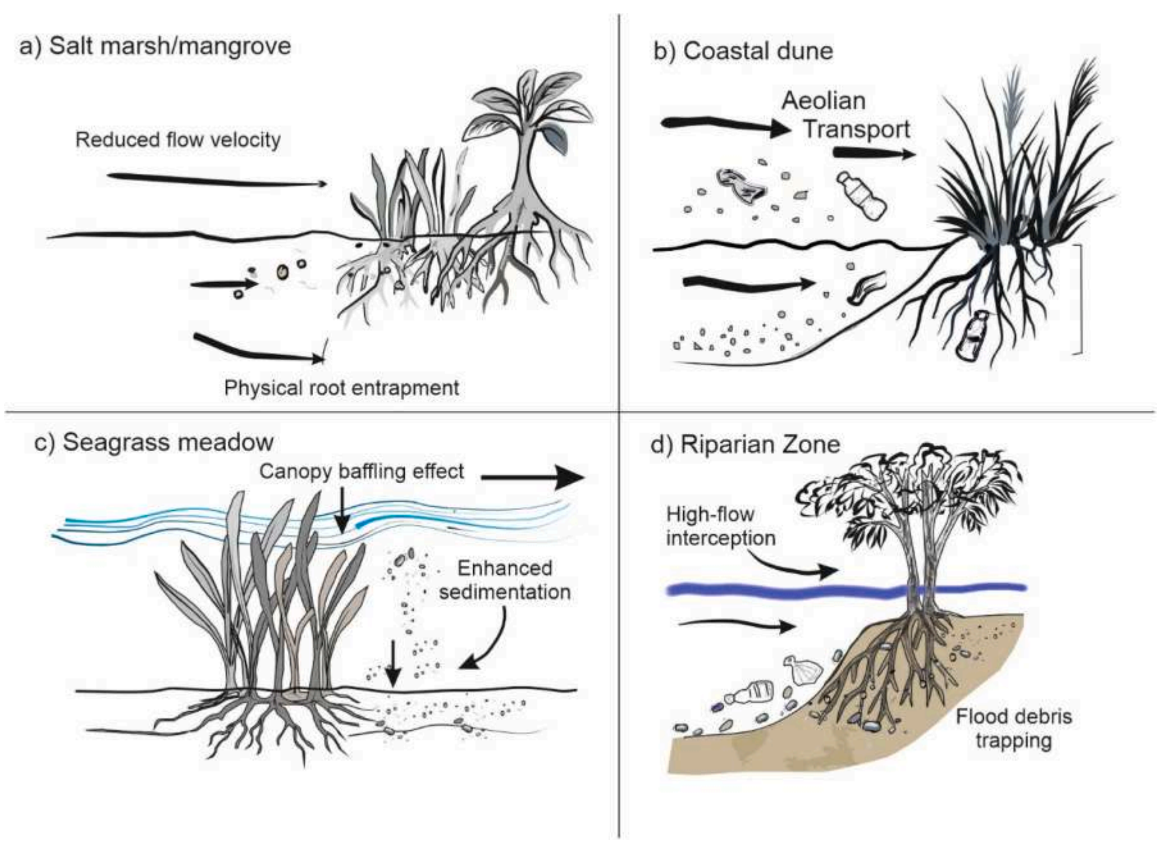


Fig. 3. Primary Physical Trapping Mechanisms of Plastic Debris in Different Vegetated Ecosystems. (a) Salt marsh and mangrove ecosystems trap debris through diminished flow velocity and the physical entanglement of roots. (b) Coastal dunes trap marine and aeolian (wind-transported) debris. (c) Seagrass meadows facilitate the entrapment of suspended particles via their canopy baffling effect, thereby promoting sedimentation. (d) Riparian zones intercept floating debris during periods of high flow or flooding.

Table 3
Data on cross-habitat plastic accumulation in vegetated ecosystems, categorized by matrix and unit. (a) Sediment microplastics are reported as items/kg of dry sediment, with the dry basis specified or marked as NR if not provided. (b) Litter from surface, strandline, canopy, or dune surface is reported as items/m^2. (c) Water-column microplastics are reported as items/L. Comparisons are made only within the same matrix and unit; no normalization across different matrices was performed, due to inconsistent reporting of essential metadata like sampling depth, bulk density, moisture or porosity, grain size, and size-class cutoffs across studies. NR indicates that metadata are not reported.

a) Sediment microplastics (items/kg dry sediment)

Ecosystem	Main vegetation	Sediment MPs (items/kg)	Main polymer	Main shape	Key trapping mechanism	QT	Ref.
Mangrove forests	*Avicennia, Rhizophora, Bruguiera*	~350–5738 (Zhang 2024: 350; Zhou: 5738; generally 1000–5000	Mainly PE, PP, PS, PES	Mainly fragments & fibers (but also foams, films and pellets)	Pneumatophore interception; tidal attenuation and deposition; enrichment toward higher tidal zones; accumulation linked to human activities; MPs undergo weathering and support carbon- and sulfur-cycling microbial colonization.	4–5	[71, 86–91]
Salt marshes	*Juncus maritimus, Spartina spp., Phragmites australis, other local saltmarsh plants*	~279–3313 (up to 9600 surface)	HDPE, PE, PP, PS, minor PET, PVC, PU	Fibers > fragments > films/ particlesmesoplastics	Canopy baffling ("vegetative roughness") traps particles and limits resuspension, tidal deposition and strandline wrack enhance accumulation; inputs from urban runoff, aquaculture, and industry; biofouling alters retention and sinking behavior.	4–5	[71, 92–96]
Seagrass meadows	*Posidonia, Zostera, Cymodocea, Halophila, Enhalus acoroides,* mixed seagrass meadows	0–1890 (vs 120 bare; up to 1630)	PE, PP, PA, PS, minor others	Fibers (most abundant), fragments, films, occasional foam	Canopy reduces near-bed velocity; epiphytes increase roughness and adhesion MPs are trapped in sediments and among shoots, with retention influenced by meadow structure (plant density, arrangement, canopy height) and increasing with seagrass cover; macro-litter similarly rises with greater vegetation complexity.	3–5	[16,78, 97–100]

b) Surface / strandline / dune-surface litter (items/m²)

Ecosystem	Main vegetation	Surface/strandline density (items/m²)	Main polymer	Main shape	Key trapping mechanism	QT	Ref.
Mangrove forests (surface litter)	*Avicennia, Rhizophora, Bruguiera*	0.98 ± 0.05–2.96 ± 0.25 (mean 1.4 ± 0.61; n = 9)	Plastics ≈ 80% of ground litter	Bags most common item	Canopy + floor retention (interception/ entanglement by vegetation structure)	3–4	[101,102]
Salt marshes (strandline)	*Spartina, Sarcocornia, Juncus*	Up to 20,060	HDPE, PE, PET	Films & mesoplastics	Canopy baffling concentrates debris at the high-tide strandline	4–5	[92–94, 96]
Seagrass meadows (surface density)	*Posidonia, Zostera, Cymodocea*	~0.06	PA (nylon), PE	Filaments & fragments	Canopy reduces near-bed velocity; epiphytes increase roughness and adhesion; blade-surface retention	3–4	[16,79,97]
Coastal dunes (surface litter)	*Ammophila, Carpobrotus, Salsola*	0.01–0.04 (active dune)	PS, PE (incl. EPS/foam)	Large fragments (macro-litter >2.5 cm)	Wind interception + vegetation windbreak (invasive plants can increase trapping)	2–4	[103–108]

c) Water column microplastics (items/L)

Ecosystem	Main vegetation	Water column MPs (items/L)	Main polymer	Main shape	Key trapping mechanism (context)	QT	Ref.
Mangrove forests	*Avicennia, Rhizophora, Bruguiera*	~1.13 **(0.8–2.5 range)**	PE, PP, PES	Fibers dominant (e.g., 67–80%)	Flow attenuation + interception promotes retention within vegetated zones (reduced export)	**4.-5**	[109, 110]
Wetland	*Wetland vegetation*	86–252 items/L (mean 86 ± 43.75; 144.25 ± 59.62	PE, PVC (also PET, PP)	Filaments dominant (≈78%); threads (≈20%); pellets (≈2%)	Flood/runoff inputs + low-energy/vegetation-influenced retention; fine/OM-rich wetland setting promotes deposition and persistence	**4**	[111, 112]
Saltmarshes	*Spartina spp., Phragmites australis*	0.5–15 (canopy zone)	PP, PE, PS	Fibers>fragments	Canopy baffling reduces export; tidal trapping	**4–5**	[21]
Seagrass meadows	Zostera, Posidonia, Cymodocea	0.1–3.2 (meadow interior)	PA, PE, PP	Fibers dominant	Canopy slows flow; epiphyte adhesion retains MPs	**3–4**	[29]

Note Quality Tier (QT, 1–5 scale): 5 = FTIR/Raman polymer ID with blanks and complete metadata (depth, size cutoffs); 4 = explicit QA/QC with high transparency; 3 = partial methods reported; 1–2 = limited data or review-only.

Avicennia and *Sonneratia* species, serves as a strong physical barrier [77, 115–117]. This structure (Fig. 4) significantly reduces wave and tidal energy, thereby generating low-energy zones that facilitate the settling of suspended particles, including plastics [77,118]. This accumulation is especially notable at the microscale, as studies indicate the highest concentration of MPs occurs in the immediate root hair zone (0–2 cm from the root), with smaller particles tending to migrate towards the root system [119].

Furthermore, the effectiveness of mangroves and salt marshes as plastic sinks varies across different areas, forming a heterogeneous mosaic influenced by external human activities and internal hydrodynamic processes. The amount and type of plastic entering these ecosystems are closely linked to their proximity to human settlements. Mangrove forests, especially in Avicennia marina along the Saudi Red

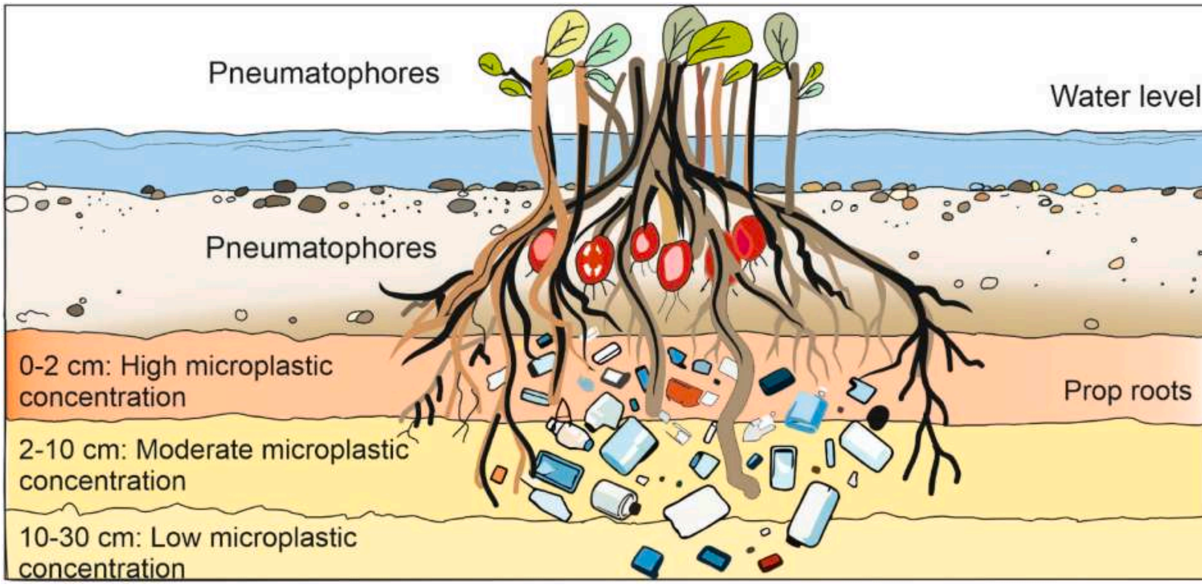


Fig. 4. Vertical stratification of microplastic accumulation in the mangrove rhizosphere. The network of pneumatophores and prop roots helps sediment accumulation and traps plastic debris. The diagram shows a decreasing plastic concentration with depth, with the surface layer (0–2 cm) acting as a high-accumulation zone due to biofilm and physical interception. Deeper layers (2–30 cm) have lower concentrations, indicating limited vertical movement of plastic. This surface accumulation forms a hotspot, increasing exposure risks for benthic fauna and plant roots.

Sea and Arabian Gulf, act as macroplastic sinks with litter densities of ~0.7–1.2 items/m², over 92% plastics. Denser stands trap more debris, with item types accumulating in specific areas, and mangroves retain more large/heavy items than nearby beaches [120]. For example, studies have observed significantly higher litter densities in mangroves near residential areas than in uninhabited areas [102]. A transect survey found surface litter levels between 0.98 ± 0.05 and 2.96 ± 0.25 items/m² (average 1.4 ± 0.61 items/m²), with plastics making up about 80% of the ground litter and single-use plastic bags being the most frequently encountered item (Table 3) [101]. Therefore, plastic levels in vegetated areas are strongly linked to population density and urban development [121]. Pollution sources, such as nearby mariculture, industry, or urban runoff, also influence the types of plastics found, creating localized hotspots of specific polymers, including foams or fibers [122]. Internally, tidal fluctuations significantly affect the distribution of plastics entering these systems. Research indicates that microplastic abundance tends to increase from low to high tidal zones, with the high-tide strandline serving as a primary accumulation zone where debris settles and remains [92,123]. Consequently, understanding the role of a mangrove or salt marsh as a plastic sink requires consideration of its physical structure, landscape context, and the dynamic effects of tides.

This trapping mechanism is notably higher in mangrove sediments than in nearby unvegetated areas, with plastic concentrations notably higher in mangrove sediments. For example, studies indicate that mangrove sediments can contain 1.6–2.9 times more MPs than non-vegetated sediments [87,100]. In some Brazilian mangroves, litter densities averaged 22.8 items/m², making them among the most polluted globally [102]. The density of the vegetation itself significantly affects trapping efficiency; dense mangrove pneumatophores enhance microplastic accumulation in sediments and increase surface adhesion/attachment through direct contact [90,117]. The trapped MPs are mainly composed of fibers, fragments, and pellets of PE, PP, and PS. In certain areas, concentrations of tiny particles (<300 μm) have reached as high as 3840 particles per kilogram [86,88].

Likewise, salt marshes, particularly those dominated by species like *Spartina anglica* and *Suaeda salsa*, enhance sediment accumulation and create vegetative roughness that prevents the transport and resuspension of MPs [76,92,95,114]. This process is part of a broader phenomenon known as 'bio-geomorphic feedback,' in which vegetation affects sediment transport, thereby increasing particle retention, including plastics [124]. Sediment properties also influence accumulation; higher levels of MPs often associate with greater silt content and particulate organic carbon (POC) [87,122].

In addition to plant structure, the vertical burial of plastics is significantly influenced by bioturbation by fauna, such as crabs, which actively disturb and rework the sediment [76]. Consequently, both mangroves and salt marshes serve as essential long-term reservoirs for plastic pollution in coastal regions, as reported by [125]. Similarly, mangrove sediment cores from the Mae Klong River mouth (Thailand) contained MPs throughout the profile (to 142 cm), dominated by fibres [126]. This long-term sink function is consistent with evidence from Mediterranean coastal wetlands, where decades-scale litter accumulation, dominated by plastics, was observed under drought/water stress [127].

4.1.2. Seagrass meadows: subtidal canopies as particle sinks

In subtidal coastal zones, seagrass meadows are increasingly seen as necessary for trapping marine plastics [78,128]. However, compared with other coastal wetlands, they appear to be less dominant sinks; a comprehensive meta-analysis found that plastic concentrations in seagrass meadows are generally lower than those in mangrove forests and tidal marshes [71]. The thick canopies formed by species like Zostera marina and Posidonia oceanica act as barriers, altering local water flow by reducing currents and wave energy [16,129]. Field surveys in four South African estuaries show dense Zostera capensis meadows usually harbor more MPs than patchy meadows or unvegetated sediments, supporting the idea that seagrasses act as local particle sinks [130]. This "canopy baffling" effect can reduce flow velocity by 40–60%, thereby facilitating the settling of suspended particles, including MPs, to the bottom and their accumulation in the sediment beneath [100,131].

The scale of this contamination can be significant, with reported microplastic abundances in seagrass sediments ranging from 0 to 1817 particles per kilogram of dry sediment [31]. As a result, research shows that seagrass sediments often contain significantly higher concentrations of MPs, ranging from 2.1 to 2.9 times those in nearby areas without vegetation [100].

Microplastic composition in these systems is distinct. Numerous studies consistently show that MPs in seagrass meadows, both in sediment and on leaves, are mostly fibers. One study found that fibers accounted for 91.8% of all MPs identified, with textile fibers (60%) and synthetic lines (20%) as the primary sources [29,129].

The effectiveness of this trapping mechanism varies with the meadow's structural characteristics. Hydraulic flume simulations have demonstrated that trapping efficiency depends on factors such as plant density, height, and spatial arrangement. [16]. Notably, meadows with lower planting density and random spatial distribution were generally more effective at capturing MPs than denser, grid-patterned meadows. This is probably because their irregular flow patterns promote greater particle deposition [16]. However, in situ evidence shows higher sediment MP abundances in dense seagrass areas than in patchy or bare ones, with one estuary showing higher MPs in unvegetated areas, highlighting local hydrodynamics and source proximity [130].

Beyond sediment accumulation, seagrasses also trap plastics through two additional mechanisms. First, microplastic fibers and fragments can adhere directly to the surface of seagrass blades, thereby increasing the plastic reservoir within the canopy [29,129]. Second, the Mediterranean seagrass Posidonia oceanica offers a unique natural process for removing plastics. When the seagrass sheds its leaves, the natural fibers intertwine with plastic debris under wave action, forming dense aggregates called "seaballs" or aegagropilae [78]. These buoyant seaballs (Fig. 5) can trap up to 200 plastic items per ball and are eventually washed ashore, effectively removing plastics from the marine environment and functioning as a novel ecosystem service [78]. However, the role of seagrass as an enhanced sink is not consistent across contexts; some studies report no significant difference in microplastic levels between seagrass and bare sediments, suggesting that local water movement and proximity to plastic sources often have a greater impact on accumulation than vegetation presence [129].

4.1.3. *Coastal dunes and backshore vegetation: barriers to aeolian and marine transport*

Landward of the coast, psammophilous vegetation on dunes and backshores acts as a crucial natural barrier, capturing large amounts of litter carried by wind and waves [107,108]. The beach's strandline is often the main area for this debris, which frequently consists of buoyant, lightweight materials like foam fragments and cigarette butts that are easily blown or washed inland toward the dunes [132]. As the litter moves inland, plant communities block its path, trapping and accumulating it [133,134]. The strong negative relationship between vegetation cover and litter levels suggests that denser plant growth effectively slows or stops the inland movement of debris.

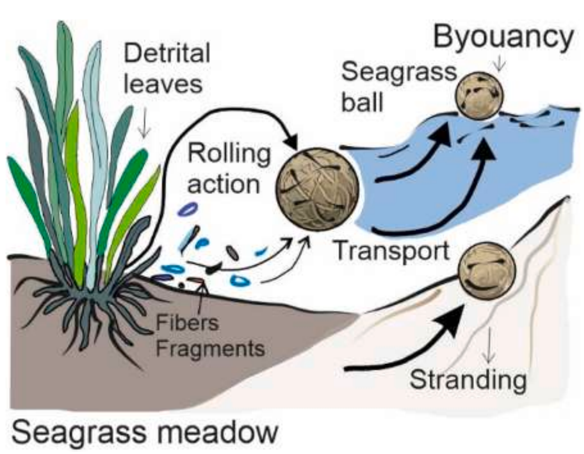


Fig. 5. Unique removal of MPs process in *Posidonia oceanica* seagrass meadows. Detrital leaves and fibers roll across the seafloor, collecting plastic fibers and fragments. This creates buoyant "seaballs" that are transported by currents and eventually wash ashore.

This creates a clear trapping hierarchy: high-efficiency species such as dense stands of invasive *Carpobrotus spp*. and native dune builders like *Ammophila* can capture > 80% of incoming litter; medium-efficiency species (50–80%), including *Cakile maritima* and the low, thorny *Salsola kali*, retain substantial amounts due to their extensive root systems or compact canopies; whereas low-efficiency pioneer plants capture < 50% of debris [104,108,135,136]. Other species, such as *Phragmites australis, Spartina versicolor*, and *Anthemis maritima*, interact directly with trapped expanded polystyrene (EPS) [106]. Furthermore, studies indicate a specific pattern of debris accumulation, with most debris accumulating at the seaward edge of vegetation patches rather than at their centers. This phenomenon is referred to as the 'Plant-edge litter effect' [136].

While much of the focus has been on visible macro-litter, studies have also measured microplastic pollution in dune sediments, revealing concentrations comparable to those on adjacent beaches, ranging from 450 to 1150 particles per kilogram [80]. The distribution of these MPs appears to be associated with sediment characteristics, with a positive correlation with the percentage of very fine sand. Compositionally, these dune MPs are often primarily composed of semi-synthetic fibers (40%), such as rayon, followed by PE (~30%) and PP (~20%). This dominance of fibers indicates a significant input from atmospheric deposition in addition to sea spray [80]. Vertically, these plastics are most concentrated in the top 0–5 cm of sediment, decreasing rapidly with depth.

While foredunes serve as the first line of defense, the backshore and back-dune areas are increasingly recognized as major long-term sinks for marine debris [105,137,138,139]. Lighter materials, especially EPS, are vulnerable to wind transport and tend to accumulate heavily in back dune reedbeds [106,140]. Furthermore, it is worth noting that human activities can unintentionally exacerbate this accumulation; for instance, daily beach cleaning can dislodge debris into back-beach vegetation, where it becomes trapped and often escapes subsequent cleanup efforts [141]. This underscores that typical beach clean-ups may overlook a significant reservoir of plastic pollution, highlighting the need for targeted efforts in these sensitive, vegetated areas [108].

4.1.4. *Riparian and freshwater vegetation: halting and transporting fluvial plastic*

In freshwater environments, vegetation plays a vital and complex role in determining the fate of plastics as they are transported from land sources toward the ocean [142]. Riparian plants along riverbanks serve as key retention points for macroplastics within the river system [30]. Riparian forest species can intercept up to 93.9% of riverine macrolitter, with trees, shrubs, and reeds accounting for approximately 85% of the total litter [30]. During periods of high discharge and flooding, when plastic transport increases, trees, shrubs, and reeds along the banks act as natural filters, physically capturing floating debris displaced from the main channel [81,143]. Structures with high structural complexity, such as overhanging trees, dense vegetation, and large wood jams, are particularly effective at creating "hotspots" where macroplastics accumulate, thereby significantly reducing pollutant flow downstream [144,145]. At the wetland habitat level, MP distributions can be distinctly divided by flow or deposition zones: [146] observed microfibers were mainly found in mudflats without vegetation, whereas microfragments were more common along vegetated channel edges. For hydrodynamic

Within the water column, both submerged and floating macrophytes affect plastic transport. Submerged plants, such as *Hydrilla verticillata*, can directly trap MPs on their intricate leaf surfaces through physical adhesion [147], and MP abundance can be higher in sediments immediately surrounding submerged vegetation than in nearby unvegetated sediments [148]. In wetlands and low-flow areas, dense vegetation such as common reeds (Phragmites australis) effectively filters MPs from wastewater and urban runoff, leading to their settling and accumulation in sediments. Consistent with this filtering role, microplastics in a tidal freshwater urban wetland were significantly lower in dense vegetation compared to mudflats, channel edges, and drift lines within the tidal wetland. The abundance of microfibers was negatively associated with vegetation cover and stem density, indicating that vegetation intercepts MPs before they reach the marsh interior [146]. Studies have found that microplastic levels in reed beds are approximately 20–30% higher than in adjacent open water, indicating the efficient trapping of MPs from flooding waters [112,149,150]. Some freshwater plants are so efficient at retaining MPs that they are being studied as natural biomonitors. For instance, aquatic mosses such as *Fontinalis antipyretica* have been shown to capture microplastic fibers and films, enabling analysis to assess river pollution over time and have been used specifically to map microplastic pollution in European rivers [151].

Floating aquatic vegetation, particularly invasive species such as water hyacinths (*Eichhornia crassipes*), plays a complex dual role. These plants form dense, wide mats that are highly effective at collecting and trapping large amounts of floating macroplastics (Fig. 6) [152]. In this way, they serve as a significant temporary sink. However, this creates a floating vegetation paradox: while they act as temporary sinks, these plastic-loaded mats are not fixed; they are transported by river currents, effectively becoming large-scale carriers. Research indicates that floating mats can transport up to 78% of river plastics downstream, releasing them in new areas when they strand or fragment [153].

Environmental dynamics and timescales underscore the designation of a temporary sink. For riparian habitats, flood pulses and seasonal high-discharge events are crucial, as they can resuspend plastics previously trapped in vegetation or floodplains and redeposit them downstream or into new sinks [76,144]. The ability of riparian vegetation to act as a sink depends heavily on timing and hydrological flow rates. During base-flow conditions (0.1–0.3 m/s), vegetation serves as an efficient trap, capturing a large fraction of macroplastics over months [30]. In moderate floods (0.5–1.2 m/s), retention remains high at 60–90%, though some plastics are remobilized (10–20%) as flow energy increases [153]. During extreme events ($>$3 m/s), the sink function collapses: retention falls below 10%, and most of the stored plastics are remobilized (80–95%) [144,153]. Consequently, evaluating the long-term success of micro- and nanoplastics removal in river systems requires considering these time-dependent processes of entrapment and release. This reveals a dynamic in which vegetation can both reduce and increase the transport of plastic pollution through river systems. This sink-to-source switching implies a management need: accumulated edge macrolitter and plastic-laden floating mats should be treated as pre-event priority targets for removal/containment when flood-stage warnings are issued (see Section 5.3).

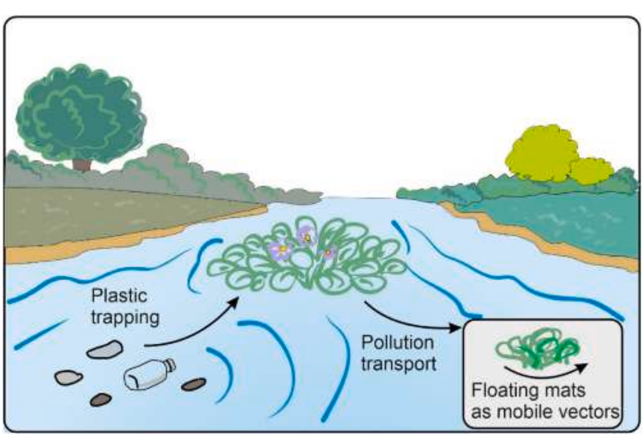


Fig. 6. The dual role of floating vegetation. Dense mats of floating vegetation, like water hyacinth, are highly effective at trapping floating macroplastics. However, these mats are not stationary and can be transported downstream by currents, serving as vectors for the transport of physical pollution.

4.2. Surface adhesion as a trapping mechanism

This section uses terminology from Section 2.4 (Table 1), distinguishing between adsorption/attachment and absorption/uptake, and clarifying terms like EPS, biofilm, eco-corona, and plastisphere.

While the habitat-specific examples in Section 4.1 highlight large-scale physical interception, retention also relies on micro-scale processes. In addition to entanglement, the surface characteristics of plastics and plants play a key role in trapping, particularly for smaller particles. This section analyzes these important surface adhesion mechanisms.

Beyond large-scale physical filtration, microplastic retention is largely influenced by surface adhesion mechanisms, especially for smaller particles that may not be physically blocked but can instead adhere to plant surfaces [147]. For MPs, this interaction primarily involves adsorption (external attachment) rather than absorption (internal uptake), as observed in the roots of submerged macrophytes such as Egeria densa, where particles attach to the root surface without penetrating the tissue [154] and in free-floating duckweed (*Lemna minuta*), where SEM observations showed MPs adsorbed on frond and root surfaces [155]. However, research on smaller plastic particles, or nanoplastics, reveals a more complex process, showing that particles smaller than 1 μm can potentially pass through root pores and leaf stomata, leading to accumulation in plant tissues [156].

A key factor driving this adhesion is the formation of biofilms (Fig. 7). Both plastic particles and plant surfaces become colonized by microbial communities that secrete extracellular polymeric substances (EPS), which act like a "glue" [157–160]. The composition of these films varies among habitats; for example, aquatic wetland mosses and seagrasses release sticky mucilage that binds plastics in water, while the waxy cuticles of terrestrial leaves (such as those in riparian forest canopies) are efficient at trapping airborne microfibers [161]. The significance of this binding agent is supported by direct quantitative evidence; for example, a study on macroalgae reported a strong positive correlation between EPS content and microplastic contamination, with approximately 15 microplastic particles per milligram of EPS [162].

The resulting organic coating, known as the "eco-corona," modifies the surface properties of plastic [163]. Environmental weathering of the plastic can accelerate this process by degrading its surface, promoting the formation of the microbial layer, and increasing its ability to adhere to plant surfaces [164]. The surface texture of plants is also crucial. For example, mangrove leaves efficiently trap atmospheric MPs through micro-features such as waxy cuticles, glandular hairs, and salt crystals, which enhance surface roughness and create more attachment points for particles [117]. Additionally, electrostatic and chemical forces assist in adhesion. Studies on algae indicate that positively charged

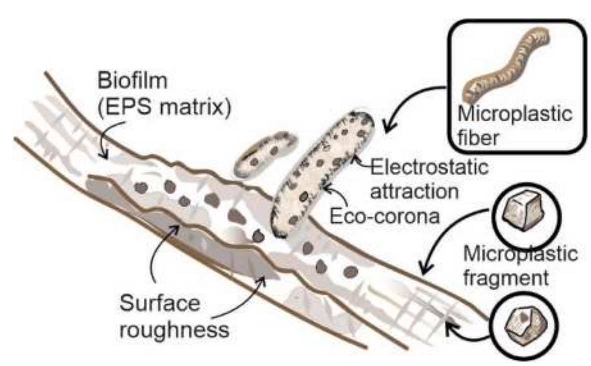


Fig. 7. Micro-scale Adhesion Mechanisms. The trapping of small particles depends on surface properties. Weathered microplastic fibers and fragments can acquire an eco-corona that modifies surface charge and hydrophobicity, and may precede/enhance microbial biofilm formation (an EPS matrix), strengthening adsorption/attachment to plant surfaces, such as root hairs, through electrostatic attraction and other forces.

nanoparticles are more easily adsorbed onto negatively charged algal surfaces [165]. Conversely, some additives or the biofilms that form on plastics can alter their charge, thereby affecting their interactions with plant surfaces [166]. The cellulose in plant cell walls can also generate electrostatic forces, influencing how charged plastic particles attach [147].

4.3. Interacting factors governing plastic trapping and retention

The efficiency of a vegetated ecosystem in trapping plastics depends on complex interactions among the plastic's properties, the vegetation, and the environment, rather than on a single factor.

4.3.1. Plastic characteristics

The plastic's characteristics, including both physical and chemical properties, primarily determine its environmental fate (Table 1).

Size is crucial: larger macroplastics are more likely to become trapped by physical barriers such as mangrove roots or wood jams, while smaller micro- and nanoplastics tend to settle in low-flow environments or adhere to surfaces [16,119]. Shape also influences behavior: fibers often entangle in canopies, whereas flakes and fragments tend to settle in sediments [82]. Polymer density affects buoyancy: high-density plastics, such as PET and PVC, generally sink, interact with sediments and benthic plants, while low-density plastics, such as PE and PP, float at the surface or along high-tide lines [143,167].

The specific polymer type and its aging or weathering process also matter, as environmental exposure alters a particle's surface, density, and biofouling potential, thereby affecting its transport and entrapment likelihood.

A crucial factor is surface roughness: weathered plastics, such as UV-degraded fragments, develop micro-rough surfaces that facilitate biofilm and nutrient adsorption, thereby strengthening binding to plant surfaces and sediments [88,164].

4.3.2. Vegetation characteristics

Vegetation characteristics, including species, morphology, and density, are key factors (Fig. 8). Ecosystems with high structural complexity, such as the intricate root systems of mangroves, the dense canopies of seagrasses, or the multi-layered riparian forests, are more effective at debris trapping than simpler structures [147,168]. In mangroves, researchers have measured this structural complexity with 3D Vegetation Indices, revealing a strong link between vegetation diversity and the effectiveness of trapping macroplastics [18]. Total aboveground biomass is a measurable indicator of microplastic interception rates in mangroves [118], with higher biomass directly associated with greater trapping capacity.

The influence of density is complex: while dense vegetation can slow water flow, some flume experiments suggest that lower, randomly spaced seagrass densities may generate more turbulence, thereby increasing trapping efficiency compared to uniform, high-density arrangements [16]. This pattern, often called the “seagrass paradox,” shows that medium, irregular densities can trap 65–80% of particles, whereas dense, uniform meadows trap 55–70%.

Moreover, invasive species with varied morphologies, such as those with dense mat-forming growth, could capture litter more effectively than native plants [104], with *Carpobrotus spp.* in dune systems being a notable example of higher trapping efficiency driven by plant morphology.

4.3.3. Environmental and hydrodynamic context

Environmental context plays a crucial role in plastic transport and its availability for trapping. Major hydrodynamic forces, such as river flow velocity, tidal currents, and wave action, are the primary influences [24,169]. According to de Los Santos et al. [22], a clear inverse relationship exists between hydrodynamic energy and retention capacity: in low-energy regimes (e.g., <0.5 m/s), habitats like mangrove interiors, lagoons, and ponds serve as highly effective sinks, with retention rates exceeding 85%. Here, vegetation density primarily drives trapping, allowing even fine MPs to settle and attach to biofilms. In contrast, high-energy settings (>2.5 m/s), such as exposed coastlines or river rapids, see hydrodynamic forces overpower vegetation friction. In these conditions, vegetation acts only as a temporary buffer instead of a permanent sink.

Large floods and other extreme hydrological events are particularly significant, as they mobilize plastics from riverbanks and floodplains, redistributing them to new locations [81,153]. These events act as system “reset points,” shifting riparian zones from sinks during base flow to sources during peak discharge, highlighting the temporal nature of trapping efficiency.

Vegetated systems are dynamic “sinks” where retention shifts over time with disturbance regimes. During calm periods, plastics are deposited and buried in sediments and soils. However, storms and floods can remobilize stored material, causing short-lived export pulses (Table 4) [81,170,171]. Coastal evidence shows high event sensitivity: wave–sediment experiments in blue-carbon environments reveal that storm conditions (significant wave height up to ~0.809 m) greatly reduce retention, with over 80% of microplastics lost compared to calm conditions [124]. Storm-surge scarping of foredunes can quickly turn dunes from long-term storage into secondary sources, with items recovered during high waves and winds, indicating accumulation over

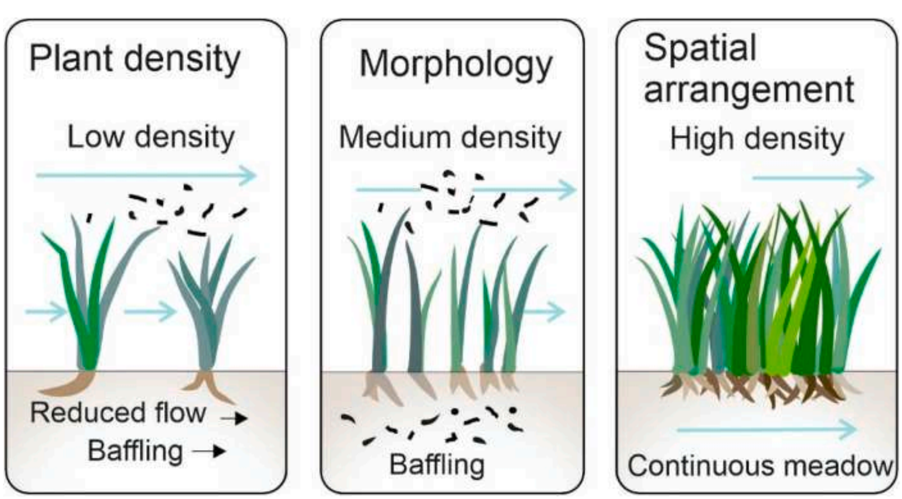


Fig. 8. Vegetation structure impacting plastic trapping efficiency.

Table 4
Temporal dynamics and drivers of extreme events that cause sink-to-source shifts in vegetated systems.

Driver - timescale	Dominant process in vegetated habitats	Expected direction	Example(s)	Implication for synthesis - monitoring
Quiescent / background (weeks to months)	Deposition, canopy baffling, root and leaf interception; burial and sediment accretion; aging and fragmentation.	Sink (storage increases)	Sediment and soil archives can record multi-decadal accumulation and burial of plastics [171,172].	Consider this as the baseline state; report depth and depositional environment.
Tidal cycles / seasonal discharge (hours tomonths)	Bidirectional transport, with temporary retention on banks or vegetation, allows exchange between the water column and margins.	Alternating within a day or season, net export might be small compared to gross transport.	Net plastic transport accounts for approximately 20–33% of the total over entire tidal cycles, with transport showing a correlation with discharge ($R^2 \approx 0.76$) [170].	Report the gross versus net flux; sampling across the entire tidal and seasonal cycles.
Storm waves / coastal erosion (hours to days)	Erosion and/or resuspension of surface sediments, release of recently deposited MPs, and their redistribution along strandlines or into vegetation.	Sink-to-source pulse with local redeposition.	Wave–sediment experiments showed that storm forcing, with Hs reaching approximately 0.809 m, decreased retention and caused over 80% loss of surface MPs compared to calm conditions [173]. Dune scarping resulted in the recovery of 263 items after a storm surge, during which the maximum Hs was about 7.9 m and wind speeds reached roughly 25 m s^{-1} [172].	Include wave and flow metrics; Consider storm windows as separate event layers.
Extreme river floods (days)	Bank overtopping and floodplain inundation mobilize debris, interacting strongly with riparian vegetation and flood lines.	Upstream source pulse; strong mid-reach retention; patchy redistribution	Transport exceeds 100 times, peaking at about 363 times; roughly 29–33% of annual transport occurs within 6 days. Downstream transport decreases by approximately 70–90% over 131 km because of bank, floodplain, and vegetation retention [81]. Flume experiments suggest a mobility threshold near RD ≈ 1 and demonstrate that a 40% increase in discharge during a 'flood" step enhances mixing and incorporation of plastics into migrating dunes [174].	Event-weight annual budgets; add adaptive monitoring around forecast floods.
Post-event stranding (days to weeks)	Debris accumulates at the flood line and becomes trapped in riparian vegetation or canopy, leading to re-burial as water levels drop.	System returns to sink, creating new hotspots	Plastic densities along the riverbank rise sharply during floods, with vegetation trapping plastics on banks and floodplains [81].	Survey flood lines soon after events; estimate the residence time until the next remobilization.
Long-term legacy reservoirs (years to decades)	Buried or embedded macro- and mesoplastics found in dunes, soils, and riverbanks become exposed during erosion events.	A dormant sink transforms into an episodic source.	Storm-eroded foredunes can expose plastics that are 38–57 years old, redistributing them inland or along the coast shoreline. Coastal dunes may retain these containers for decades before storms release them [107,172].	Include legacy stock and connect extreme-event frequency to the likelihood of remobilization.

years followed by event-driven release [172,173].

In tidal rivers and estuaries, bidirectional flow further complicates the sink–source distinction. Sub-hourly measurements across tidal cycles show that net transport is only 20–33% of gross transport, with retention higher during low discharge and in areas with dense riparian vegetation and suitable bank morphology (Pearson's R^2 ~0.76 with discharge) [170]. Extreme floods can dominate annual transport: during the July 2021 Meuse flood, macroplastic transport increased by more than 100 times (peaking at ~363 ×), accounting for about 29–33% of the annual flux in six days [81]. Meanwhile, transport declined by 70–90% over 131 km due to deposition on riverbanks, floodplains, and vegetation, indicating a redistribution from sink to source back to sink, not just downstream export [81]. Flume experiments show plastic mobility relative to sand can be approximated by the submerged specific-gravity–diameter product (RD), with a mobility threshold near RD ≈ 1, and a 40% discharge flood promotes vertical mixing and inclusion into bedforms [174]. Floodplain soils are long-term storage areas, episodically connected to channels—seasonal flooding affects microplastic mobility, leading to deposition, accumulation, and particle translocation to depths of ~2 m.

The geomorphological setting, including features such as river meanders versus straight reaches or high-tide strandlines versus low-tide flats, creates distinct accumulation zones that determine where vegetation can most effectively trap plastics [92,123]. Meanders, slackwater zones, and tidal deposition fronts are particularly efficient at accumulating debris, underscoring the importance of vegetation in these areas. Human-made structures, such as dams and weirs, also dramatically alter the environment by creating artificial sinks, causing plastics to accumulate in upstream reservoirs and reducing downstream transport [153,167]. In addition to engineered structures, human land use also significantly impacts sink capacity. For instance, transforming riparian forests into farmland or removing vegetated buffers significantly reduces an ecosystem's natural filtering capacity. These complex factors suggest that local retention rates may not fully reflect the catchment as a whole, especially when vegetation belts are patchy or discontinuous, allowing most plastics to bypass natural filters and flow downstream.

4.3.4. *Substrate and mineral interactions*

In environmental systems, MPs not only interact directly with plant compartments but also interact with minerals in sediments and soils. In water-based systems, these interactions are influenced by colloidal forces such as electrostatic attraction and repulsion, van der Waals forces, hydrophobic effects, and mechanisms like ligand exchange or hydrogen bonding [175]. This occurs during sediment deposition or during vertical or horizontal movement within the water column, affecting the behavior of both MPs and mineral components [67,176]. The formation of MPs, mineral conjugates, can affect the transfer and bioavailability of compounds in plant systems. This is particularly clear with suspended sediment (SS), where MPs may adsorb onto mineral surfaces and aggregate with mineral particles [177]. Iron oxides, silica, and clays are common mineral components in soil and sediments [178]. Their surface properties are crucial for the deposition, transport, and weathering of MPs, as well as their uptake by organisms in vegetation-rich environments. Additionally, mineral texture influences reactivity, with the specific surface area and particle size often dictating a mineral's ability to adsorb MPs and its affinity for them.

In most natural waters with a pH around ~8, MPs generally carry a negative surface charge [67]. This results in MPs having a strong affinity for positively charged minerals, such as iron oxides, leading to hetero-aggregation between particles. Consequently, this enhances the sedimentation and immobilization of MPs, potentially increasing accumulation in water systems enriched with iron oxides [179]. Weathering and aging can further intensify this interaction by altering the surface functional groups of MPs. The increase of oxygen-containing functional groups leads to the greater electronegativity and wettability, thereby increasing affinity for positively charged surfaces [180]. This interaction could directly affect plants and vegetated areas, where MPs bound in sediments through hetero-aggregation may come into contact with plant roots or other organisms. Conversely, clay and most silica minerals have negatively charged surfaces, which typically repel MPs and limit aggregation [181]. However, studies show that hetero-aggregation between MPs and clays can be significant in water with high cation concentrations, such as in sweaters [176,182]. Therefore, the chemical composition of the aqueous matrix also plays a crucial role in determining the fate of MPs. Monovalent or divalent cations like Na^{+}, Ca^{2+}, and Mg^{2+} can shield MP charges, affecting their adsorption and aggregation behaviors [183]. Additionally, minerals such as goethite and hematite can promote the photodegradation of PP and PE particles [184]. Mineral-bacteria communities also serve as specific sites for the breakdown and aging of plastic [185].

4.4. The sink-hazard paradox: pollutant concentration and exposure mechanisms

The effective physical trapping mechanisms discussed in the preceding sections give rise to a significant trade-off, known as the "Sink-Hazard Paradox" (Fig. 9). While vegetation serves as a biotic filter, reducing downstream transport by decreasing flow velocity and facilitating sedimentation, it also actively traps anthropogenic debris within the ecosystem's substrate. Data compiled in this review show that vegetated sediments act as accumulation "hotspots," retaining microplastics at concentrations ranging from ~2.05–2.82 times higher than in nearby unvegetated areas [87,100], with some mangrove sinks reaching densities as high as 3840 particles per kilogram [86,88]. Once trapped, these high-density deposits become chemically active reservoirs through three distinct pathways.

First, the weathering of entrapped debris within the root zone accelerates the leaching of inherent chemical additives. As shown in Section 3.2, plastic degradation releases harmful compounds [186]. In vegetated sinks, however, reduced water flow due to canopy baffling limits chemical dilution. Consequently, leached substances, such as phthalates, BPA, and flame retardants, accumulate in pore water and remain effectively confined near the roots [64].

Secondly, the biofilm adhesion mechanisms described in Section 4.2 do more than trap particles; they actively gather external pollutants, entering the food web [97]. The extracellular polymeric substances (EPS) that enable physical adhesion also act as sorbents for heavy metals and hydrophobic organic pollutants [53,187]. Additionally, "eco-corona" coatings and subsequent biofilm/EPS development can modify the plastic surface into a biological vector, creating a "plastisphere" refers to the plastic-associated biofilm community that significantly increases the presence of antibiotic-resistant genes (ARGs) and pathogens beyond normal sediment levels [157,159].

Finally, the mineral interactions discussed in Section 4.3.4 help stabilize these hazards through hetero-aggregation. Negatively charged microplastics attach to positively charged iron oxides, securely anchoring pollutant-laden particles into the substrate [179,188]. This creates a persistent interface for contaminant exchange among plastics, sediment, and benthic organisms. Vegetated ecosystems are crucial in intercepting global plastic flux, but they also form localized zones with higher chemical risks. The potential physiological impacts of this concentrated exposure on plants are examined in a separate study.

5. Research gaps and future directions

From the above review, vegetated ecosystems trap plastics effectively. While evidence suggests that mangroves, seagrasses, salt marshes, dunes, and riparian zones are significant sinks for plastic, our ability to quantify and model these processes remains underdeveloped. Knowledge gaps hinder our understanding of plastic fate and impede the development of effective mitigation strategies. Addressing these needs requires targeted, interdisciplinary research to standardize methods, improve models, and use vegetation as a nature-based solution.

5.1. Key knowledge gaps in trapping mechanisms

A key challenge is the lack of standardized sampling methods, extracting, and measuring plastics in vegetated habitats. Studies report item abundance using different units (e.g., items/m^2, items/kg dry sediment, items/L) and use varying extraction techniques and size definitions, making direct comparisons and global meta-analyses very difficult [31,77]. A significant geographic and habitat bias exacerbates this issue: research tends to focus primarily on accessible coastal areas, such as coastal zones or mangroves, whereas many other critical regions, including freshwater wetlands, salt marshes, and polar environments, are underrepresented [189,190].

Furthermore, most studies are static snapshots. Our understanding of the long-term fate and degradation dynamics of plastics once entrapped

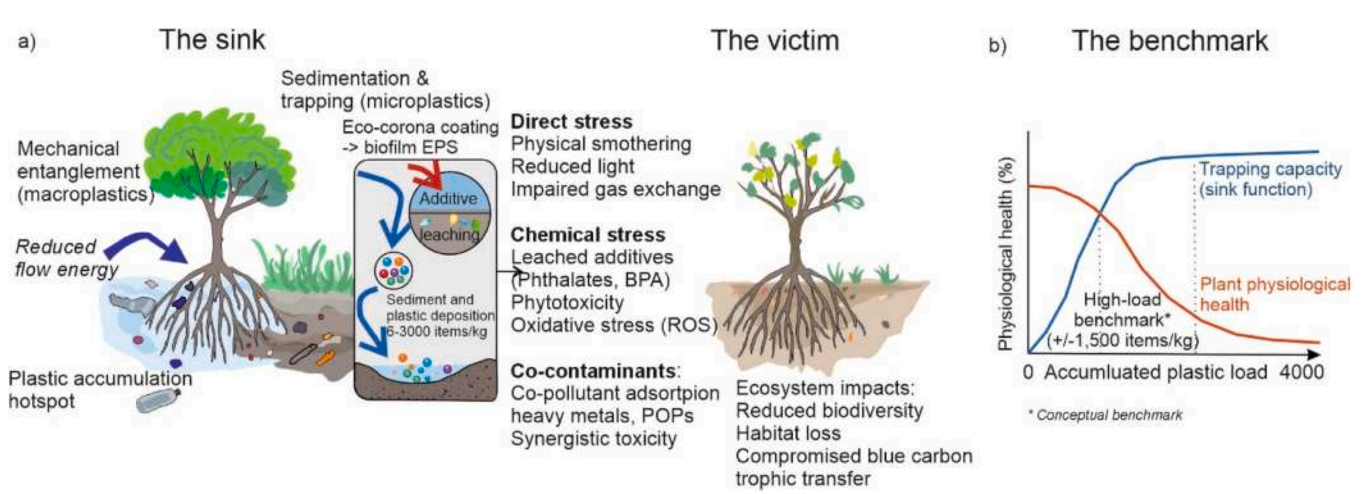


Fig. 9. The "Sink-Hazard Paradox." (Left) The Sink: Vegetation reduces downstream pollution by trapping debris through root entanglement and canopy baffling. (Right) The Hazard: High accumulation turns the sink into a stressor for the plant via.

remains limited. It is uncertain whether vegetated habitats serve as permanent repositories for securely burying plastics or merely transient traps that fragment plastics into more hazardous micro- and nanoplastics before remobilization by high-energy events [81,191]. The specific mechanisms responsible for trapping nanoplastics (particles less than 1 μm in size) are particularly underexplored. Unlike larger particles, which are influenced predominantly by physical interception, nanoplastics are likely governed by processes such as surface adhesion, biofilm interactions (the "eco-corona"), and colloidal forces. These mechanisms are currently subjects of emerging research [156,164]. These gaps are summarized in Table 5.

Finally, a critical gap remains in understanding the ecological limits of the "Sink-Hazard Paradox" discussed in Section 4.4. Although we now understand how pollutant concentrations are controlled, there is insufficient quantitative data on the load thresholds at which a vegetated sink shifts from a beneficial filter to a toxic source. It is also unclear at what levels of microplastics or additives mangroves and seagrasses become vulnerable, leading to the "sink-victim" condition. Identifying these capacity limits is critical for defining safe pollution levels in coastal restoration efforts.

- Physical: Smothering roots and blocking light
- Chemical: Leaching additives and adsorbing heavy metals like Cadmium on Polyamide
- Biological: Hosting pathogenic biofilms ("plastisphere").

Note: The dashed line (~1500 items kg^{-1}) indicates a high-load benchmark, rounded from 1466 items kg^{-1} [99]*. It serves as an illustrative upper limit rather than a definitive threshold. Future research should determine precise tipping points using standardized exposure–response datasets.*

5.2. A Roadmap for future mechanistic research

Addressing these gaps requires a collaborative, multi-pronged research initiative (Fig. 10):

The priority is to develop and implement standardized monitoring protocols. The field needs to move towards unified methods, as suggested by several researchers ([31,192]. This involves standardizing reporting units (e.g., particles per kilogram for sediment and particles per cubic meter for water), using consistent size-class definitions, and establishing best-practice protocols for sampling complex matrices, including dense roots and organic sediments. Such standardization is essential for developing comparable global datasets, which are crucial for accurate hotspot detection and trend analysis. Standardization should include exposure durations in plant bioassays, as some responses are time-dependent. In Lemna minuta, MP exposure reduced growth and chlorophyll mostly at 28 days, showing MP impacts can be chronic and may be underestimated by standard 7-day tests [155].

While there are reference nanoplastics offered by many companies (polymer type, size, shape, concentration, functionalized surface), there are no reference microplastics for sizes smaller than 20 μm. And even when the nature of the available microplastics is mentioned (type of polymer, e.g., PP, PE, PS, etc.), the additives present are never specified. It is therefore essential to have reference polymers available—including specific shapes (sphere, filament, polygonal, random), size distribution (classes ranging from mm to nm), chemical composition (major, minor, and trace elements), and functionalized or non-functionalized surface—for any laboratory study involving transport or ecotoxicity modeling. At the same time, it is necessary to define precise vocabulary, protocols for sampling, storage, filtration-purification, labeling, analysis, and expression of homogeneous results. In their absence, intercomparison of studies will remain difficult, with the relevance and reliability of the data obtained questionable.

Secondly, integrating advanced modeling with in-situ validation is essential. Future research should move beyond basic correlations to develop more complex numerical models that improve understanding of temporal dynamics. These models must integrate hydrodynamic forces (e.g., river discharge, flood pulses, and wave action) with biological and structural elements (e.g., vegetation density, species-specific morphology, and root complexity) [118]. Structural metrics that can be quantitatively measured, such as 3DVI, which is strongly associated with macroplastic loads, are helpful for parameterizing these models [18]. The models then require validation through long-term, in situ monitoring and tracking experiments, such as particle-tracer experiments, to understand temporal changes in retention and remobilization [144,145].

Third, it is crucial to investigate the dynamics of trapping under climate change scenarios. We must understand how plastic trapping mechanisms will shift under future climate conditions. This requires multi-stressor experiments that assess how increased storm frequency, sea-level rise, and altered flood regimes will affect the retention capacity and structural integrity of these vegetated sinks [193]. At the same time, new evidence indicates that microplastics in wetlands can affect soil organic carbon cycling and greenhouse gases by altering sediment and microbial processes, linking accumulation areas to climate-related ecosystem functions [194]. For example, more frequent, intense floods

Table 5
Critical knowledge gaps in vegetation-plastic interactions and recommended research priorities.

Gap category	Specific gap	Impact on science & management	Recommended approach	Priority
Methodological Standardization	> 50 sampling protocols currently in use; high heterogeneity in units prevents global comparison.	Impact: Prevents meta-analysis and identification of regional hotspots. Management: Impossible to set regulatory baselines.	Develop and enforce a unified global sampling protocol (e.g., standardized reporting units of items/kg dry weight).	Critical
Geographic Bias	Research is heavily skewed toward the Indo-Pacific (China, Indonesia) and Europe; Africa and polar regions are underrepresented.	Impact: Global models are biased toward specific climatic zones. Managment: Strategies may not apply to high-biodiversity tropical sinks outside Asia.	Prioritize funding for under-researched regions (e.g., Western Africa, Oceania) to create a truly global dataset.	High
Temporal Dynamics	Most studies are static "snapshots"; long-term data on seasonal flux (monsoons/floods) is rare.	Impact: Fate of "buried" plastics is unknown; remobilization risk during storms is unquantified. Management: Cannot predict long-term sink capacity.	Implement long-term monitoring sites; install autonomous samplers for flood events.	High
Nanoplastic (NP) Mechanisms	Studies on NPs (<1 μm) are scarce compared to MPs; detection methods are insufficient.	Impact: The most bioavailable fraction, capable of penetrating plant tissues, is ignored. Management: Toxicity risks to crops and wildlife are underestimated.	Develop standardized detection methods for NPs in complex organic matrices (e.g., pyrolysis-GC-MS).	High
Sink-Hazard Thresholds	The specific contaminant loads that trigger the "Sink-Victim" response (Section 4.4) are unknown.	Impact: Unknown if plastic accumulation degrades the sink's ability to function. Management: Cannot determine carrying capacity thresholds.	Integrate plant stress physiology (e.g., photosynthesis, oxidative stress) into monitoring.	High
Extreme Event Dynamics	Fate of plastics during floods and cyclones is largely unmapped.	Impact: Climate change resilience of these sinks is unknown. Management: Risk of massive "plastic pulses" released downstream.	Couple hydrodynamic modeling with event-triggered field sampling.	Med-High

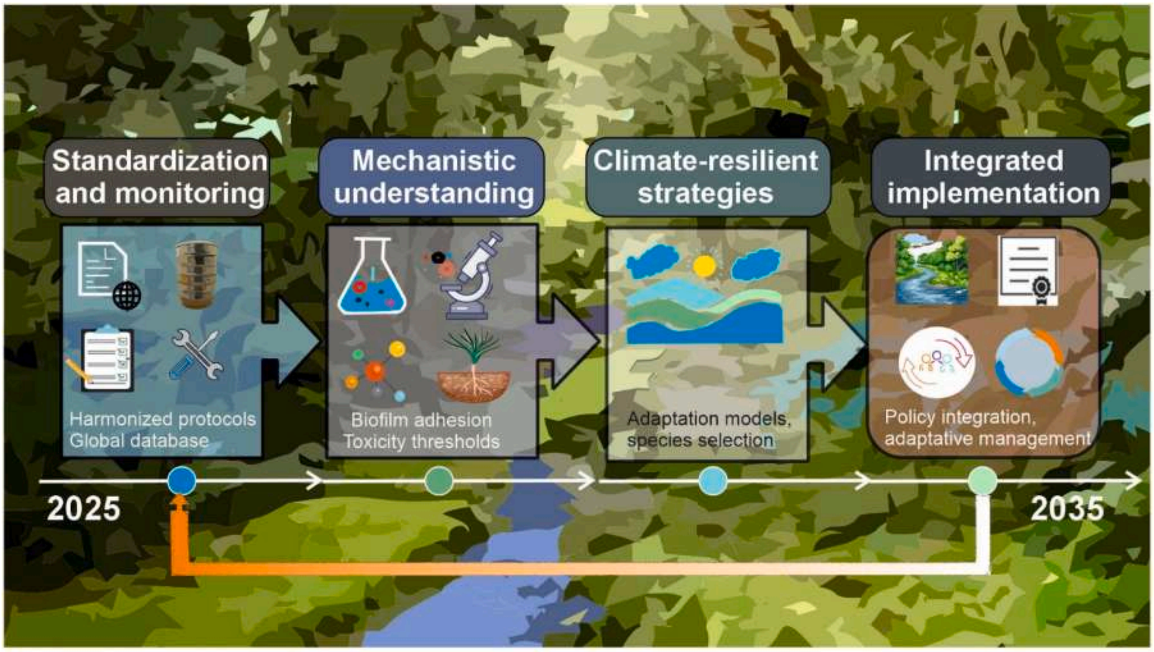


Fig. 10. A Roadmap for Future Research for 2025–2035. The framework progresses from immediate needs, such as standardized protocols, to advanced modeling of transport and retention. It then shifts to assessing climate resilience and using eco-engineered solutions for plastic mitigation.

may overwhelm the trapping capacity of riparian zones or lead to mass remobilization of previously "sequestered" plastics [81,193].

- Ultimately, the goal is to harness mechanistic knowledge for eco-engineered Nature-Based Solutions (NBS), applying this understanding to transition vegetation from a passive sink to an active, controlled mitigation tool (Fig. 11). Future studies should focus on: Eco-engineering for enhanced trapping efficiency: Strategically investigate how vegetation's inherent trapping capabilities can be enhanced as a form of "green infrastructure' for pollution reduction [30]. This involves conducting field and flume experiments to examine how restoration strategies, such as planting density, spatial layout, and species selection, can improve capture and retention of plastics [149]. For instance, hydraulic simulations indicate that lower-density, randomly planted seagrass can generate more turbulence and trap more MPs than dense, uniform grids [16]. Such insights can be applied directly to engineered systems like Constructed Treatment Wetlands (CTWs), which serve as effective MP sinks [149], or in designing Vegetative Buffer Strips (VBS) to intercept agricultural and road runoff.
- Climate resilience and dynamic redistribution: It is essential to analyze trapping mechanisms within climate change scenarios to understand their future development. This involves conducting multi-stressor experiments to assess how increased storm frequency, sea-level rise, and changing flood patterns affect the retention capacity and structural stability of vegetated sinks [172]. For example,

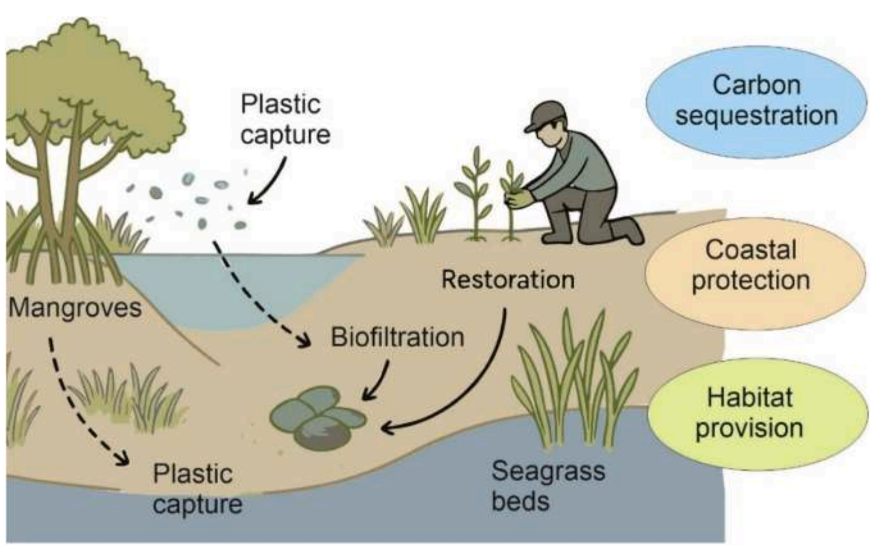


Fig. 11. Nature-based solutions for mitigating plastic pollution via vegetated ecosystems and biofiltration, emphasizing ecosystem service co-benefits. Dense habitats, such as mangroves, salt marshes, wetlands, and seagrass beds, naturally filter plastic debris through root entanglement and sedimentation. Filter feeders, such as mussels and oysters, aid in biofiltration, and restoration enhances these roles. Besides pollution mitigation, they offer co-benefits such as carbon sequestration, habitat preservation, and coastal protection, making ecological restoration and pollution control key components of nature-based solutions.

more frequent and severe flooding could surpass the trapping ability of riparian zones or cause previously stored plastics to be remobilized [169], [172]. Additionally, studies should explore how microplastics in wetlands impact soil organic carbon cycling and greenhouse gas emissions by altering microbial activity [23].]

- Adaptive Management and Biomass Protocols: To ensure NBS function as controlled mitigation tools rather than unmanaged sinks, we operationalize NBS via a risk-aware adaptive management framework (Section 5.3) that specifies monitoring indicators, triggers, interventions, and safe handling of contaminated biomass.

5.3. Operationalizing nature-based solutions: a risk-aware adaptive management framework

To move NBS from a general concept to something that can be implemented and defended in practice, we propose an adaptive management framework (AMF) built around four elements: what to monitor, which decision thresholds ("triggers") should prompt action, which interventions are appropriate, and how to handle contaminated biomass so that plastics are not re-released during routine maintenance or extreme events. This framework is meant to work both in natural vegetated sinks such as mangroves, marshes, and riparian buffers, and in engineered or managed systems such as constructed treatment wetlands and vegetated buffer strips.

Table 6 provides an operational roadmap for transitioning NBS from theoretical accumulation concepts to risk-aware management strategies. By incorporating the "Sink-Hazard Paradox" within an Adaptive Management Framework (AMF), this decision matrix identifies key monitoring parameters, such as 3D Vegetation Indices (3DVI) and plant stress markers induced by MP, to protect the sink's ecological health. The framework clearly defines intervention triggers, using the approximate ∼1500 items/kg dry weight high-load threshold from the combined data for active mitigation. Crucially, it also addresses secondary release risks by providing protocols for the controlled harvesting and specialized disposal of plastic-saturated biomass, ensuring that managed coastal and riparian zones do not become secondary pollution sources during extreme weather events.

Table 6
Operational decision framework for managed vegetated sinks.

Management Phase	What to Monitor	Trigger for Intervention	Managed Action / Intervention
Baseline Monitoring	Sediment MP loads (items/kg dry wt); 3D Vegetation Indices (3DVI).	MP concentration exceeds habitat-specific "Sink-Hazard" benchmarks (e.g., ∼1500 items/kg).	Initiate health assessments; evaluate need for controlled biomass harvesting.
Risk Assessment	Plant stress markers (photosynthetic efficiency, oxidative stress).	Significant decline in photosynthetic efficiency or biomass density.	Soil amendments (e.g., biochar) to reduce MP-induced stress; plant replacement or diversification.
Event-Based Response	Post-storm strandline density; post-flood bank deposition.	Extreme flood/ storm event (>3 m/s flow or high surge) causing > 80% retention loss.	Targeted "mop-up" of remobilized macro-debris in riparian/dune buffers to prevent downstream export.
End-of-Life / Sink Capacity	Vertical MP translocation depth; saturation of root-zone attachment sites.	Pollutant saturation is reaching toxicity thresholds for benthic fauna.	Controlled harvesting of plastic-saturated biomass; sediment capping or replacement.

5.3.1. Monitoring: minimum operational indicators

Monitoring should be tiered to match resources while still enabling clear decisions. A core set of indicators can be collected through routine field sampling and standard laboratory workflows, while more advanced indicators are added where capacity allows them to refine diagnosis and optimize performance. In operational terms, the minimum monitoring package should capture the plastic load retained by the system (e.g., particles per kilogram of dry sediment or item-based measures for macrolitter), the rate at which debris accumulates at vegetation edges and strandlines (where trapping and early warning are usually strongest), and a habitat-relevant proxy for hydrodynamic forcing such as discharge stage, tidal range category, or storm-wave warning level. These forcing indicators matter because high-energy events can rapidly switch a vegetated sink into a source through erosion, scouring, and remobilization. In parallel, vegetation condition should be tracked using simple stress proxies that are fast to assess and sensitive to deterioration, including canopy cover/density, visible smothering, expansion of dieback patches, and, where feasible, rapid leaf chlorophyll or fluorescence indices.

Where risk profiles justify it, monitoring should be extended beyond plastics alone. In particular, co-contaminants associated with plastics and their eco-corona (selected additives, metals, or persistent organic pollutants) should be measured in settings where "sink–hazard" conditions are plausible. Because remobilization is largely event-driven, it is also useful to track indicators of remobilization susceptibility, such as the near-surface fraction of plastics in the upper sediment layer (e.g., 0–5 cm) and simple markers of bank instability or erosion.

5.3.2. Triggers: when monitoring requires action

Triggers should be explicit and conservative, because delayed responses increase both remobilization risk and vegetation stress. Practically, three trigger types are most useful. First, load-based triggers identify situations where retained plastics are approaching levels associated with "sink–victim" dynamics; for example, sustained sediment loads on the order of > 1500 particles/kg, which has been reported as potentially critical, should prompt intervention planning even if vegetation condition still appears acceptable. Second, event-based triggers align management with forecasted or observed exceedance of habitat-relevant thresholds such as flood-stage warnings, storm surges, or extreme discharge categories. In these situations, pre-event actions become priority because they can prevent secondary release, for instance by removing accumulated edge macrolitter, securing floating mats used as traps, or temporarily containing debris at known hotspots. Third, condition-based triggers rely on measurable vegetation decline, such as rapid canopy thinning, expanding dieback, persistent smothering, or a marked drop in chlorophyll/fluorescence proxies; these signals should initiate mitigation before the sink function collapses.

5.3.3. Intervention toolbox (risk-aware options)

Interventions should prioritize plastic removal while minimizing habitat disturbance and reducing the likelihood of re-release during high-energy events. In natural systems, this typically means focusing effort on accumulation edges, strandlines, patch margins, and riparian trapping points, rather than attempting intrusive, whole-habitat disturbance that can damage the very structure responsible for retention. In managed or engineered NBS, interventions can include planned harvesting of plastic-laden biomass (for example, in constructed wetlands or floating macrophyte systems used as traps), but only when paired with safe downstream handling to avoid fragment shedding and redistribution. Where systems are designed or retrofitted, operational improvements may involve adjusting planting density or spatial layout, adding sacrificial trapping zones, or installing low-impact upstream screens or booms, but only when these features reduce habitat intrusion and make removal simpler and safer. Finally, because many releases are event-driven, a defined post-event rapid response window should be adopted: after floods or storms, known hotspots should be inspected and newly deposited debris removed quickly to limit fragmentation into microplastics.

5.3.4. Handling contaminated biomass to avoid secondary release

Whenever implementation involves harvesting or routine maintenance—common in constructed wetlands, floating vegetation traps, and buffer strips—biomass should be treated as potentially contaminated with plastics and sorbed co-pollutants. Operationally, this means that collection and transport must prioritize containment to prevent shedding of fragments and fibers, using sealed and tear-resistant containers rather than open handling. If dewatering is required, it should occur on an impermeable surface with leachate capture where relevant, so that runoff does not become a pathway for microplastic release. Visible macrolitter should be separated from biomass, and shredding or mulching should be avoided until a decontamination and disposal decision is made, because mechanical processing increases fragmentation and dispersal. End-of-life routes should be controlled and appropriate to the jurisdiction and contamination profile—such as regulated waste handling, thermal treatment or co-processing, or controlled landfill—and should explicitly avoid open composting or uncontrolled land application that would redistribute plastics back into the environment. Throughout the process, documentation should be maintained through chain-of-custody records and mass-balance estimates (biomass removed, debris mass/volume, and disposal route), both to support accountability and to feed back into adaptive learning.

Specific disposal/treatment pathways will depend on national and local waste regulations and contamination profiles; however, the non-negotiable principle is to prevent fragmentation and redistribution through open handling, uncontrolled composting, or land application of contaminated material.

6. Conclusions

This review provides a comprehensive overview of how vegetated ecosystems mitigate plastic pollution. Evidence clearly shows that mangroves, seagrass beds, salt marshes, coastal dunes, and riparian plants act as important, mostly passive, sinks for both macro- and MPs. The main trapping methods involve (1) physical interception through the complex 3D structures of roots, stems, and canopies, and (2) hydrodynamic attenuation, where vegetation reduces water and wind flow, causing plastics to settle, strand, and build up. On a microscopic level, this process is further supported by microbial biofilms (EPS matrix) and "eco-corona" coatings, which enhances surface adhesion.

The efficiency of these processes varies and is influenced by complex interactions among factors, including plastic properties (size, shape, and density), vegetation characteristics (structural complexity and density), and environmental conditions (hydrodynamic energy and geomorphology). This review specifically addresses the physical and mechanistic aspects of trapping. However, the biological impacts of this accumulation, such as ecotoxicological effects on plants and microbes, the "sink-victim" paradox, and the reduction or loss of ecosystem services, are a separate and equally important area of study that may be addressed in future work.

By identifying how entrapment operates, this review lays the groundwork for subsequent key steps. Moving forward, efforts should focus on standardizing monitoring methods (as detailed in our roadmap) and on using this mechanistic understanding to develop effective, nature-based solutions to control the global movement of plastic pollution. This highlights the interdisciplinary nature of the problem—combining perspectives from ecology, hydrology, and materials science is essential to combat plastic pollution effectively.

Environmental implication

Vegetation traps plastics 2.0–2.9 × more than bare sediments, concentrating hazardous additives such as flame retardants, phthalates, and persistent organic pollutants within rhizospheres. Weathered microplastics develop biofilms capable of adsorbing heavy metals and pathogens, thereby creating toxic hotspots that threaten plant health, microbial communities, and carbon sequestration efforts. It is imperative that nature-based solutions balance trapping efficiency with hazard thresholds through standardized monitoring and eco-engineering practices to prevent potential sink-to-source shifts in contaminated ecosystems.

CRediT authorship contribution statement

Simeoni Umberto: Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Coltorti Massimo:** Writing – review & editing, Funding acquisition, Conceptualization. **Nardin William:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Lazarou Alexandre:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Corinne Corbau:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Vlatka Filipović Marijić:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Le Coustumer Philippe:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Bajda Tomasz:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Skalny Mateusz:** Writing – review & editing, Visualization, Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the ADRIPLAST project (No. 00140), which addresses plastic and microplastic pollution in the Adriatic Sea and freshwater environments, funded by the EU Interreg VI B IPA Adriatic Ionian Programme. The project focuses on cross-border research in the Adriatic-Ionian region. The bibliography was compiled and formatted with Zotero.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2026.141908.

Data availability

No data was used for the research described in the article.

References

[1] Mejjad, N., Safhi, A.E.M., Laissaoui, A., 2025. Insightful analytical review of potential impacts of microplastic pollution on coastal and marine ecosystem services. J Hazard Mater Adv 17. https://doi.org/10.1016/j.hazadv.2024.100578.

[2] Plastic Europe, "Plastics – the Fast Facts 2025." Accessed: Oct. 29, 2025. [Online]. Available: 〈https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2025/?utm_campaign=97902806-Fast%20Facts%202025&utm_source=press-release〉.

[3] Jambeck, J.R., Johnsen, K., Jul. 2015. Citizen-based litter and marine debris data collection and mapping. Comput Sci Eng 17 (4), 20–26. https://doi.org/10.1109/mcse.2015.67.

[4] Ashrafy, A., et al., Feb. 2023. Microplastics pollution: a brief review of its source and abundance in different aquatic ecosystems. J Hazard Mater Adv 9, 100215. https://doi.org/10.1016/j.hazadv.2022.100215.

[5] Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., Jun. 2016. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic

environment. Environ Sci Technol 50 (11), 5800–5808. https://doi.org/10.1021/acs.est.5b05416.
[6] Carr, S.A., Liu, J., Tesoro, A.G., Mar. 2016. Transport and fate of microplastic particles in wastewater treatment plants. Water Res 91, 174–182. https://doi.org/10.1016/j.watres.2016.01.002.
[7] Shahul Hamid, F., Bhatti, M.S., Anuar, N., Anuar, N., Mohan, P., Periathamby, A., Oct. 2018. Worldwide distribution and abundance of microplastic: how dire is the situation? Waste Manag Res 36 (10), 873–897. https://doi.org/10.1177/0734242X18785730.
[8] Lu, H.-C., Ziajahromi, S., Neale, P.A., Leusch, F.D.L., Aug. 2021. A systematic review of freshwater microplastics in water and sediments: recommendations for harmonisation to enhance future study comparisons. Sci Total Environ 781, 146693. https://doi.org/10.1016/j.scitotenv.2021.146693.
[9] Mutuku, J., Yanotti, M., Tocock, M., Hatton MacDonald, D., Jun. 2024. The abundance of microplastics in the world's oceans: a systematic review. Oceans 5 (3), 398–428. https://doi.org/10.3390/oceans5030024.
[10] Mai, H., et al., Aug. 2023. Distribution of microplastics in surface water of tropical urban lakes: a case study in Ha Noi, Vietnam. Vietnam J Earth Sci. https://doi.org/10.15625/2615-9783/18595.
[11] Welsh, B., Aherne, J., Paterson, A.M., Yao, H., McConnell, C., Dec. 2022. Spatiotemporal variability of microplastics in Muskoka-Haliburton headwater lakes, Ontario, Canada. Environ Earth Sci 81 (24), 551. https://doi.org/10.1007/s12665-022-10670-9.
[12] Wu, J., et al., Dec. 2021. Microplastic contamination assessment in water and economic fishes in different trophic guilds from an urban water supply reservoir after flooding. J Environ Manag 299, 113667. https://doi.org/10.1016/j.jenvman.2021.113667.
[13] Sun, X., et al., Feb. 2023. Real-time variabilities in microplastic abundance and characteristics of urban surface runoff and sewer overflow in wet weather as impacted by land use and storm factors. Sci Total Environ 859, 160148. https://doi.org/10.1016/j.scitotenv.2022.160148.
[14] Rangel, D.F., Costa, L.L., Ribeiro, V.V., De-la-Torre, G.E., Castro, Í.B., 2024. Protective personal equipment on coastal environments: Identifying key drivers at a global scale. J Hazard Mater 468. https://doi.org/10.1016/j.jhazmat.2024.133839.
[15] Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., Janssen, C.R., Oct. 2015. Microplastics in sediments: A review of techniques, occurrence and effects. Mar Environ Res 111, 5–17. https://doi.org/10.1016/j.marenvres.2015.06.007.
[16] Cousins, A., et al., Apr. 2025. Evaluating microplastic trapping efficiency in seagrass meadows using hydraulic flume simulations. Mar Pollut Bull 213, 117660. https://doi.org/10.1016/j.marpolbul.2025.117660.
[17] Cozzolino, L., Nicastro, K.R., Seuront, L., McQuaid, C.D., Zardi, G.I., 2022. The relative effects of interspecific and intraspecific diversity on microplastic trapping in coastal biogenic habitats. Sci Total Environ 848. https://doi.org/10.1016/j.scitotenv.2022.157771.
[18] Gallitelli, L., Cutini, M., Cesarini, G., Scalici, M., 2025. Plastic hotspot areas in riverine habitats: Riparian vegetation diversity and structure entrap riverine plastics. Curr Plant Biol 41. https://doi.org/10.1016/j.cpb.2025.100450.
[19] Adyel, T.M., Macreadie, P.I., Oct. 2021. World's Largest Mangrove Forest Becoming Plastic Cesspit. Front Mar Sci 8. https://doi.org/10.3389/fmars.2021.766876.
[20] Zhang, Y., et al., Dec. 2024. Mass concentrations, compositions and burial fluxes of nano- and micro-plastics in a multi-species saltmarsh. Environ Pollut 363, 125181. https://doi.org/10.1016/j.envpol.2024.125181.
[21] Trusler, M.M., Cook, S., Lomax, B.H., Vane, C.H., Feb. 2025. Microplastic pollution in salt marsh and urban tributary sediment cores of the River Thames estuary, UK: Spatial and temporal accumulation trends. Mar Pollut Bull 211, 117360. https://doi.org/10.1016/j.marpolbul.2024.117360.
[22] de los Santos, C.B., Krång, A.-S., Infantes, E., 2021. Microplastic retention by marine vegetated canopies: Simulations with seagrass meadows in a hydraulic flume. Environ Pollut 269. https://doi.org/10.1016/j.envpol.2020.116050.
[23] Liu, S., et al., Mar. 2024. Impact of polyamide microplastics on riparian sediment structures and Cd(II) adsorption: A comparison of natural exposure, dry-wet cycles, and freeze-thaw cycles. J Hazard Mater 466, 133589. https://doi.org/10.1016/j.jhazmat.2024.133589.
[24] Zhou, Y., et al., Jun. 2021. Microplastic contamination is ubiquitous in riparian soils and strongly related to elevation, precipitation and population density. J Hazard Mater 411, 125178. https://doi.org/10.1016/j.jhazmat.2021.125178.
[25] Song, W., Lin, L., Oh, S., Grossart, H.-P., Yang, Y., Jul. 2025. Tire wear particles in aquatic environments: From biota to ecosystem impacts. J Environ Manag 388, 126059. https://doi.org/10.1016/j.jenvman.2025.126059.
[26] Atmaja P.S.P, Suardana A.P., Laharjana, I. K. A. K., Suteja Y., Purwiyanto A.I.S., "Macro Debris Accumulation in Seagrass Meadows Along Varying Levels of Tourism Pressure in Bali, Indonesia," 2025, SSRN. https://doi.org/10.1016/j.rsma.2025.104482.
[27] Rangel-Buitrago, N., González-Fernández, D., Defeo, O., Neal, W., Galgani, F., 2024. Rethinking plastic entrapment: Misconceptions and implications for ecosystem services in coastal habitats. Mar Pollut Bull 205. https://doi.org/10.1016/j.marpolbul.2024.116665.
[28] Sjafrie, N.D.M., et al., Dec. 2024. Monetary value of ecosystem services in unhealthy seagrass meadows in Indonesia. Ecosyst Serv 70, 101668. https://doi.org/10.1016/j.ecoser.2024.101668.
[29] Cozzolino, L., Nicastro, K.R., Zardi, G.I., De Los Santos, C.B., Jun. 2020. Species-specific plastic accumulation in the sediment and canopy of coastal vegetated habitats. Sci Total Environ 723, 138018. https://doi.org/10.1016/j.scitotenv.2020.138018.
[30] Gallitelli, L., Cutini, M., Cesarini, G., Scalici, M., Dec. 2024. Riparian vegetation entraps macroplastics along the entire river course: Implications for eco-safety activities and mitigation strategies. Environ Res 263, 120224. https://doi.org/10.1016/j.envres.2024.120224.
[31] Greenshields, J., Anastasi, A., Irving, A.D., Capper, A., Dec. 2024. A systematic review to assess current surface water and sediment microplastic sampling practices in seagrass and mangrove ecosystems. Environ Sci Pollut Res 31 (59), 66615–66629. https://doi.org/10.1007/s11356-024-35690-9.
[32] Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., Nov. 1972. Polystyrene Spherules in Coastal Waters. Science 178 (4062), 749–750. https://doi.org/10.1126/science.178.4062.749.
[33] Thompson, R.C., Courtene-Jones, W., Boucher, J., Pahl, S., Raubenheimer, K., Koelmans, A.A., Oct. 2024. Twenty years of microplastic pollution research—what have we learned? Science 386 (6720), eadl2746. https://doi.org/10.1126/science.adl2746.
[34] Cerasa, M., Teodori, S., Pietrelli, L., Oct. 2021. Searching Nanoplastics: From Sampling to Sample Processing. Polymers 13 (21), 3658. https://doi.org/10.3390/polym13213658.
[35] Samaei, S.H.-A., et al., Apr. 2025. What Does the 'Trojan Horse' Carry? The Pollutants Associated with Microplastics/Nanoplastics in Water Environments. ACS EST Water 5 (4), 1530–1545. https://doi.org/10.1021/acsestwater.4c01089.
[36] Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M., De France, J., May 2019. Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Res 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054.
[37] "ISO/TR 21960 Plastics — Environmental aspects — State of knowledge and methodologies.," Feb. 2020.
[38] "ISO 24187 Principles for the analysis of microplastics in the environment.," ISO, Dec. 2023.
[39] Andrade-Muñoz, A.S., Miserendino, M.L., Quinteros, C.P., Dromaz, W.M., Abrial, E., Di Prinzio, C.Y., 2025. Macroplastic pollution in riparian corridors of urban and pristine mountain streams in Patagonia (Argentina). Sci Total Environ 959. https://doi.org/10.1016/j.scitotenv.2024.178092.
[40] Masiá, P., Ardura, A., Gaitán, M., Gerber, S., Rayon-Viña, F., Garcia-Vazquez, E., Jun. 2021. Maritime ports and beach management as sources of coastal macro-, meso-, and microplastic pollution. Environ Sci Pollut Res 28 (24), 30722–30731. https://doi.org/10.1007/s11356-021-12821-0.
[41] Schwarz, A., Lensen, S., Langeveld, E., Parker, L., Urbanus, J.H., 2022. Plastics in the Global Environment Assessed Through Material Flow Analysis, Degradation and Environmental Transportation. SSRN J. https://doi.org/10.2139/ssrn.4265609.
[42] Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., Apr. 2017. Combined Effects of UV Exposure Duration and Mechanical Abrasion on Microplastic Fragmentation by Polymer Type. Environ Sci Technol 51 (8), 4368–4376. https://doi.org/10.1021/acs.est.6b06155.
[43] Acarer Arat, S., Jan. 2024. An overview of microplastic in marine waters: Sources, abundance, characteristics and negative effects on various marine organisms. Desalin Water Treat 317, 100138. https://doi.org/10.1016/j.dwt.2024.100138.
[44] Tursi, A., et al., 2022. Microplastics in aquatic systems, a comprehensive review: origination, accumulation, impact, and removal technologies. RSC Adv 12 (44), 28318–28340. https://doi.org/10.1039/d2ra04713f.
[45] Singh, P., Varshney, G., Kaur, R., Oct. 2024. Primary Microplastics in the Ecosystem: Ecological Effects, Risks, and Comprehensive Perspectives on Toxicology and Detection Methods. J Environ Sci Health Part C 42 (4), 314–365. https://doi.org/10.1080/26896583.2024.2370715.
[46] Ahmed, M.B., et al., Jun. 2021. Microplastic particles in the aquatic environment: A systematic review. Sci Total Environ 775, 145793. https://doi.org/10.1016/j.scitotenv.2021.145793.
[47] Yurtsever, M., Jun. 2019. Glitters as a Source of Primary Microplastics: An Approach to Environmental Responsibility and Ethics. J Agric Environ Ethics 32 (3), 459–478. https://doi.org/10.1007/s10806-019-09785-0.
[48] Huber, M., Archodoulaki, V.-M., Pomakhina, E., Pukánszky, B., Zinöcker, E., Gahleitner, M., Jan. 2022. Environmental degradation and formation of secondary microplastics from packaging material: A polypropylene film case study. Polym Degrad Stab 195, 109794. https://doi.org/10.1016/j.polymdegradstab.2021.109794.
[49] Zhang, Y., Gao, T., Kang, S., Allen, S., Luo, X., Allen, D., Mar. 2021. Microplastics in glaciers of the Tibetan Plateau: Evidence for the long-range transport of microplastics. Sci Total Environ 758, 143634. https://doi.org/10.1016/j.scitotenv.2020.143634.
[50] Liu, L., Xu, M., Ye, Y., Zhang, B., Feb. 2022. On the degradation of (micro) plastics: Degradation methods, influencing factors, environmental impacts. Sci Total Environ 806, 151312. https://doi.org/10.1016/j.scitotenv.2021.151312.
[51] Yang, S.-S., et al., Feb. 2021. Biodegradation of polypropylene by yellow mealworms (Tenebrio molitor) and superworms (Zophobas atratus) via gut-microbe-dependent depolymerization. Sci Total Environ 756, 144087. https://doi.org/10.1016/j.scitotenv.2020.144087.
[52] Niu, L., Wang, Y., Li, Y., Lin, L., Chen, Y., Shen, J., May 2023. Occurrence, Degradation Pathways, and Potential Synergistic Degradation Mechanism of Microplastics in Surface Water: A Review. Curr Pollut Rep 9 (2), 312–326. https://doi.org/10.1007/s40726-023-00262-x.
[53] Bao, R., Fu, D., Fan, Z., Peng, X., Peng, L., Aug. 2022. Aging of microplastics and their role as vector for copper in aqueous solution. Gondwana Res 108, 81–90. https://doi.org/10.1016/j.gr.2021.12.002.
[54] Fueser, H., Mueller, M.-T., Weiss, L., Höss, S., Traunspurger, W., Dec. 2019. Ingestion of microplastics by nematodes depends on feeding strategy and buccal

cavity size. Environ Pollut 255, 113227. https://doi.org/10.1016/j.envpol.2019.113227.
[55] Mahon, A.M., et al., Jan. 2017. Microplastics in Sewage Sludge: Effects of Treatment. Environ Sci Technol 51 (2), 810–818. https://doi.org/10.1021/acs.est.6b04048.
[56] Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., Jun. 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci Total Environ 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368.
[57] Kabir, M.S., Wang, H., Luster-Teasley, S., Zhang, L., Zhao, R., Oct. 2023. Microplastics in landfill leachate: Sources, detection, occurrence, and removal. Environ Sci Ecotechnology 16, 100256. https://doi.org/10.1016/j.ese.2023.100256.
[58] Wang, C., O'Connor, D., Wang, L., Wu, W.-M., Luo, J., Hou, D., Oct. 2022. Microplastics in urban runoff: Global occurrence and fate. Water Res 225, 119129. https://doi.org/10.1016/j.watres.2022.119129.
[59] Di, M., Wang, J., Mar. 2018. Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. Sci Total Environ 616–617, 1620–1627. https://doi.org/10.1016/j.scitotenv.2017.10.150.
[60] Wang, W., Yuan, W., Chen, Y., Wang, J., Aug. 2018. Microplastics in surface waters of Dongting Lake and Hong Lake, China. Sci Total Environ 633, 539–545. https://doi.org/10.1016/j.scitotenv.2018.03.211.
[61] Jiang, J., He, L., Zheng, S., Liu, J., Gong, L., Apr. 2024. A review of microplastic transport in coastal zones. Mar Environ Res 196, 106397. https://doi.org/10.1016/j.marenvres.2024.106397.
[62] Rios Mendoza, L.M., Karapanagioti, H., Álvarez, N.R., Feb. 2018. Micro (nanoplastics) in the marine environment: Current knowledge and gaps. Curr Opin Environ Sci & Health 1, 47–51. https://doi.org/10.1016/j.coesh.2017.11.004.
[63] Hasan Anik, A., Hossain, S., Alam, M., Binte Sultan, M., Hasnine, Md.T., Rahman, Md.M., Dec. 2021. "Microplastics pollution: A comprehensive review on the sources, fates, effects, and potential remediation. " Environ Nanotechnol Monit & Manag 16, 100530. https://doi.org/10.1016/j.enmm.2021.100530.
[64] Li, J., Shan, E., Zhao, J., Teng, J., Wang, Q., Apr. 2023. The factors influencing the vertical transport of microplastics in marine environment: A review. Sci Total Environ 870, 161893. https://doi.org/10.1016/j.scitotenv.2023.161893.
[65] Andrady, A.L., Aug. 2011. Microplastics in the marine environment. Mar Pollut Bull 62 (8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.
[66] Zhang, M., et al., Jul. 2024. Interactions between Iron Minerals and Dissolved Organic Matter Derived from Microplastics Inhibited the Ferrihydrite Transformation as Revealed at the Molecular Scale. acs.est.4c03322 Environ Sci Technol. https://doi.org/10.1021/acs.est.4c03322.
[67] Zhu, Z., et al., Jul. 2024. The environmental effects of microplastics and microplastic derived dissolved organic matter in aquatic environments: A review. Sci Total Environ 933, 173163. https://doi.org/10.1016/j.scitotenv.2024.173163.
[68] Li, H., et al., Feb. 2023. Uptake and distribution of microplastics of different particle sizes in maize (Zea mays) seedling roots. Chemosphere 313, 137491. https://doi.org/10.1016/j.chemosphere.2022.137491.
[69] Botterell, Z.L.R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R.C., Lindeque, P.K., Feb. 2019. Bioavailability and effects of microplastics on marine zooplankton: A review. Environ Pollut 245, 98–110. https://doi.org/10.1016/j.envpol.2018.10.065.
[70] Azizi, N., Nasseri, S., Nodehi, R.N., Jaafarzadeh, N., Pirsaheb, M., Apr. 2022. Evaluation of conventional wastewater treatment plants efficiency to remove microplastics in terms of abundance, size, shape, and type: A systematic review and Meta-analysis. Mar Pollut Bull 177, 113462. https://doi.org/10.1016/j.marpolbul.2022.113462.
[71] Ouyang, X., et al., Feb. 2022. Fate and Effects of Macro- and Microplastics in Coastal Wetlands. Environ Sci Technol 56 (4), 2386–2397. https://doi.org/10.1021/acs.est.1c06732.
[72] Bilgin, M., Yurtsever, M., Karadagli, F., Dec. 2020. Microplastic removal by aerated grit chambers versus settling tanks of a municipal wastewater treatment plant. J Water Process Eng 38, 101604. https://doi.org/10.1016/j.jwpe.2020.101604.
[73] Tatsii, D., et al., Jan. 2024. Shape Matters: Long-Range Transport of Microplastic Fibers in the Atmosphere. Environ Sci Technol 58 (1), 671–682. https://doi.org/10.1021/acs.est.3c08209.
[74] Lim, J.-H., Kang, J.-W., May 2024. Assessing biofilm formation and resistance of Vibrio parahaemolyticus on UV-aged microplastics in aquatic environments. Water Res 254, 121379. https://doi.org/10.1016/j.watres.2024.121379.
[75] Liu, P., Zhan, X., Wu, X., Li, J., Wang, H., Gao, S., Mar. 2020. Effect of weathering on environmental behavior of microplastics: Properties, sorption and potential risks. Chemosphere 242, 125193. https://doi.org/10.1016/j.chemosphere.2019.125193.
[76] Di, X., Sun, T., Hu, M., Wang, D., Zhang, H., Apr. 2025. Significant microplastic accumulation and burial in the intertidal sedimentary environments of the Yellow River Delta. J Hazard Mater 487, 137134. https://doi.org/10.1016/j.jhazmat.2025.137134.
[77] Luo, Y.Y., Not, C., Cannicci, S., 2021. Mangroves as unique but understudied traps for anthropogenic marine debris: A review of present information and the way forward. Environ Pollut 271. https://doi.org/10.1016/j.envpol.2020.116291.
[78] Sanchez-Vidal, A., Canals, M., De Haan, W.P., Romero, J., Veny, M., Jan. 2021. Seagrasses provide a novel ecosystem service by trapping marine plastics. Sci Rep 11 (1). https://doi.org/10.1038/s41598-020-79370-3.
[79] Jones, K.L., Hartl, M.G.J., Bell, M.C., Capper, A., Mar. 2020. Microplastic accumulation in a Zostera marina L. bed at Deerness Sound, Orkney, Scotland. Mar Pollut Bull 152, 110883. https://doi.org/10.1016/j.marpolbul.2020.110883.
[80] Anderson, R.J., Turner, A., 2024. Microplastic transport and deposition in a beach-dune system (Saunton Sands-Braunton Burrows, southwest England). Sci Total Environ 909. https://doi.org/10.1016/j.scitotenv.2023.168535.
[81] Van Emmerik, T.H.M., Frings, R.M., Schreyers, L.J., Hauk, R., De Lange, S.I., Mellink, Y.A.M., Jun. 2023. River plastic transport and deposition amplified by extreme flood. Nat Water 1 (6), 514–522. https://doi.org/10.1038/s44221-023-00092-7.
[82] McIlwraith, H.K., Lindeque, P.K., Miliou, A., Tolhurst, T.J., Cole, M., Mar. 2024. Microplastic shape influences fate in vegetated wetlands. Environ Pollut 345, 123492. https://doi.org/10.1016/j.envpol.2024.123492.
[83] Menicagli, V., Balestri, E., Fulignati, S., Raspolli Galletti, A.M., Lardicci, C., 2023. Plastic litter in coastal sand dunes: Degradation behavior and impact on native and non-native invasive plants. Environ Pollut 316. https://doi.org/10.1016/j.envpol.2022.120738.
[84] Menicagli, V., Balestri, E., Giommoni, F., Vannini, C., Lardicci, C., 2023. Plastic litter changes the rhizosphere bacterial community of coastal dune plants. Sci Total Environ 880. https://doi.org/10.1016/j.scitotenv.2023.163293.
[85] Macan, G.P.F., et al., Dec. 2024. Macro- and microplastics leachates: Characterization and impact on seed germination. J Hazard Mater 480, 136013. https://doi.org/10.1016/j.jhazmat.2024.136013.
[86] Siregar, L.Y., Yucharoen, M., Muchlisin, Z.A., Pradit, S., 2025. "ACCUMULATION OF MICROPLASTICS (<300 μM) IN MANGROVE SEDIMENTS OF BANDA ACEH CITY, INDONESIA,". Appl Ecol Env Res 23 (2), 3245–3258. https://doi.org/10.15666/aeer/2302_32453258.
[87] Zhang, P., Zhao, W., Zhang, J., Gao, Y., Wang, S., Jian, Q., Apr. 2024. Human activities altered the enrichment patterns of microplastics in mangrove blue carbon ecosystem in the semi-enclosed Zhanjiang Bay, China. Front Mar Sci 11. https://doi.org/10.3389/fmars.2024.1362170.
[88] Zhou, Q., et al., 2020. Characteristics and distribution of microplastics in the coastal mangrove sediments of China. Sci Total Environ 703. https://doi.org/10.1016/j.scitotenv.2019.134807.
[89] Deng, H., et al., 2023. Mangrove degradation retarded microplastics weathering and affected metabolic activities of microplastics-associated microbes. J Hazard Mater 445. https://doi.org/10.1016/j.jhazmat.2022.130535.
[90] Duan, J., et al., May 2021. How mangrove plants affect microplastic distribution in sediments of coastal wetlands: Case study in Shenzhen Bay, South China. Sci Total Environ 767, 144695. https://doi.org/10.1016/j.scitotenv.2020.144695.
[91] Li, Y., et al., 2022. Microplastics distribution in different habitats of Ximen Island and the trapping effect of blue carbon habitats on microplastics. Mar Pollut Bull 181. https://doi.org/10.1016/j.marpolbul.2022.113912.
[92] Girones, L., et al., Feb. 2024. Spatial distribution and characteristics of plastic pollution in the salt marshes of Bahía Blanca Estuary, Argentina. Sci Total Environ 912, 169199. https://doi.org/10.1016/j.scitotenv.2023.169199.
[93] Pinheiro, L.M., Carvalho, I.V., Agostini, V.O., Martinez-Souza, G., Galloway, T.S., Pinho, G.L.L., Sep. 2021. Litter contamination at a salt marsh: An ecological niche for biofouling in South Brazil. Environ Pollut 285, 117647. https://doi.org/10.1016/j.envpol.2021.117647.
[94] Pinheiro, L.M., et al., 2022. Salt marshes as the final watershed fate for meso- and microplastic contamination: A case study from Southern Brazil. Sci Total Environ 838. https://doi.org/10.1016/j.scitotenv.2022.156077.
[95] Almeida, C.M.R., Sáez-Zamacona, I., Silva, D.M., Rodrigues, S.M., Pereira, R., Ramos, S., Apr. 2023. The Role of Estuarine Wetlands (Saltmarshes) in Sediment Microplastics Retention. Water 15 (7), 1382. https://doi.org/10.3390/w15071382.
[96] Yao, W., et al., Dec. 2019. Micro- and macroplastic accumulation in a newly formed Spartina alterniflora colonized estuarine saltmarsh in southeast China. Mar Pollut Bull 149, 110636. https://doi.org/10.1016/j.marpolbul.2019.110636.
[97] Bonanno, G., Orlando-Bonaca, M., Sep. 2020. Marine plastics: What risks and policies exist for seagrass ecosystems in the Plasticene? Mar Pollut Bull 158, 111425. https://doi.org/10.1016/j.marpolbul.2020.111425.
[98] Menicagli, V., Balestri, E., Vallerini, F., De Battisti, D., Lardicci, C., Feb. 2021. Plastics and sedimentation foster the spread of a non-native macroalga in seagrass meadows. Sci Total Environ 757, 143812. https://doi.org/10.1016/j.scitotenv.2020.143812.
[99] Walther, B.A., Bergmann, M., Dec. 2022. Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. Emerg Top Life Sci 6 (4), 371–387. https://doi.org/10.1042/etls20220017.
[100] Huang, Y., Xiao, X., Xu, C., Perianen, Y.D., Hu, J., Holmer, M., Feb. 2020. Seagrass beds acting as a trap of microplastics - Emerging hotspot in the coastal region? Environ Pollut 257, 113450. https://doi.org/10.1016/j.envpol.2019.113450.
[101] Neelavannan, K., et al., May 2025. Geospatial distribution and anthropogenic litter impact on coastal mangrove ecosystems from the Saudi Arabia coast of the Gulf. Sci Rep 15 (1). https://doi.org/10.1038/s41598-025-98136-3.
[102] dos Reis Cavalcante, E., Ribeiro, V.V., Taddei, R.R., Castro, Í.B., Alves, M.J., 2024. High levels of anthropogenic litter trapped in a mangrove area under the influence of different uses. Mar Pollut Bull 200. https://doi.org/10.1016/j.marpolbul.2024.116045.
[103] Battisti, C., Fanelli, G., Gallitelli, L., Scalici, M., 2023. Dunal plants as sink for anthropogenic marine litter: The entrapping role of Salsola kali L. (1753) in a Mediterranean remote beach (Sardinia, Italy). Mar Pollut Bull 192. https://doi.org/10.1016/j.marpolbul.2023.115033.

[104] Calderisi, G., Cogoni, D., Loni, A., Fenu, G., 2023. Difference between invasive alien and native vegetation in trapping beach litter: A focus on a typical sandy beach of W-Mediterranean Basin. Mar Pollut Bull 192. https://doi.org/10.1016/j.marpolbul.2023.115065.

[105] Corbau, C., Buoninsegni, J., Olivo, E., Vaccaro, C., Nardin, W., Simeoni, U., 2023. Understanding through drone image analysis the interactions between geomorphology, vegetation and marine debris along a sandy spit. Mar Pollut Bull 187. https://doi.org/10.1016/j.marpolbul.2022.114515.

[106] Poeta, G., Fanelli, G., Pietrelli, L., Acosta, A.T.R., Battisti, C., 2017. Plastisphere in action: evidence for an interaction between expanded polystyrene and dunal plants. Environ Sci Pollut Res 24 (12), 11856–11859. https://doi.org/10.1007/s11356-017-8887-7.

[107] Andriolo, U., Gonçalves, G., Jan. 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. Mar Pollut Bull 174, 113307. https://doi.org/10.1016/j.marpolbul.2021.113307.

[108] Gallitelli, L., Battisti, C., Scalici, M., 2023. Dunal plants intercepting macrolitter: Implications for beach clean-ups. Mar Pollut Bull 187. https://doi.org/10.1016/j.marpolbul.2023.114585.

[109] Gonçalves, G.R.L., Grey, C., Koomson, A., Aggrey-Fynn, J., Nyarko, B.K., Narayanaswamy, B.E., Apr. 2025. Patterns and implications of plastic accumulation in mangrove ecosystems and sandy beaches in Western and Central regions of Ghana, West Africa. Environ Sci Pollut Res 32 (19), 11996–12012. https://doi.org/10.1007/s11356-025-36359-7.

[110] Pinto, R.B., Bogerd, L., van der Ploeg, M., Duah, K., Uijlenhoet, R., van Emmerik, T.H.M., 2024. Catchment scale assessment of macroplastic pollution in the Odaw river, Ghana. Mar Pollut Bull 198. https://doi.org/10.1016/j.marpolbul.2023.115813.

[111] Ar, N., Ch, S., Sep. 2024. Microplastics in the Surface Waters and Sediment in an Agrarian Part of Vembanad-Kol Wetlands, the Largest Ramsar Site—Southwest India. Water Air Soil Pollut 235 (9). https://doi.org/10.1007/s11270-024-07356-2.

[112] Liu, Q., Hu, H., Xiong, X., Zhao, E., Wang, K., Wu, C., Jul. 2022. Urban natural wetland as a sink for microplastics: A case from Lalu Wetland in Tibet, China. Sci Total Environ 828, 154399. https://doi.org/10.1016/j.scitotenv.2022.154399.

[113] Nagalakshmi, R., et al., Aug. 2024. Microplastic Contamination in Kollidam River Estuary, East Coast of India: A Comparative Study Across Inner, Outer and Mangrove Estuarine Regions. Water Air Soil Pollut 235 (8). https://doi.org/10.1007/s11270-024-07276-1.

[114] Ogbuagu, C.C., Kassem, H., Udiba, U.U., Stead, J.L., Cundy, A.B., Sep. 2022. Role of saltmarsh systems in estuarine trapping of microplastics. Sci Rep 12 (1). https://doi.org/10.1038/s41598-022-18881-7.

[115] Kesavan, S., Xavier, K.A.M., Deshmukhe, G., Jaiswar, A.K., Bhusan, S., Sukla, S.P., 2021. Anthropogenic pressure on mangrove ecosystems: Quantification and source identification of surficial and trapped debris. Sci Total Environ 794. https://doi.org/10.1016/j.scitotenv.2021.148677.

[116] Luo, Y.Y., Vorsatz, L.D., Not, C., Cannicci, S., Apr. 2022. Landward zones of mangroves are sinks for both land and water borne anthropogenic debris. Sci Total Environ 818, 151809. https://doi.org/10.1016/j.scitotenv.2021.151809.

[117] Sudhakar, B.J., Mathew, G., Sep. 2025. Comparison of mangroves and other coastal vegetation in effectively trapping microplastics. Estuar Coast Shelf Sci 323, 109382. https://doi.org/10.1016/j.ecss.2025.109382.

[118] Jiao, M., et al., Jul. 2022. Mangrove forest: An important coastal ecosystem to intercept river microplastics. Environ Res 210, 112939. https://doi.org/10.1016/j.envres.2022.112939.

[119] Li, T., Wang, Y., Jiao, M., Zhao, Z., Li, R., Qin, C., Nov. 2023. Distinct microplastics abundance variation in root-associated sediments revealed the underestimation of mangrove microplastics pollution. Sci Total Environ 899, 165611. https://doi.org/10.1016/j.scitotenv.2023.165611.

[120] Martin, C., Almahasheer, H., Duarte, C.M., Apr. 2019. Mangrove forests as traps for marine litter. Environ Pollut 247, 499–508. https://doi.org/10.1016/j.envpol.2019.01.067.

[121] Gonçalves, G.R.L., Koomson, A., Aggrey-Fynn, J., Nyarko, B.K., Narayanaswamy, B.E., Feb. 2025. Invisible Peril: Assessing microplastic pollution in Ghanaian mangroves. Mar Pollut Bull 211, 117361. https://doi.org/10.1016/j.marpolbul.2024.117361.

[122] Li, R., Yu, L., Chai, M., Wu, H., Zhu, X., Mar. 2020. The distribution, characteristics and ecological risks of microplastics in the mangroves of Southern China. Sci Total Environ 708, 135025. https://doi.org/10.1016/j.scitotenv.2019.135025.

[123] Zhang, L., Wang, S., Jian, Q., Zhang, P., Lu, Y., Liu, H., Jul. 2022. Tidal variation shaped microplastic enrichment patterns in mangrove blue carbon ecosystem of northern Beibu Gulf, China. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.927884.

[124] Xu, N., et al., 2023. The role of bio-geomorphic feedbacks in shaping microplastic burial in blue carbon habitats. Sci Total Environ 861. https://doi.org/10.1016/j.scitotenv.2022.160220.

[125] Paduani, M., 2020. Microplastics as novel sedimentary particles in coastal wetlands: A review. Mar Pollut Bull 161. https://doi.org/10.1016/j.marpolbul.2020.111739.

[126] Chaisanguansuk, P., Phantuwongraj, S., Jirapinyakul, A., Assawincharoenkij, T., 2023. Preliminary study on microplastic abundance in mangrove sediment cores at Mae Klong River, upper Gulf of Thailand. Front Environ Sci 11. https://doi.org/10.3389/fenvs.2023.1134988.

[127] Battisti, C., Cesarini, G., Gallitelli, L., Moretti, F., Scalici, M., Apr. 2024. Anthropogenic litter in a Mediterranean coastal wetland: A heterogeneous spatial pattern of historical deposition. Mar Pollut Bull 201, 116163. https://doi.org/10.1016/j.marpolbul.2024.116163.

[128] Martinez, M., et al., May 2024. The power of Posidonia oceanica meadows to retain microplastics and the consequences on associated macrofaunal benthic communities. Environ Pollut 348, 123814. https://doi.org/10.1016/j.envpol.2024.123814.

[129] Unsworth, R.K.F., Higgs, A., Walter, B., Cullen-Unsworth, L.C., Inman, I., Jones, B.L., 2021. Canopy Accumulation: Are Seagrass Meadows a Sink of Microplastics? Oceans 2 (1), 162–178. https://doi.org/10.3390/oceans2010010.

[130] Boshoff, B.J., Hull, K.L., Von Der Heyden, S., Mar. 2025. The interaction between seagrass meadow density and microplastic retention in four cool-temperate estuaries. Mar Pollut Bull 212, 117502. https://doi.org/10.1016/j.marpolbul.2024.117502.

[131] Navarrete-Fernández, T., Bermejo, R., Hernández, I., Deidun, A., Andreu-Cazenave, M., Cózar, A., Jan. 2022. The role of seagrass meadows in the coastal trapping of litter. Mar Pollut Bull 174, 113299. https://doi.org/10.1016/j.marpolbul.2021.113299.

[132] Fong, J., et al., Nov. 2023. Litter traps: A comparison of four marine habitats as sinks for anthropogenic marine macro-litter in Singapore. Mar Pollut Bull 196, 115645. https://doi.org/10.1016/j.marpolbul.2023.115645.

[133] Mo, A., D'Antraccoli, M., Bedini, G., Ciccarelli, D., 2021. The role of plants in the face of marine litter invasion: A case study in an Italian protected area. Mar Pollut Bull 169. https://doi.org/10.1016/j.marpolbul.2021.112544.

[134] Sivadas, S.K., et al., 2022. Litter and plastic monitoring in the Indian marine environment: A review of current research, policies, waste management, and a roadmap for multidisciplinary action. Mar Pollut Bull 176. https://doi.org/10.1016/j.marpolbul.2022.113424.

[135] Ben-Haddad, M., Abelouah, M.R., Hajji, S., Rangel-Buitrago, N., Alla, A.A., 2023. The halophyte Cakile maritima Scop. 1772 as a trap of plastic litter on the Moroccan coast. Mar Pollut Bull 187. https://doi.org/10.1016/j.marpolbul.2023.114574.

[136] Gallitelli, L., D'Agostino, M., Battisti, C., Cózar, A., Scalici, M., 2023. Dune plants as a sink for beach litter: The species-specific role and edge effect on litter entrapment by plants. Sci Total Environ 904. https://doi.org/10.1016/j.scitotenv.2023.166756.

[137] Andriolo, U., Gonçalves, G., Bessa, F., Sobral, P., 2020. Mapping marine litter on coastal dunes with unmanned aerial systems: A showcase on the Atlantic Coast. Sci Total Environ 736. https://doi.org/10.1016/j.scitotenv.2020.139632.

[138] Corbau, C., Lazarou, A., Simeoni, U., Jul. 2025. Fishing-Related Plastic Pollution on Bocassette Spit (Northern Adriatic): Distribution Patterns and Stakeholder Perspectives. JMSE 13 (7), 1351. https://doi.org/10.3390/jmse13071351.

[139] Olivelli, A., Hardesty, B.D., Wilcox, C., Jul. 2020. Coastal margins and backshores represent a major sink for marine debris: insights from a continental-scale analysis. Environ Res Lett 15 (7), 074037. https://doi.org/10.1088/1748-9326/ab7836.

[140] Cresta, E., Battisti, C., 2021. Anthropogenic litter along a coastal-wetland gradient: Reed-bed vegetation in the backdunes may act as a sink for expanded polystyrene. Mar Pollut Bull 172. https://doi.org/10.1016/j.marpolbul.2021.112829.

[141] Portz, L., Manzolli, R.P., Villate-Daza, D.A., Fontán-Bouzas, Á., 2022. Where does marine litter hide? The Providencia and Santa Catalina Island problem, SEAFLOWER Reserve (Colombia). Sci Total Environ 813. https://doi.org/10.1016/j.scitotenv.2021.151878.

[142] Owowenu, E.K., Nnadozie, C.F., Akamagwuna, F., Noundou, X.S., Uku, J.E., Odume, O.N., Jun. 2023. A critical review of environmental factors influencing the transport dynamics of microplastics in riverine systems: implications for ecological studies. Aquat Ecol 57 (2), 557–570. https://doi.org/10.1007/s10452-023-10029-7.

[143] Martuscelli, D., Francalanci, S., Innocenti, L., Solari, L., Oct. 2025. Riparian vegetation as a natural barrier: experimental analysis of plastic particle retention in a vegetated reach. Environ Adv 21, 100645. https://doi.org/10.1016/j.envadv.2025.100645.

[144] Liro, M., Mikuś, P., Wyżga, B., Sep. 2022. First insight into the macroplastic storage in a mountain river: The role of in-river vegetation cover, wood jams and channel morphology. Sci Total Environ 838, 156354. https://doi.org/10.1016/j.scitotenv.2022.156354.

[145] Newbould, R.A., Powell, D.M., Whelan, M.J., Sep. 2021. Macroplastic Debris Transfer in Rivers: A Travel Distance Approach. Front Water 3. https://doi.org/10.3389/frwa.2021.724596.

[146] Helcoski, R., Yonkos, L.T., Sanchez, A., Baldwin, A.H., Jan. 2020. Wetland soil microplastics are negatively related to vegetation cover and stem density. Environ Pollut 256, 113391. https://doi.org/10.1016/j.envpol.2019.113391.

[147] Wu, M., Goh, Y.L., Mowe, M.A.D., Todd, P.A., Yeo, D.C.J., Apr. 2025. The effects of microplastics size and type on entrapment by freshwater macrophytes under vertical and lateral deposition. J Limnol 84. https://doi.org/10.4081/jlimnol.2025.2218.

[148] Chen, Z., et al., Dec. 2024. Multiple effects of submerged plants on microplastics-heavy metals redistribution and combination in the hyporheic sediment. J Hazard Mater 480, 135918. https://doi.org/10.1016/j.jhazmat.2024.135918.

[149] Büngener, L., Postila, H., Löder, M.G.J., Laforsch, C., Ronkanen, A.-K., Heiderscheidt, E., Dec. 2023. The fate of microplastics from municipal wastewater in a surface flow treatment wetland. Sci Total Environ 903, 166334. https://doi.org/10.1016/j.scitotenv.2023.166334.

[150] Yin, L., et al., Oct. 2021. Microplastics retention by reeds in freshwater environment. Sci Total Environ 790, 148200. https://doi.org/10.1016/j.scitotenv.2021.148200.

[151] Carrieri, V., Varela, Z., Aboal, J.R., De Nicola, F., Fernández, J.A., Dec. 2022. Suitability of aquatic mosses for biomonitoring micro/meso plastics in freshwater ecosystems. Environ Sci Eur 34 (1). https://doi.org/10.1186/s12302-022-00653-9.
[152] Schreyers, L., et al., 2021. Plastic Plants: The Role of Water Hyacinths in Plastic Transport in Tropical Rivers. Front Environ Sci 9. https://doi.org/10.3389/fenvs.2021.686334.
[153] Van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., Jan. 2022. Rivers as Plastic Reservoirs. Front Water 3. https://doi.org/10.3389/frwa.2021.786936.
[154] Senavirathna, M.D.H.J., Zhaozhi, L., Fujino, T., Mar. 2022. Root Adsorption of Microplastic Particles Affects the Submerged Freshwater Macrophyte Egeria densa. Water Air Soil Pollut 233 (3). https://doi.org/10.1007/s11270-022-05556-2.
[155] Ceschin, S., Mariani, F., Di Lernia, D., Venditti, I., Pelella, E., Iannelli, M.A., Jan. 2023. Effects of Microplastic Contamination on the Aquatic Plant Lemna minuta (Least Duckweed). Plants 12 (1), 207. https://doi.org/10.3390/plants12010207.
[156] Yu, Z., Xu, X., Guo, L., Jin, R., Lu, Y., Jan. 2024. Uptake and transport of micro/nanoplastics in terrestrial plants: Detection, mechanisms, and influencing factors. Sci Total Environ 907, 168155. https://doi.org/10.1016/j.scitotenv.2023.168155.
[157] Adomako, M.O., Wu, J., Lu, Y., Adu, D., Seshie, V.I., Yu, F.-H., Mar. 2024. Potential synergy of microplastics and nitrogen enrichment on plant holobionts in wetland ecosystems. Sci Total Environ 915, 170160. https://doi.org/10.1016/j.scitotenv.2024.170160.
[158] Auta, H.S., et al., Feb. 2022. Enhanced microbial degradation of PET and PS microplastics under natural conditions in mangrove environment. J Environ Manag 304, 114273. https://doi.org/10.1016/j.jenvman.2021.114273.
[159] Li, N., Zhong, B., Guo, Y., Li, X., Yang, Z., He, Y., May 2024. Non-negligible impact of microplastics on wetland ecosystems. Sci Total Environ 924, 171252. https://doi.org/10.1016/j.scitotenv.2024.171252.
[160] Wingender, J., Neu, T.R., Flemming, H.-C., 1999. Microbial Extracellular Polymeric Substances. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-60147-7.
[161] Tatlı, H., Altunışık, A., Jun. 2025. Microplastic footprints in marsh frogs (Pelophylax ridibundus) from two Turkish lakes. Environ Sci Eur 37 (1), 88. https://doi.org/10.1186/s12302-025-01134-5.
[162] Sfriso, A.A., Tomio, Y., Juhmani, A.-S., Sfriso, A., Munari, C., Mistri, M., Oct. 2021. Macrophytes: A Temporary Sink for Microplastics in Transitional Water Systems. Water 13 (21), 3032. https://doi.org/10.3390/w13213032.
[163] Witzmann, T., et al., Jul. 2022. Repulsive Interactions of Eco-corona-Covered Microplastic Particles Quantitatively Follow Modeling of Polymer Brushes. Langmuir 38 (29), 8748–8756. https://doi.org/10.1021/acs.langmuir.1c03204.
[164] Arienzo, M., Ferrara, L., Trifuoggi, M., Jun. 2021. The Dual Role of Microplastics in Marine Environment: Sink and Vectors of Pollutants. JMSE 9 (6), 642. https://doi.org/10.3390/jmse9060642.
[165] Karalija, E., et al., 2022. Interplay of plastic pollution with algae and plants: hidden danger or a blessing? J Hazard Mater 438. https://doi.org/10.1016/j.jhazmat.2022.129450.
[166] Sooriyakumar, P., et al., May 2022. Biofilm formation and its implications on the properties and fate of microplastics in aquatic environments: A review. J Hazard Mater Adv 6, 100077. https://doi.org/10.1016/j.hazadv.2022.100077.
[167] Han, N., Ao, H., Mai, Z., Zhao, Q., Wu, C., Jan. 2023. Characteristics of (micro) plastic transport in the upper reaches of the Yangtze River. Sci Total Environ 855, 158887. https://doi.org/10.1016/j.scitotenv.2022.158887.
[168] Chai, M., Li, R., Li, B., Wu, H., Yu, L., Apr. 2023. Responses of mangrove (Kandelia obovata) growth, photosynthesis, and rhizosphere soil properties to microplastic pollution. Mar Pollut Bull 189, 114827. https://doi.org/10.1016/j.marpolbul.2023.114827.
[169] Liu, S., et al., Feb. 2024. Temporal and spatial variation of microplastics in the urban rivers of Harbin. Sci Total Environ 910, 168373. https://doi.org/10.1016/j.scitotenv.2023.168373.
[170] Schreyers, L.J., et al., Feb. 2024. River plastic transport affected by tidal dynamics. Hydrol Earth Syst Sci 28 (3), 589–610. https://doi.org/10.5194/hess-28-589-2024.
[171] Weber, C.J., Opp, C., Prume, J.A., Koch, M., Andersen, T.J., Chifflard, P., May 2022. Deposition and in-situ translocation of microplastics in floodplain soils. Sci Total Environ 819, 152039. https://doi.org/10.1016/j.scitotenv.2021.152039.
[172] Turner, A., Amos, S.L., Williams, T., Dec. 2021. Coastal dunes as a sink and secondary source of marine plastics: A study at Perran Beach, southwest England. Mar Pollut Bull 173, 113133. https://doi.org/10.1016/j.marpolbul.2021.113133.
[173] Xu, N., et al., Mar. 2023. Effects of waves, burial depth and material density on microplastic retention in coastal sediments. Sci Total Environ 864, 161093. https://doi.org/10.1016/j.scitotenv.2022.161093.
[174] Russell, C.E., Fernández, R., Parsons, D.R., Gabbott, S.E., Jul. 2023. Plastic pollution in riverbeds fundamentally affects natural sand transport processes. Commun Earth Environ 4 (1). https://doi.org/10.1038/s43247-023-00820-7.
[175] Al Harraq, A., Bharti, B., Jan. 2022. Microplastics through the Lens of Colloid Science. ACS Environ Au 2 (1), 3–10. https://doi.org/10.1021/acsenvironau.1c00016.
[176] Li, M., Zhang, X., Yi, K., He, L., Han, P., Tong, M., Oct. 2021. Transport and deposition of microplastic particles in saturated porous media: Co-effects of clay particles and natural organic matter. Environ Pollut 287, 117585. https://doi.org/10.1016/j.envpol.2021.117585.
[177] Mancini, M., Serra, T., Colomer, J., Solari, L., Sep. 2023. Suspended sediments mediate microplastic sedimentation in unidirectional flows. Sci Total Environ 890, 164363. https://doi.org/10.1016/j.scitotenv.2023.164363.
[178] C.T. Johnston and E. Tombácz, "Surface Chemistry of Soil Minerals".
[179] Oriekhova, O., Stoll, S., 2018. Heteroaggregation of nanoplastic particles in the presence of inorganic colloids and natural organic matter. Environ Sci Nano 5 (3), 792–799. https://doi.org/10.1039/C7EN01119A.
[180] Brewer, A., Dror, I., Berkowitz, B., Jan. 2021. The Mobility of Plastic Nanoparticles in Aqueous and Soil Environments: A Critical Review. ACS EST Water 1 (1), 48–57. https://doi.org/10.1021/acsestwater.0c00130.
[181] Nie, X., et al., Mar. 2023. Impact of iron/aluminum (hydr)oxide and clay minerals on heteroaggregation and transport of nanoplastics in aquatic environment. J Hazard Mater 446, 130649. https://doi.org/10.1016/j.jhazmat.2022.130649.
[182] Wang, Y., Chen, X., Wang, F., Cheng, N., Jan. 2023. Influence of typical clay minerals on aggregation and settling of pristine and aged polyethylene microplastics. Environ Pollut 316, 120649. https://doi.org/10.1016/j.envpol.2022.120649.
[183] Peng, L., Wang, Y., Oct. 2022. Sediment organic carbon dominates the heteroaggregation of suspended sediment and nanoplastics in natural and surfactant-polluted aquatic environments. J Hazard Mater 440, 129802. https://doi.org/10.1016/j.jhazmat.2022.129802.
[184] Ding, L., et al., Dec. 2022. Insight into the Photodegradation of Microplastics Boosted by Iron (Hydr)oxides. Environ Sci Technol 56 (24), 17785–17794. https://doi.org/10.1021/acs.est.2c07824.
[185] Dodhia, M.S., et al., Mar. 2023. Microbe-mineral interactions in the Plastisphere: coastal biogeochemistry and consequences for degradation of plastics. Front Mar Sci 10, 1134815. https://doi.org/10.3389/fmars.2023.1134815.
[186] Liu, Y., et al., 2020. Occurrence and characteristics of microplastics in the Haihe River: an investigation of a seagoing river flowing through a megacity in northern China. Environ Pollut 262. https://doi.org/10.1016/j.envpol.2020.114261.
[187] Jia, H., Wu, D., Yu, Y., Han, S., Sun, L., Li, M., Feb. 2022. Impact of microplastics on bioaccumulation of heavy metals in rape (Brassica napus L.). Chemosphere 288, 132576. https://doi.org/10.1016/j.chemosphere.2021.132576.
[188] Ding, L., Huang, D., Ouyang, Z., Guo, X., 2022. The effects of microplastics on soil ecosystem: a review. Curr Opin Environ Sci Health 26. https://doi.org/10.1016/j.coesh.2022.100344.
[189] Gallitelli, L., Scalici, M., Dec. 2024. Conceptual model of global plants entrapping plastics. Environ Rev 32 (4), 470–484. https://doi.org/10.1139/er-2023-0141.
[190] Melvin, J., Bury, M., Ammendolia, J., Mather, C., Liboiron, M., Jul. 2021. Critical Gaps in Shoreline Plastics Pollution Research. Front Mar Sci 8, 689108. https://doi.org/10.3389/fmars.2021.689108.
[191] Feng, S., Wang, H., Wang, Y., Cheng, Q., Dec. 2023. A review of the occurrence and degradation of biodegradable microplastics in soil environments. Sci Total Environ 904, 166855. https://doi.org/10.1016/j.scitotenv.2023.166855.
[192] Rohais, S., et al., 2024. A source-to-sink perspective of an anthropogenic marker: A first assessment of microplastics concentration, pathways, and accumulation across the environment. Earth-Sci Rev 254. https://doi.org/10.1016/j.earscirev.2024.104822.
[193] Walther, B.A., Bergmann, M., 2022. Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. Emerg Top Life Sci 6 (4), 371–387. https://doi.org/10.1042/ETLS20220017.
[194] Adomako, M.O., et al., Dec. 2024. Mechanisms underpinning microplastic effects on the natural climate solutions of wetland ecosystems. Sci Total Environ 954, 176491. https://doi.org/10.1016/j.scitotenv.2024.176491.