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Microplastics pollution in Indian marine environment: sources, effects and solutions

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Microplastic pollution has emerged as a significant environmental challenge globally, posing threats to biodiversity, marine life, and human health. Studies indicate that marine organisms, from plankton to larger fish species, and ultimately humans are ingesting microplastics, leading to physiological harm such as inflammation, digestive blockages, tissue injury, hormonal imbalance, reproductive failure and biomagnification through the food chain. Therefore, there arises an urgent need and demand for implementing effective and sustainable remediation solutions. Though, various mitigation technologies are developed, less information is available on the advantages and disadvantages of the technological advancements. The present review highlights the significant information available on the sources, types, transport of microplastics along with the analytical methods to detect the microplastic pollutions. The global perspective of microplastic pollutions with respect to Indian Marine scenario was highlighted. The recent and advanced mitigation technologies and solutions in preventing, reducing and recycling these microplastic pollutions were also addressed. This review further underscores the need for comprehensive strategies to monitor, manage and mitigate microplastic pollution, including policy interventions, public awareness campaigns, and sustainable waste management practices. Addressing this issue is essential for preserving the health of India's marine ecosystems and safeguarding the livelihoods of mankind.

KEYWORDS

microplastics, pollution, Indian marine environment, sources, types, mitigation strategies

Introduction

Microplastic pollution has emerged as a significant environmental concern globally in both terrestrial and aquatic environments. Plastics have become essential due to their versatility, durability, and cost-effectiveness. However, their extensive use has resulted in the presence of microplastics in land and marine environment, leading to significant concern. Microplastics are small plastic particles of less than 5 mm and originate from a variety of sources, including the breakdown of larger plastic debris, synthetic fibers from textiles and so on (Rochman et al., 2013). Small plastic debris is pervasive throughout aquatic environments, contaminating various habitats including coastal areas, deep-sea regions, near-shore zones, and open-ocean pelagic habitats, and indeed microplastics are sequestered by sediments, water and living organisms, before impacting health (Prapanchan et al., 2023). Environmental conditions significantly impact the decomposition of plastics in aquatic environments. Factors such as temperature, UV radiation, and microbial activity play crucial roles. A study by Andrady (2011) has reported that the degradation of plastics on beaches causes their surfaces to become brittle and crack, breaking them into microparticles that are then transported into the water by wind or wave action. However, plastics often resist chemical breakdown in water, leading to long-term persistence (Viel et al., 2023). UV light can degrade surface layers, but complete decomposition is rare, resulting in microplastic accumulation (Rochman et al., 2013). Global trends indicate that these accumulations are on the rise, aligning with the significant increase in plastic production, which poses escalating threats to wildlife (Thompson et al., 2004; Goldstein et al., 2012). A study by Alam et al. (2023) has revealed that varying levels of water and sediment pollution in the Ganges River basin in Bangladesh has been contaminated with microplastic, when analyzed using Nemerov pollution index (NPI), contamination factor (CF), pollution load index (PLI), polymer hazard index (PHI), and potential ecological risk. Microplastic aging and the type of polymer may enhance microbial colonization and biofilm formation leading to their classification as "plastispheres", which is currently becoming an alarming issue (Verma et al., 2024). However, a study by Jain et al. (2023) has reported that microbial degradation results in significant reduction of microplastic pollution.

With its extensive coastline and rich biodiversity, India faces unique challenges related to the overflooding of microplastics in marine environments. Recent studies indicate that the Indian marine ecosystem is increasingly affected by microplastic contamination, with various surveys revealing substantial concentrations of microplastics in coastal waters, sediments, and marine organisms (Chinglenthoiba et al., 2023; Vaid et al., 2021). The sources of microplastics in India are multifaceted. Urbanization, population growth, and inadequate waste management contribute to the discharge of plastic waste into all water bodies including river, lake and marine environments. Our previous study examined the potential contamination of microplastics in various commercially valuable marine fish species captured off the south coast of India, specifically from the Adyar and Ennore regions (Harikrishnan et al., 2023). Microplastic pollution was found to be more pronounced in the Ennore region. Microplastics were detected in both carnivorous and planktivorous fish from both study sites, with the highest concentrations found in the fish guts. Pelagic fish exhibited the lowest levels of microplastics, followed by mid-water and demersal fish. The study identified four types of polymers such as polyethylene, polypropylene, polystyrene, and polyamide. These findings highlight the extent of microplastic contamination in fish tissues from the coastal regions of Adyar and Ennore in southern India. In another study, toxicity tests were conducted to assess the effects of microfibers (MFs) released from deteriorating surgical facemasks on the early gametes and life stages of the marine sedentary polychaete Hydroides elegans. Our results showed that exposure to MFs reduced the successful development rate of gametes, significantly slowed mitotic cell division, and delayed larval hatching, while also impairing embryogenesis. When sperm were exposed to MFs, the fertilization rate dropped drastically. In contrast, while exposure of eggs to MFs did not inhibit fertilization, but caused a delay in early embryonic development (Harikrishnan et al., 2024a). Similarly, weathered polyethylene (wPE) microplastics impacted the immunological and hematological markers of *Danio albolineatus*. In this study, fish exposed to wPE microplastics exhibited significant changes in lysozyme levels, antimicrobial and antiprotease activity, as well as differential blood cell counts. The findings indicate that male fish were more vulnerable than females following 40 days of chronic exposure (Harikrishnan et al., 2024b).

A study by Napper et al. (2021) represents the first examination of microplastic abundance, characteristics, and temporal variation along the Indian Ganges River. It is estimated that the Ganges, along with the combined flows of the Brahmaputra and Meghna rivers, may release up to 1–3 billion microplastics into the Bay of Bengal, each day. This research marks an initial step toward understanding microplastic contamination in the Ganges and its contribution to the overall microplastic burden in the ocean. Similarly, Aryan et al. (2019) has employed the Life Cycle Assessment (LCA) technique to evaluate the potential environmental impacts of both existing and proposed plastic waste management scenarios in Dhanbad city, India. The analysis focuses on two major types of plastic waste such as Polyethylene Terephthalate (PET) and Polyethylene (PE), across various impact categories. The results indicated that the scenario, which involves the recycling of PET and PE waste, had the lowest environmental impacts across most impact categories, primarily due to reduced emissions and resource consumption during the recycling process compared to producing virgin PET and PE flakes. On the other hand, the proposed scenario of incineration with energy recovery was more environmentally favorable in terms of fossil fuel depletion and acidification potential. This study assists policymakers in developing more effective plastic waste management strategies.

Hence, both aquatic ecosystems and human health are at risk, necessitating continuous national monitoring of microplastics, comprehensive research, awareness and proactive policy measures to address this dreadful issue. Furthermore, there is a significant lack of understanding regarding their distribution, sources, toxic effects, analytical techniques, and removal technologies. Therefore, this review explores the distribution and prevalence of microplastics in Indian marine environments, along with analytical methods, remediation technologies and associated health risks.

Global perspectives of microplastic production and pollution

Over the past 70 years, global plastic production has increased phenomenally to about 359 million tonnes, and is predicted to reach 500 million tonnes by 2025 (Bui et al., 2020; Huang et al., 2021). China leads the world in production, contributing 17.5% of the total. In the Mediterranean region, Turkey generates the highest amount of plastic waste, at 144 tonnes per day. Microplastics contribute up to 75% of marine debris, with land-based sources accounting for 80–90% of the pollution, while ocean-based sources contribute only 10–20% (Osman et al., 2023). When combined with production from other Asian countries, the total rises to about 114 million tonnes. The European Union generates nearly 50 million tonnes, while North America contributed around 49 million tonnes. In contrast, Latin America, Commonwealth Nations, Africa, and the Middle East together accounted for 37 million tonnes of plastic production (Ryan, 2015). In a study by Vermeiren et al. (2016), microplastics pollution were detected across all major oceanic gyres and in samples collected from the Arctic to the Antarctic (Vermeiren et al., 2016). Likewise, Eerkes et al. (2019) found microplastics in every freshwater system they studied, including lakes, rivers, and groundwater.

The study by Prapanchan et al. (2023) reports the global concentration and distribution of microplastics globally, with studies across diverse regions revealing widespread presence in both marine and freshwater ecosystems. To mention a few countries, Simcoe Lake in Ontario, Canada, marked the first discovery of microplastics originating from human activities, where microplastic particles were found in sediments and surface waters (Felismino et al., 2021). In South Korea's Nakdong River, the concentration of microplastics ranged between 260 and 1410 items/m3 in summer, rising to 15,560 items/m^3 during the wet season (Kang et al., 2020). Similarly, Peninsular Malaysia's coastlines revealed a density of 265 microplastic items/m^2, including polystyrene and polyethylene particles (Fauziah et al., 2015). Microplastic concentrations were also found to vary in European rivers, with the Rhine and Main Rivers in Germany showing levels ranging from 228 to 3763 items/kg and 786 to 1368 items/kg, respectively (Klein et al., 2015). Wang et al. (2017) identified about 178 to 544 items/kg of microplastics in Beijing River sediments. In contrast, microplastic levels in the Laurentian Great Lakes and Lake Huron in Canada were much lower, with an average of 20,264 items/km^2 [(Free et al., 2014). In Australia, Ziajahromi et al. (2017) measured microplastics in treated wastewater, finding concentrations of 0.28 to 2 items/L, primarily from synthetic apparel and personal care products. In the southeast Pacific, with densities ranging from 1 to 805 items/m^2 (Hidalgo-Ruz and Thiel, 2013). The northeast Atlantic Ocean showed an average concentration of 2 items/m^3, with polyethylene and polyamide being the most common polymers (Lusher et al., 2014). In the Arctic, Obbard et al. (2014) found microplastics in ice cores, with particle abundance ranging from 38 to 234 items/m^3, composed mainly of polyamide, polypropylene, polystyrene, and polyethylene.

In India, plastic consumption stands at 11 kg per capita/year, which is significantly lower than the global average of 28 kg (Bhattacharya et al., 2018). Despite this low consumption rate, India ranks as the second-largest producer of plastic polymers in the world, with an output of 14.17 million tonnes (Liang et al., 2021). Furthermore, COVID-19 pandemic has driven the healthcare sector's demand for approximately 2.5 million sets of plastic-based personal protective equipment (PPE) each day (Parashar and Hait, 2021). In another study, the PLI indicated that sediments on the west coast of India are moderately contaminated with microplastics, while those on the east coast of India show lower levels of contamination (Ranjani et al., 2021). In India, microplastic pellets were found in large quantities on the beaches of Goa, with the southern coast showing a much higher concentration [1150 pellets] compared to the northern coast [505 pellets] (Veerasingam et al., 2016). These studies underscore the global scale of microplastic pollution and the varying concentrations across regions, driven by both natural processes and human activities. Jambeck et al. (2015) has reported that a significant portion of global ocean plastic enters into the Indian Ocean, with up to 15% of all coastal plastic and 20% of all riverine plastic wastes. Half of the top 10 countries contributing to ocean plastic pollution are located along the Indian Ocean's coastline, including Indonesia, Thailand, Malaysia, India and Bangladesh. Furthermore, two of the largest and most polluted rivers such as the Ganges and Indus empty into the Indian Ocean. It is also estimated that the Indian Ocean contains the second-largest plastic load in the ocean, after the North Pacific (Eriksen et al., 2014).

Considering the above reports, it becomes indispensable to create an awareness and minimize the production and usage of plastics in India to protect our environment.

Sources, types and transport of microplastics

A study by Schwarz et al. (2019) has reported that 80% of marine litter comes from land-based sources, while the remaining 20% originates from the sea and ocean. Over the last 50 years, the composition of waste has changed significantly, shifting from organic materials to recyclable items, and now to synthetic waste. Marine litter is generally categorized into two types: waste from land sources and waste from the ocean. Examples of marine litter include plastic bags, balloons, ropes, medical waste, glass and plastic bottles, cigarette butts, lighters, beverage cans, polystyrene, fishing nets, and various types of waste from ships. Cruise ships and oil rigs are considered as significant contributors to beach litter (Pimentel et al., 2021). It is estimated that 80% of all marine litter consists of plastic waste. Plastic waste exposed to solar UV radiation undergoes photo-oxidation, a process that causes it to slowly break down into smaller fragments, eventually transforming into microplastics and nanoplastics. The deterioration of plastic materials in outdoor conditions is influenced by a combination of solar UV radiation and other weathering factors like temperature (Jansen et al., 2024). Plastics require dry conditions to decompose, and in aquatic environments, they do not break down chemically, despite the presence of other materials such as organic matter or microbes in the water (Crippa et al., 2019). With the ongoing impacts of climate change, these processes are expected to evolve in the future. As a result, plastic degradation is likely to occur at a less predictable rate, leading to changes in the distribution of degradation products and variations in the release of harmful substances into the environment (Jansen et al., 2024).

The American Society of Plastics Industry has developed a standardized coding system to identify and differentiate the key types of plastic. There are around 50 distinct types of plastics, each with numerous variations. These plastics are classified into seven main categories such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), vinyl/polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), among other types of plastics such as PET, HDPE, PVC, PE, PS, Polyvinylidene Fluoride (PVDF), Polylactic Acid (PLA), etc (Bhattacharya et al., 2018). The polymer composition of microplastics isolated from beach sand, sediments, water, salt samples collected from the different areas of India were identified as PET, HDPE, PVC, PE, PS and nylon (Chinglenthoiba et al., 2023). Only larger, thicker particles of polyethylene (PE), polypropylene (PP), and (EPS) are likely to be transported from rivers to the ocean. Plastic items significantly influenced by wind, such as containers like PET bottles and expanded polystyrene (EPS) are carried to riverbanks.

The amount of plastic waste entering the ocean from land-based sources is influenced by factors such as population density, waste management infrastructure, and economic development. Higher population densities typically correlate with increased plastic waste generation, especially in regions with inadequate waste management systems (Jambeck et al., 2015). Additionally, ineffective recycling practices and low public awareness exacerbate the issue. Climate change and extreme weather events can also increase runoff and littering, further contributing to marine plastic pollution. Jambeck et al. (2015) reports that in oceans, plastic waste primarily originates from three sources: land-based plastics from coastal regions, specific plastics from rivers and materials from oceanic sources. By correlating global data on solid waste, population density and economic conditions, the volume of land-based plastic waste entering the ocean was estimated as 275 million metric tons (MT) of plastic waste generation in 2010 across 192 coastal countries, with between 4.8 and 12.7 million MT making its way into the ocean. The primary factors influencing the amount of uncaptured waste that can contribute to plastic marine debris are population size and the effectiveness of waste management systems. If waste management infrastructure is not improved, the total volume of plastic waste likely to enter the ocean from land is projected to increase significantly by 2025 (Jambeck et al., 2015).

Furthermore, to curb the transmission of COVID-19, there has been widespread use of personal protective equipment (PPE) and packaging materials. Unfortunately, these items are often not managed properly, leading to significant plastic waste in both land and ocean (Igalavithana et al., 2022). The plastic waste generated after pandemic contributes approximately 1.5 ± 0.2% of the total plastic discharge from rivers into the ocean (Lebreton et al., 2012). In India, the Ganges is among the most polluted rivers contributing as much as 1.05×10^4 tons of plastic to the Indian Ocean each year (Lebreton et al., 2017). On average, the river discharges between 1 and 3 billion microplastics into the ocean, everyday (Napper et al., 2021). Even in rural areas, dams can accumulate significant amounts of plastic, particularly in the form of MFs. During rainfall, MFs from sewage sludge can be washed into rivers and dams, which then is transported into ocean (Li et al., 2018). River transport accounts for 2.8–18.6% of global marine plastic emissions (Lebreton et al., 2017). Jayasiri et al. (2013) assessed the plastic litter on four sandy beaches in Mumbai, with an average of 7.49 grams and 68.83 items per square meter recorded. The study revealed that the Juhu Beach had the highest concentration of microplastics, accounting for 55.33%, followed by Versova, Aksa, and Dadar. The primary contributors to this abundance include the varied uses of the beaches such as for recreation, religious activities, and fishing, indicating that land-based sources are the main drivers of plastic pollution on these beaches. Plastic waste enters the ocean from coastal sources, carried by wind, tides, and rivers. Hoornweg and Bhada-Tata (2012) estimated that in 2010, the total plastic waste produced by countries along the Indian Ocean rim was approximately 41 million tons. Despite relatively low levels of plastic production in this region, a significant proportion ends up in the environment due to inadequate waste management in many Asian and African countries. According to Jambeck et al. (2015), around 73% of plastic waste along the Indian Ocean rim is poorly managed and ultimately released into the environment. The sources of microplastics reaching the marine environment of the east and west coasts of India is represented in Table 1.

With this overview on sources, types and way of transport of plastic wastes into marine environment, the following section emphasizes the potential health risks associated with microplastic pollution and consumption along with the potent analytical methods for identification of microplastics and its mitigating solutions.

Potential health risks associated with microplastics pollution

Microplastics pose significant risks, as they can cause physical and mechanical harm such as internal injury or blockages, obstruction of digestive systems, reduced organ function, increased stress, bioaccumulation and chemical exposure, damage to respiratory systems to marine organisms that inadvertently ingest them, potentially leading to abnormalities in internal organs (Lei et al., 2018). Ecotoxicity can arise from the polymers themselves, unreacted monomers, impurities such as residual catalysts or by-products, additives like stabilizers, or other substances within the polymer matrix including dyes, lubricants or plasticizers. Furthermore, microplastics can enter the human body when they are not filtered out during sewage treatment processes, or they may flow into the ocean, posing risks to both ecosystems and human health. Numerous instances of damage from microplastics have been documented, including their accumulation in marine and aquatic

TABLE 1 The sources of microplastics reaching the marine environment of the east and west coasts of India.

S. No	Sources of Microplastics	East Coast of India	West Coast of India	References
1.	Microplastic waste from coastal areas	East coast is particularly vulnerable to high levels of microplastic pollution, primarily due to waste from fishing, tourism, and religious activities	Western coasts experience comparable pollution, with tourism, fishing, and religious practices	Jambeck et al., 2015; Lebreton et al., 2017; Thiemann, 2023
2.	River Discharge	Ganges and Godavari discharge significant quantities of microplastics into the Bay of Bengal	Narmada, Mahi, and Tapti contribute to microplastic contamination in the Arabian Sea	Jambeck et al., 2015; Lebreton et al., 2017
3.	Plastic Waste from Fisheries	Microplastics from fishing gear, nets, ropes and fishing-related activities in the east coast of India	West coast also affected with plastic waste from fishing activities	Dowarah and Devipriya, 2019; Maharana et al., 2020
4.	Tourism related Plastic Waste	Tourist spots leads to significant plastic pollution, including microplastics	Tourism contributes to microplastic pollution, especially in popular beach areas.	Pandey et al., 2022; Pavithran, 2021
5.	Land-based Sources	Urban runoff and industrial activities leading to microplastic pollution in the east coast of India	West coast is polluted by microplastic through industrial discharge and urban runoff	Jahandari, 2023; Pavithran, 2021; Datta et al., 1898
6.	Microplastic wastes from agriculture	Microplastic from agricultural wastes reaches the east coast of India	Microplastic pollution from agricultural wastes contaminates west coast of India	Pandey and Kumar, 2023; Veerasingam et al., 2020

organisms, which can result in malnutrition, inflammation, reduced fertility and increased mortality rates (Lee et al., 2023). A study by Ranjani et al. (2021) represents the first effort to assess the ecological risks posed by microplastics in sediments along the Indian coast using meta-data. Using PHI, PLI, and Potential Ecological Risk Index (PERI), the sediment quality was assessed. High PHI values were found in areas with significant concentrations of hazardous polymers like polyamide (PA) and polystyrene (PS). Furthermore, the PERI values revealed greater ecological risks in sediments near metropolitan cities, river mouths, potential fishing zones and remote islands (Ranjani et al., 2021).

Globally, the population consumes between 39,000 and 252,000 microplastics each year, contributing to many diseases (Novotna et al., 2019). Due to the reason that humans are unknowingly ingesting significant amounts of microplastics every day, humans may be classified as "plasticterians" (Chinglenthoiba et al., 2023). Saha et al. (2021) investigated the presence of microplastics within the Sal Estuary in Goa, Central West Coast of India and reported significant microplastics pollution in Indian seafood, acting as a major threat to Indian marine environment. Higher concentrations of microplastics were found in the marine species such as shellfish, *Crassostrea* sp., *Perna viridis, Paphia malbarica, Mugil cephalus, Gerres filamentosus, Arius jella, Etroplus suratensis* and lesser prevalence in biota. Among the 37 polymer types identified, polyacrylamide (PAM), polyacetylene, ethylene vinyl alcohol (EVOH), polyvinyl chloride (PVC), and polyamide (nylon) were the most abundant. This finding underscores the presence of microplastics in commercially important shellfish and finfish from the Sal estuary in Goa, which delivers potential hazards to the consumers (Saha et al., 2021). A study assessing microplastic contamination in water, beach sand and fish samples from seven of the most popular and heavily trafficked beaches along the eastern coast of India has reported that the average microplastic concentration was found to be 80 ± 33 microplastics/m^3 in water and 4 ± 2 microplastics/kg dry weight in sand, with polyethylene predominating in water samples and polystyrene in sand samples (Mandal et al., 2023). The Polymer Hazard Index classified the water samples under hazard level IV and the sand samples under hazard level V, both indicating high risk. The study also found that about 30% of commercially important fish species sampled from these locations contained microplastics, with PET and polypropylene being the most prevalent types. Similarly, microplastic contamination across the inner, outer and mangrove regions of the Kollidam River estuary on India's east coast was examined by Nagalakshmi et al. (2024). The average microplastic abundance was noted to be 2.42 particles/m^3 in surface water and 1580 ± 705 particles/kg dry weight in sediment. The most common polymer types identified were polypropylene, polyethylene and polyacrylic.

Various pathways such as ingestion, inhalation and dermal contact were identified as a major route through which microplastics can be encountered. Notably, ingesting microplastics has been associated with gastrointestinal issues, endocrine disruption, and the potential transfer of harmful bacteria. Inhalation of airborne microplastics is particularly concerning, as it may impact respiratory and cardiovascular health. While dermal contact though less frequently studied, it raises concerns about possible skin irritation and allergic reactions (Emenike et al., 2023).

Bisphenol A (BPA), phthalates, and certain brominated flame retardants used in household products and food packaging have been shown to act as endocrine disruptors, posing risks to human health when ingested or inhaled (Cingotti and Jensen, 2019). These endocrine-disrupting chemicals (EDCs) has been linked to a range of diseases and conditions, including hormonal cancers such as breast, prostate and testicular cancers, reproductive issues like genital malformations and infertility, metabolic disorders including diabetes and obesity, asthma, and neurodevelopmental disorders such as learning disabilities and autism spectrum disorders. The process by which microplastics exert toxic effects is complex and influenced by various factors including their physical and chemical properties, exposure duration, and additives. Microplastics are not only considered as inherently toxic, but they also act as carriers for numerous pollutants that can infiltrate biological tissues and organs (Yue et al., 2023). Due to the limited direct research involving humans, this study provided a brief overview of the significant effects using cells, organoids and animal models. These effects include oxidative stress, DNA damage, organ dysfunction, metabolic disorders, immune response alterations, neurotoxicity, and reproductive and developmental toxicity. Additionally, epidemiological evidence indicates that exposure to microplastics may be linked to a range of chronic diseases. Microplastics smaller than 20 µm are believed to have the potential to penetrate organs, while those around 10 µm in size may be capable of accessing all organs, crossing cell membranes, penetrating the blood-brain barrier, and reaching the placenta, provided that distribution occurs in secondary tissues such as the liver, muscles, and brain (Campanale et al., 2020). The above reports provide evidence for the need to mitigate the microplastics pollution in the land and marine environment.

Analytical techniques for microplastic detection

Recently, numerous methods have been employed for detecting microplastics in the environment (Huang et al., 2023; Randhawa, 2023; Guanglong et al., 2020). Cutting-edge techniques for analyzing microplastics include visual analysis, laser diffraction particle sizing, dynamic light scattering, light microscopy, atomic force microscopy, scanning electron microscopy (SEM), Polarizing microscopy, Fourier-transform infrared spectroscopy (FT-IR), Micro-Raman spectroscopy, thermal analysis, aptamer selection, *in vitro* techniques, flow cytometry, pyrolysis gas chromatography, Inductively coupled plasma mass spectroscopy, liquid chromatography mass spectrometry (LC-MS/MS), time-of-flight (TOF) secondary ion mass spectrometry and atmospheric solid analysis probe (ASAP) paired with quadrupole mass spectrometry (Huang et al., 2023; Randhawa, 2023; Guanglong et al., 2020; Huike et al., 2023). The various techniques are represented in Figure 1.

Effective sampling method is crucial for accurate microplastic analysis. Current approaches for extracting microplastics from the environment include visual inspection (manual sorting), density separation, flotation, sieving or filtration (size separation), digestion methods, biological removal and ingestion and various chemical treatments (Fu et al., 2020; Mai et al., 2018; Padervand et al., 2020).

Recent mitigation strategies and solutions

Understanding the impacts of microplastics on ecosystems and human health, it is crucial to develop effective mitigation strategies (Thacharodi et al., 2024). Inadequate waste management infrastructure is projected to exacerbate marine plastic pollution by 2025, leading to increased volumes of plastic waste entering oceans. Without improved collection, recycling, and disposal systems, higher plastic leakage from urban areas is likely, particularly in developing regions (Jambeck et al., 2015). This could result in greater harm to marine ecosystems, biodiversity loss, and negative impacts on human health through the food chain. Moreover, failing to address these challenges may hinder efforts to achieve sustainability and circular economy goals (Li et al., 2020). Key criteria for assessing the effectiveness of technologies for reducing microplastics and macroplastics include removal efficiency, particle size range effectiveness and operational feasibility. Removal efficiency, often measured as a percentage of particles captured, is critical for evaluating technology performance (Zhang et al., 2023). Additionally, the ability to target a wide range of particle sizes, including nanoscale microplastics, is essential. Also, operational feasibility including cost, scalability, and energy consumption, plays a significant role in determining the practical applicability of these technologies. Traditional waste management approaches often fall short in addressing microplastic pollution due to the difficulty in capturing these tiny particles and the variety of their sources (Vanapalli et al., 2021). In response, a range of innovative technologies and methods have emerged to capture and eliminate microplastics from the environment, including filtration systems and biodegradation techniques (Gao et al., 2022). However, implementing these strategies present challenges such as cost-effectiveness, scalability, and the risk of unintended harm to non-target organisms. Additionally, removing microplastics from marine and terrestrial environments is complicated by their widespread distribution and the inaccessibility of some areas (Pan et al., 2022). Instead of solely focusing on removal, researchers are increasingly investigating ways to repurpose microplastics, which could mitigate their environmental impact while addressing waste management challenges. This innovative approach spans various fields, including materials science, engineering and art (Bhat, 2024; Walker and Fequet, 2023). A recent study has developed a new type of polyethylene made from renewable oils. This innovative material enhances recyclability, allowing for the recovery of most of the original polymers and creating a closed-loop system. This advancement represents a significant step toward achieving the long-sought goal of sustainable plastics (Häußler et al., 2021). The growing interest in sustainable plastics has enhanced the search of petroleum-based biodegradable plastics, which on the contrary, has led to consumer confusion, as many mistakenly refer these products as bioplastics, resulting in widespread uncertainty about proper waste disposal (Charlebois et al., 2022).

Several current and future approaches to mitigate plastic and microplastic pollutions include extended producer responsibility programs, initiatives aimed at reducing single-use plastic consumption, and the Plastics Treaty, which will address the entire plastics life cycle. This treaty aims to curb production, promote a circular economy, establish environmental reporting standards, raise consumer awareness, and enhance performance measures (Diggle and Walker, 2020; Bezerra et al., 2021). Prata et al. (2019) has recommended ten crucial ways for reducing plastic pollution such as

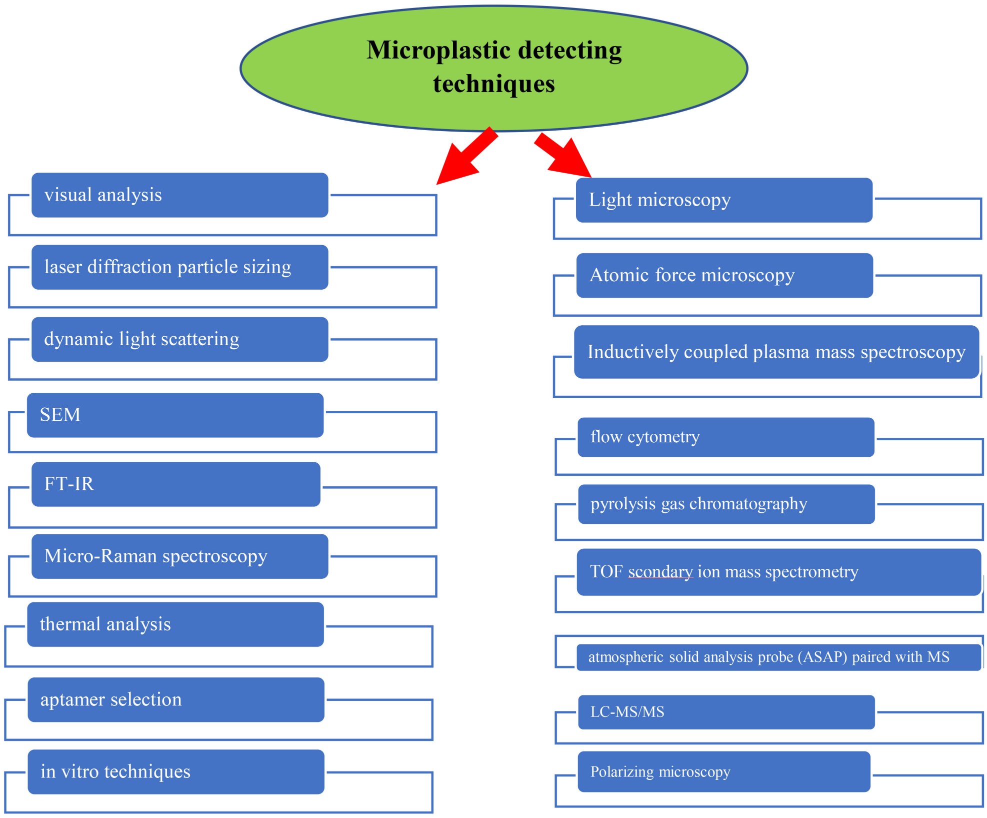

FIGURE 1
Various analytical techniques for microplastic detection.

regulating production and consumption, implementing eco-design principles, boosting demand for recycled plastics, minimizing plastic usage, utilizing renewable energy in recycling processes, establishing extended producer responsibility for waste management, enhancing waste collection systems, prioritizing recycling initiatives, promoting the use of bio-based and biodegradable plastics and improving the recyclability of electronic waste.

In addition to conventional treatment methods, advanced techniques such as membrane bioreactors, rapid sand filtration, electrocoagulation, and photocatalytic degradation have also been explored for the removal of microplastics, which has been proven effective, achieving removal efficiencies exceeding 99%. Bioremediation strategies have shown that species like seagrasses, lugworms, and blue mussels can act as natural traps for microplastic pollutants, making them potential candidates for integration into wastewater treatment plants. Furthermore, it is crucial to implement effective laws and regulations to control the use and unregulated release of microplastics into the environment (Krishnan et al., 2023). Innovative technologies for capturing and eliminating microplastics include advanced filtration systems, such as membrane filtration, which effectively remove microplastics from wastewater (Zhang et al., 2023). Magnetic nanoparticles are being explored for their ability to bind to microplastics, enabling easy removal with magnets (Shi et al., 2022). Emerging strategies to address microplastics include micro- and nanomotors such as tiny, self-propelled devices powered by chemical fuels or light. These motors are designed to autonomously recognize, capture, and break down pollutants. Previously, various micromotors were developed to efficiently remove and degrade soluble organic contaminants. Current research focuses on the rational design and surface functionalization of these devices to enable them to capture, transport, and release microplastics of diverse shapes and chemical compositions. Catalytic micromotors utilizing photocatalysis and photo-Fenton chemistry show particular promise for degrading common plastic materials (Hermanová and Pumera, 2022). These technologies represent significant advancements in addressing microplastic pollution.

To demonstrate how the cleaning method operates, a case study was conducted in the Mediterranean Sea, evaluating two technologies for removing plastic from water before it reaches the ocean. For macroplastics of size larger than 5 mm in diameter, a floating barrier was designed to collect litter in rivers. However, for microplastics (smaller than 0.05 mm), a filtration system intended for wastewater treatment plants was developed (European Union, 2023). The framework employed is a form of multi-criteria decision analysis (MCDA), which systematically informs decision-making by considering various relevant interests. The technologies were assessed based on four criteria such as annual costs of investment and operation, reduced exposure of Natura 2000 areas to plastic pollution, decrease in plastic pollution at aquaculture finfish and shellfish sites and reduction in plastic pollution in critical habitats for cetaceans. It was found that for microplastics, the most sensitive criterion was the cost of reducing plastic pollution. In contrast, for macroplastics, the most sensitive factor was the number of monitoring points in cetacean critical habitats where at least 80% of the targeted reduction is achieved. However, the effectiveness of these technologies in reducing plastic pollution in the sea will depend on factors such as the number of installations, their locations, and their operational efficiency (European Union, 2023). Similar technological approaches were discussed to mitigate microplastic pollution in the Indian marine environment along with a roadmap for multidisciplinary action (Sivadas et al., 2022). In India, the amendment to the Plastic Waste Management Rules, 2016, has banned the manufacture, import, stocking, distribution, sale, and use of specific single-use plastic items that have low utility and high potential for littering. India took a leading role in proposing the resolution on "Addressing Single-Use Plastic Product Pollution," highlighting the global need for coordinated action against single-use plastic pollution (Kanwar et al., 2023).

Insights from this review can guide the development of targeted mitigation strategies for microplastic pollution in the Indian marine environment by identifying effective technologies and practices tailored to local conditions. Understanding the specific sources and pathways of microplastics can help prioritize interventions, such as improved waste management and public awareness campaigns. Additionally, integrating innovative filtration and clean up methods can enhance existing efforts, fostering a holistic approach to combatting microplastic pollution in coastal and marine ecosystems. Overall, this review presented most recent technologies implemented for mitigating microplastic pollutions in the marine environment, which can be further improvised for enhanced efficacies and a greener environment.

Conclusion

Mitigating microplastic pollution is crucial for protecting both environmental and human health. Microplastics, which can persist in ecosystems for decades, pose significant risks to marine life, as they can be ingested by a wide range of organisms, leading to harmful effects on biodiversity and food chains. Furthermore, microplastics can accumulate toxic pollutants and enter the human food supply through seafood consumption, raising concerns about potential health impacts. Addressing this issue is essential not only for preserving marine ecosystems and the species that inhabit them but also for ensuring the safety of our food sources and maintaining the integrity of our natural resources for future generations. Comprehensive efforts to reduce microplastic pollution are vital to fostering a healthier planet and sustainable communities.

Author contributions

JA: Conceptualization, Writing – original draft, Writing – review & editing. SV: Investigation, Writing – review & editing. AK: Conceptualization, Formal analysis, Investigation, Writing – review & editing. KT: Validation, Visualization, Writing – review & editing. TH: Formal analysis, Writing - review & editing. VR: Supervision, Visualization, Writing – review & editing. DG: Supervision, Validation, Visualization, Writing – review & editing. KR: Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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