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Global plastic waste exports and the implications for continued microplastic pollution: toward a science policy interface for sustainable futures

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This study examines how the global plastic waste trade amplifies microplastic pollution through informal recycling, dumping, and burning in importing regions with limited waste management capacity. Synthesising evidence across aquatic, terrestrial, atmospheric, and human exposure pathways, we show that transboundary plastic waste redistribution contributes to environmental inequality and increased pollution risks. We further propose a science–policy framework linking waste trade governance, monitoring, and microplastic mitigation strategies.

Plastic pollution has become one of the most pressing environmental challenges of the 21st century. Driven by a linear economic model of produce-use-discard, global plastic production exceeded ~400 million tonnes in 2021[1,2]. The global trade of plastic waste, once touted as a solution to managing excessive plastic production and consumption in developed countries, has exacerbated environmental degradation, particularly in developing countries that receive these imports[1,3]. Following China's 2018 "National Sword" policy, plastic waste exports have shifted to Southeast Asia, Turkey, Mexico, and parts of Africa, where limited waste management infrastructure has driven unregulated dumping, burning, and informal recycling, accelerating micro and nanoplastic pollution. As plastic waste accumulates, it degrades into microplastics (<5 mm) and nanoplastics (often referred to as plastic particles <1000 nm)[4]. These microplastics are pervasive across environments, from the ocean trenches to the mountain peaks, infiltrating ecosystems, food chains, and even human bodies[5,6]. Recent studies indicate that microplastics are also present in the atmosphere, contributing to air pollution and spreading over long distances via wind and precipitation[7–10], including mountain regions and the Arctic[8–12].

At the process level, the generation and dispersion of microplastics associated with global plastic waste trade are governed by a combination of physical fragmentation, thermal degradation, and environmental transport processes. Mechanical handling during sorting and recycling generates primary fragments, while exposure to ultraviolet radiation, oxidation, and mechanical abrasion accelerates secondary fragmentation in open dumps and landfills. In parallel, open burning produces thermally altered microplastic particles, and atmospheric and hydrological transport processes redistribute these particles across terrestrial, freshwater, and marine systems. Integrating these mechanisms into assessments of global plastic waste trade is essential for understanding how transboundary material flows translate into spatially distributed environmental exposure and risk.

This paper explores the implications of global plastic waste imports on continued microplastic pollution to the environment, highlights key policy responses and research gaps, and proposes strategies to mitigate their impact. Unlike previous studies that examine plastic pollution, microplastics, or waste trade in isolation, this study explicitly integrates global plastic waste trade dynamics with microplastic generation, cross-compartment environmental pathways, and human exposure. Specifically, we link transboundary plastic waste flows to downstream microplastic emissions and synthesise evidence across terrestrial, aquatic, and atmospheric systems, framing microplastic pollution as a systemic outcome of global trade and environmental inequality. Building on this integrated perspective, we develop a practical science–policy interface that connects material flows, environmental processes, and governance mechanisms relevant to emerging international frameworks, including the Global Plastics Treaty. To ensure a coherent analysis, the discussion is structured around the causal pathway from global plastic waste trade through microplastic generation and environmental transport to human and ecological exposure, providing a basis for targeted policy interventions.

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Table 1 | Key statistics on global plastic waste trade, management, and leakage

Key Statistic	Detail	Source
Global plastic waste trade (2016)	≈14 million metric tonnes traded; >60% of exports from U.S., EU, and Japan	1,167
Shift in importers post-China ban	Malaysia became largest importer, receiving >750,000 tons in 2018	17
Mismanaged exports	Up to 60% of exported plastic waste is mismanaged, leading to environmental leakage	42
Land vs ocean leakage	Plastic leakage to land estimated to be 3–10× higher than to the marine environment	168
Source of waste	~⅔ of plastic waste comes from short-lived products (textiles, packaging, consumer goods)	1

The scale of global plastic waste trade and its shifting geography

For decades, high-income nations have exported large volumes of plastic waste to low- and middle-income countries, shifting the burden of waste management. This global waste trade has grown alongside an exponential growth in global plastic production, allowing high-consuming countries to avoid the full social and environmental impacts of plastic overconsumption[13]. In 2018, China implemented the "National Sword" policy, banning the import of plastic waste, among others, due to environmental concerns. This policy disrupted global plastic waste flows, leading to increased exports to Southeast Asian countries such as Malaysia, Indonesia, and Vietnam[3].

Southeast Asia already struggles to manage their domestic wastes[14], and now existing recycling capacity[15] is taken up by plastic waste exported from the developed world. The export of plastic waste for "recycling" when a vast majority of plastic has never been recycled only serves to perpetuate current unsustainable rates of plastic production and consumption, distracting from the urgent need to regulate the ever-expanding production of virgin plastics. Table 1 provides some key statistics on plastic waste.

This global redistribution of plastic waste has led to unregulated open dumping, burning, and informal recycling, particularly in low- and middle-income countries, which significantly contributes to environmental degradation and microplastic generation[16]. These global flows and their downstream impacts are illustrated in Fig. 1, highlighting key exporting regions, receiving hotspots, and pathways of plastic breakdown. Recipient countries have inadequate waste management infrastructure, which has exacerbated microplastics leakage into the environment, a phenomenon well documented across Turkey, Malaysia, Indonesia and more[3,17]. However, even in areas with better infrastructure, mechanical recycling has been found to cause microplastic pollution[18–23].

Recent trade data from the United Nations Comtrade database and reporting under the Basel Convention indicate that Southeast Asia remains a major node in global plastic waste flows following China's 2018 import restrictions. Malaysia has emerged as the largest exporter of plastic waste in the region, with annual exports of plastic scrap (HS code 3915) estimated at approximately 300,000–400,000 tonnes in 2022–2023, following peak imports of nearly 870,000 tonnes in 2018–2019. Thailand and Indonesia also contribute substantially, exporting approximately 200,000–300,000 tonnes and 150,000–250,000 tonnes per year, respectively, while Vietnam exports smaller but still significant volumes[3,24–27]. These data highlight the role of Southeast Asia as a processing and redistribution hub, where imported plastic waste is often re-exported after partial treatment. Such transboundary flows increase the risk of environmental leakage and microplastic generation, particularly in contexts where waste management infrastructure and regulatory oversight remain limited.

Furthermore, satellite imagery and trade databases reveal persistent illegal or under-reported plastic waste shipments that circumvent the Basel Convention, a multilateral agreement that controls the transboundary movement of hazardous waste, raising concerns about compliance and enforcement[28–30]. Since China's ban, even as foreign plastic waste ends up in stockpiles and fires in destination countries, recent research highlights a rising accumulation of domestic plastic waste also in exporting nations, underscoring the urgency to reduce plastic production and promote sustainable waste management solutions[1,3,31].

Distinct sources and pathways of microplastics associated with the global trade in plastic waste

Microplastics emerge from both primary sources, e.g., intentional uses such as microbeads or encapsulates in cosmetics, detergents and agricultural products[32], and secondary sources, generated through the degradation and fragmentation of larger plastic items[33]. This includes degraded plastic waste or synthetic textiles released during washing and production, for example. Some definitions also include tyre and road particles, generated through the wear of vehicle wheels on the world's transport networks. This is typically thought to dominate other sources of secondary microplastics, and potentially even larger plastics (macroplastics), in terms of the mass emitted to the environment[34].

Emissions of primary microplastics associated with the global trade in plastic waste are likely to be limited. Some primary microplastics, such as plastic pre-production pellets, have known significant environmental emissions during production, transport, loading and cleaning[35], but are not associated with the global trade in plastic waste. At a country level, it is expected that primary microplastics represent only a fraction of the emissions of secondary microplastics[36,37].

Global models of microplastic emissions often rely on country-specific production and consumption data to estimate emissions to the environment. However, a major gap acknowledged in these models is the lack of material flows representing import and export data of plastic products and waste[1,31,34,38]. Receiving countries may primarily be waste-dumping and waste-landfilling countries, and it is understood that the share of mismanaged municipal solid waste can be high. For example, mismanaged waste as a proportion of all municipal solid waste may be as high as 93% of in Africa and 90% in India, according to a report to UNEP[39–41]. Globally, an estimated 20–30% of plastic waste is mismanaged, with substantial regional variation and significantly higher fractions in low- and middle-income countries[1,42,43].

Considering that around half of all macroplastic losses to the environment are accounted for through mismanaged municipal solid waste, ultimately, this litter will act as a source of secondary microplastics, as it too weathers and fragments in the receiving environment. Previous research has suggested that this fragmentation happens at an average rate of approximately 3% per year[44], equating to 26% of microplastics breaking down into microplastics over the course of a decade. However, this rate is highly uncertain, very variable and strongly dependent on polymer composition and the degradation stresses (such as sunlight, hydrolysis, biodegradation and mechanical power) encountered in the environment. Models that can integrate plastic properties and environmental conditions to estimate fragmentation rates[45–47] may prove useful in improving these predictions to provide insight into the timescales at which this significant global redistribution of plastic waste and subsequent loss to the environment through mismanagement will impact microplastic releases to these receiving environments, which would otherwise not be exposed to this source. That being said, we can already use this limited information to visualise polymer mass flows from globally traded waste (≈14 million tonnes) to microplastic releases from this mismanaged fraction (≈2.2 million tonnes), as shown in Fig. 2. To provide a clearer linkage between global plastic waste trade and microplastic generation, a simplified mass-flow perspective can be applied. Approximately 14 million tonnes of plastic waste are traded globally each year, of which an estimated 20–60% may be mismanaged depending on

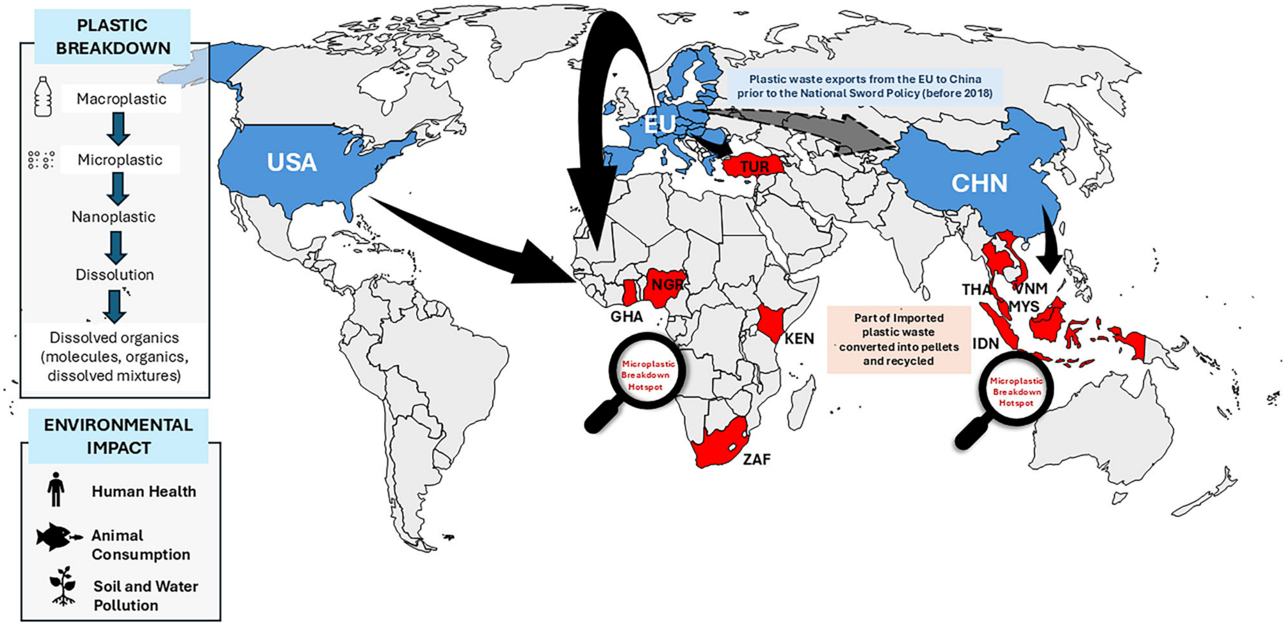

Fig. 1 | Global plastic waste trade flows, breakdown hotspots, and multi-pathway environmental impacts. The map illustrates major international plastic waste trade routes (black arrows) from primary producing regions (highlighted in blue: USA, EU, China) to major importing hubs (highlighted in red: Africa, Southeast Asia, and Turkey). Red outlines and magnifying glass symbols identify examples of 'Microplastic Breakdown Hotspots' where environmental degradation is most accelerated, with a significant contribution from the global waste trade. Country abbreviations (e.g., NGR: Nigeria, MYS: Malaysia, TUR: Turkey) identify key importing nations. The Breakdown inset (left) details the fragmentation process from macroplastics through to nanoplastics and the molecular dissolution into dissolved organics. The Environmental Impact inset (bottom left) highlights the three primary risk categories: human health, animal consumption and pollution of soils and waters.

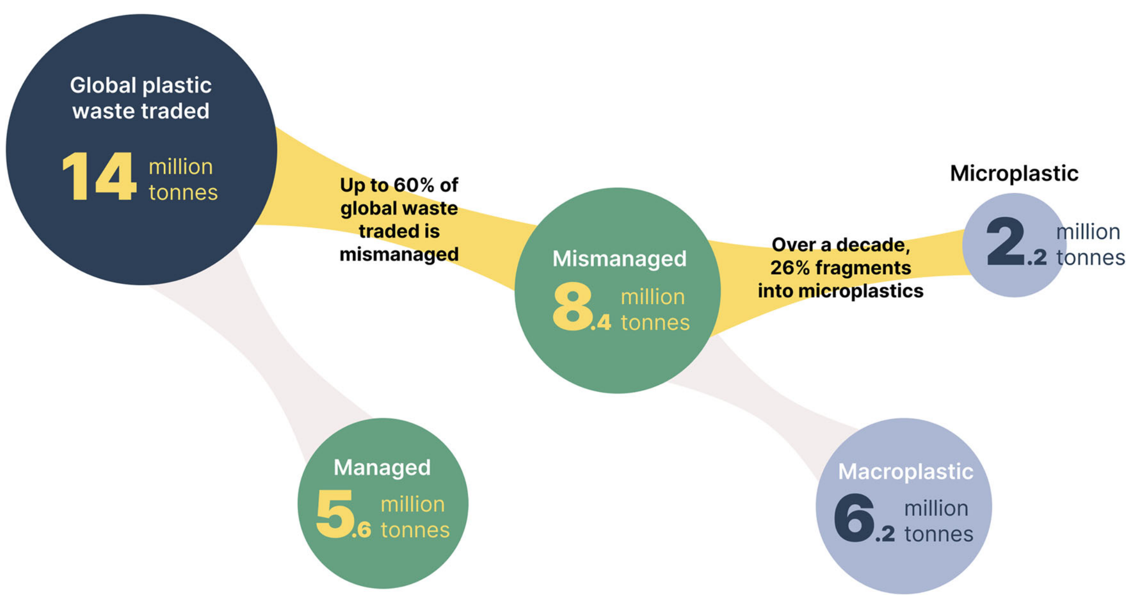

Fig. 2 | Mass flows of global plastic waste traded to micro- and macroplastics for mismanaged sources. Up to 60% of global plastic waste traded[2,167] is mismanaged[42], and from the mismanaged fraction, approximately 26% fragments to microplastics over the course of a decade[44]. Indicative mass flows are given, showing that of the approximately 14 million tonnes of global plastic waste traded, 2.2 million tonnes will end up as microplastic releases (yellow mass flow connections), though there is a large degree of uncertainty in these values.

regional waste management capacity. This corresponds to roughly 3–8 million tonnes of plastic entering uncontrolled environmental pathways annually. Assuming indicative fragmentation rates on the order of a few percent per year, this mismanaged fraction represents a substantial and persistent source of secondary microplastics over decadal timescales. For example, even a conservative fragmentation rate of ~3% yr^{-1} implies that hundreds of thousands to over a million tonnes of microplastics could be generated from traded waste within a decade. While these estimates are subject to considerable uncertainty due to variability in polymer types, environmental conditions, and waste handling practices, they provide an order-of-magnitude indication of how global waste trade can amplify microplastic emissions in receiving regions.

Another aspect of the mismanagement of waste, traded globally, is the open burning of plastic waste. Open burning has been identified as presenting a high risk of harm to waste pickers, with the generation of particulate matter and volatile chemicals during open burning being of concern[48]. A recent study identified open dumping and burning as a source of thermally degraded microplastics in soils, indicating a hitherto too unappreciated source[49]. There are insufficient data available to appreciate the relative contribution of open burning and incomplete combustion of plastic waste to the emissions of thermo-degraded microplastics to the environment, nor whether these carry specific risks distinct from other weathered and aged plastics. Irrespective, the global trade in plastic waste and subsequent mismanagement through open burning represents a global health inequality where the highest risks are concentrated in the Global South[48].

Distinct microplastics emissions associated with the trade and management of plastic waste are not only limited to practices associated with mismanagement, but also practices such as recycling, where the shredding phase commonly associated with mechanical recycling is a significant generator of microplastic particles[50]. As well as being present in aqueous waste streams[19] these microplastics can be found in the dust fall in manual mixing areas of recycling centres, indicating not only an environmental emission through the air, but also an occupational exposure to airborne microplastics during recycling[19,51]. Mechanical recycling has been estimated to contribute to 3.1% of global microplastic emissions in 2017, with an estimated discharge increasing from a predicted 0.017Mt in 2000, to reach 0.749 Mt in 2060[1,31,34]. At the global scale, such emissions occur within a plastics system that remains far from circular. Syntheses by the OECD estimate that only around 9% of plastic waste is ultimately recycled globally once sorting inefficiencies and processing losses are accounted for, with the remainder landfilled, incinerated, or mismanaged[52]. In high-consumption regions, recycling capacity is further constrained by polymer complexity, contamination, economic viability, and market demand for secondary plastics, even where collection rates for specific streams appear relatively high. For example, while the EU reports recycling rates of ~40–45% for plastic packaging, this represents only one waste stream and does not reflect losses, downcycling, or the limited capacity to process mixed or low-quality plastics domestically.

These structural and economic constraints have been identified as one factor driving continued exports of plastic waste from consuming regions to other countries for processing, effectively shifting sorting, recycling, and disposal burdens abroad. Analyses of European plastic waste exports show that such flows can occupy limited recycling capacity in receiving countries and displace the management of domestic waste, a phenomenon described as "recycling displacement" or offshoring[15]. Where downstream environmental controls are weaker, this transfer of material can result in elevated environmental leakage and increased occupational exposure to plastic dusts and microplastics in importing countries, exposures that would otherwise occur within the consuming region. Together, this evidence indicates that plastic waste trade does not simply reflect a benign matching of recycling capacity, but can externalise environmental and health risks, reinforcing the need for upstream production reduction and stricter governance of waste trade alongside improvements in recycling technology and worker protection. This integrated perspective demonstrates that microplastic emissions cannot be fully understood without accounting for transboundary waste flows, which modify both the magnitude and spatial distribution of secondary microplastic generation. Within this global system, international waste trade introduces additional pathways of microplastic generation, particularly in regions where waste management practices differ substantially from those in exporting countries.

How does the global trade in plastic waste introduce specific hazards and impacts associated with microplastics?

The specific hazards and impacts of microplastics associated with the global trade in plastic waste are largely driven by a shift in exposure of these plastics, from consuming countries to those that receive imports of plastic waste, rather than any unique hazards or toxicity associated with microplastics arising from waste plastic as compared with other sources. From a mechanistic perspective, the environmental fate of these particles is governed by their physical and chemical properties—such as size, density, shape, and composition—as well as by the environmental conditions they encounter. Smaller particles are generally more mobile, facilitating long-range atmospheric transport and deeper infiltration into soils and aquatic systems, whereas larger fragments are more likely to accumulate in surface environments or sediments. In the context of plastic waste trade, fragmentation and degradation processes associated with handling, recycling, open dumping, and burning modify these particle characteristics, thereby influencing their transport pathways, environmental persistence, and the spatial distribution of exposure in receiving regions. These mechanistic insights have direct implications for policy design. For instance, the recognition that mechanical recycling and waste handling processes generate microplastics highlights the need for emission controls and filtration technologies in recycling facilities. Similarly, the role of open dumping and burning in accelerating fragmentation and atmospheric release underscores the importance of strengthening waste management infrastructure and enforcing restrictions on informal disposal practices. Integrating process-level understanding into policy frameworks, therefore, enables more targeted interventions that address the specific pathways through which microplastics are generated and dispersed.

To illustrate, taking the example of the trade in waste for recycling, this may introduce a distinct local source of microplastics in untreated effluent, discharged in washwater from the shredding and washing process[19,50]. This presents a risk to receiving waters that would otherwise not be present, thus representing a new risk associated with the global trade in plastic waste. However, these microplastics are likely to be structurally similar to other secondary microplastics and so the mechanisms of toxicity and environmental hazards will be consistent with what we know for microplastics more generally.

What becomes important therefore, is how waste management performance varies significantly across regions, with mismanaged waste exceeding 50–90% in parts of Africa and 40–80% in parts of Asia due to limited infrastructure and rapid urbanisation[40,52]. In contrast, Europe and the United States maintain mismanagement rates below 5% through near-universal collection and advanced treatment systems, although high consumption levels and historical waste exports continue to externalise environmental impacts[1]. Globally, approximately 40–45% of plastic waste remains mismanaged, representing a major source of terrestrial and marine pollution[1,30]. The accumulation of microplastics in marine, freshwater and terrestrial ecosystems is therefore closely linked to improper plastic waste management in plastic waste-receiving nations[31,42]. This accumulation of waste can act as a reservoir of plastic with the potential to degrade and fragment into secondary microplastics, as discussed in the previous section.

Microplastics pose significant emerging risks to marine, freshwater and terrestrial ecosystems. They are ingested by a wide variety of organisms, with >1,500 species documented to ingest microplastics to date[53–55]. This can lead to harms associated with the plastic fragments themselves, such as disruption of feeding and reproduction[56–59]. Plastics also contain a complex mixture of chemical additives, with over 13,000 substances identified as associated with plastics, and more than 3,200 of these chemicals shown to have one or more hazardous properties of concern[60,61]. This presents a challenging mix of both physical and chemical harms to the environment, operating at different scales, as plastic items degrade and fragment into ever smaller micro and nanoplastics.

For humans, the ingestion and inhalation of microplastics raise concerns about potential toxicological effects, due to their similarities with other airborne particulate pollutants, including inflammation, hormonal disruption, and increased risks of chronic diseases[59,62]. In 2025, The Lancet published a "Countdown on health and plastics", suggesting an independent health-focused, indicator-based global monitoring system which would allow reporting on progress towards reducing exposure and harms to humans and the environment over time[59]. Microplastics have been proposed as an ecological indicator for exposure, with monitoring in freshwater, seawater, sea ice or glaciers suggested as options which may be developed and taken forward. For human internal microplastic exposure, indicators at this stage are expected to focus on tracking progress towards characterisation of internal human exposure, as the evidence base so far is deemed in need of further validation before indicators for human internal exposure can be developed.

It is important to note, though it is difficult to establish safe levels of microplastics in the environment at present (for wildlife or for humans), the continued release, degradation and fragmentation of macroplastics and microplastics in the environment raises the concern that, whilst it is uncertain when safe levels will be exceeded, in all likelihood, safe levels will be exceeded in the future[36,62,63].

Trade-driven redistribution of microplastic pollution in importing regions

The global redistribution of plastic waste following trade restrictions—most notably China's *National Sword Policy*—has led to a rapid spatial reconfiguration of microplastic pollution. Between 2016 and 2018, plastic waste exports from high-income countries to Southeast Asia increased by over 150–300%, shifting environmental burdens to regions with limited waste management capacity[1,3,26]. In these settings, inadequately processed imported plastics undergo fragmentation through mechanical handling, ultraviolet exposure and open burning, generating substantial secondary microplastic emissions to terrestrial, freshwater and atmospheric environments[34,64].

Southeast Asia (SEA). SEA became the primary destination for displaced plastic waste flows after 2018. Countries such as Malaysia, Thailand and Vietnam experienced sharp import surges (e.g., Malaysia's imports increased by ~273% in 2018). Limited infrastructure has resulted in widespread informal recycling, illegal dumping and open burning, intensifying leakage pathways from land to ocean[3,26,39,40,42]. River systems such as the Mekong are recognised as significant contributors to global marine plastic inputs, with a large proportion of riverine plastic emissions originating from rivers in Asia, facilitating downstream transport and accumulation of microplastics in coastal ecosystems and fisheries[14,42,65].

South Asia. The informal recycling systems dominate plastic waste processing in South Asia, including imported low-grade plastics that are difficult to recycle. Manual sorting and shredding generate fine microplastic particulates, while open burning—still widely practised—releases microplastics into the atmosphere along with toxic co-pollutants[3,19,39,50]. Recent studies have detected airborne microplastics in urban environments, suggesting an additional pathway of human exposure through inhalation[9,66].

Sub-Saharan Africa. Emerging plastic waste destinations in Sub-Saharan Africa have seen increasing imports due to regulatory gaps. Mismanaged waste is frequently co-disposed in open dumpsites, where fragmentation and weathering lead to microplastic accumulation in soils[3,38–40,67]. Microplastics in agricultural soils have been shown to affect soil structure, reduce water retention capacity and disrupt microbial activity, with potential implications for crop productivity and food security[68–70].

Latin America. Plastic waste imports have risen in countries such as Mexico and Chile following global trade shifts. Inadequate recycling capacity has resulted in increased landfill leakage and coastal contamination. Recent quantitative analyses of plastic scrap trade and waste management capacity across 18 Latin American countries identified several regional "plastic pollution hotspots," where high imports of difficult-to-recycle plastics coincide with elevated rates of mismanaged waste. Following China's 2018 import ban, low-quality plastic wastes such as PVC and polystyrene increasingly circulated within the region toward countries with lower waste management capacity, further amplifying environmental risks and regional inequalities[71]. Microplastics have been detected in marine sediments and biota, indicating their incorporation into food webs and potential trophic transfer in economically important fisheries[3,39,54].

Small Island Developing States (SIDS). Although not major importers of plastic waste, these regions experience disproportionate environmental impacts through the transboundary movement of plastic debris and microplastics across ocean basins. Model estimates suggest that a significant fraction of marine plastic debris is redistributed across ocean basins, leading to accumulation even in regions with relatively low local waste generation and results in the deposition of macro- and microplastics along coastlines, within lagoon systems, and across coral reef systems[72,73].

In addition to environmental impacts, SIDS face socio-economic burdens associated with managing externally sourced pollution. Limited waste management infrastructure, high costs of waste collection and disposal, and dependence on coastal resources exacerbate vulnerability. Tourism-dependent economies are particularly affected, as plastic pollution degrades coastal aesthetics and ecosystem integrity. Thus, the global plastic waste trade contributes to a form of environmental externalisation, whereby pollution generated and traded elsewhere is effectively transferred to geographically remote but highly vulnerable regions. This underscores the inequitable distribution of plastic pollution impacts and highlights the need for stronger global governance frameworks that account for downstream and transboundary consequences.

Collectively, these observations demonstrate that plastic waste trade acts as a vector for the global redistribution of microplastic pollution. The displacement of waste from high-income to lower-income regions has resulted in unequal environmental exposure, where inadequate infrastructure amplifies fragmentation and leakage processes. This reframes microplastic pollution as a systemic consequence of global trade dynamics and environmental inequality, rather than solely a local waste management issue. While these regional patterns highlight where microplastic pollution accumulates, understanding its consequences requires examining the specific environmental pathways through which impacts occur.

Pathways and mechanisms of microplastic impact in receiving environments

While the global redistribution of plastic waste reshapes the geography of microplastic pollution, the resulting environmental consequences are governed by local waste management practices and the pathways through which plastics are processed, degraded, and released into the environment. Specific environmental impacts arising from the global redistribution of plastic waste are increasingly documented in receiving countries, where limited waste management capacity amplifies leakage pathways and microplastic generation[3,34,39,42]. In these settings, imported plastic waste is frequently subject to informal recycling, open dumping and burning, which enhances fragmentation into secondary microplastics across environmental compartments[3,34,40].

Marine and freshwater pollution. Plastic pollution poses a global threat to marine and freshwater ecosystems, with an estimated 19–23 million metric tons of plastic waste entering aquatic environments and is predicted to reach up to 53 million metric tons per year by 2030[74] a significant portion of mismanaged plastic waste - breaking down into microplastics that threaten aquatic life through ingestion and bioaccumulation[54], or the toxicity of their chemical additives[75]. Leakage into river systems such as the Pasig River and Mekong River has intensified, with these rivers identified among the largest global contributors of plastic debris to marine environments[14,38]. Recent field evidence from Adana, Turkey, further demonstrates how plastic recycling facilities associated with imported plastic waste can act as direct point sources of microplastic contamination in connected irrigation and freshwater systems. Downstream microplastic concentrations in irrigation canals were substantially elevated relative to upstream measurements, with polymer signatures indicating recycling-related origins[76]. In Ghana, high concentrations of microplastics have been reported in the Korle Lagoon, one of the most polluted coastal lagoons in West Africa, where plastic debris accumulates and fragments under intense solar radiation[77,78]. In Nigeria, microplastics have been widely documented in the Lagos Lagoon, including in surface waters, sediments and biota, indicating widespread contamination and bioavailability within aquatic food webs[79,80]. Similarly, in Kenya, studies of the Nairobi River have identified significant microplastic loads associated with urban waste inputs, with downstream transport into marine environments along the Indian Ocean coast[81,82]. Globally, an estimated 19–23 million metric tons of plastic waste enter aquatic systems annually, representing approximately 11% of total plastic waste generation, with a substantial proportion arising from mismanaged waste streams in exporting and importing region[1,45]. Microplastics generated through degradation processes are widely detected in aquatic organisms, including commercially important fish species in Indonesia, indicating bioaccumulation and potential trophic transfer within marine food webs[83,84].

Soil contamination. Imported plastic waste is often openly burnt or illegally dumped. Open burning and illegal dumping of this nature can lead to microplastic infiltration into soils[49] In addition, plastic mulching films already contribute to agricultural field plastic contamination, either through incomplete collection of mulching films after the growing season, or intentionally tilling or burying these films into the field. Informal recycling hubs in India, including Delhi and Moradabad, process both domestic and imported waste, with residual plastics often entering surrounding agricultural systems[3,48]. In Sub-Saharan Africa, soil contamination is increasingly reported near major waste disposal and recycling sites. In Nigeria, studies around the Olusosun Landfill have identified microplastic accumulation in surrounding soils and leachate pathways, linked to long-term plastic waste deposition[85]. In Ghana, microplastics have been detected in soils near informal waste dumps and coastal zones around Accra, reflecting fragmentation of plastic waste under tropical conditions[77,86]. Reuse and recycling of agricultural plastics is currently very low, <10%[87]. Studies suggest that the presence of micro or nanoplastics hampers seed germination and seedling growth[88], while plants may have a reduced rate of photosynthesis[89], stunted growth, decreased fruit yield and low nutritional content.

Airborne Microplastics. Microplastics have been measured in air samples both in urban[90–92] and, for example, in rural mosses representing airborne deposition away from local sources[7,93]. Airborne microplastics are increasingly reported in regions where imported plastic waste is processed under uncontrolled conditions, particularly in South Asia[9]. Similar exposure pathways are emerging in Africa. In Lagos, open burning of plastic waste at landfill sites and informal dumps has been identified as a source of airborne particulates, including likely microplastic fragments[94]. In Accra, waste burning and informal recycling activities contribute to particulate emissions in urban air, with recent studies indicating the presence of plastic-derived particles in atmospheric samples[95]. Open burning of low-value plastics releases microplastic particles into the atmosphere, contributing to urban particulate pollution and long-range transport pathways. The importance and implications of microplastics as vectors for the long-range transport of chemicals is under active investigation, to understand priorities for research and regulatory actions. Microplastics have been detected in air samples from major urban centres such as Delhi and Dhaka, as well as in remote environments including rural mosses, indicating atmospheric deposition far from primary sources[9,92]. Microplastics have also been detected in remote environments, including rural and high-altitude regions, indicating long-range atmospheric transport from source regions associated with intensive waste processing[9,96,97]. These particles may act as vectors for toxic chemicals and undergo atmospheric ageing, influencing their environmental behaviour. Further, chemical transformations and transport of microplastics in air differ from those in water and soil.

Climate relevant feedback. Although climate-relevant feedback associated with microplastics are not solely driven by waste trade, the redistribution of plastic waste through global trade can influence their spatial distribution and environmental processing. Emerging evidence further suggests that airborne microplastics may interact with climate-relevant processes beyond their transport and deposition. When deposited on cryospheric surfaces such as snow and ice, dark microplastics such as those associated with tyre and road wear, which contain carbon black, could in principle reduce surface albedo, accelerating melting and altering local energy balances[11,97–99]. The importance of microplastics as compared to other particulate material, such as black carbon, still needs to be established, though early estimates predict tyre and road wear may contribute 10-30% of the radiative effects of carbon black[100]. Additionally, microplastics suspended in the atmosphere may contribute to changes in atmospheric chemistry, either by acting as vectors for adsorbed pollutants or through their own chemical constituents. Their presence in the atmosphere, especially in fine size ranges or those containing light and heat-absorbing carbon black, such as tyre and road wear particles, raises concerns about their potential contribution to radiative forcing, particularly if their abundance increases in the lower troposphere. Given that tyre and road wear particles may be the most significant component of radiative effects of microplastics, the role of the global trade in waste is perhaps less important for climate-relevant feedback. Generation of microplastics during the use phase of tyres whilst driving will be a more important immediate annual source of microplastics than degradation and fragmentation of tyres at the end of life. While still an emerging field, these interactions highlight the need to include microplastics in broader assessments of land-atmosphere feedback, climate processes and wider planetary boundaries[1,97]. The role of micro and nanoplastics, as compared to other particulates, must be carefully considered to understand whether this presents a significant contributor to these impacts.

Across these pathways, the global plastic waste trade acts as a mechanism for the redistribution of environmental risk, concentrating pollution in importing regions with limited infrastructure and regulatory capacity. These interconnected pathways drive cumulative impacts across aquatic, terrestrial, atmospheric, and human systems, underscoring microplastic pollution as a multi-compartmental environmental justice issue shaped by global trade dynamics and extending directly to human exposure.

Human health and occupational exposure pathways

Beyond environmental impacts, these pathways also translate into direct and indirect human exposure to microplastics. Specific human health impacts arise from exposure to microplastics associated with the global waste trade through:

Human health risks. Microplastics have been detected in drinking water, many food sources, and even in the human body, raising concerns about long-term health impacts[62,101]. However, substantial limitations in available information mean the weight of evidence for current human health risks from inhaled and ingested microplastics is low. Likewise, ultrafine plastic particles (nanoplastic), which may have significantly different physical and toxicological properties compared to larger microplastics, may pose greater health risks. Improvements in analytical techniques will increase our understanding of the internal fate of micro and nanoplastics within the human body and their toxicology. It is important that a high degree of certainty is achieved when detecting microplastics in human tissues in order for any link between exposure and pathologies to be robustly investigated[59]. Recent guidance on how to combine analytical methods based on independent measurement principles to increase the confidence with which we can communicate reports of microplastics in the human body has recently been published[102]. This could assist in this area.

Specific occupational exposures. Waste pickers face health risks through exposure to incompletely combusted microplastics alongside other chemicals and airborne particulate matter generated during open burning[59]. Mechanical recycling of plastics generates microplastic particles microplastics which may be airborne[50,51,103]. Workers in the recycling sector can be exposed to these airborne microplastics and associated chemicals, generated by the handling and processing of plastic waste. There is evidence of disease from occupational exposure to secondary microplastics during plastic production[55], with the majority of these cases linked to exposure to plastic dusts, many in the textile industry. There is therefore concern about similar occupational health risks to workers in the textile recycling sector.

In summary, it is not clear that secondary microplastics generated from the fragmentation of imported plastic waste experience distinct hazards from other sources of microplastics. Similar mechanisms of hazard and impact on environmental and human health are relevant for microplastics associated with the global trade in plastic waste, as are those from other sources. At a local level, the influence of the global trade in plastic waste on the risks of microplastics to environmental and human health is through a shift in exposure to these plastic materials from consuming to importing countries. In some cases, there are also specific occupational exposures related to the formal and informal sectors managing this waste.

Key research gaps in linking global plastic waste trade to microplastic pollution. Despite growing evidence of these impacts, significant uncertainties remain in quantifying and understanding the role of global plastic waste trade in driving microplastic pollution. Research gaps specific to the role of the global waste trade in plastic can be defined into several areas.

Modelling microplastic emissions associated with the global trade in plastic waste. The role of the global trade in plastic waste is a significant process that is currently not accounted for or poorly parameterised in models to predict emissions of microplastics to the environment[34]. In particular, existing studies rarely integrate transboundary material flows with microplastic generation, transformation, and exposure pathways. Addressing these gaps is essential for improving predictions of microplastic emissions and their spatial distribution under different waste management and policy scenarios. Critical gaps which would enable models to better capture the role of the global trade in plastic waste on emissions of microplastics to the environment would include:

- Improvements to model parameterisation of the fate and emissions of macro and microplastics from uncontrolled landfills, such as open dumps and other mismanaged solid waste.
- Significant flows not included in current material flow analysis models, such as import and export values for the trade in waste.
- Distinct transformation and transport pathways for microplastics to the environment are associated with the trade in global waste and subsequent mismanagement of imported plastic waste, such as through open burning and incomplete combustion of plastic and microplastics.

Chronic and long-term impacts of microplastics on environmental health. Despite the growing awareness of potentially harmful effects, significant knowledge gaps remain regarding the long-term impacts of microplastics. There is a critical need to understand how microplastics influence and respond to processes at the land-atmosphere interface. This includes their potential roles in biogeochemical cycling, long-range atmospheric transport, and climate processes. Incorporating microplastics into climate and exposure model frameworks would improve understanding of their dispersion patterns and environmental persistence.

As environmental ageing processes differ across media such as water, soil and air, the properties and potential toxicities of plastic particles may also vary. Emerging developments in ecotoxicology, including efforts to harmonise methods and risk assessment frameworks, can help to simplify these assessments and improve the robustness of microplastic risk characterisation[104]. In addition to chemical composition, plastic particle size, shape and associated co-contaminants (e.g., heavy metals, persistent organic pollutants and bacteria) play key roles in determining human health effects, since smaller particles penetrate further into the human body. Size and shape can also influence the transport of particles in the environment and therefore, determine which species or ecosystems are exposed. Innovative materials science is exploring biodegradable alternatives to reduce the time that microplastics persist in the environment before they are fully broken down into dissolved organics, volatiles and carbon dioxide (i.e., mineralised).

Monitoring and indicator assessments of environmental exposure. Indicator assessments and monitoring of litter is quite well established, for example, the OSPAR Marine Litter Indicator Assessments[105], but are less developed for micro and nanoplastics. Baseline monitoring is needed now, against which long-term trends can be compared, particularly in the context of ongoing policy developments such as the Global Plastics Treaty. Fortunately, microplastics can be detected in ambient samples with widely available vibrational spectroscopy techniques such as Raman and Fourier Transform Infra-Red and techniques such as pyrolysis Gas Chromatography – Mass Spectrometry[106–110]. However, further validation is needed to scale the application of these methods from research tools to standardised and repeatable analyses that can be applied in long-term and wide-scale monitoring programmes[111]. Advanced detection and monitoring technologies are being developed to better understand their distribution and effects, particularly of smaller particles <10 μm, for which analytical methods are not yet routine.

Internal exposure in humans to microplastics associated with the trade in plastic waste. It has been identified that the majority of the evidence base for detection of microplastics in human tissues is often focused on larger particles, which are more easily detectable using the current generation of analytics, whilst those particles most likely to translocate and truly permeate the human body are smaller than can be observed with many of these approaches[112]. High-profile reports of microplastics in human tissues, such as the brain, have led to caution in quality assurance and control measures for some analytical approaches that are subject to known interferences and can result in false positive identification of plastic polymers. For example, a Matters Arising publication was recently published by Monikh et al.[113] in response to the Nihart et al.[114] reports of microplastics in decedent human brains. There is clearly more research needed to further establish the generic risks of micro and nanoplastics to human health, which can be aided by recent frameworks proposed to assess the risk and recommendations for best practice in assessing exposure[102,115,116]. The Lancet Countdown for health and plastics could be an effective initiative to track progress on this topic and suggests it will focus on this as one of its proposed indicators[59].

Policy responses and mitigation strategies

Addressing these challenges requires coordinated policy responses that target the full lifecycle of plastics and the transboundary nature of waste trade. Waste management practices vary from country to country. However, a prioritisation of management options is often defined nationally or internationally in policy, such as the "waste hierarchy" (Fig. 3). This largely determines waste management practices in the European Union.

The Waste Hierarchy is set out at Article 4 of the revised Waste Framework (Directive 2008/98/EC) and orders management options according to their efficacy. In the hierarchy, the prevention of the generation of waste is considered the most effective management strategy, whilst disposal in landfill or through incineration of waste is considered the last option in the hierarchy. Each stage of the hierarchy influences the emissions of microplastics to the environment, but this may not always be to affect a reduction in emissions.

Similar to the generic Waste Hierarchy, prevention of waste through reduction in use of plastic materials in products, keeping products in use for

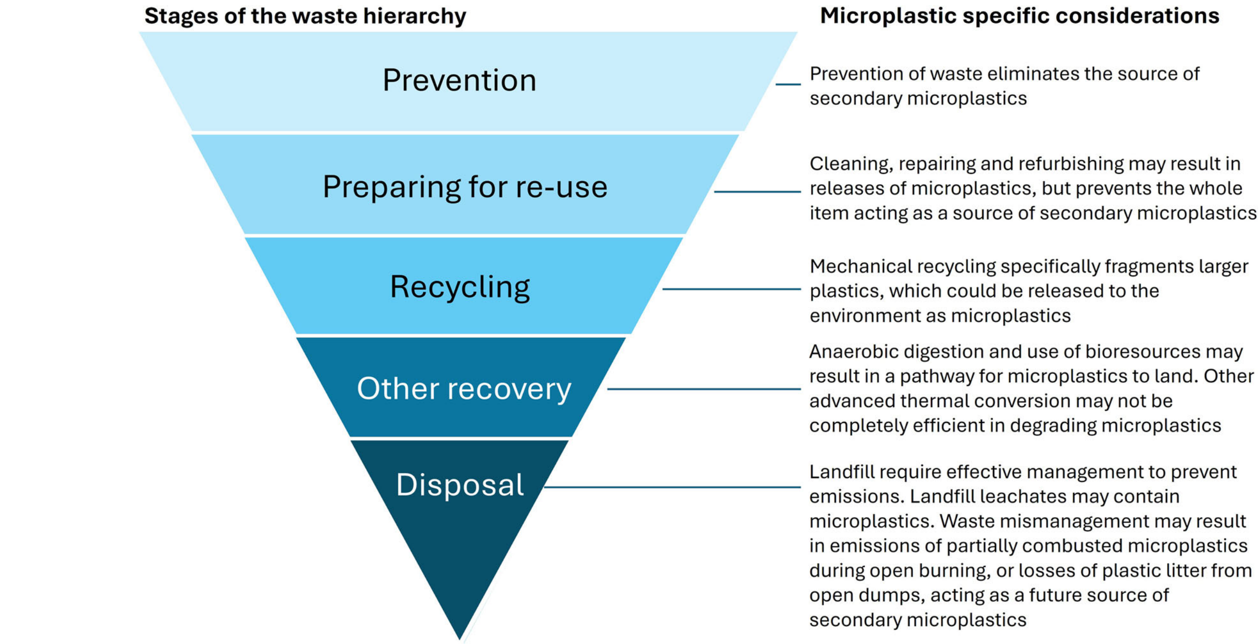

Fig. 3 | The "waste hierarchy" amended from Defra Guidance on Applying the Waste Hierarchy, 2011[169]. Alongside the stages of waste management, specific considerations when it comes to the implications of these stages for microplastic emissions are provided. The hierarchy progresses from preferred management strategies (top) to least preferred disposal options (bottom), with associated implications for microplastic emissions indicated alongside each stage.

longer and integrating re-use into the design of products is likely the most effective management of microplastics, as this directly limits the stock of plastic waste, which can act as a potential future source of secondary microplastics, the largest contributor to microplastic release. Prevention is most effectively achieved through coordination and cooperation agreements.

Wash processes are extensively used in both the preparation for re-use and in the recycling of plastic waste. These processes can result in emissions of microplastics in the wash water if control measures designed to specifically limit microplastic releases are not in place[19]. In the round, though, both preparation for re-use and recycling ultimately may contribute to a reduction in the production of plastic material (through reducing demand for new material and thus reducing supply) and so may also reduce the stock of plastic waste that then acts as a reserve of material for the generation of secondary microplastics over time.

Other recovery processes have mixed evidence for their ability to reduce microplastic emissions to the environment. Wastewater treatment, followed by anaerobic digestion of the sewage sludges, for example, is considered a management option to recover resources from waste. Whilst water and wastewater treatment are highly effective at removing microplastics tens of micrometres in size and above[117], these microplastics are not destroyed. Rather, they are separated in the settled solids of the water treatment process[118] and concentrated in the sewage sludge[119]. Countries manage this sewage sludge in different ways; however, in the UK, this is largely applied to agricultural land, acting as a source of microplastic emissions to soils. This may require its own management options to mitigate for[9]. There is mixed evidence of the ability of advanced thermal conversion of this sewage sludge to destroy microplastics[120]. Of course, the destruction and removal of microplastics is only one potential benefit of these alternative recovery processes for waste treatment and such technologies are also at present limited in the scale to which they are deployed, either through their technical or regulatory readiness for adoption, for example, as reviewed in the UK context[121].

National and international policy developments

Negotiations coordinated through the UN Environment Assembly are currently led by the Intergovernmental Negotiating Committee (INC), established by a UNEA resolution in March 2022 for an "International Legally Binding Instrument on Plastic Pollution, including in the Marine Environment (the *Global Plastics Treaty*). International agreements, such as the Basel Convention, introduced measures to regulate the transboundary movement of hazardous wastes, including plastics. However, enforcement remains inconsistent, and illegal waste shipments persist. Recent analyses further highlight persistent governance gaps, including weak enforcement mechanisms, inconsistent international regulations, and tensions between trade liberalisation and environmental protection objectives[122,123]. Enacting and strengthening these treaties and regulations, and enhancing compliance monitoring, are critical to curbing the flow of unmanaged plastic waste.

- Basel Convention Plastic Waste Amendments (2019): Strengthened global regulations on plastic waste trade, requiring exporters to obtain prior informed consent from importing countries for certain types of plastic waste[124].
- EU Single-Use Plastics Directive (2019): Aims to reduce plastic waste generation and encourage sustainable alternatives[125].
- National Bans and Restrictions: Several developing nations, including Thailand, Malaysia and Indonesia, have imposed stricter controls on plastic waste imports[126–128]. Recent policy developments highlight a global shift in plastic waste governance. Thailand, which imported over 1.1 million tonnes of plastic waste between 2018 and 2021, implemented a full ban on imports in 2025 to address pollution and health risks. Malaysia, one of the world's largest importers with approximately 433,000 tonnes in 2024, has introduced stricter controls, with estimates suggesting that 15–30% of imported waste is illegal or non-recyclable. At the same time, the European Union—exporting around 1.3 million tonnes of plastic waste annually—has adopted Regulation (EU) 2024/1157, which will ban exports to non-OECD countries from 2026 and require proof of environmentally sound management. Together, these measures indicate a transition from a globalised waste trade system toward stricter national controls and greater accountability for waste management.
- Canada's Zero Plastic Waste Agenda (2018-2030): Targets the elimination of plastic pollution through bans on harmful single-use items, Extended Producer Responsibility (EPR) policies and recycling improvements. It also prioritizes curbing microplastic emissions from

textiles, tyres and wastewater with investments in monitoring and international collaboration under the ocean plastics charter[129–132].
- India's Plastic Waste Management (Amendments 2016-2025): EPR compliance and phase out single-use plastics, emphasizing traceability, eco-friendly disposal and form a foundation for managing secondary microplastic pollution and integrating informal waste sectors into formal systems[133–136].

In addition to regulatory and industry-led approaches, non-governmental organisations (NGOs) and community-based initiatives play a critical role in addressing the impacts of imported plastic waste in receiving countries. In Southeast Asia, organisations such as the Global Alliance for Incinerator Alternatives (GAIA) have documented the environmental and social impacts of plastic waste imports and supported community-led zero-waste programmes in countries including Malaysia and Indonesia[17]. Similarly, Tearfund has worked with local partners to strengthen waste management systems and highlight the links between open burning, plastic pollution and human health risks in low- and middle-income countries[137].

In South Asia, NGOs and civil society organisations in India have developed decentralised waste management models and initiatives to integrate informal waste pickers into formal systems, improving both recycling efficiency and occupational safety. Zero-waste city approaches promoted by GAIA and partners have demonstrated reductions in residual waste and increased material recovery in urban settings[100,137–139].

In Sub-Saharan Africa, organisations such as Pure Earth have contributed to research and interventions addressing pollution exposure from waste mismanagement, including open burning and contaminated sites[140,141]. In Kenya and Ghana, NGO-supported recycling enterprises and community initiatives have improved plastic waste collection and reduced environmental leakage, while Tearfund has documented the broader environmental and health implications of unmanaged plastic waste[137,141]. Civil society groups in Nigeria and Ghana have also supported monitoring of plastic pollution in coastal and lagoon systems and advocated for stronger regulatory controls on plastic imports[17,79,142].

These examples demonstrate that NGO-led interventions can complement formal waste management systems by improving collection efficiency, reducing environmental leakage and enhancing social outcomes. Addressing plastic pollution supports key Sustainable Development Goals (SDGs), particularly those focused on human health (SDG 3), water quality (SDG 6), and climate resilience (SDG 13). These linkages underscore the importance of integrating microplastic mitigation into future international environmental agreements.

Local actions and sub-national regulatory responses

- Municipal and state authorities play a central role in plastic pollution control through waste collection, segregation, recycling enforcement, and public compliance, making them critical for reducing plastic leakage and secondary microplastic formation[1]
- Many cities and states have implemented bans on selected single-use plastic items and mandated source segregation of waste. In India, urban local bodies enforce restrictions on plastic bags, disposable cutlery, and packaging materials under the Plastic Waste Management Rules, supported by inspections and penalties[143].
- Local authorities support EPR implementation by monitoring collection targets, facilitating recycling infrastructure, and integrating informal waste pickers into formal waste systems, improving recovery rates and reducing uncontrolled disposal[144].
- Deposit-return schemes for beverage containers in several European cities achieve collection rates exceeding 90%, significantly reducing plastic litter and preventing microplastic generation[145]. Similar reuse and refill initiatives are being piloted in Asian cities through municipal bylaws and incentive schemes[146–148].
- City-level campaigns, school programmes, and community engagement initiatives promote reduced plastic consumption and improved waste segregation, contributing to lower environmental fragmentation of plastics and downstream microplastic emissions[30].
- Effective reduction of plastic pollution requires stronger coordination between local, national, and international governance frameworks to ensure policy coherence, enforcement, and long-term environmental outcomes[149].

While these policy measures represent important progress, their effectiveness depends on enforcement capacity, economic incentives, and alignment across governance levels. Evidence from existing regulations indicates that implementation gaps, informal waste sectors, and transboundary trade dynamics can undermine intended outcomes. In addition, uncertainties remain regarding the long-term effectiveness of emerging policy instruments, particularly in rapidly evolving global markets for plastics and recycled materials. Continued monitoring, evaluation, and adaptive policy design will therefore be essential to ensure that interventions achieve meaningful reductions in plastic pollution and associated microplastic emissions.

Towards systemic solutions for reducing microplastic pollution

Addressing global plastic pollution requires a coordinated, multi-level approach that combines upstream interventions, systemic innovation, and international collaboration. Systems-level modelling assessments further demonstrate that no single intervention is sufficient to substantially reduce future plastic leakage, and that meaningful reductions require simultaneous action across production, waste management, recycling, substitution, and governance pathways[150]. Effective solutions must tackle the problem across the full lifecycle of plastics—from production and use to disposal—while reducing environmental leakage and safeguarding human health. Several real-world policy and technological initiatives already demonstrate how these approaches can be operationalised in practice. Central to this effort is strengthened international cooperation, which provides the enabling framework for national policies, trade regulations, and technological innovations to function effectively. Complementing this, strategies such as caps on plastic production, circular economy initiatives, safer material design, investments in waste management infrastructure, public engagement, and scientific research work in tandem to prevent pollution, reduce microplastic emissions, and close material loops. By situating these solutions within the waste hierarchy—prioritising prevention and reuse over recycling and disposal—while embedding enforceable accountability, transparency, and evidence-based regulation, the global community can move toward a more sustainable and equitable plastics economy. By situating measures within the waste hierarchy and embedding accountability, transparency, and innovation, we create a framework that not only addresses environmental and health risks but also informs equitable and sustainable decision-making. This section underscores that effective progress depends on a robust science-policy interface, where research, monitoring, and interdisciplinary collaboration directly guide policies and practices toward a more sustainable future.

Strengthening international cooperation. Addressing global plastic pollution requires a coordinated international response that aligns policies on plastic production, waste management, and transboundary trade, while strengthening transparency and accountability. Existing multilateral frameworks, particularly the Basel Convention and initiatives such as the Basel Convention Partnership on Plastic Waste[151–153], provide important foundations for collective action. Ongoing negotiations towards a Global Plastics Treaty represent a critical opportunity to build on these efforts through a comprehensive, legally binding instrument addressing plastic pollution across its full lifecycle.

Leakage of plastic waste during international trade, and the resulting accumulation of macro-, micro-, and nanoplastics in the environment, is inherently a transboundary problem that cannot be resolved through national action alone. Effective international governance therefore depends on robust accountability and transparency mechanisms[123]. Strengthening international databases to track plastic waste shipments, verify compliance with environmental regulations, and monitor downstream management outcomes is essential. The treaty could further extend beyond existing Basel provisions by mandating prior informed consent for all categories of plastic waste and establishing a globally accessible database for microplastic measurements in water, soils and air, enabling baseline assessments and long-term trend monitoring.

Recent policy developments demonstrate that international cooperation can move beyond voluntary commitments towards enforceable trade controls. The Basel Convention Plastic Waste Amendments[153] introduced prior informed consent requirements for most mixed and contaminated plastic wastes, substantially improving export transparency. Building on this, the EU Waste Shipment Regulation (2024/1157)[128] effectively restricts plastic waste exports to non-OECD countries unless stringent environmental and processing standards are met. Together, these measures reduce the risk of waste leakage and microplastic generation in regions with limited waste infrastructure, while offering a model for regional trade governance that prevents environmental burden shifting.

At the multilateral level, the Global Plastics Treaty negotiations provide a unique opportunity to harmonise such controls globally, including through mandatory traceability systems for plastic waste shipments and linking trade permissions to verified environmentally sound management and recycling performance.

A cap on plastic production. A cap on plastic production, alongside targeted restrictions on problematic uses, emerged as one of the most impactful measures discussed during the INC-5.2 Global Plastics Treaty negotiations in August 2025. Achieving effective and sustained reductions will require a multifaceted policy approach, including legally binding targets to reduce primary plastic production[152]. By limiting the overall volume of plastics entering the market, such measures directly address the root causes of plastic pollution, rather than relying solely on downstream waste management.

Evidence indicates that voluntary corporate commitments to reduce plastic use and waste have delivered limited outcomes, while the net societal costs of reducing plastic production are substantially lower than those associated with continued growth in plastic production and its escalating environmental impacts[1,31,151]. Although waste management interventions remain necessary, growing evidence demonstrates that upstream production caps are critical for achieving meaningful reductions in plastic pollution and associated microplastic emissions.

Several countries have already begun to integrate production-side controls into national policy frameworks. For example, Canada's Zero Plastic Waste Agenda combines bans on selected single-use plastics with extended producer responsibility (EPR) and explicit targets to reduce plastic production and consumption[129–132]. In parallel, proposals advanced during recent INC negotiations call for globally binding caps on primary plastic production, analogous to emissions budgets in climate governance. Together, these approaches address the structural drivers of plastic waste generation and reduce future sources of microplastics before they enter the environment.

Promoting a circular economy whilst prioritising safer plastics and the reduction of plastic production. In the context of the global plastic waste trade, circular economy strategies are particularly relevant insofar as they influence the generation, export, and downstream handling of plastic waste. Transitioning to a circular economy for plastics requires careful design, implementation, and monitoring, given the material's persistence, chemical complexity, and propensity to generate secondary pollution. Reducing overall plastic production, alongside innovation in sustainable product design, is central to achieving a safe and effective plastics economy. Governments and industry must therefore collaborate to create incentives for reuse-based business models and invest in infrastructure that supports circularity across the full lifecycle of plastic products.

Empirical evidence from existing circular economy interventions highlights both their potential and their limitations. Deposit-return schemes implemented across countries such as Germany and Norway consistently achieve collection rates exceeding 85–95%, significantly reducing environmental leakage of beverage containers. Similarly, Extended Producer Responsibility (EPR) schemes in the European Union have contributed to increased collection and recycling rates for packaging waste, although performance varies substantially between countries depending on governance and enforcement. Early pilot programmes in Southeast Asia and Europe demonstrate that reuse systems can reduce single-use plastic consumption in targeted sectors. However, these approaches are generally most effective for well-defined, high-value waste streams and are less successful for mixed or low-value plastics, which dominate global waste trade flows.

Despite these successes, circular economy strategies face important constraints. Mechanical recycling is limited by polymer complexity, contamination, and economic viability, often resulting in downcycling rather than closed-loop reuse. In addition, recycling processes themselves are increasingly recognised as sources of microplastic emissions, particularly during shredding and washing stages. Reuse and refill systems, while promising, require significant behavioural change, infrastructure investment, and supply chain redesign, and their scalability across diverse socio-economic contexts remains uncertain. These limitations indicate that circular economy approaches, while necessary, are unlikely to fully offset the continued growth in plastic production without complementary upstream measures.

Proposed solutions that focus primarily on increased recycling and improved waste management are insufficient on their own. Reducing plastic emissions to the environment to 2010 levels (≈8 Mt yr^{-1}) through waste management alone would require more than 99% of plastic waste to be properly managed, an outcome that is widely recognised as unachievable at the global scale[31,151]. At present, only around 9% of plastic waste is recycled[1,153]. Consequently, investment in waste management must proceed in parallel with substantial reductions in plastic production and waste generation, in line with the waste management hierarchy[154].

While reducing production addresses future waste streams, the large volume of plastic already in circulation presents an ongoing challenge. Strengthening domestic recycling capacity and supporting innovative applications of recycled and reused materials in both exporting and importing countries can reduce dependence on plastic waste exports. Extended Producer Responsibility (EPR) schemes, which require manufacturers to assume responsibility for the end-of-life management of their products, represent a key policy instrument for incentivising circular economy outcomes. Evidence from the European Union indicates that EPR-based systems have contributed to plastic packaging recycling rates reaching approximately 41% in 2019, with several Member States exceeding 50%. In Germany, the long-standing "Green Dot" EPR scheme has been associated with packaging recovery rates above 65%. However, the effectiveness of EPR varies considerably depending on governance, enforcement and scheme design[155].

However, it is increasingly recognised that mechanically recycled plastics can accumulate hazardous chemicals and contaminants, either by concentrating additives originally present in plastics or by introducing new substances acquired during use, such as pesticides or pharmaceuticals. As a result, recycled plastics may, in some cases, pose greater risks to human health and the environment than virgin materials[156–158]. Mechanical recycling is also a documented source of microplastic emissions to the environment[20], highlighting the need for caution in relying on recycling as a primary solution.

Plastic-associated chemicals further impede the transition to a circular economy by limiting the safe reuse and recyclability of plastic products. Investment in safer and more sustainable material design is therefore critical. Approaches based on chemical simplification and transparency—such as eliminating hazardous substances of concern and reducing polymer complexity—can facilitate safer recycling and reuse by minimising the accumulation of unwanted additives and contaminants. Although chemical recycling is often proposed as an alternative to mechanical recycling, it remains largely unproven at scale and is associated with significant energy demand, emissions, and water use[156,157,159,160].

Reflecting these constraints, circular economy strategies are increasingly shifting beyond recycling toward reuse, refill, and redesign systems. Deposit-return schemes implemented across several European countries achieve collection rates exceeding 90% for beverage containers, substantially reducing environmental leakage. Similarly, reuse platforms in the packaging and food sectors—such as standardised refillable containers for consumer goods—demonstrate that material loops can be closed without repeated mechanical recycling, thereby avoiding additional microplastic generation.

Crucially, such approaches are being embedded within EPR frameworks in regions including the EU and India, where producers are legally accountable for post-consumer impacts. When robustly enforced, EPR schemes incentivise safer material choices, reduced polymer complexity, and longer product lifetimes—key prerequisites for a genuinely circular and low-risk plastics economy.

Plastic chemical complexity represents a major barrier to achieving a safe and functional circular economy. Rather than eliminating performance-critical additives, simplifying polymer formulations refers to minimizing unnecessary chemical diversity, phasing out hazardous substances of concern, and improving transparency in additive use while preserving essential material performance[156]. Emerging safe and sustainable by design approaches demonstrate that plastics can be planned to meet their intended mechanical, thermal, and chemical operating requirements using streamlined polymer systems and compatible additives, without compromising functionality[157]. Practical examples already exist across multiple sectors. Mono-material polyethylene and polypropylene packaging systems have been shown to retain mechanical strength and barrier properties while enabling higher-quality and more efficient recycling, thereby reducing additive accumulation during repeated recycling cycles[158]. Similarly, textile polymers redesigned with reduced additive complexity have been proposed to limit microplastic emissions and associated chemical release while maintaining durability and performance[161]. Design strategies such as polymer standardization, elimination of incompatible additives, and substitution with safer alternatives improve recyclability without degrading material functionality. By reducing the accumulation of hazardous chemicals during reuse and recycling cycles, these approaches lower environmental and human health risks and support accessible, lower-risk circular economic solutions[151].

Beyond recycling-focused approaches, several jurisdictions are already implementing circular economy models centred on reuse, refill, and reduction systems. For example, deposit-return schemes across countries such as Germany, Norway, and the Netherlands consistently achieve return rates exceeding 90%, significantly reducing environmental leakage and subsequent microplastic generation[145,162]. In parallel, large-scale reuse platforms—such as standardised refillable packaging systems piloted in France and Indonesia—demonstrate that consumer goods can circulate without repeated mechanical recycling, thereby avoiding secondary microplastic generation during processing[151,163].

At the policy level, the European Union's Circular Economy Action Plan and India's Extended Producer Responsibility (EPR) framework are increasingly embedding reuse targets and design-for-durability requirements. These approaches shift responsibility upstream to producers, incentivising reduced material throughput, simplified polymer design, and longer product lifetimes. Such initiatives illustrate that effective circular economy strategies must prioritise material reduction and system redesign, rather than relying predominantly on recycling.

Technological innovations to reduce microplastic emissions from recycling

Technological advances are beginning to address the previously overlooked issue of microplastic emissions during recycling itself. Pilot facilities in Europe and East Asia have introduced closed-loop water filtration systems, fine-mesh capture technologies, and air-handling units that substantially reduce microplastic release during shredding and washing processes. Additionally, innovations in textile recycling, including fibre-to-fibre chemical processes, aim to reduce the release of microfibres that contribute disproportionately to airborne and aquatic microplastic pollution. Similarly, improved air filtration systems have been shown to reduce airborne microplastic emissions in controlled industrial environments. While such technologies are not yet universally deployed, their increasing adoption highlights the importance of embedding microplastic emission standards into recycling facility permitting and environmental impact assessments[151,164,165].

Regional waste management agreements and infrastructure investment

Regional cooperation has also emerged as a viable alternative to long-distance waste exports. In parts of Southeast Asia and Latin America, bilateral and regional agreements are increasingly focused on building domestic recycling capacity, supported by international financing and technology transfer, rather than exporting waste abroad[1,3,30,151]. These initiatives help retain responsibility within producing regions and reduce environmental leakage associated with long transport chains, informal processing, and illegal dumping.

Raising public awareness and engagement

Public participation is crucial in combating plastic pollution. Education campaigns can empower companies, communities, and individuals to reduce plastic purchasing and usage, participate in separation-at-source programmes for waste, and advocate for stronger environmental policies. Corporate and consumer choices, such as offering and opting for reusable and refillable products, as well as low-waste product delivery systems or reverse logistics to collect waste, also play a vital role.

Advancing scientific research

Continued research is essential to fully understand the impacts of plastic waste and microplastics and to develop effective mitigation strategies. Funding interdisciplinary studies and fostering collaboration between scientists, policymakers, and industries will enhance our capacity to address this multifaceted problem. Specific advances in ecotoxicology, in collaboration with other disciplines to assess micro and nanoplastic hazards beyond conventional standard hazard testing, could improve our understanding of the interactions between microplastics and population-level effects and ecosystem functioning[36] and allow for a more holistic understanding of the future risks of microplastics as they continue to accumulate in the environment.

To simulate microplastic interactions with climate processes (such as atmospheric transport, radiative forcing, albedo alteration, and ensuring transparency in deposition patterns), and thereby inform integrated climate-risk assessments, it is essential to quantify their chemical composition and role in earth system dynamics. Developments in mechanistic and data-driven modelling approaches will be useful tools to advance our scientific understanding in this area.

Establishing standardized protocols for sampling and analysis is essential to generate consistent and comparable datasets across regions. Harmonized methodologies will enable more accurate assessments of exposure and risk, thereby supporting the development of evidence-based regulatory thresholds. These will also be essential for ensuring accountability and transparency as part of international agreements, for example. Proactive regulation, grounded in robust scientific data, is critical for managing plastic pollution and safeguarding public health.

Strengthening science policy interface for sustainable futures

Building on the integrated synthesis presented in this study, we propose a practical science–policy interface that links global plastic waste trade, microplastic emissions, and exposure pathways to actionable governance frameworks[52,151]. Translating emerging evidence on microplastics into enforceable policy requires clearly defined institutional roles, standardised data systems, and mechanisms for embedding scientific indicators into regulatory processes[121].

Key indicators should include harmonised measurements of microplastic size distributions, polymer composition, mass and number concentrations, and associated toxicity metrics across air, water, soil, and biota[62,104,111]. These should be complemented by mandatory reporting of plastic production, trade flows, and waste management outcomes[52,151,153]. In parallel, circular economy metrics—such as recycling and reuse rates, Extended Producer Responsibility (EPR) collection targets, and leakage indicators—together with science-based production caps aligned with lifecycle assessments and carbon budgets, can guide sustainable production and consumption pathways[52,123,150].

Institutionally, coordination at the international level could be led through the Global Plastics Treaty framework under the United Nations Environment Programme, building on existing mechanisms within the Basel Convention[25,153,166]. A global plastics observatory could serve as a central platform to harmonise data on plastic production, transboundary trade, waste management, and environmental microplastic concentrations. At the national level, environmental agencies would be responsible for implementing standardised monitoring protocols, compiling national inventories, and reporting through treaty compliance systems. Sub-national authorities, including municipalities, would support implementation through waste reporting, identification of leakage hotspots, and enforcement of EPR schemes[52,151,155].

Operationally, these indicators can be integrated into existing policy instruments, including national inventory systems, EPR reporting frameworks, and environmental impact assessments. Digital reporting platforms and interoperable global databases would enable traceability of plastic flows and support near real-time monitoring of transboundary waste movements and environmental exposure.

Implementation would require a combination of regulatory instruments and technical systems, including mandatory reporting requirements, harmonised monitoring methodologies, and certification schemes to verify environmentally sound management of exported waste. Trade controls could be strengthened by linking export permissions to demonstrated downstream processing capacity and environmental performance in receiving countries. Emerging digital tools, such as material tracking systems integrated with customs reporting, offer additional opportunities to enhance transparency and enforcement.

Embedding these indicators within policy frameworks would enable a direct linkage between scientific evidence and regulatory action. Within the Global Plastics Treaty (UNEP), they could underpin national action plans, compliance reporting, and periodic global stocktakes. At the national scale, integration into EPR schemes would extend producer responsibility beyond collection and recycling targets to include downstream environmental leakage and microplastic emissions (CPCB, ECA, ECHA etc)[1,150,152,155]. Similarly, incorporating microplastic indicators into permitting and regulatory processes would ensure that facilities are assessed based on their contribution to pollution across environmental compartments.

Together, these elements demonstrate that a science–policy interface for microplastics can be operationalised through existing governance structures, provided that standardised indicators, reporting mechanisms, and accountability frameworks are systematically integrated across scales. Strengthening collaboration between scientists, policymakers, industry, and civil society through co-produced assessments and capacity-building initiatives will be essential to support adaptive governance and accelerate the transition toward a more sustainable and equitable plastics economy. By maintaining a consistent focus on the role of transboundary plastic waste trade in shaping microplastic generation and exposure pathways, this study provides a more coherent and mechanistically grounded basis for policy intervention.

Conclusion

Plastic pollution has emerged as one of the most pressing planetary crises of the 21st century, intertwining environmental degradation, human health risks, and global inequities in waste management. The challenges of global plastic waste exports and microplastic pollution are deeply interconnected and require urgent, comprehensive action. Scientific evidence shows that we have exceeded the safe operating space of the "planetary boundary" for chemicals and plastic pollution[151,159]. Annual production and releases of "novel entities" are exceeding global capacity for assessment and monitoring, and threatening vital Earth system processes. The global plastic waste trade has enabled the expansion of plastic production and significantly contributed to microplastic pollution, disproportionately affecting developing nations with environmental and health risks.

While recent policy developments signal progress, further action is required to reduce plastic waste exports, improve waste management systems, and curb microplastic contamination. Governments, industries, and consumers must collaborate to establish a sustainable approach to plastic production and disposal, safeguarding both environmental and human health. Without transformative action, emissions from plastic waste could rise to 53 million metric tons annually by 2030[74,151], underscoring the urgent need for extraordinary efforts in waste reduction, management, and recovery. By strengthening international regulations, advancing innovative solutions, and fostering global cooperation, we can mitigate the impacts of plastic pollution and move towards a more sustainable future.

This study provides a novel integrated framework linking global plastic waste trade to microplastic generation, cross-compartment environmental transport, and human exposure pathways. By explicitly connecting material flows with environmental processes and policy mechanisms, this study advances current understanding beyond isolated assessments of plastic pollution or waste trade and provides a more integrated scientific basis for designing effective policy interventions.

This paper calls on stakeholders across sectors to join forces in addressing one of the defining environmental crises of our time, as addressing plastic pollution is not solely a waste management challenge, but a systemic issue requiring integrated governance, scientific leadership, and international cooperation. A strengthened science–policy interface—anchored in interdisciplinary research, transparent data, and equitable global participation—is essential to drive the transformative changes needed. Decisive, science-informed action must now be implemented at scale to reduce plastic pollution, protect planetary health, and secure a resilient and sustainable future.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

S.V.S. conceived the idea and prepared the original draft. R.K.C, S.H and M.N.R. contributed significantly to the writing reviewing and editing. EE generated Figure 1. S.D.B. and P.Y.W. contributed to the writing and reviewing. G.H. and S.D.G. contributed through reviewing and editing. All authors discussed and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

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