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Closing the gap between micro- and nano plastics science and policy

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Micro- and nanoplastics (MNPs) are increasingly being identified across environmental matrices, the food chain, and drinking water, with documented effects on human health, yet policy on how to translate this evidence into pollution-reduction action lags well behind the pace at which the underlying data are being generated. This Comment synthesizes the current state of environmental MNP data collection across oceanic, freshwater, and cryospheric matrices, showing that ocean surveys currently offer the most robust field datasets, while lake, river, soil, food, and polar measurements remain comparatively sparse and methodologically heterogeneous. Building on this assessment, we outline a forward-looking research and policy agenda for translating improved data into action once more comprehensive datasets become available. This agenda spans three interconnected priorities: advancing analytical precision and ecosystem-level research, from reference materials and machine-learning-assisted detection to toxicology and biogeochemical impacts; harmonizing global policy frameworks, including regulatory standards, extended producer responsibility, and the emerging Global Plastics Treaty; and addressing the equity and governance trade-offs that arise when translating MNP science into practice, particularly through a One Health lens that links environmental, plant, animal, and human health. Together, these sections aim to bridge the gap between what we currently know about MNP occurrences in the environment, the more broadly documented human health evidence, and what must be done, scientifically and politically, to manage the risks they pose.

The core problem: nanoplastics are much harder to find than microplastics

The vast majority of plastic-pollution data collected to date describes microplastics; genuine field measurements of nanoplastics (generally defined as plastic particles below 1 µm) remain comparatively rare[1]. This asymmetry is not a matter of research priorities but of instrumentation: the visual and spectroscopic sorting techniques that work well for microplastics cannot resolve particles at the nanoplastic scale, because nanoplastics are chemically similar to natural organic matter and too small for those methods to distinguish[2]. The gap is widened further by a genuine physicochemical distinction, not just a size cutoff — nanoplastics differ from microplastics in colloidal transport, aggregation, and reactivity, a distinction formalized in a widely cited working definition of nanoplastics and their proposed formation pathways[3]. Closing the resulting data gap has required the field to spend the last decade mostly building and validating detection methods capable of resolving the nanoplastic fraction, rather than accumulating large environmental datasets the way microplastic research has[2]. This effort is itself hampered by a "causality dilemma": certifying reference materials depends on validated methods, while validating methods simultaneously requires certified reference materials[4,5].

Pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS), often coupled to tandem mass spectrometry (MS) or high-resolution thermal desorption–proton transfer reaction mass spectrometry (TD-PTR-MS), has become the workhorse for mass-based MNP quantification in complex environmental matrices because it does not rely on being able to see or count individual particles. A Py-GC–qQq-MS (triple quadrupole) method with dynamic multiple reaction monitoring was developed and validated to quantify 12 common polymers at nanogram levels (1–126 ng) in water, sediment, and biological tissue, using field samples from the Gulf of Mexico and Texas coast[6]. Complementary approaches include single-particle inductively coupled plasma mass spectrometry (ICP-MS) and its time-of-flight variant (ICP-TOF-MS) — both used for metal-doped or metal-associated MNP tracers — field-flow fractionation for size-based separation, and emerging artificial intelligence (AI)-assisted 4D physicochemical characterization for rapid in situ water screening[7,8]. Several recent reviews[4,9,10] converge on the same conclusion: detection sensitivity has improved substantially, but throughput remains too low, and no method is yet standardized across labs, which is the main reason environmental datasets are still sparse and hard to compare. Current methods may still underestimate nanoplastic abundance: hyperspectral stimulated Raman scattering (SRS) microscopy of bottled water detected roughly 10^5 plastic particles per liter, about 90% of them nanoplastics, while also highlighting concerns that many reported concentrations are insufficiently corrected for laboratory blank contamination[11,12].

Microplastics are well known to harbor distinct bacterial communities on their surfaces (the so-called "plastisphere"), and nanoplastics likely do too, which suggests that bacteria-detection methods could offer another

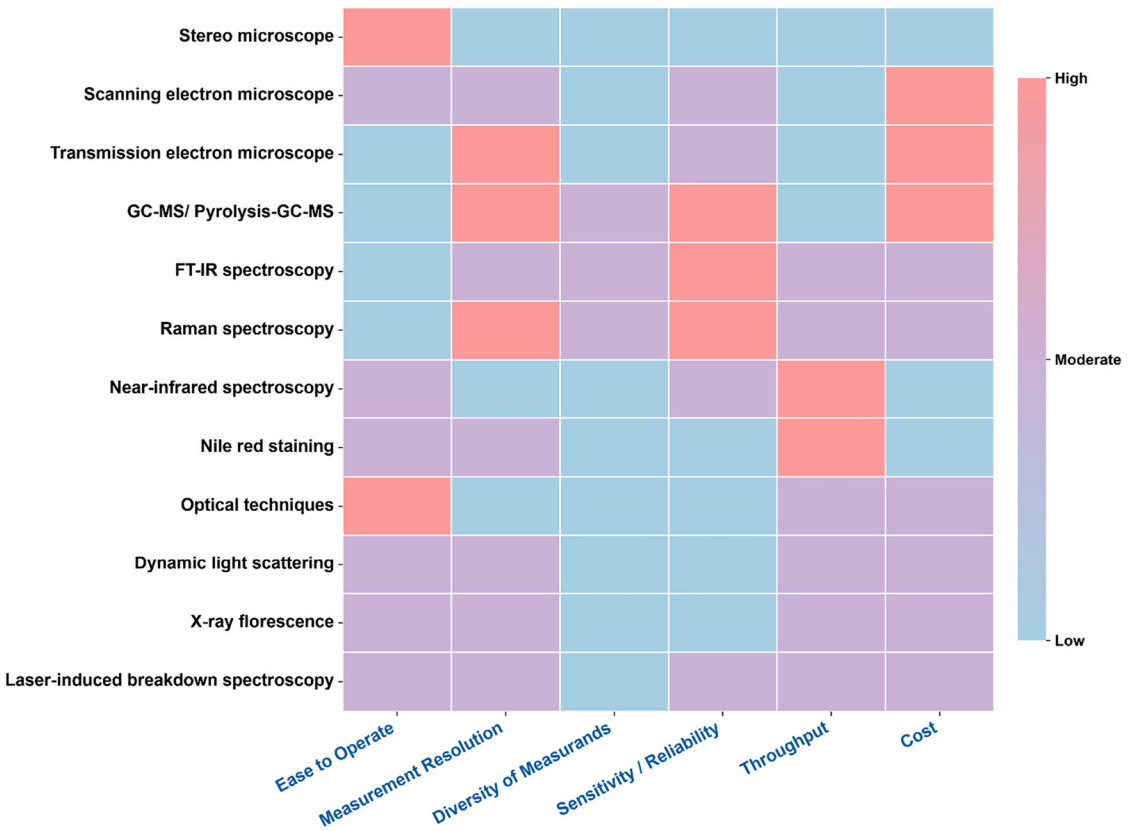

Fig. 1 | Heat map assessing MNP detection methods across key analytical performance metrics. Evaluation scores (1 = Low, 2 = Moderate, 3 = High) were assigned based on a comprehensive synthesis of recent literature[108–110] to compare relative operational strengths, spatial resolution, measurand diversity, sensitivity, throughput, and cost. GC-MS: Gas chromatography-Mass spectrometry; FT-IR: Fourier-Transform Infrared Spectroscopy.

indirect route to nanoplastic screening[13]. Biofilm/epiphyte-based nanoplastic assessment — fluorescent molecular rotor probes applied to submerged vegetation biofilms in Lake Saint Pierre in Canada — is one emerging, cheaper screening approach along these lines for lake and river systems; a median concentration of about 1.05×10^9 nanoplastics per milligram of biofilm dry weight was reported using this method, though it is still being validated against mass-based methods[14]. Whether nanoplastics shape their own distinct plastisphere community, or simply inherit the one already described for microplastics, remains undefined and is a priority for future study.

As summarized in Fig. 1, detection techniques also exhibit inherent trade-offs among sensitivity, throughput, cost, and operational complexity, with no single method excelling across all performance metrics. In addition, this trade-off is systematic rather than incidental: the methods best suited to resolving the nanoplastic fraction — Py-GC-MS, ICP-TOF-MS, TD-PTR-MS — score highest on sensitivity but lowest on throughput, while the faster, cheaper methods that dominate microplastic monitoring are largely blind to particles below a few micrometers. Because funding for plastic-pollution monitoring has historically followed the cheaper, higher-throughput microplastic methods, closing the data gap will require deliberately rebalancing investment toward the costlier, lower-throughput techniques nanoplastics require — not simply funding "more detection" in the aggregate, but funding it disproportionately toward the nanoplastic-capable end of the cost–sensitivity trade-off shown in Fig. 1. Standardized metadata reporting and open-access spectral databases for MNPs would help stretch that investment further by enhancing data comparability across research groups[7,15,16].

Ocean data: the largest field datasets so far. In the foundational field study in 2017[17], researchers isolated the colloidal fraction of seawater from the North Atlantic Subtropical Gyre and confirmed nanoscale plastic debris — polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE) — via dynamic light scattering — the first direct evidence of nanoplastics in open ocean water. This was followed by a 2024 study in which researchers used correlative Raman imaging to directly observe and identify individual nanoplastic particles in ocean water samples[18].

A recent advance is a basin-scale transect study across the North Atlantic, from the subtropical gyre to the European shelf[19]. The study measured PET, PS, and PVC nanoplastics throughout the water column, with concentrations ranging from approximately 1.5 to 32.0 mg m^{-3}. The team sampled seawater at 12 stations along a transect from the Azores to the European continental shelf, using thermal-desorption proton-transfer-reaction mass spectrometry (TD-PTR-MS) to resolve the colloidal, sub-micron fraction after removing larger particles, with detection limits as low as 0.01 μg L^{-1}. Concentrations were about 1.4 times higher in the mixed layer than at intermediate depth and 1.8 times

higher in the gyre than outside it at intermediate depth. The study extrapolated a mixed-layer nanoplastic mass of approximately 27 million tonnes for the temperate-to-subtropical North Atlantic alone, a value that rivals or exceeds previous mass-budget estimates for micro- and macroplastics combined. This extrapolation carries substantial uncertainty: the authors report a plausible range of roughly 11 to 27 million tones depending on scaling assumptions, and the method could not yet resolve polyethylene and polypropylene — two of the most heavily produced global polymers — meaning the true MNP mass may be underestimated rather than overestimated. The accompanying commentary[20] frames this as evidence that nanoplastics, rather than larger fragments, may dominate the ocean's plastic burden by mass, thereby reopening the long-standing "missing plastic" mass-budget problem.

Lake and freshwater data: much thinner, and mostly still at the microplastic scale. This is the weakest part of the field. True sub-micron nanoplastic field data from lakes is rare; most "lake" studies to date have quantified microplastics (particles down to a few µm, sometimes reported loosely as "micro/nanoplastics") rather than the nanoscale fraction proper, because the analytical methods that work at ocean-basin scale are still being adapted to smaller, more logistically constrained freshwater sampling campaigns. The major studies to date fall into the following six groups:

Lake sediment characterization. At Lake Bracciano, Italy, a multi-analytical characterization of lake sediments using FTIR, Raman, thermal analysis, and NMR found PET particle concentrations of 0.8–36 ppm, with strong site-to-site variability. The study also confirmed the presence of the nanoscale size fraction alongside microplastics, making it one of the few studies explicitly extending into the nanoplastic range in a freshwater sediment matrix[21].

High-altitude urban lakes. At Dal Lake in the Kashmir Himalaya, researchers characterized and quantified microplastics in both surface water (140 ± 20 to 846 ± 136 particles/L) and sediment (2616 ± 1016 to 12,966 ± 496 particles/kg dry weight), with sediment acting as the dominant reservoir — a pattern reported consistently across lake studies generally[22].

Global lake surveys. A comparative study of Lake Tahoe (USA) and dozens of other freshwater lakes and reservoirs worldwide found that some lakes—Tahoe among them—carry microplastic loads higher than oceanic gyres despite low local population density, implicating atmospheric transport and legacy contamination[23]. Great Lakes monitoring (e.g., Lake Michigan) similarly reports concentrations spanning roughly 0.0001–1.15 particles/L[24]. These studies are valuable context but are microplastic, not nanoplastic, datasets.

Mechanistic/lab studies using real lake water. Several transport and fate studies (e.g., polystyrene nanoplastic transport through sand columns using Lake Geneva water) use authentic lake water chemistry to study nanoplastic aggregation and mobility, but are laboratory experiments rather than field surveys of ambient lake nanoplastic concentrations[25,26].

Rivers. Genuine sub-micron field data also exist beyond lakes. Pyrolysis-GC-MS quantification of nine polymer targets along the full stretch of the Pearl River, China, detected six polymers — most frequently polystyrene (PS), polyvinyl chloride (PVC), and polyamide 66 (PA66, a type of nylon) — providing one of the first spatiotemporal pictures of nanoplastic loading in a major river system[27].

Wastewater treatment plants. Using metal-doped (palladium- and indium-labeled) plastics as tracers, a pilot-scale wastewater treatment plant study tracked nanoplastic particle and microplastic fiber flux through every treatment stage over a 40-day run; although most nanoplastics were retained in sludge, treated effluent — which discharges directly into rivers and lakes — remained a measurable, ongoing nanoplastic input pathway to those receiving waters[28].

Cryosphere and remote-environment data. Materić and colleagues[29] have produced some of the only true nanoplastic (sub-micron) field datasets outside the ocean, using Py-GC-MS/TD-PTR-MS on snow and ice:

Alpine snow. An original method established nanogram-range chemical identification and semi-quantification of nano/microplastics in snow[30].

Polar ice. Nanoplastic mass concentrations averaged 13.2 ng/mL in a 14 m Greenland firn core and 52.3 ng/mL in Antarctic sea ice, with PE, PP, PET, PS, PVC, and tire-wear particles identified — direct evidence that nanoplastics reach even the most remote polar environments, with obvious implications for glacial meltwater feeding downstream freshwater/lake systems[29].

High-altitude glaciers. A citizen-science sampling network (mountaineers) combined with TD-PTR-MS found nanoplastic concentrations of 2–80 ng/mL at 5 of 14 remote glacier sites, dominated by tire wear (41%), polystyrene (28%), and polyethylene (12%) — again pointing to atmospheric deposition as a transport pathway that ultimately feeds glacial and alpine lake systems[31].

Overall picture and gaps. Our review of the current literature shows that oceans have the best field data, culminating in the 2025 North Atlantic transect, which suggests nanoplastics could be the dominant mass fraction of marine plastic pollution. Freshwater lakes lag well behind; most lake "micro/nanoplastic" studies are really microplastic surveys (sediment as the main reservoir is a consistent finding); genuine sub-micron nanoplastic field quantification in lakes is limited to a handful of studies (e.g., Bracciano) and is an active methodological frontier rather than an established monitoring practice. The cryosphere/remote-environment work (Alpine snow, glaciers, polar ice) is arguably ahead of lake research in measuring true nanoplastics in situ and is directly relevant to lakes because glacial and snowmelt are documented input pathways. Finally, standardization is the bottleneck. Multiple recent reviews independently flag the same gap[2,4,9,10,32]: a lack of harmonized sampling, extraction, and quantification protocols across labs prevents cross-study comparison and larger-scale environmental risk assessment, more than any single technical detection limit. A closely related concern is inadequate control for procedural (laboratory) blank contamination, which several practitioners argue has led to both over- and under-reporting of environmental nanoplastic concentrations. These same measurement gaps constrain everything that follows: the human health risk assessments and policy frameworks discussed below inherit whatever uncertainty remains in the underlying exposure and occurrence data[12]. Overall, Table 1 summarizes the major studies evaluating nanoplastics across different environments.

Table 1 | Nanoplastic types, reported concentrations, detection methods, and matrices identified across the ocean, freshwater (lake and river), and cryosphere studies reviewed here, ordered approximately ocean → freshwater → cryosphere

Environment/Matrix	Nanoplastic types identified	Reported concentration	Detection method	Reference
North Atlantic ocean — water column (mixed layer to deep), basin-scale transect	PET, PS, PVC	1.5–32.0 mg/m³ throughout water column; ~27 million tonnes estimated in mixed layer (temperate–subtropical N. Atlantic)	Pyrolysis-GC-MS, quantitative field transect	19
North Atlantic subtropical gyre — seawater, colloidal fraction	PVC, PET, PS, PE	Not quantified (first qualitative field detection of ocean nanoplastics)	Ultrafiltration + dynamic light scattering, pyrolysis-GC-MS	17
Open ocean water (case study)	Polystyrene	Individual-particle level; not a bulk concentration	Correlative Raman imaging	18
Gulf of Mexico & Texas coast — water, sediment, biological tissue	12 common polymers (method validation panel, incl. PE, PP, PET, PS, PVC)	1–126 ng (method quantification range on field samples)	Py-GC-qQq-MS with dynamic multiple reaction monitoring	6
Lake Bracciano, Italy — sediment	PET (dominant); PE, PP also detected	0.8–36 ppm (site-dependent)	FTIR, Raman, thermogravimetric analysis, NMR	21
Lake Saint Pierre, St. Lawrence River — epiphytic biofilm on submerged vegetation	Polystyrene (assay calibration standard); polymer-specific ID not yet resolved	Median ≈1.05×10^9 nanoplastics per mg biofilm dry weight	Fluorescent molecular rotor probe (DCVJ) spectrophotometry	14
Dal Lake, Kashmir Himalaya — surface water *	Microplastics; PE, PP, PET common (sub-µm nanofraction not resolved)	140 ± 20 to 846 ± 136 particles/L	FTIR / optical microscopy	22
Dal Lake, Kashmir Himalaya — sediment *	Microplastics; PE, PP, PET common (sub-µm nanofraction not resolved)	2,616 ± 1,016 to 12,966 ± 496 particles/kg dry weight	FTIR/optical microscopy	22
Pearl River, China — surface water, full-river transect	Six polymers detected; most frequent were PS, PVC, and polyamide 66 (PA66)	Spatiotemporal survey across 15 sites, two seasons (qualitative/semi-quantitative)	Pyrolysis-GC-MS	27
Global freshwater lake comparison, incl. Lake Tahoe & Lake Michigan — surface water *	Microplastics, polymer types not nano-resolved	Tahoe ≈5.4 particles/m³; Michigan 0.0001–1.15 particles/L	Visual sorting/FTIR (microplastic scale)	23,24
Greenland ice sheet — 14 m firn core	PE, PP, PET, PS, PVC, tire wear	13.2 ng/mL average	Py-GC-MS/TD-PTR-MS	29
Antarctic Sea ice	PE, PP, PET	52.3 ng/mL average	Py-GC-MS/TD-PTR-MS	29
High-altitude remote glaciers (14 sites, citizen science)	Tire wear (41%), polystyrene (28%), polyethylene (12%)	2–80 ng/mL at 5 of 14 sites	TD-PTR-MS, citizen-science sampling	31

* Denotes studies reporting microplastics (µm-scale) rather than confirmed sub-micron nanoplastics; included for context since these are commonly labeled "micro/nanoplastic" studies in the lake literature. *PE* polyethylene; *PP* polypropylene; *PET* polyethylene terephthalate, *PS* polystyrene, PVC polyvinyl chloride.

Human health effects: an emerging and consequential blind spot. The analytical challenges complicating environmental monitoring extend directly to food, drinking water, and biological matrices. Although measurements remain limited—and inconsistent sampling, extraction, and quantification protocols hinder cross-study comparisons—recent analytical advances have confirmed pathways connecting environmental occurrence to human exposure[33,34]. An expanding body of evidence confirms that MNPs cross biological barriers and accumulate in human tissues[33–37].

Food and drinking water serve as primary exposure vectors. Physicochemical analyses of MNP uptake across the gut mucosa indicate that particle size, surface chemistry, and protein-corona formation govern whether ingested particles cross the intestinal epithelium into systemic circulation[38], mirroring principles established for engineered drug-delivery nanocarriers. Once across these mucosal barriers, MNPs translocate widely; they have been detected in human blood, placenta, breast milk, and the central nervous system[33–37]. Notably, analysis of postmortem and surgical brain tissues revealed MNPs in nearly all evaluated samples, with significantly higher concentrations in peritumoral tissue compared to non-neoplastic controls, along with a positive correlation between microplastic surface area and tumor proliferation[33–37]. These observations provide compelling evidence of MNP presence in the living human brain, extending earlier postmortem findings[35,39].

Mechanistically, *in vitro* and animal models implicate oxidative stress, genotoxicity, and chronic low-grade inflammation as core pathways driving MNP-mediated pathology[33]. These impacts are often exacerbated when particles act as vectors for sorbed chemical co-contaminants, such as heavy metals and per- and polyfluoroalkyl substances (PFAS)[40,41]. Physiologically based kinetic modeling and multi-route exposure scenario analyses indicate that cumulative body burdens—driven by combined ingestion, inhalation, and dermal contact—vary substantially across demographic and occupational groups[42–44]. However, intra-body particle migration and biotransformation continue to complicate simple dose–response extrapolations from experimental systems[45].

To contextualize these broader environmental impacts alongside human exposure, the scope of ecosystem-level research must expand beyond baseline monitoring to evaluate how MNPs disrupt global biogeochemical cycles and food webs[46–48]. Recent studies demonstrate that MNPs

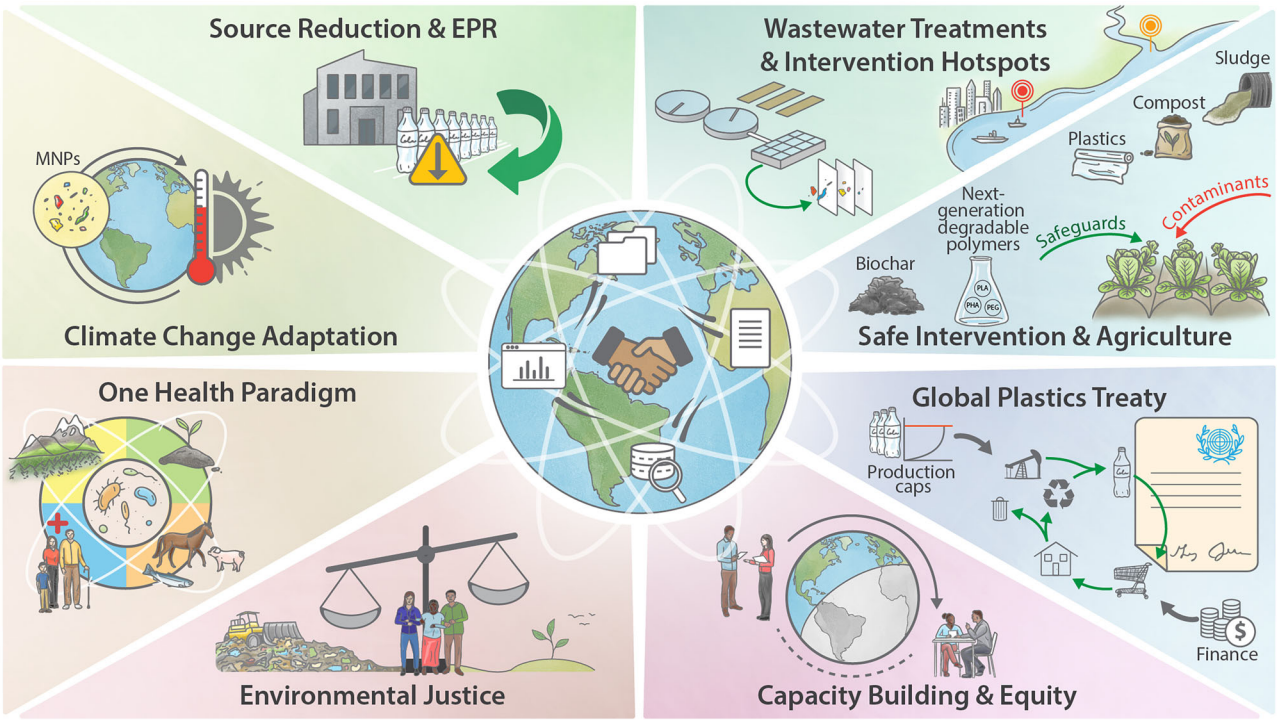

Fig. 2 | A coordinated global agenda for translating MNP science into policy and practice, spanning eight interconnected priorities. Source reduction and extended producer responsibility (EPR) target upstream plastic design and production; wastewater treatment and intervention hotspots direct investment to where nanoplastic release is most concentrated; safe innovation and agriculture covers next-generation degradable polymers, adsorbent filtration, biochar, and safeguards for agricultural plastics and sludge; the Global Plastics Treaty provides the central multilateral mechanism for capping production and setting binding, life-cycle-wide obligations; capacity building and equity addresses the uneven distribution of monitoring and research infrastructure between the Global North and South; environmental justice ensures protections reach the communities most exposed to plastic pollution; the One Health paradigm links environmental, plant, animal, and human health through shared microbiota and exposure pathways; and climate change adaptation situates nanoplastic governance within the broader context of a warming climate. At the center, international cooperation and equitable data-sharing hold these priorities together as a single, coordinated response.

—particularly biodegradable variants—can stimulate greenhouse gas emissions (e.g., CH_4, N_2O) while suppressing photosynthetic rates and net primary productivity across marine and terrestrial flora[49–53]. Furthermore, plastic-associated biofilms (*the plastisphere*) alter microbial communities, acting as vectors for opportunistic pathogens and facilitating the horizontal transfer of antimicrobial resistance genes[54].

Future research must prioritize how biofouling modulates vertical particle transport and trophic transfer in aquatic systems, as well as how climate-driven extreme weather events (e.g., hurricanes and severe flooding) mobilize and redistribute environmental MNP reservoirs[55–59]. To capture these dynamics, next-generation fate and transport models must integrate comprehensive empirical datasets and account for all diffuse environmental sources[60]. Finally, remediation paradigms must pivot away from conventional physical separation technologies—which remain hampered by membrane fouling and secondary waste disposal challenges[61], toward advanced chemical and catalytic degradation methods. Promising strategies including photocatalysis, interfacial solar evaporation, electrochemical sensing, and magnetic microrobots offer scalable pathways for complete mineralization and high-sensitivity detection[62–68].

Recommended policy agenda: harmonization and global governance. Because regulatory action ultimately depends on being able to measure what is being regulated, closing the detection, standardization, and data-comparability gaps identified above is itself a policy prerequisite and not merely a technical one. Building on the environmental data reviewed above, the following sections outline the research, policy, and governance agenda needed to translate this evidence base into meaningful action as more comprehensive MNP datasets become available. Policy literature specifically addressing nanoplastics remains limited, and existing regulatory approaches largely address MNPs or broader plastic pollution. Therefore, the policy priorities discussed below are considered within the broader MNP framework while recognizing the need for greater nanoplastic-specific evidence. Figure 2 summarizes the coordinated agenda outlined below.

Regulatory frameworks for MNP pollution are currently inadequate, largely due to a lack of comprehensive data on long-term toxicological and socioeconomic impacts[69–71]. While the European Union has progressed toward harmonized frameworks through instruments like the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) on synthetic polymer microparticles, many other countries—particularly in middle- and low-income economies—rely on fragmented bans with limited enforcement capacity[72,73]. California has pioneered a tiered framework for monitoring microplastics in drinking water, providing a structured model for risk characterization[70,74]. Despite these efforts, only a small number of countries explicitly address MNPs in their legislation, revealing a critical global policy gap[72].

Moving forward, establishing a comprehensive risk characterization and governance framework is essential, integrating scientifically sound risk assessment with transparent decision-making[75–77]. High-priority policy actions include adopting standardized definitions and universal monitoring protocols to ensure that data generated in different regions is comparable[70,78]. Policymakers should prioritize interventions in hotspot areas and invest in state-of-the-art wastewater treatment technologies before contaminants enter vulnerable water bodies[79]. Strengthening scientific and institutional capacity, particularly in low-income regions, will be crucial for the formulation of evidence-based public policies[78,79].

Source reduction must become a central pillar of the policy agenda, utilizing Extended Producer Responsibility (EPR) to incentivize manufacturers to design products for durability, reuse, and recycling[72,74,80]. Future innovation should focus on developing the "next generation" of polymers with shorter environmental turnover times[80]. A circular economy approach is viewed as the most promising path, but it must be carefully managed to ensure that recycling activities do not inadvertently increase the release of secondary MNPs into the environment[80,81]. Policies must also address the unintentional release of MNPs from agricultural plastics, composts, and sludges to protect agricultural soil and food security[82]. Materials such as biochar have shown considerable potential to enhance the adsorption of MNPs, thereby reducing their mobility and bioavailability; however, empirical evidence warrants long-term studies[83].

The ongoing negotiations for the Global Plastics Treaty represent a pivotal opportunity to close regulatory gaps, yet current draft texts lack robust provisions for addressing microplastics in critical areas like drinking water and atmospheric transport[70,84]. To be effective, the treaty must transition from general aspirations to a "hardwired operational reality" by mandating regional action plans and establishing a dedicated financial mechanism for equitable participation[85]. The treaty should embrace a full lifecycle approach, capping virgin plastic production and regulating hazardous chemicals[86]. Success will hinge on reconciling divergent socioeconomic and political interests of various countries, whether they view plastic as a "villain," "victim," or "hero"—to reach a consensus on binding obligations and a transparent implementation review process[73,87].

Barriers and trade-offs: equity and the One Health paradigm. Significant economic and technical barriers currently obstruct the governance of MNPs and impede a united global response. For many consumers, avoiding products containing MNPs is complicated by the lower cost of conventional items and a lack of trustworthy labeling[88]. There is a pronounced geographic inequity in research, where wealthier "technology developers" in the Global North focus on health and remediation. At the same time, "baseline pioneers" in the Global South are often limited to basic monitoring despite facing high volumes of plastic waste[89,90]. The resulting lack of standardized protocols generates inconsistent dataset structures, posing a major challenge for regional risk modeling and comprehensive meta-analyses[90,91].

To overcome these hurdles, transnational governance must move beyond fragmented mechanisms toward integrated models that collaborate with both public and private actors[92,93]. High governance costs often limit participation, but innovative cooperation models that emphasize cost- and benefit-sharing can significantly increase willingness to engage in MNP research and management[93]. Public perception is a critical factor for success; while there is high awareness of plastic risks, there is often very low institutional trust in government and scientific media[94–96]. Future governance should engage the informed public as a strategic ally, utilizing enhanced risk communication to bridge the gap between scientific knowledge and public concern[95,96].

Environmental justice must be a core principle guiding the development and implementation of future policy frameworks and treaties. Negotiators must strive for distributive justice, acknowledging that plastic pollution disproportionately harms vulnerable populations, and procedural justice, ensuring that Indigenous peoples and marginalized communities participate meaningfully in plastic governance[97]. The Precautionary Principle and the Polluter Pays Principle should be applied to hold high polluters accountable and protect ecosystems even in the face of scientific uncertainty[97]. Furthermore, addressing the shifting geopolitics of plastic waste, such as the redistribution of waste exports following changes in national policies, is essential for a holistic global approach[98].

The field is experiencing a decisive intellectual pivot toward a "One Health" approach, recognizing the interconnected risks of MNPs to the environment, plants, animals, microbiota, and human health[99–102]. While research has predominantly focused on aquatic organisms and humans, the impacts on farm animals, such as the bovine embryo model, and the presence of MNPs in animal-derived food products remain critically understudied[100,103]. Evidence suggests a bidirectional link between MNPs and non-communicable diseases (NCDs), where MNP-induced inflammation can exacerbate disease, and existing NCD-related inflammation can increase particle uptake[104]. Adopting a One Health perspective enriches our understanding of MNPs as a population-level "occupational hazard" and provides a structured entry point for cross-sectoral coordination[99,105]. Future governance must be adaptive, integrating the dual crises of plastic pollution and climate change, as rising temperatures and extreme weather continue to accelerate the fragmentation and global distribution of these emerging contaminants[106,107].

Conclusions

The evidence reviewed here shows that nanoplastic contamination is a genuine and likely widespread feature of aquatic and cryospheric environments, but our ability to characterize it remains constrained by an uneven and still-developing evidence base. Ocean systems benefit from the most mature field data, while lakes, rivers, polar regions, food, drinking water, and soil environments still rely disproportionately on laboratory proxies, microplastic-scale measurements, or isolated case studies rather than systematic, sub-micron field surveys. Closing this gap will require sustained investment in harmonized sampling and detection protocols, validated reference materials, and cross-laboratory comparability, without which risk assessments and regulatory decisions will remain built on an incomplete picture. At the same time, the agenda outlined above makes clear that better data alone will not be sufficient: translating improved detection capacity into meaningful protection requires parallel progress on regulatory harmonization, equitable distribution of research capacity and governance costs between the Global North and South, and integration of environmental, animal, and human health considerations under a One Health framework. As global instruments such as the Global Plastics Treaty and national frameworks like REACH continue to evolve, the research community has an opportunity, and an obligation, to ensure that emerging MNP science keeps pace with the policy decisions it is increasingly being asked to inform.

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M.M. is a co-founder and director of the Academic Parity Movement (www.paritymovement.org), a non-profit organization dedicated to addressing academic discrimination, violence and incivility. M.M. is also a co-founder of and shareholder in Targets' Tip, AlbuDerm, and XProteome Inc., and he receives royalties and honoraria for his published books, plenary lectures and licensed patents.

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