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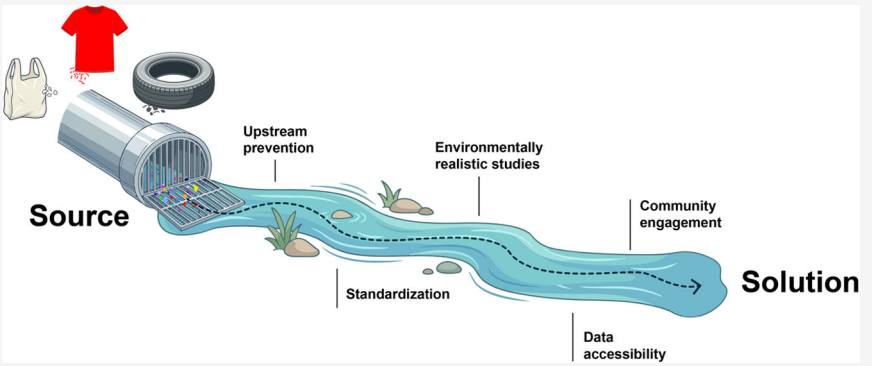
From Sources to Solutions: The San Francisco Bay–Delta System as a Microcosm for Microplastic Science

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ABSTRACT: Microplastics (MPs) are a pervasive and persistent class of pollutants found in nearly every aquatic habitat. Substantial advances have been made in characterizing MP sources, environmental transport, fate, and biological effects. However, significant challenges remain due to the vast diversity of MP characteristics, which complicates cross-study comparability, monitoring, and risk assessment. A central focus of this paper is the San Francisco Bay–Delta, one of the most intensively managed and studied estuarine systems in the world, which provides a valuable setting for advancing MP science within a real-world management context. California was the first jurisdiction to formally define MPs and has since implemented statewide monitoring strategies to support method development and the generation of actionable data. Work in this region can therefore serve as a model for management- and solutions-focused MP science. Drawing on discussions from a symposium focused on MP pollution in the San Francisco Bay–Delta, together with global and California-focused research, we highlight priorities, including stronger standardization, environmentally realistic studies, improved risk assessment frameworks, increased data accessibility and transparency, expanded community engagement, and upstream prevention. Together, these efforts are critical for informing MP research, monitoring, and management in the San Francisco Bay–Delta and beyond.

1. INTRODUCTION

1.1. Microplastics: An Emerging Class of Diverse Contaminants

Synthetic plastics are now embedded in almost every part of modern society and are produced on increasingly expansive scales.[1,2] The persistence of plastics, combined with inadequate waste management, has resulted in an estimated 19–23 million tons entering aquatic environments annually, with drastic increases predicted if production and disposal practices remain unchanged.[3]

Microplastics (MPs) are an emerging class of contaminants—the term "microplastics" was first coined in 2004 to describe microscopic plastic particles found in the ocean.[4] Since then, MPs have gained increasing scientific, public, and regulatory attention due to their ubiquity in the environment and growing evidence of biological effects. These effects span levels of biological organization, from cellular and physiological disruption to altered growth, reproduction, and survival, while emerging evidence of potential human health effects has added urgency to understanding and addressing MP pollution.[5] In 2020, the California State Water Resources Control Board became the first agency in the world to adopt a formal definition of MPs specifically for drinking water, defining MPs as solid polymeric materials between 1 nm and

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5 mm in size, with particles smaller than 1 μm commonly referred to as nanoplastics.[6] MPs are broadly categorized as either primary particles intentionally produced at small sizes or secondary particles generated through fragmentation of larger plastic debris.[5]

A major challenge in MP research is the vast diversity of particle properties, including differences in size, shape, weathering, and chemical composition, all of which influence environmental fate, bioavailability, and toxicity.[7,8] Knowledge gaps surrounding MP transport, weathering, and source tracking further complicate monitoring and management efforts.[9] As a result, effective management strategies must account for regional differences in transport pathways, dominant MP sources, and ecosystem characteristics.[10]

The San Francisco Bay–Delta provides a valuable system for MP research due to its ecological importance, extensive monitoring infrastructure, and complex intersection of urban, agricultural, and industrial inputs. California has also emerged as a leader in MP monitoring and policy efforts through initiatives such as a statewide drinking water monitoring strategy.[11] MPs were further identified as an emerging pollutant of concern in the Delta Science Program's 2024 Grand Challenges in Delta Science Essay,[12] positioning the San Francisco Bay–Delta as a model system for advancing management-relevant MP science.

1.2. Delta Science Program – UC Davis Symposium

To advance dialogue and coordination around the scientific and management challenges posed by MPs, the Delta Science Program (DSP) partnered with the University of California (UC) Davis Coastal and Marine Sciences Institute (CMSI) to host *Microplastic Pollution: Impact on the San Francisco Bay–Delta and Remediation Strategies,* a symposium held at UC Davis on May 9, 2025. The symposium brought together more than 60 researchers, policymakers, and stakeholders from academia, government, and nonprofit sectors to discuss the growing impacts of MPs on aquatic ecosystems, particularly within the San Francisco Bay–Delta. Discussions focused on MP sources and transport, ecological and physiological effects, monitoring approaches, risk-assessment frameworks, and policy solutions, highlighting the need to better connect advancing science with management and decision-making.

This paper builds on these discussions by examining MP research and management across scales, from molecular and physiological effects to ecosystem-level impacts and broader policy approaches. We highlight recent advances, persistent knowledge gaps, and emerging priorities in the field, with particular emphasis on the San Francisco Bay–Delta as a model system for management-relevant MP science. In Section 2, *What We Know*, we summarize current understanding of MP sources, transport pathways, environmental fate, and biological effects. In Section 3, *What We Are Doing*, we highlight ongoing efforts in monitoring, data integration, and hazard and risk assessment. In Section 4, *Where We Are Going*, we outline future priorities for research, standardization, public engagement, and management.

2. WHAT WE KNOW

2.1. Sources and Pathways

MPs enter aquatic environments through multiple sources, creating complex exposure scenarios across trophic levels. While MPs originate from both primary sources and direct release, fragmentation of larger plastic items is widely considered a dominant contributor to environmental MP burdens. The durability of plastics during use, coupled with resistance to degradation at end of life, promotes long-term accumulation and progressive fragmentation, although rates and timescales remain poorly understood.[5]

Wastewater treatment plants (WWTPs) are an important urban point source of MPs to aquatic systems.[13] Although they remove 90–99% of MPs from influent water, the remaining 1–10% still results in billions of particles discharged daily.[14] Microbeads from personal care products, synthetic fibers from laundry, and degraded plastics are primary wastewater sources.[14,15] In addition to WWTPs, stormwater runoff transports substantial MP loads from urban sources to receiving waters.[16] Tire wear particles are a major source of MPs in urban runoff[17] and are estimated to comprise 5–10% of plastics entering the oceans.[18] Seasonal storm events can further increase MP concentrations through stormwater runoff pulses,[19] as observed in the San Francisco Bay for both MPs[16] and plastic-associated chemicals.[20]

Agricultural practices are another source that can introduce MPs to aquatic environments.[21] Plastic mulch films, covering an estimated 20 million hectares globally, break down into MPs and accumulate in soils and nearby waterbodies.[22] Application of biosolids transfers WWTP-captured MPs to terrestrial systems, where erosion and leaching transport them to aquatic environments.[23] While terrestrial runoff represents a major pathway of MP inputs, atmospheric transport is also an important and often underestimated pathway, with fibers dominating atmospheric fallout samples.[24] Airborne MPs can undergo long-range transport and deposit into remote aquatic ecosystems far from their sources.[25] Ocean-based activities are another source of marine plastic pollution, with abandoned, lost, or discarded fishing gear representing an important source that can fragment into MPs over time.[26]

Freshwater systems are important pathways transporting MPs from terrestrial to marine environments, with rivers acting as both temporary sinks and conduits to the ocean.[27] MP abundance and distribution are strongly influenced by anthropogenic activity, including population density and land use.[28]

2.2. Environmental Fate

Once in the environment, MPs are widely and variably distributed across aquatic systems through physical transport and hydrodynamic processes. Horizontal transport is driven by currents and wind, while vertical distribution is influenced by turbulence, mixing, MP properties, and weathering.[29] These processes enable continual redistribution across environmental compartments, resulting in MP presence even in remote environments such as Arctic ice and deep-sea sediments and creating spatially and temporally variable exposure for aquatic organisms.[30,31]

In freshwater systems, MP fate is governed by hydrological conditions, including discharge, flow velocity, channel structure, and retention features, which determine whether particles are transported downstream or retained within river networks.[32] Once MPs enter estuarine and marine waters, circulation patterns determine whether particles remain nearby, move along the coast, or are transported offshore.[33] Ocean circulation can trap MPs in convergence zones such as subtropical gyres, creating hotspots of exposure.[34]

MP specific gravity determines whether particles float or sink, their position in the water column, and associated

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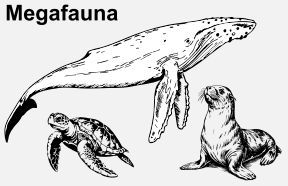
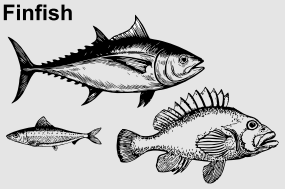
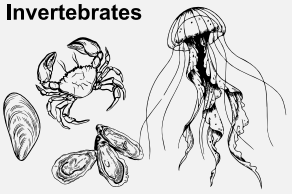
	Exposure Route	Cell/Molecular Level	Organism Level	Population/Ecosystem Level
Megafauna 	ingestion prey translocation	immune genes ↑	tissue damage ↑ mortality ↑	reproduction ↓
Finfish 	ingestion branchial uptake prey translocation	ROS ↑ neurotoxicity ↑ steroidogenesis ↓	growth ↓ altered feeding condition factor ↓ tissue damage ↑ altered behavior mortality ↑	reproduction ↓ biomass ↓
Invertebrates 	ingestion adherence prey translocation	ROS ↑ immune response ↑ proteome altered	growth/mass ↓ metabolic rate ↑ tissue damage ↑ altered behavior mortality ↑	reproduction ↓ population density ↓
Algae 	adherence direct contact physical trapping	ROS, stress ↑ cell damage ↑ cell number ↓ apoptosis ↑ photosynthesis ↓	growth ↓ pigment loss/necrosis tissue damage ↑ feeding ↓ aggregation/sinking	biomass ↕

Figure 1. Summary of documented microplastic exposure routes and associated effects in representative marine taxa, including megafauna, finfish, invertebrates, and algae. Effects are organized by biological level from cellular and molecular responses to organismal and population, and ecosystem-level outcomes. Figure adapted from Brander et al. (2025).[42]

exposure risks. In marine systems, polymers with a specific gravity greater than 1.025 g/cm^3 (approximately that of seawater) are expected to sink, while those with lower values float.[35] For example, low-density polyethylene (LDPE) MPs (0.89–0.93 g/cm^3) are typically buoyant and commonly derived from single-use items such as plastic bags and food storage containers, whereas polymers such as polyethylene terephthalate and polyvinyl chloride (1.16–1.39 g/cm^3) are denser than seawater and sink.[35] Low-density MPs are more likely to be ingested by pelagic organisms, while higher-density MPs are consumed by benthic fish and deposit feeders.[36]

Processes such as biofouling and weathering can alter MP density and buoyancy over time, changing their vertical position and bioavailability.[37] Biofouling is the process by which plastics become coated with organic and inorganic material and rapidly colonized by microbial biofilms within minutes to hours. These biofilms, composed of bacteria, algae, protozoans, and fungi, increase MP density and can drive sinking and accumulation in sediments.[37,38] A mismatch between MP accumulation in surface waters and rising plastic production suggests that much of this "missing plastic" is transported to deeper waters and stored in sediments.[39]

MP movement and accumulation are difficult to predict because physical, chemical, and biological processes interact in complex and sometimes opposing ways. For example, biofouling can increase particle density and drive sinking, while subsequent defouling can return particles to the surface, allowing repeated cycling through the water column.[38] Continued advances in monitoring and modeling will be critical for resolving how these interacting processes control MP movement, accumulation, and fate in aquatic environments.

2.3. Biological Effects

Over the past two decades, understanding of physiological and behavioral responses to MP exposure in aquatic organisms has increased substantially.[40−42] The toxicological impacts of MPs arise through multiple mechanisms, including physical (e.g., food dilution and internal tissue damage), chemical, and biological effects, or their interactions[43] (Figure 1).

2.3.1. Chemical Reservoirs and Exposure Pathways. Plastics act as complex chemical reservoirs, containing intrinsic additives, sorbed environmental contaminants, and transformation products. These compounds can leach from plastics into environmental compartments (e.g., water, soil, and sediment), creating exposure pathways for organisms. One notable case is 6PPD-quinone, a transformation product of the tire antiozonant additive 6PPD. In urban streams, stormwater runoff mobilizes 6PPD-quinone from tire wear particles into surface waters, where concentrations can trigger recurrent mass mortality events in coho salmon.[44] Despite its high acute toxicity to sensitive species, the underlying toxicological mechanism remains poorly understood and is still an active area of investigation. In the San Francisco–San Joaquin Delta, surface water monitoring between 2018 and 2024 revealed widespread

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detection of 6PPD-quinone at concentrations ranging from 0.43 to 21 ng/L; although all concentrations remained below reported LC50 values for juvenile and adult coho salmon (41 and 95 ng/L, respectively), some exceeded the EPA acute aquatic life screening level of 11 ng/L.[45] Other commonly used additives such as bisphenols and phthalates, as well as sorbed chemicals (e.g., polyaromatic hydrocarbons (PAHs)), have been shown to interfere with reproduction and alter early development in aquatic organisms.[42,46,47] The potential for MPs to act as chemical vectors via desorption in the gastrointestinal tract—the so-called *microplastic vector effect*—has been hypothesized but remains unsubstantiated as a significant exposure pathway. When evaluated against all uptake processes, chemical transfer via microplastic ingestion and subsequent desorption is currently considered a minor contributor to overall contaminant bioavailability, as the relative importance of MPs as chemical vectors depends not only on chemical affinity for plastic but also on the abundance of MPs relative to other environmental media and exposure pathways.[8,48−50] However, plastic chemicals, of which more than 16,000 have now been identified, are being released into the environment in large quantities and exert impacts independently and in combination with plastic particles.[51] Furthermore, many plastic chemicals act as endocrine disruptors, which can exert effects on organisms at low doses[52,53] in a nonmonotonic manner. Thus, more research and improved analytical instrumentation are needed to better understand how particles entrapped in tissues may leach chemicals over extended periods.

Pathogens can also associate with MPs and act as an additional stressor, with interactive effects on organisms.[54,55] Protozoan parasites including *Toxoplasma gondii*, *Giardia*, and *Cryptosporidium* have been shown to associate with biofilms on MP surfaces,[55] and oysters co-exposed to polyester microfibers and protozoan parasites accumulated higher pathogen loads than those exposed to parasites alone.[56] Many MP toxicology studies have relied on simplified exposure models using a single particle type, such as pristine polystyrene spheres, limiting alignment with the diversity of MP sizes, shapes, and materials in natural environments.[57,58] More recent studies have expanded beyond single chemicals and uniform plastic spheres to more environmentally relevant particles and multistressor exposures, resulting in responses more representative of actual exposure scenarios.[5,59,60]

2.3.2. Toxicity. Research on fish and invertebrates across freshwater and marine systems has identified several common responses to MP exposure, in some cases across particle types.[42,60−62] Early-life exposure often results in food dilution, where ingested particles lead to altered growth or weight.[47,63,64] This may reflect reduced nutrient absorption or food intake due to false satiation, and can depend on particle size.[41,65,66] Other anthropogenic particles, such as cellulosic fibers resembling synthetic microfibers, can produce similar but generally less severe effects.[64,67,68] Recent studies with rubber particles show reduced fecundity in freshwater invertebrates, including delayed reproduction and fewer neonates.[69,70] Effects on reproduction may co-occur with reduced growth, as both energy availability and size influence fecundity.[71] In adult fish, polyethylene exposure has been linked to altered metabolic enzyme expression, disrupted oogenesis, and behavioral abnormalities in zebrafish,[72] as well as multigenerational effects in fathead minnows and marine medaka, including impacts on growth and stress responses.[73,74]

MPs can also cause more subtle impacts. Behavioral studies show a trend toward hypoactivity in the presence of MPs,[63,64,75] suggesting exposed individuals may respond more slowly to threats or be less likely to interact with conspecifics.[76] Both fish and invertebrates can exhibit increased thigmotaxis (wall-hugging) or freezing behavior across a range of particle types. However, responses vary by species, with some exhibiting hyperactivity instead.[77]

As with other contaminants, MPs can alter gene expression and biochemical endpoints, including the formation of reactive oxygen species (ROS).[42] These pathways remain poorly resolved, and a clear mechanism of action has yet to be established, largely due to the diversity of sizes, shapes, and chemistries. One response observed in several species of fish is altered muscle function, possibly linked to particle translocation,[60,78−80] which is estimated to occur in aquatic organisms with particles smaller than 83 μm, including microfibers.[61]

2.3.3. Community- and Ecosystem-Level Effects. In addition to MP effects on individual organisms, some impacts have been demonstrated at the community level via mesocosm studies.[81,82] Large-scale, in-lake experiments conducted as part of the pELAstic project at the International Institute for Sustainable Development's Experimental Lakes Area (IISD-ELA) in Ontario, Canada, provide an opportunity to examine MP fate and effects in natural communities at larger experimental scales. Recent work from this project demonstrated that MPs redistribute across ecosystem compartments over time, with most particles eventually settling to the bottom of the mesocosms.[83] Overall, community-level effects observed in these experiments have generally been subtle, with recent experiments detecting only minor changes in plankton community structure and reproduction,[84,85] and no detectable effects on ecosystem metabolism or N_2 dynamics.[86]

Trophic transfer of MPs has also been demonstrated in aquatic food webs through the consumption of contaminated prey, with evidence that ingested MPs can translocate from the gastrointestinal tract into other tissues.[87] This process can increase MP exposure at higher trophic levels, including predatory fish and marine mammals.[88,89] However, whether trophic transfer results in biomagnification depends on multiple factors, including ingestion, gut retention, and egestion.[90] Mechanistic modeling approaches can help bridge effects across levels of biological organization, including the use of dynamic energy budget models to translate individual-level effects to populations and food-web models to examine MP dynamics across trophic levels.[91−93]

2.3.4. Factors Influencing MP Toxicity. More generally, particle toxicity appears to increase with decreasing size, which may also extend retention time within organisms.[94] This is especially worrisome given that MPs, including synthetic microfibers, continue to fragment and weather over time, producing smaller and more abundant particles with greater potential for biological uptake and toxicity.[60,95] Microfibers and tire particles—among the most commonly detected types—often elicit stronger responses, and weathering may further increase their palatability.[96−99] Early-life stages of mysid shrimp and larval silversides ingest more UV-weathered tire particles than unweathered particles, leading to greater reductions in growth.[99] Weathered microfibers can also generate nanoparticles, potentially increasing toxicity and the likelihood of translocation.[60,100] Life stage and life history traits can also influence responses, with larger organisms generally less sensitive and

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planktotrophic species more sensitive to early-life exposure than lecithotrophic or yolk-sac bearing organisms.[60,101] More work is needed to resolve linkages among the responses discussed above, including implications of associated chemical exposure, species-specific sensitivity, and impacts on population size and biodiversity.

Building on the advances and challenges in MP science discussed in this section, the following sections examine how these broader developments are being addressed within the San Francisco Bay–Delta through monitoring, data integration, and risk assessment, and identify research, management, and policy priorities needed to advance MP science more broadly.

3. WHAT WE ARE DOING

3.1. State of the Data

Compared with legacy contaminants such as mercury (Hg), dichlorodiphenyltrichloroethane (DDT), and polychlorinated biphenyl compounds (PCBs), for which decades of monitoring data exist, MPs have only been monitored over the past two decades, and most available data lack standardized methods.[5] As a result, baseline datasets of their occurrence across environmental matrices and exposed species are still being developed. MPs also present unique cross-disciplinary challenges relative to traditional and emerging contaminants due to their multidimensional nature, including the particles themselves, associated chemicals, degree of weathering, and variable biofilm or eco-corona coatings.[8,102] Consequently, methods and quality control frameworks developed for chemical monitoring are often not directly applicable.[103] This has driven the need to develop new methods, reporting standards,[104,105] and conceptual models for investigating fate, transport, and biological impacts.[8,106]

The disconnect between rapidly expanding MP research and the translation of scientific data into management-ready evidence has been highlighted as a major barrier to regulatory progress, underscoring the need for coordinated, cross-sector efforts to develop tools that can translate multidimensional MP data into formats suitable for regulatory monitoring and risk assessment.[8,103,107] Tiered monitoring approaches that combine multiple analytical methods depend on these frameworks to maximize data utility while minimizing logistical and resource constraints.[107] This has led to the development of tools such as One4All, an open-source data validation and harmonization portal designed to accommodate the multidimensional nature of MP data and support transparent, accessible, and consistent data sharing across studies and regulatory programs.[108]

Previous studies have documented MPs in the San Francisco Bay–Delta, with most monitoring efforts focused on surface waters and limited data on sediments[16,109–114] (Figure 2). Monitoring by the San Francisco Estuary Institute (SFEI), although now several years old, remains among the most comprehensive efforts worldwide, with concurrent data for surface water, sediment, fish, bivalves, and key pathways including wastewater effluent and urban stormwater runoff.[16,109–112] These data show that MPs, especially fragments and fibers, are abundant across Bay matrices and identify urban stormwater runoff as a more significant pathway than treated wastewater discharges, with concentrations ranging from 1.1 to 24.4 versus 0.003 to 0.182 particles/L, respectively, representing an approximately 140-fold difference in mean concentrations.[16,109,111] This pathway is especially important in the Bay Area because California has largely separate wastewater and stormwater systems, and stormwater collection systems generally discharge directly to receiving waters without treatment.

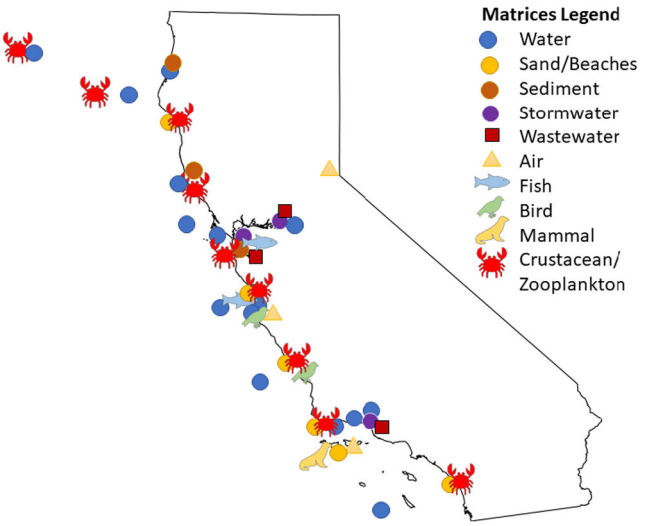


Figure 2. Visual summary of microplastic monitoring studies conducted in California. Icons indicate the type of matrices monitored and locations where monitoring has been conducted. Studies span coastal and inland locations across the state, with monitoring conducted across a range of environmental matrices. A list of studies represented on the map, including sampling locations, matrices, microplastic size ranges, and predominant particle types, is provided in Table S1 of the Supporting Information. Credit: Lin et al. 2026 Statewide Plastics Monitoring Strategy and Planning Framework.[115]

3.2. Hazard and Risk Assessment

Studies of MPs in marine wildlife in California, along the U.S. West Coast, and globally show that a wide range of organisms ingest or internalize MPs, including plankton, mollusks, fish, seabirds, marine mammals, and humans.[88,116–119] Despite clear evidence that MPs can harm aquatic organisms, their wide range of physical and chemical characteristics complicates hazard and risk assessment. MPs act as multiple, simultaneous stressors that vary in composition among and within particles, with particle, pathogen, and chemical leachate components contributing to biological effects. They are also released from numerous point and nonpoint sources, can be transported over long distances, and must be managed alongside other environmentally relevant stressors (e.g., pesticides, effluent-derived contaminants, pharmaceuticals, and climate change effects). Despite many toxicity studies, substantial uncertainty remains regarding the concentrations likely to adversely affect aquatic ecosystems. Several studies have compared environmental MP concentrations with toxicity data and proposed ecological risk thresholds, including probabilistic and species sensitivity distribution approaches.[61,118] However, these estimates remain constrained by limited fit-for-purpose toxicity data, inconsistencies between laboratory exposures and environmental MP mixtures, and uncertainty associated with derived thresholds.[61,120] Tools such as the Toxicity of Microplastics Explorer (ToMEx; https://microplastics.sccwrp.org/) have improved synthesis of available data and highlighted remaining gaps.[41,120] MP risk assessment is further limited by sampling and analytical challenges, as well as the lack of laboratory data using environmentally relevant particle types.

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Given these uncertainties, current thresholds are not yet suitable for assessing beneficial use support for listing a waterbody as impaired under Clean Water Act Section 303(d) because of limitations in both monitoring data and threshold reliability.[121] However, they may still inform Clean Water Act 305(b) water quality condition reporting. The 2024 California Integrated Report placed three San Francisco Bay waterbodies (Lower and Central San Francisco Bay and San Leandro Bay) in Category 3 (insufficient data to determine beneficial use support, but potential impairment) and four (South San Francisco Bay, San Pablo Bay, Suisun Bay, and a segment of the Pacific Ocean off Marin County) in Category 2 (insufficient data to determine core beneficial use support).[121]

Bayesian networks (BNs) are widely used in environmental assessments,[122] including ecological risk assessment.[123] They offer several advantages over more conventional regulatory approaches: they are probabilistic, explicitly represent uncertainty, support evaluation of alternative management scenarios, and are easily communicated as discrete model files. BNs also integrate exposure–response relationships, mixture interactions, and spatial variability. Recent applications incorporate climate change projections, linking changes in water temperature and dissolved oxygen with contaminant concentrations to estimate risk in aquatic systems.[124,125] Endpoints can include species diversity, water quality, and population dynamics, and management scenarios such as MP reduction can be evaluated across outcomes ranging from organism-level effects to long-term population changes. Model outputs such as HC_5 values (hazardous concentrations affecting 5% of species) derived from Species Sensitivity Distributions (SSDs) can be incorporated to estimate the proportion of species potentially affected.

Unlike well-characterized contaminants such as bifenthrin and Hg, which have defined exposure–response relationships,[126] MPs and associated chemicals present challenges for risk assessment due to their unintended effects and multistressor, multidimensional nature. An extensive analysis of contaminant risk in the Upper San Francisco Estuary has been synthesized[126] and later adapted[127] to include tire particles in the San Francisco Bay. This work suggests that MP particles and their leachates can be evaluated alongside well-studied contaminants such as Hg and bifenthrin, while highlighting key considerations for comparative risk assessment. In the San Francisco Bay–Delta, Hg and bifenthrin have been monitored far more extensively than MPs, meaning that the upper tails of MP exposure distributions are likely underrepresented. Long-term monitoring is therefore needed to better characterize exposure distributions across the diversity of MP types present in the San Francisco Bay–Delta system.

Adverse outcome pathways (AOPs) provide a framework linking mechanistic effects of stressors to adverse outcomes at higher levels of biological organization and are useful for predicting effects on species and ecosystem services.[128] For MPs, AOP development is especially important because particles and their leachates interact with environmental stressors in complex ways, shaping synergistic, antagonistic, and persistent effects. Relevant AOPs must capture particle properties such as size, shape, and weathering-driven transformations, along with multistressor interactions from additives, sorbed contaminants, and associated microbial communities that influence behavior and toxicity. They must also account for pathways such as mechanical damage and food competition that differ from those in traditional receptor-based models (e.g., endocrine disruption). Although AOPs have seen limited application in MP toxicity and risk assessment, existing work shows they can be integrated into BN frameworks,[129] providing a potential approach for incorporating mechanistic MP toxicity data into BN-based risk assessment efforts already underway in the San Francisco Bay–Delta.

4. WHERE WE ARE GOING

4.1. Research Priorities

The most pressing knowledge gaps and research priorities for the next three to five years span experimental work, monitoring, risk assessment, and data regulation. In laboratory studies, greater emphasis is needed on chronic, multigenerational, and transgenerational exposures capable of capturing persistent and delayed effects.[73,74] Particle translocation and retention also remain important priorities, particularly how size and shape influence movement across biological barriers and subsequent accumulation within tissues. Fibers warrant particular attention given their ubiquity in environmental samples and limited understanding of their behavior once internalized.[60,61]

There is a growing need to better resolve how the physical and chemical properties of MPs interact to influence toxicity, including chemical partitioning and exchange between particles, organisms, and environmental matrices.[8,48–50] Given the labor and cost associated with MP characterization, machine-learning approaches may help automate time-intensive steps such as particle identification, with recent advances combining Nile Red fluorescence imaging with supervised machine learning to detect and classify MPs.[130]

Greater emphasis is also needed on effects at higher levels of biological organization. Key questions include how MPs move through food webs, whether they bioaccumulate across trophic levels, and how organism-level effects translate to populations, communities, and ecosystems.[87,90] Addressing these questions will require a combination of larger-scale experiments, field observations, and modeling approaches capable of integrating effects across levels of biological organization.[83,91–93]

Stronger quantitative exposure–response data and approaches capable of accommodating the multidimensional nature of MPs are needed. While EC_{50} (median effective concentration) and LC_{50} (median lethal concentration) values are useful for risk assessment, studies should prioritize testing more concentrations to better capture dose–response curve shape, improve cross-study comparability, and strengthen the quantitative basis for regulatory decision-making. SSD approaches have been applied to MP assessment by integrating species-specific effect thresholds with environmental exposure distributions to estimate ecological risk.[118] However, traditional SSD approaches have limitations given the multidimensional and particle-specific nature of MPs.[131] Although widely used in regulatory contexts,[132,133] SSDs may not fully capture the complexity, variability, and mode-of-action heterogeneity characteristic of MP exposures.[131] More recent approaches incorporate community-level and habitat-specific SSDs and align effect thresholds with probabilistic representations of environmentally relevant MP exposures.[133]

Finally, improved data infrastructure is needed to integrate monitoring and toxicity information across studies and regulatory programs. Existing resources such as ToMEx provide a strong example, offering a free, open-source framework for uploading, exploring, and synthesizing toxicity data, including development of SSDs and derivation of hazard thresholds.[120] California's Environmental Data Exchange Network (CEDEN)

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is another valuable resource for environmental monitoring, but its structure is not yet optimized for MP-specific data. A dedicated platform is needed to integrate MP monitoring data into a unified and accessible system. Nanoplastics are another critical research priority. Although studies are accumulating, substantial gaps remain in understanding their hazards and effects, and risk assessment frameworks must account for size-specific properties unique to the nanoscale that may not align with conventional particle- or chemistry-based approaches.[5]

4.2. Standardization Challenges

A persistent challenge in MP toxicity research is reconciling two priorities: standardized exposures that enable comparison across studies and environmentally realistic exposures that reflect the particles organisms encounter. Many laboratory experiments rely on commercially available particles, such as uniform polystyrene spheres.[58] These particles are convenient and reproducible, providing a common basis across studies, but do not resemble the fragments and fibers that dominate natural systems. Efforts are underway to address this mismatch by producing secondary MPs that better represent environmentally relevant particles.[5] Some laboratories use cryogenic milling to generate fragments and cryotomes to produce textile fibers with more complex shapes and surfaces that more closely resemble particles found in nature. Well-characterized reference materials are also available through select commercial providers and research laboratories, offering standardized options for experimental exposures and quality control. Continued development and use of these resources will help ensure that laboratory exposures more closely align with environmental conditions. Long-term monitoring can help identify common MP mixtures across ecosystems and change over time.

A challenge of developing reference materials for MPs is that the number of possible combinations of polymers, shapes, and sizes is essentially limitless.[57] No reference set will ever capture every context. To remain environmentally relevant, exposures need to reflect the particles that dominate in a given location. Even within California, where landscapes and watersheds vary dramatically, MP mixtures can differ over small distances. The goal is not to create a universal material, but to establish reference sets that provide common benchmarks while still allowing mixtures to be tailored to local conditions. One recent approach is the development of environmentally relevant microplastic mixtures.[134] This approach links environmental MP mixtures to biological responses and health outcomes, providing a clearer basis for management strategies that reflect regional realities. As consumer behavior, industrial practices, and land use continue to evolve, the types of MPs found in any location will also shift, reinforcing the need for strategies that balance comparability with environmental relevance.

Even as reference sets and context-specific exposures are developed, significant bottlenecks remain in standardization. Protocols for sampling and toxicity testing have advanced, including new standard operating procedures (SOPs) from state agencies,[135−137] but key steps such as extraction and polymer characterization still limit comparability and are influenced by differences in instrumentation age, availability, and design. Methods optimized for MPs also often fail for co-contaminants; for example, digestion protocols suitable for isolating MPs may destroy pathogens, while tire wear particles require pyro-GC/MS or other specialized workflows that cannot easily be integrated with FTIR or Raman pipelines. These challenges highlight the need for protocols that are flexible enough to capture particle diversity and co-occurring contaminants yet standardized enough to support reproducibility across studies. Continued investment in evidence-based method development and validation will be critical to achieving this balance.

4.3. Citizen Science and Community Engagement

Connecting research with communities and building meaningful collaboration is important for advancing MP research and management. Plastic is embedded in daily life, giving the public a direct stake in MPs as an environmental issue. Many people are aware of MPs and are concerned about their impacts but lack clear pathways for engagement.[117] While MP analysis often requires specialized equipment and training, macroplastics provide an accessible entry point. Communities can begin with local trash cleanups that remove waste and may generate records, with resources such as the International Coastal Cleanup and International Trash Trap Network (Ocean Conservancy) supporting coordination and data collection. Mobile apps such as Clean Swell (Ocean Conservancy), TrashBlitz (5 Gyres), and Litterati allow volunteers to log data in real time, turning individual efforts into broader datasets that inform research and management. Another example is the annual brand audits coordinated by Break Free from Plastic, which engage thousands of volunteers across dozens of countries and generate large datasets identifying top corporate polluters and supporting accountability campaigns.[138]

Beyond macroplastics, new citizen-science protocols are making MP sampling and analysis accessible at the high-school and undergraduate levels. Another critical aspect of community engagement is participation in surveys and studies that shed light on overlooked pollution pathways. Research shows that household dryers are a major, underestimated source of MP fibers to the environment.[139,140] SFEI highlights this pathway in its Microplastics Monitoring and Science Strategy,[141] noting that community input through household laundry surveys provides essential data to quantify the problem and guide solutions. In the San Francisco Bay Area, community participation is important for identifying dominant MP sources across highly variable urban and industrial land use. These efforts expand the range of locations studied and improve understanding of how particles travel from known hotspots. Community involvement gives nonscientists a sense of agency and investment in the issue, which is critical to maintaining public support for deploying solutions.

Effective engagement requires more than enlisting volunteers. Scientists must reduce jargon, simplify communication, and meet people in familiar spaces, whether in schools, laundromats, or along local shorelines. Engagement should be a two-way exchange: communities gain knowledge of the science, while scientists gain insights from local experience and perspectives. In this way, citizen science becomes more than data collection; it becomes shared ownership of both the problem and the solutions. Science communication takes many forms and often benefits from trained communicators who help translate technical results for broader audiences, including through creative expressions such as art and poetry. While scientists are highly credible sources, combining their expertise with trusted community voices and diverse forms of communication can make scientific information more accessible and effective.

The public shows an appetite for stronger policies to limit plastic pollution, including from consumer goods (e.g., WWF 2024, Ipsos 2023, NRDC 2024). Scientists have a role in informing legislative and regulatory processes to help ensure decisions are grounded in the best available science. Engagement with lawmakers and international negotiators suggests

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scientific participation in policymaking is valued, although challenges remain. Working through intermediary organizations, such as the Scientists' Coalition for an Effective Plastics Treaty and the International Science Council, can help scientists navigate policy processes and form effective cohorts.[142] Some scientists are concerned that making policy recommendations may undermine their perceived objectivity or authority; however, limiting advice to areas of expertise can help address this concern.[143] Efforts by industry actors to question or discredit individual scientists have occurred in contentious policy processes, including plastics, highlighting the importance of institutional support and clear expectations for scientific engagement.[144]

4.4. Management Strategies

In management, there is a need to prioritize source control while also recognizing the important role of downstream mitigation in reducing MP inputs.[145] While cleanup technologies are advancing and remain important for removing existing macroplastic pollution, greater long-term impact will come from upstream measures. Additional work is needed to evaluate the effectiveness of MP pollution controls such as tire particle capture systems, including vehicle- and stormwater-based approaches, and to test their performance under real-world conditions. For fibers and textiles, research should focus on identifying high-shedding materials and reducing shedding at the design and production stages. In the meantime, legislation requiring filters on new washing machines and reducing fiber pollution from clothes dryers should be prioritized.

At the policy level, action needs to extend even further upstream. Strategies to reduce MP emissions must span the full spectrum, from emission reductions and product reformulation (e.g., tires and paints) to the development of alternative materials and reimagining of entire systems such as transportation. Alternative materials may include biodegradable polymers designed to break down more readily in the environment, although these must be evaluated given their potential to behave similarly to traditional plastics. Other options include low-shedding textile blends and natural formulations that substitute for synthetic paints. Paint remains one of the most pervasive yet under-addressed sources, highlighting the need for innovation in both materials and application methods.[146] Policy solutions must recognize that MP emissions occur at every stage of a product's lifecycle, from production and use to disposal. Incremental steps such as reformulation are important, but durable progress depends on policies capable of driving transformative systems-level change, reducing reliance on plastics for nonessential uses and lowering MP emissions over the long term. This includes aligning regulations across sectors, incentivizing industry innovation, and coordinating efforts from local to international scales to address MP pollution at the required pace and scale.

Many approaches exist to mitigate MP and MP-related chemical releases, from preventative measures that reduce use and emissions to remedial measures that remove MPs from pathways (e.g., wastewater, urban runoff) or surface waters. However, removal is not practical at scale, and effective management depends on understanding MP sources and dominant transport pathways. The San Francisco Bay and Delta lack major polymer production facilities, so nurdle spills are less of a threat than in other regions (e.g., the Gulf Coast). SFEI and others have identified approaches to mitigate common MPs, including tire wear particles and fibers, across multiple actors (e.g., industry, government, nongovernmental organizations, consumers),[98,147] but implementation mechanisms, policy questions, and broader environmental implications have yet to be addressed. An in-depth evaluation of these measures and their trade-offs would help prioritize actions.

Stormwater and wastewater treatment can substantially reduce MP inputs to receiving waters and should be applied in pathway-specific ways. Green stormwater infrastructure, while costly, can remove MPs and provide co-benefits such as increased urban green space; for example, a bioretention rain garden in the Bay Area reduced MP concentrations ten-fold.[148] Wastewater treatment can reintroduce MPs into waterways through land application of sludge.[149,150] Installation of filters on 10% of washing machines in a small Canadian city significantly reduced microfiber concentrations in treated wastewater effluent by an average of 41%.[151] Ongoing projects in California, Oregon, and Washington piloting downstream approaches to reduce tire particles and microfibers can inform efforts to pass legislation requiring stormwater mitigation and filtration on washers, dryers, and dishwashers.

The California Ocean Protection Council recently convened a series of workshops to understand perspectives on MP pollution and prioritize solutions and data gaps. Separate workshops focused on tire wear particles[152] and textile fibers,[153] two of the most commonly detected MP types globally, including in California. Both workshops brought together academic, government, industry, and nonprofit perspectives and evaluated issues across the full lifecycle of these plastics. Participants agreed that reducing production and consumption, product redesign with safety and sustainability in mind, and downstream mitigation in stormwater and wastewater should be prioritized.

4.5. Upstream Prevention and Policy Approaches

It is widely understood that reducing overall plastic production and use is critical to limiting MP releases, yet current trends point in the wrong direction, with global plastic production predicted to nearly double by 2050.[154] Few policies have been introduced to reverse this trajectory. Negotiations around the global plastics treaty (International Legally Binding Instrument to Reduce Plastic Pollution) are deadlocked over whether to include an obligation to reduce plastic production and consumption to "sustainable" levels; although 106 countries support this provision, it remains blocked by a handful of petrochemical states, including the United States.

Even without U.S. participation or ratification, a plastics treaty can establish global standards that California can adopt and incorporate into state-level legislation. This would include definitions and lists of unnecessary and problematic products, such as single-use packaging and items most likely to end up in the environment. California's Safer Consumer Products program is already taking steps to regulate MPs as a contaminant suite by designating them as candidate chemicals, illustrating how existing chemical regulatory frameworks may provide an additional pathway for addressing plastic pollution.[155] A major focus of the treaty should be identifying and restricting plastic chemicals of concern, including additives, nonintentionally added substances, and breakdown products. Here again, California can act before the federal government, although care will be needed to avoid running afoul of the interstate commerce clause. A global Polymer Production Fee has been proposed to fund plastic remediation and transition efforts. Unlike a carbon price designed to reduce emissions through pricing, it would be too low to significantly reduce production but could raise substantial financial resources.[156] Because California lacks

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polymer production facilities, this would have to be established at the national or international level.

Restrictions on plastic products, including those containing primary MPs, are widespread but incomplete, with at least 177 product-specific bans in California targeting items most easily lost to the environment, such as thin-film bags, food containers, straws, and other single-use packaging.[157] Plastic bag bans and fees reduce the prevalence of regulated bags in environmental cleanups but do not achieve absolute reductions, highlighting the limits of product-by-product regulation;[158] however, they remain important stepping stones to broader regulation. The Scientists' Coalition for an Effective Plastics Treaty advocates for a more restrictive "essential use" framework,[159] rather than regulating products individually.

California state policy on plastics is highly dynamic; SB 54 set ambitious recycling goals for plastic packaging, but draft regulations are substantially weaker and introduce large loopholes. More generally, the high recycling rates set in SB 54 may not be technically achievable or desirable, as most plastics can be recycled at most once and thermosets are essentially nonrecyclable.[160] Recycling is also not a panacea; mechanical recycling can be a major source of MP pollution and increase concentrations of hazardous plastic chemicals.[161,162] Chemical recycling technologies are controversial, as they primarily convert plastics into fuel and therefore do not function as recycling,[163] and the link between increased recycling rates and reduced plastic emissions remains uncertain.[164] Another viable proposal is to expand the current, partial ban on microbeads in wash-off cosmetics to a wider range of personal care products, cleaning products, and coatings.[155]

5. CONCLUSIONS

Over the past decade, MP research has moved beyond establishing ubiquity in aquatic environments toward more integrated efforts examining sources, transport pathways, biological interactions, and broader policy implications. The San Francisco Bay–Delta system exemplifies this progression, where advances in monitoring, source and pathway characterization, method development, and emerging risk-assessment approaches have strengthened understanding of MP pollution while also identifying critical gaps that continue to constrain management. These include limited comparability across studies, a lack of environmentally realistic and multistressor research, and difficulty translating complex, multidimensional datasets into actionable guidance. Addressing these challenges in the San Francisco Bay–Delta and beyond will require stronger coordination across research, management, and policy, alongside continued advances in standardized methods, environmentally realistic exposure studies, accessible data infrastructure, and closer alignment between scientific outputs and management needs. Future progress will also depend on prioritizing upstream prevention and source control, expanding community engagement, and securing sustained funding to support long-term monitoring, method development, and interdisciplinary research needed to address the scale and complexity of MP pollution.

■ ASSOCIATED CONTENT

Data Availability Statement

No new data were generated or analyzed as part of this study.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.6c01560.

Table S1. Summary of studies represented in Figure 2, including study locations, sampled matrices, microplastic size ranges, and predominant particle types (XLSX)

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