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REVIEW

Toxic and synergistic effects of micro-nanoplastics with radioactive contaminants on aquaculture: Their occurrence, distribution, role as vectors, detection and removal strategies

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Abstract Although inexpensive plastic items are helpful, they have greatly improved modern living. The increased micro-nanoplastics pollution has become a primary worldwide environmental concern, and aquaculture is becoming a research hotspot for investigation. They are small enough to be ingested by a wide range of organisms and may cross some biological barriers at a nano-scale. Micro-nanoplastics in aquatic habitats seriously threaten the entire food web. Micro-nanoplastics enter marine ecosystems through rivers, runoff, and atmospheric deposition, while radioactive contaminants come from industrial discharges and nuclear waste. Moreover, micro-nanoplastics can absorb hazardous contaminants i.e. radioactive isotopes and release harmful compounds, which degrade the aquaculture environment. Marine life can experience developmental delays and reproductive problems due to the micro-nanoplastics buildup in aquatic habitats and with radioactive contaminants exacerbating these effects. Thus, there needs to be more concern about aquaculture's ability to turn a profit. Promising techniques have also been observed for ecological purification and interception. To lessen the impacts of micro-nanoplastics contamination, several removal techniques, including filtering, coagulation, and sophisticated oxidation procedures, have been investigated. Additionally, improving aquaculture management practices, enhancing fishing gear, and utilizing better packaging materials are practical solutions currently being implemented. Developing portable monitoring systems for micro-nanoplastics and using remote sensing technology are anticipated to play significant roles in managing this pollution.

Keywords Nano-plastics . Micro-plastics . Radioactive contaminants . Environmental pollution . Toxicological effect . Detection method

Introduction

Plastics have almost completely replaced natural materials and have become essential to our lives, permeating every aspect of modern society. Over 450 million tonnes of plastic are produced annually, with more than 40% allocated to single-use packaging, contributing significantly to global plastic waste (Geyer et al. 2017). The lifespan of plastic items can range from one year to over fifty years, leading to a staggering accumulation of waste in the environment. Alarmingly, it is estimated that 71% of the energy from recycled plastics is lost, while only 9% is effectively collected for recycling, and 8% ends up in landfills (Lebreton et al. 2017). This mismanagement has turned plastic waste into a pressing international environmental concern. Since the 1950s, plastic production has surged from 1.5 million tonnes to

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approximately 450 million tonnes in 2023, with projections indicating that output may double by 2025 and quadruple by 2050 (Plastics Europe 2023). Coastal nations alone generated 275 million tonnes of improperly disposed plastic waste in 2010, contributing to the estimated 2.5 billion tonnes of solid waste produced globally (Jambeck et al. 2015). Between 4.8 and 12.7 million tonnes of this debris are believed to have entered marine environments, exacerbating the crisis. Because plastics are produced and used in large quantities, they have accumulated in natural ecosystems, which has had detrimental effects on the biota and the economy (Wagner and Lambert 2018).

Plastics are categorized into microplastics (MPs), particles ranging from 0.1 µm to 5 mm, and nanoplastics (NPs), smaller than 0.1 µm. MPs are often intentionally produced for uses such as microbeads in cosmetics, while NPs are found in various products including paints and medical delivery systems (Huang et al. 2021). The breakdown of larger plastics into these smaller particles poses significant environmental risks. Hydrolysis, biodegradation, mechanical abrasion, wave action, and UV radiation contribute to this fragmentation process, resulting in an increasing concentration of NPs in aquatic ecosystems over time (Wang et al. 2020).

The co-exposure of micro- and nanoplastics (MNPs) with radioactive materials presents a significant environmental concern, particularly in aquatic ecosystems. Recent studies have demonstrated that MNPs can exacerbate the toxic effects of radiation on aquatic organisms by disrupting cellular functions, increasing oxidative stress, and impairing immune responses (Lerebours et al. 2018). Radioactive isotopes adsorbed onto MNPs have the potential to bioaccumulate in fish and shellfish, which can subsequently enter the human food chain, raising serious health risks associated with seafood consumption. The interaction between MNPs and radioactive contaminants not only threatens aquatic life but also poses long-term implications for human health, as these contaminants can persist in the environment and accumulate through trophic levels (Wang et al. 2020).

The potential harm that MPs and NPs pose to aquatic life has garnered increased attention in recent years. Marine habitats are particularly vulnerable to plastic pollution, a significant component of marine debris. These materials often cannot be recycled effectively and do not biodegrade, leading to their accumulation in landfills and waterways (Gupta et al. 2022). NPs are considered more hazardous than MPs due to their smaller size and higher surface-to-volume ratio, which enhances their interaction with biological systems (Hazeem et al. 2020). Furthermore, the increasing discharge of plastics into marine environments has garnered extensive research and public attention regarding their classification, sources, and impacts. Studies indicate that microbial communities in these environments struggle to degrade plastic waste effectively, leading to an aggravation of the resulting environmental effects (Li et al. 2023). As MNPs proliferate in aquatic habitats, effective management strategies and regulatory measures become critical to mitigate their impact on marine ecosystems. This includes understanding the complex interactions between MNPs and other environmental stressors, which could further enhance their toxicity and bioaccumulation potential.

Recent studies have documented the ingestion of micro- and nanoplastics by various aquatic organisms, revealing various toxicological effects, including oxidative stress, reproductive toxicity, and impaired growth (de Ruijter et al. 2020). As these contaminants enter food webs, they pose risks to individual species and entire ecosystems. Addressing these challenges is essential for preserving aquatic biodiversity and ensuring food safety for human populations reliant on seafood. This review summarizes the toxic and synergistic effects of Micro-Nanoplastics with radioactive contaminants on Aquatic life. It also discusses aquatic animals' source and health risks and rising concerns about plastic with radioactive compounds and its mitigation strategies.

The physical characteristics and effects of MNPs on aquatic organisms

Microplastics' size, color, density, and shape are some of their most researched physical characteristics, and each contributes differently to their unfavorable outcomes. Figure 1 shows the characteristics and applications of plastics. Lighter than metals, plastics are used in various products, such as vehicles, spaceships, and airplanes (Huang et al. 2022; Adamcová and Vaverková 2014).

Types

There are different types of plastics. Polyethylene (PE) is the most common plastic, available in various densities i.e., Low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Polypropylene (PP), Polyvinyl Chloride (PVC) Polyethylene Terephthalate (PET or PETE) , Polystyrene (PS), Durable and transparent polycarbonate (PC) and Acrylic (PMMA) are also types of plastics . Table 1 shows several types of plastic and their codes (Dey et al. 2024; Campanale et al. 2020).

Size

"Micro-plastics" refer to plastics with dimensions less than 5 mm. When MPs break apart, NPs with 1 to 100 nm diameters are created. Figure 2 illustrates the size categorization of plastic particles based on biological structures.

Color and shape

Many marine animals, including copepods and turtles, often ingest MPs that mimic the colors of their natural prey, with fish larvae frequently consuming blue MPs that match their environment, leading to confusion, causing predators to mistakenly consume MPs instead of natural food, harming their health (Yuan et al. 2022). Red and transparent fibers are ubiquitous in the diets of benthic organisms. Additionally, specific colors, like white or transparent, can confuse predators, causing them to consume MPs instead of natural food mistakenly. The MP's form also affects how organisms absorb it. In the chosen studies, fibers were the most often eaten objects (23%), followed by fragments (21%), films (8%), and pellets (4%) (Botterell et al. 2019).

Occurrence and sources

MNPs are present in the hydrosphere, lithosphere, atmosphere, and biosphere, including all major cities,

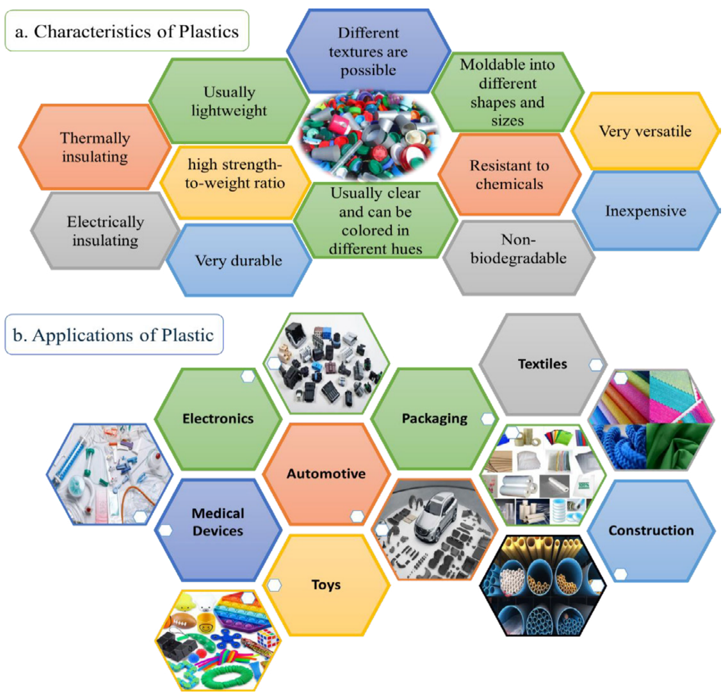
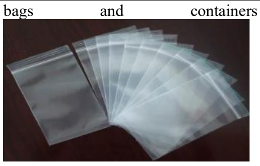
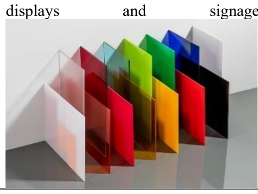


Fig. 1 (a) Characteristics: Plastic containers are more affordable, widely accessible, lightweight, and highly corrosion-resistant. (b) Application of Plastics: Polymers last a very long time. It may also take on any form because of its extreme flexibility. Plastic is widely used across various industries, from furniture to toys and household items. The most commonly used plastic, polystyrene, can be found in many products, including toys, medical equipment, industrial packaging, the food industry (drink, dairy, pickles, jam, squash, and soft drinks), cutlery, and building insulation.

rivers, and oceans. MNPs are absorbed by many aquatic and terrestrial species and are found in most water bodies, sediments, and soils. The majority of research on MNP contamination focuses on aquatic habitats. Plastic garbage finds its way into the marine environment due to human industrialization and urbanization

Table 1 Types of plastic with its characteristics and examples

Types	Characteristics	Consumption	Examples	References
Low-density polyethylene (LDPE)	flexible	PE was the most prevalent polymer type, accounting for 23% of the overall consumption. PE consumption was highest in Asia (21%), followed by Europe (17%), America (15%), and Africa (14%), with much less in North America (5%)	bags and containers 	Malik (2023)
high-density polyethylene (HDPE)	stronger		bottles and piping 	Tesfaw et al. (2022)
Polypropylene(PP)	flexibility and heat resistance	PP overall 12% consumption. MPs were not discovered in market contexts and were found in higher amounts in freshwater (8.5%) and saltwater (7.9%) than in fish culture (5.4%) and the coastal zone (3.1%).	food containers and automotive parts 	Maddah (2016)
Polyvinyl Chloride (PVC)	Durable and weather-resistant	PVC accounts for roughly 10% of global plastic production	construction materials like pipes and flooring 	Hussein and Cheremisinoff (2020)
Polyethylene Terephthalate(PET or PETE)	Known for its strength and recyclability.	-	food and drink packaging 	Benyathiar et al. (2022)
Polyethersulfone (PES)	High heat resistant, strong, chemically resistant	PES overall 9% consumption, PES was detected in higher concentrations in North America (12.2%), South America (22%), Asia (14.2%), Oceania (13.6%), Europe (8.3%), and Africa (3.1%)	Components in industrial machinery, medical devices, 	(da Costa et al. 2023).
Polystyrene (PS)	versatile	The overall consumption is 22%. The most popular plastics in production and demand are PS and PE, whose percentages in laboratory research were 40% and 30%, respectively	insulation and disposable flatware 	Arfin et al. (2015)
Polycarbonate(PC)	Durable and transparent	-	Protective equipment and eyeglass lenses. 	Kyriacos (2017)
Acrylic (PMMA)	lightweight, break-resistant alternative to glass	Overall 6% consumption	displays and signage 	Oyinloye et al. (2021)

through sewage, industrial effluent, urban waterways, hydric cycles, and connections to all seas and coastal regions. MPs concentrations in urban streams and glaciers are the highest of any water body. Their stability affects how they enter the environment as MNPs (Nabi et al. 2024). Radioactive contamination in marine environments primarily arises from several historical and ongoing sources. The 1986 nuclear accident released significant amounts of radioactive isotopes into the atmosphere, which subsequently settled into oceans and coastal areas, affecting marine life and aquaculture. Conducted in the 1950s and 1960s, these tests released isotopes such as cesium-137 (137Cs) into the environment, which have since been detected in marine ecosystems (Povinec1994). Facilities like Sellafield in the UK and La Hague in France have historically released various radioactive isotopes into the sea, contributing to contamination levels (Gwynn et al. 2024). Dense plastics like PVC and PET tend to settle in sediments and deep waters, while less dense plastics like PE, PP and expanded PS float on surface waters and shores (Hu et al. 2021). MNPs originate from various primary sources, such as microbeads in cosmetics, tire wear particles, and synthetic textile fibers, as well as secondary sources resulting from the degradation of larger plastic items due to physical abrasion and environmental exposure (Jiang et al. 2020). MNPs enter marine ecosystems through rivers, runoff, and atmospheric deposition, while radioactive contaminants can be introduced from industrial discharges and nuclear waste, compounding the pollution problem. In terms of geography, Asia ranked first (77%), followed by North America (75%), Africa (75%), and Europe (72%). MP consumption was highest in the saltwater environment (80%), then in aquaculture, market/freshwater, and estuaries (75%, 71%, and 75%, respectively) (Lim et al. 2022).

Human activities

Toothpaste, shampoos, and cosmetics often contain microplastics, which are exacerbated by the washing of synthetic materials, with nylon and acrylic also contributing to microplastic pollution during laundering (Carney et al. 2018). Textile wastewater: The release of synthetic fibers during manufacturing and washing processes significantly contributes to fibrous microplastics in rivers, with additional pollution from wastewater generated by food, automotive, and packaging industries.Domestic sewage: Due to the massive sewage discharge, many microplastics are still entering rivers, even with the current wastewater treatment procedure having some treatment impact (Sun et al. 2019). Agricultural plastic waste: Numerous plastic materials, including films, pipes, and other items, deteriorate, producing microplastics carried into rivers by rain and wind (Guerranti et al. 2017). Directly from land: Microplastics in aquaculture primarily originate from nearby garbage through weathering and degradation, atmospheric sedimentation via wind and rain, and extreme weather events like typhoons that transport terrestrial plastics into water sediments (Dong et al. 2021).

Fishing gear, feeding and packaging

Microplastics enter the aquaculture ecosystem through fishing gear. They are generated by the wear and UV degradation of nets and ropes, lost or discarded equipment, and the degradation of other plastic materials

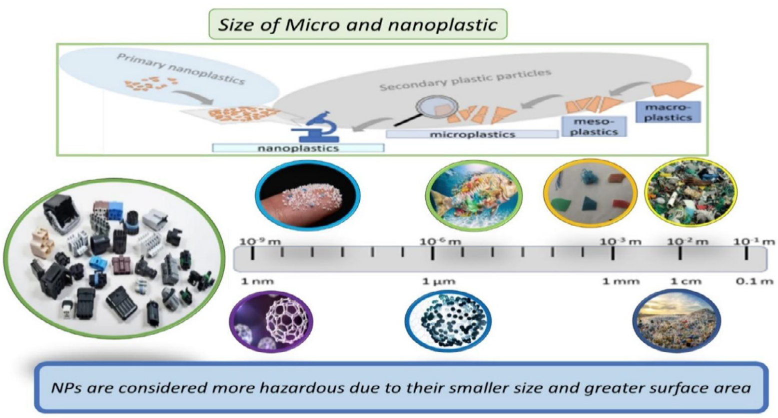


Fig. 2 Size classification of plastics particles in relation to biological structures

like fencing and expanded polystyrene floats (Chen et al. 2022). Due to contamination, fish and shrimp meal sources can introduce microplastics into aquaculture habitats. Packaging for aquaculture products, often made from expanded polystyrene, can release microplastic fibers, with polystyrene having the highest release rates, i.e., rainbow trout (Skirtun et al. 2022). The poor decomposition rate of macroplastics leads to the production of MNPs.

Interactions between MNPs and radioactive contaminants

The increasing presence of micro- and nanoplastics in aquatic ecosystems raises significant concerns for aquaculture health and sustainability. These tiny plastic particles can interact with various contaminants, including radioactive materials, leading to detrimental effects on aquatic organisms and their habitats. Radioactive materials can enter aquatic systems through various pathways, such as nuclear waste disposal, accidents at nuclear facilities, and runoff from mining activities. Combining these contaminants with microplastics amplifies the potential dangers to ecosystems and aquaculture practices as shown in Figure 3. The interaction between microplastics and radioactive materials raises critical concerns for aquaculture. The bioaccumulation of radioactive isotopes in fish and shellfish can occur when these organisms consume contaminated microplastics. This process risks human health when consuming contaminated seafood, potentially leading to harmful radioactive exposure. In aquatic environments, micro- and nanoplastics can develop an eco-corona—a layer of organic matter that enhances their interaction with contaminants. This formation may increase aquatic organisms' internalization of these particles and their associated radioactive materials, further complicating the risks involved (Troell et al. 2023; Trevisan et al. 2022).

Transfer of MNPs and radioactive compounds in oceans

MNPs are significant environmental contaminants found in various ecosystems, with approximately 1.9 million particles/square meter detected on the seafloor, primarily from land-based sources that account for about 80% of ocean pollution (Patil et al. 2022).

Radioactive compounds enter the ocean through various pathways, including nuclear accidents, atmospheric fallout, and discharges from nuclear facilities. The most significant recent event was the Fukushima Daiichi nuclear disaster in 2011, which resulted in the release of large amounts of radioactive isotopes such as iodine-131, cesium-134, and cesium-137 into the Pacific Ocean. These isotopes have varying half-lives, with cesium-137 persisting for decades, leading to long-term contamination concerns. Microplastics primarily enter the ocean through rivers, with various sources i.e. soil runoff, air precipitation, sewage overflows, and tourism contributing to this contamination; wastewater treatment plants often fail to effectively remove all microplastics, allowing them to escape into marine habitats (Lots et al. 2017). Plastic debris may be carried by the wind and released straight onto the sea surface, far from coastal areas. However, unless there are exceptional circumstances like storms or hurricanes, it can only transport MNPs for long-distance

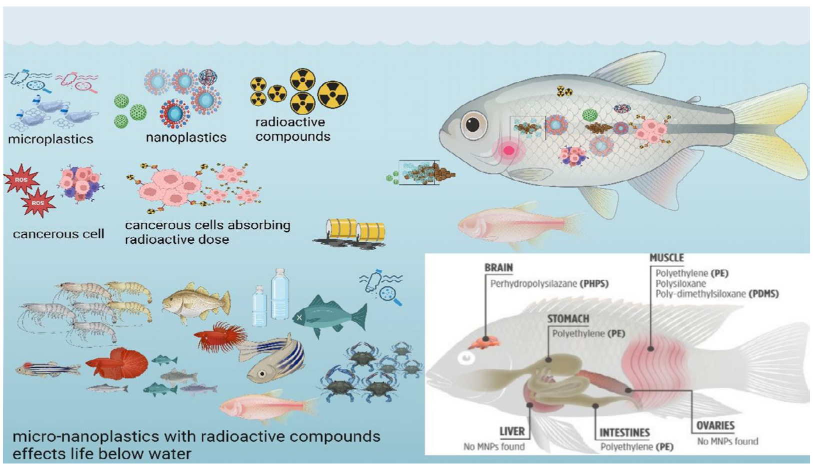


Fig. 3 Micro-nanoplastics and radioactive compounds interactions effects the health of life below water

trips (Thompson 2015). Rain runoffs and tidal washing are two ways that soil-born plastic litter, such as agricultural films and plastic pesticide and fertilizer packing materials, might end up in the ocean (Ng et al. 2018).

Navigating the waters of pollution: the role of MNPs in aquaculture systems worldwide

Recent studies indicate that MNPs are globally present with diverse compositions and sizes. Table 2 details the sources, shapes, and abundance of MNP pollution in different countries.
China is the world's largest plastics manufacturer, with an annual production of 59.08 tons. The United States is ranked second with 37.83 tonnes, ahead of results for Germany (14.48), Brazil (11.85), Japan (7.99), Nigeria (6.41 tonnes), Pakistan (5.96 tonnes), Nigeria (5.84 tonnes), Russia (5.84 tonnes), Turkey (5.6 tonnes), and Egypt (5.46 tonnes). India ranked fifteenth globally for plastic manufacture (Kutralam-Muniasamy et al. 2021).

Effects of MNPs on aquaculture species

Recent studies indicate that micro and nanoplastics can significantly impact marine species (Gupta et al. 2022). Numerous investigations have shown that various conditions negatively impact the physiology of aquatic species across different ecological niches. Crustaceans accounted for 45% of all animal studies, with fish (21%), mollusks (18%), annelid worms (7%), echinoderms (7%), and rotifers (2%) following closely behind.

A. Direct physical effect

Microplastics are small plastic fragments formed when larger plastic debris degrades. Because they are small, aquatic organisms may easily swallow them, causing them to accumulate in their bodies and disrupt their natural processes. Additionally, by swallowing these microplastics, animals may get trapped in things such as thrown away fishing gear, resulting in suffocation, starvation, or drowning. These microplastics pose a unique ecotoxicological risk to aquatic animals by combining physical stress with chemical exposure. Studies should consider both individual and interactive effects of microplastics and associated chemicals, which may result in synergistic, additive, or antagonistic impacts (Pittura et al. 2018). Micro-plastic (MP) particle mass, nature, and density determine whether aquatic filters, suspension, and deposit-feeders may directly ingest the particle. High-density MPs, such as PS and PVC, sink, whereas low-density MPs, such as PP and PE, float, influencing their availability to various feeders. Currently conducted studies are examining the physiological and molecular effects of MPs and NPs on aquatic creatures, revealing effects on immunological responses, stress responses, cell signaling, and energy balance (effect 1). Reported consequences at the individual level include inflammation, cytotoxic effects, decreased fertility, and slower development (Doyle et al. 2022).

MPs (microplastics) can absorb organic pollutants and serve as vectors for these compounds, resulting in bioaccumulation and bio-magnification. Plastic additives in MPs can have a significant Eco-toxicological impact on marine environments. These consequences include acute and chronic adverse effects on a variety of aquatic animals, including Daphnids, annelids, crustaceans, tilapia, and Japanese medaka, which result in reduced predatory performance, metabolic and endocrine abnormalities, and other deadly results (Da et al. 2022). These adverse effects are shown in Figure 4.

B. Biological impact

Microplastics (MPs) and nanoplastics (NPs) can generate a false sensation of fullness, disrupt appetite, and induce internal obstructions or digestive damage. MPs and NPs aggregate in the digestive tract, whereas smaller particles may enter the circulatory system, affecting development and reproduction. Additionally, exposure to these particles may decrease fertility, growth, survival, metabolism, oxidative stress, hepatic stress, loss of energy reserves, genotoxicity, immunotoxicity, and neurotoxicity as shown in Figure 5. Some nanoparticles can even penetrate the epidermis of fish larvae, accessing muscle tissues

Table 2 Micro and nano plastics pollution in aquaculture worldwide

Country	Source	Site	Shape	Main composition	Abundance	References
Canada	Marine sediment	Baynes Sound and Lambert Channel, British Columbia	dry sediment Micro-beads, microfibers, micro-fragments	-	Up to 25,000 n/kg	Kazmiruk et al. (2018)
	Aquatic sediments	Ottawa River,	Fiber	-	220	Vermaire et al. (2017)
	Marine water	Baynes Sound, British Columbia,	Fibers, films, fragments	-	1.7±1.2 particles/g	Davidson and Dudas, (2016)
China	Water	Hubei province	Fibers, fragments	PP, PE, PET, PE, cellulose, cellophane	1.3±0.1 particles/L	Zhang et al. (2021a)
	Marine sediment	Xiangshan Bay,	Fibers	RY, PP, PA, AN, PET	73.94±30.43 items/kg d.w	Wu et al. (2020)
	Sediment	Yellow Sea, Bohai Sea,	Fibers, fragments, films	Cellophane, PET, PE	2.8±1.30-46.8±4.81 items/50g	Mohsen et al. (2019)
	Marine water	Weihai	Fragments, fibers	PE, PP, PS	11.49 particles/m	Zhang et al. (2021b)
		Cultured ponds in Longjiao Bay	Fibers films, granules, fragments, foams	PE, PS, PET	1594±1352 particles/m3	Chen et al. (2020)
		Ma'an Archipelago marine ranching area	Fibers, fragments, films	PE, PP, PE-PP,PS, PA	0.2±0.1–0.6±0.2 items/L	Zhang et al. (2020)
		Maowei Sea, Beibu Gulf,	Fibers, foam, film	PET, POM, PE	1.47–7.61 particles/L	Zhu et al. (2021)
		Oyster farm in Yantai,	Fibers, fragments	Cellophane and polyester	4.53 items/g wet weight	
	Fresh water	Pearl River Estuary of Guangzhou	Fibers, fragments, films	PP, PE	10.3–60.5 particles/L 33.0–87.5 particles/L	Ma et al. (2020)
		Stations for cultivating rice and fish in Chongming, Shanghai	Films, fibers	PE, PP	0.5±0.1–0.9±0.2 items/L	Lv et al. (2019)
Colombian Caribbean	Lagoon water	Lagoon complex of Cienaga Grande de Santa Marta	Fibers, granules, fragments, films, foams	PP, HDPE, PE, PS	0.00–0.22 items/L	Garc´es-Ordo´nez ˜ et al. (2022)
	Fresh water	Huila region	Fragments, films, fibers	PET, PES, PE, PP	44 % samples of *O. niloticus*	Garcia et al. (2021)
England	Aquatic sediments	River Thames,	Fragment (91%)		185±42-660±7	Horton et al. (2017)
French Polynesia	Surface water	Pearl-farming lagoons	Fibers, Fragments	PP, PE, PS, PET, PU	0.9±0.9–3.3±2.3 item/m3	Gardon et al. (2021)
	Lagoon water	Pearl-farming lagoons		PE, PET, PP, PS, EVA	23.0±20.7-137.6±89.4 MP/individual	
Italy	Lagoon sediment	Mussel farm, Venice,	fibers, Irregular fragments, films and granules	PE, PP, PS	1237 n/kg d.w.	Vianello et al. (2013)
	Marine water	Fish farms	Microfibers, micro-fragments	PET, PTFE	sea bream: 0.48 items/specimen Common carp: 0.11 things/specimen.	Savoca et al. (2021)
India	Marine water	Kalamukku, Kerala,	Foam, Fragments, fibers,	EPDM, PE, PP, PS	0.054±0.098 items/g(in inedible tissues) 0.005±0.02 items/g (in edible tissues)	Daniel et al. (2020)
	Aquatic sediment	Netravathi river,	Fragment	-	96	Amrutha et al. (2020)
Iran	River	Caspian Sea	-	PP, PA, PS	40–460 particles kg $^{-1}$ 200–5000μm	Gholizadeh and Cera (2022)
Indonesia	Surface water	Surabaya-River	Fibres, fragments, films, foams, pellets		0.0008–0.04311 particles/L	Lestari et al. (2020)
	Aquatic sediments	Ciwalengke river,	Fiber		58.5±32.8	Alam et al. (2019)
	Surface water Sediment	Ciwalengke River	Fibres, fragments, others		2.57–9.13 particles/L 14.4-46.2 particles/kg	
	Surface water	Citarum-River	Films, fragments		0.00004–0.00009 particles/L	Sembiring et al. (2020)
	Sediment				12452–20316 particles/kg	
Japan	Marine water	Kindai University's Oshima Hatchery, Aquaculture Technology and Production Centre	Chips, fibers, particles	PS, PEVA		Okada et al. (2014)
Korea	Aquatic sediments	Nakdong-river,	Fragment		1970±62	Eo et al. (2019)
Malaysia	Surface Water	Dungun-River	Fibres, films, fragments,		0.04–0.30 particles/L	Hwi et al. (2020)
		Cherating-River	Films, Fibres. Fragments, beads, foam		0.000004–0.00001 particles/L	Pariatamby et al. (2020)
	Sediment	Skudai-River Tebrau-River			120–280 particles/kg 540–820 particles/kg	Sarijan et al. (2018)
Mexico	Marine water	Baja California,	Fibers, fragments	PET, PAN, PE, PP, PS, PA, T. elastomer	0.22±0.20-0.38±0.14 MPs org−1	Lozano-Hern´ andez et al. (2021)
		Gulf of California eoregion,	Filaments, subangular, spheroidal	PA, PES, PS, PE, NY	18.5±1.2 micro-plastics/shrimp	Valencia-Castaneda ˜ et al. (2022)

Table 2 Continued

Portugal	Marine water	Ramalhete marine station, Faro	Fibers, fragments, microfilm pieces	PP, LDPE, HDPE	median 28.5/animal	Oliveira et al. (2020)
Spain	Marine water	Tenerife, Canary Islands	Fibers, fragments, films, lines	PP, PE	0.6±0.8-2.7±1.85 particles/fish	Granby et al. (2018)
	Wastewater	Fuerteventura		PES, PP, PE	4.4–40 items/L 200–400μm	Pérez-Reverón et al. (2022)
Thailand	Estuary, Sediment	Chao Phraya	Fragments, fibers, films	PP, PE, PP-PE, PS	48±8 items/m3	Ta and Babel, (2020)
	Aquatic sediments	River	Fragment, fiber		91±13	
	Surface water		Fibres, films, fragments		41.77 particles/L	
			Foams, beads, Hard and soft plastics,		0–0.052 particles/L	Johansson and Ericsson (2018)
Tunisia	Lagoon water	The lagoon of Bizerte	Fibers, fragments, films	PP, PE	703.95±109.80 to 1482.82±19.20 items/kg wet weight	Abidli et al. (2019)
U.S	Fresh water	The sources of drinking water for Bloomington, Illinois's McLean County,			1 to 49/No. Fish	Hurt et al. (2020)
Vietnam	Aquatic sediment	To Lich river	Fiber		55,950±10,111	Duong et al. (2023)
	Surface water	Saigon River	Fibers, fragments		0.01–519 particles/L	Lahens et al. (2018)

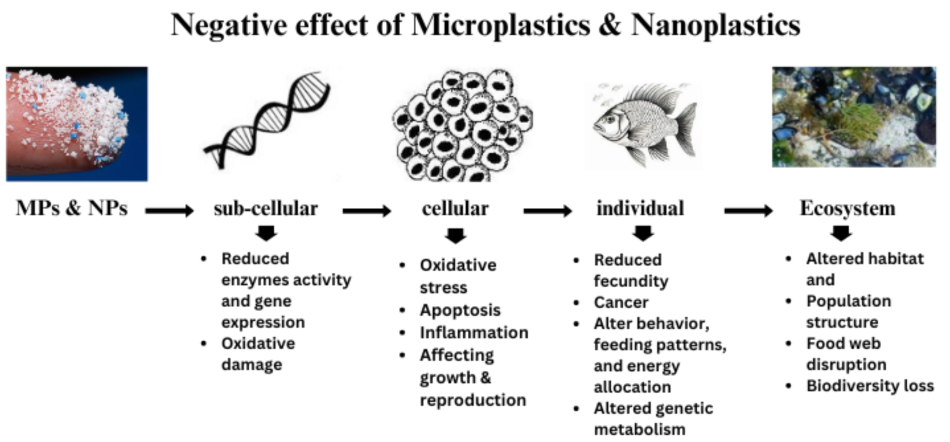


Fig. 4 Negative effect of MNPs on subcellular, cellular, individual and ecosystem level

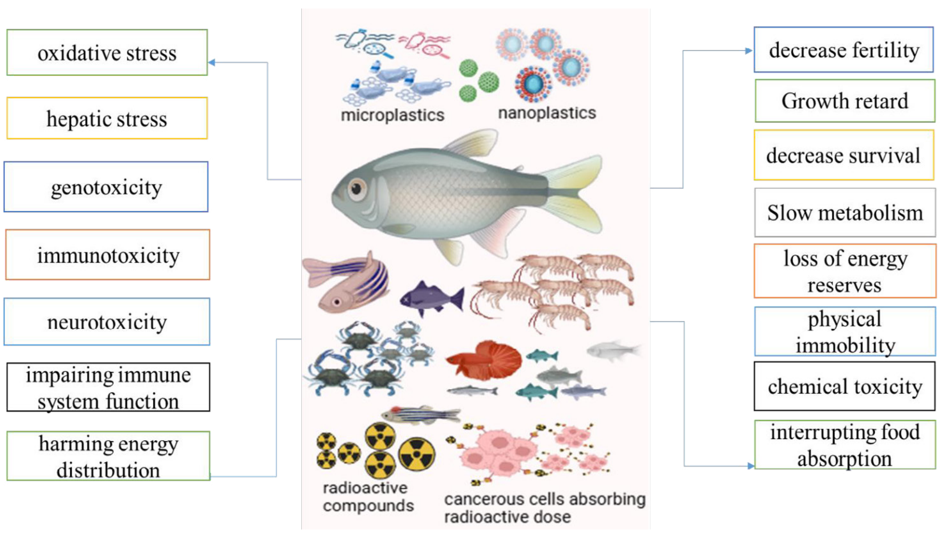


Fig. 5 Exposure of MNPs and radioactive compounds water and its biological impact in aquaculture

and influencing muscular nerve fibers, neurotransmitter release, and the larvae's swimming abilities. The excessive accumulation of MPs and NPs in fish tissues may lead to physical immobility and chemical toxicity, interrupting food absorption and harming energy distribution, impairing immune system function (Yang et al. 2024).

MPs may penetrate the intestinal epithelium and cause severe damage, with different consequences depending on their form. Fibrous MPs are highly poisonous, often entangling the intestines and causing death since they cannot be adequately expelled. Fibrous MPs aggregate more in oysters than spherical or other forms, resulting in gastrointestinal injury or intestinal obstruction (Du et al. 2021). Microplastics (MPs) may inhibit reproduction in marine creatures, including copepod plankton, sea urchins, Daphnia, and Pacific oysters. MPs accumulate in reproductive organs. MPs produce oxidative stress in male river prawns, sex hormone abnormalities in mussels, and decreased sperm function and fertilization rates in oysters. Furthermore, if MPs are consumed as food, they impact nematode reproduction (Yang et al. 2024).

C. Trophic level

Evidence suggests that microplastics (MPs) increase the trophic chain in aquatic environments. MPs impact nearly 700 aquatic species, accumulating in low-trophic creatures and migrating through the food web via predation. Studies have shown that MPs in mussels transmit to crabs and zooplankton transfer to mysid shrimps, demonstrating a linking impact in the food web. MPs consumed by lower trophic animals like algae can progress to higher trophic levels, affecting the ecology. However, other studies believe MPs may be immediately filtered in organisms, reducing their influence on higher trophic levels shown in Figure 6 (Du et al. 2021).

Microplastic transmission is a significant danger since humans are the last consumers of marine seafood contaminated with microplastic. Tap water, sea salt, and bottled water have all been shown to contain microplastics, according to research on how microplastics can enter the human body (Saha et al. 2021).

D. Ecological and economic impact

MPs can change species relationships in aquatic habitats, upend food webs, and impact ecosystem functioning. When ingested by primary producers such as planktonic organisms, MPs can affect the nutrient cycle and primary productivity. The subsequent absorption of MPs in the food chain may risk ecosystem stability

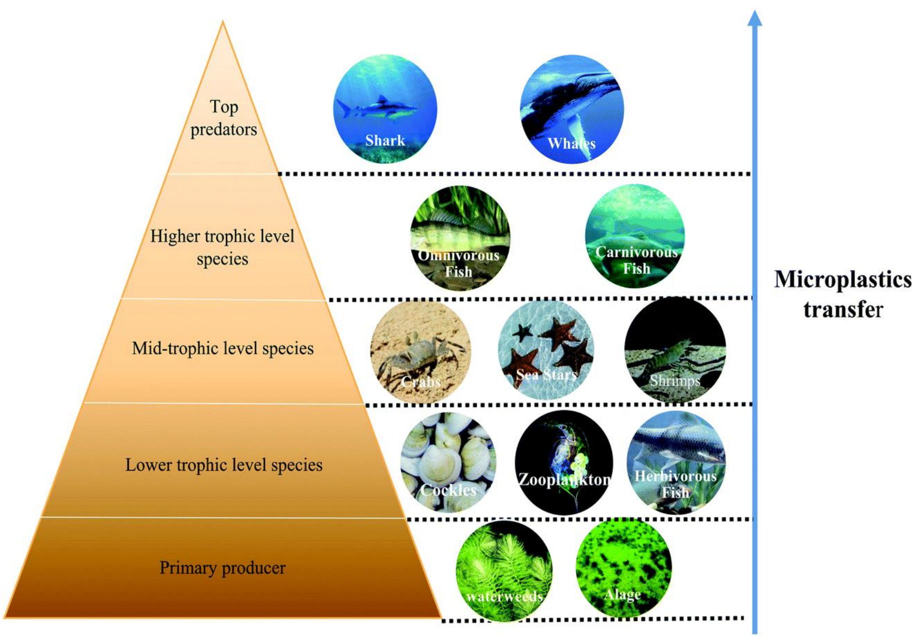


Fig. 6 Potential pathways of MPs for nutritional level migration in water environment (Du et al. 2021)

and biodiversity via cascading impacts on higher trophic levels. Economic effects are closely linked to ecological ones. For instance, MPs in fish and seafood can lower market value and customer trust in the fishing sector. Moreover, enterprises that depend on aquatic resources and coastal communities may need help managing and cleaning up MP contamination because of the associated expenses (da Costa et al. 2023). The effects of MNPs on different aquaculture species are shown in Table 3.

Impact of radioactive contaminants on aquatic life

The impact of radioactive contaminants on aquatic life is a significant global concern, particularly in regions heavily reliant on nuclear power, such as China, which has over 50 nuclear power plants along its eastern coast. This reliance increases the risk of radioactive contamination entering marine environments through accidents and routine discharges. Since 1966, substantial amounts of nuclear waste have been disposed of in the northern East Sea, and the Fukushima disaster released 7 to 50 petabecquerels (PBq) of cesium-137 (137Cs) into the ocean, raising long-term environmental concerns. The Fukushima Daiichi Nuclear Plant accident had profound atmospheric and oceanic impacts, resulting in extensive contamination due to radionuclides released during the incident (Hirose 2016). Major nuclear incidents like Chernobyl and Fukushima have significantly contributed to the presence of 137Cs in marine ecosystems, with atmospheric nuclear testing from the mid-20th century also influencing its distribution. The Fukushima nuclear accident has had notable effects on marine life in the surrounding waters, primarily due to the release of radioactive contaminants (Figure 7). Ocean currents, particularly from the North Pacific to the China Seas, are crucial in redistributing 137Cs. At the same time, rivers can transport it from terrestrial sources into coastal areas, albeit to a lesser extent. The residual effects of global fallout from past nuclear activities continue to be a source of 137Cs in marine environments (Cao et al. 2022).

Improper nuclear waste disposal can contaminate nearby water bodies, affecting local aquaculture. Runoff from mining operations can introduce radioactive materials into aquatic ecosystems, further complicating the contaminated landscape. Notably, studies indicate that the apparent half-lives of 137Cs are approximately 15.1 years for the East China Sea and 7.7 years for the Yellow Sea, making it a valuable indicator for tracing water mass movement and interactions. The transport and bioaccumulation of 137Cs in aquatic ecosystems are influenced by various factors, including sediment composition and water chemistry, which complicate its environmental fate. Additionally, the continuous recirculation of 137Cs in biological systems highlights its long-term impact on marine life (Ashraf et al. 2014). The distribution and accumulation of artificial radionuclides such as cesium-137 (137Cs) in marine products around the Korean Peninsula have raised concerns regarding food safety and environmental health (Kim et al. 2019).

Synergistic effects of MNPs with radioactive contaminants on aquatic life

The synergistic effects of microplastics and radioactive contaminants can have severe consequences for aquatic organisms, particularly in aquaculture settings. Co-exposure to these pollutants can elevate stress levels in species like fish and shellfish, weakening their immune systems and increasing susceptibility to diseases. The combined presence of microplastics and radioactive materials can also impair growth rates, reproductive success, and survival, posing challenges to maintaining healthy populations (Adeleye et al. 2024; Bhagat et al. 2021).

A. Increased stress

The dual exposure to microplastics and radioactive materials heightens stress in aquatic organisms, which can compromise their immune responses and make them more susceptible to diseases (Li et al. 2023).

B. Impaired growth and reproduction

Exposure to both microplastics and radioactive contaminants can hinder growth rates and reproductive success in aquatic species, threatening the viability of populations (Pelamatti et al. 2022).

Table 3 Effects of MNPs on Aquaculture species

Aquaculture species	Organisms	Exposure date	MNPs types	MNPs size/ abundance	Main effects	References
Crustacean	*Daphnia magna*	24h	PET	62–1400μm	• Uptake • intestinal retention times • Survival, • Reproduction • Feeding of offspring	Kokalj et al. (2022)
		96h	PE	1–100μm	• Immobilization • Uptake	Arp et al. (2021)
		-	PS	2μm-100nm	• Reproduction • Body burden • feeding rate estimation,	Vo and Pham (2021)
		48h	PMMA		• Acceptance • buildup • depuration	
		21-days	PS	10μm-50μm	• halt rate, • oxidative stress, • death	Rist et al. (2019)
Fish	*Danio rerio*	10-days	PE, PP, PS, PVC	0.1,1,5μm	• Intestinal damage • Mortality • morphological abnormalit ies	Vagi et al. (2021)
		-	PS	0.07,5,20μm	• liver metabolism decline • Oxidative stress • Particle accumulation in the fish's gills, intestines, and liver	Kleinteich et al. (2018)
		-	PS	10μm	The assessment of MP accumulation in larval • existence, • hatching • larval growth, • reactions of oxidant/anti-oxidant • cellular detoxification	
	Medaka *Oryzias melastigma*	14-days	PS	-	• Uptake • Death • liver stress, • bioaccumulation, • formation of tumor	Cong et al. (2019)
	Oreochromis niloticus	-	PET, PES, PE, PP	-	• 44% of freshwater sampl es include microplastics	Garcia et al. (2021)
	Oncorhynchus mykiss	69-days	PS	3000	• genotoxicity endpoint fre quencies noticeably higher.	Jakubowska et al. (2022)
			PET,	3000μm	• yolk sac absorption rate notably decreased	
		29-days	PE,	150–180μm	• Fish exposed from the embryonic stage had much greater amounts of corticosterone.	
	European sea bass (*Dicentrarchus labrax*)		PMMA	45nm 0–20mg/L	• Modify molecular signaling system • obstruct lipid metabolism	Barboza et al. (2018)
Mollusks	Mytilus spp	-	PS	2mm	• Malformation development defects	Fonte et al. (2016)
	Corbicula. fluminea	3-days	PS	80nm	• GR, • GST, • GSH, • GSH, • MDA, • Histological observation, • IBR	
	Oysters (*Ostrea edulis*)	-	HDPE, PLA	103μm 66μm	• High rates of respiration • Changes in benthic assemblage structures	
	Pinctada margaritifera	1-2days	PP, PE,	<5mm	• trochophore, • stage D larvae • dead larvae	Wang et al. (2019)
	Meretrix meretri	1,4,7-days	PS-COOH PS-NH	200nm 100nm	• Hatching rate, • Developing rate, • Deformity rate, • Metamorphosis rate, • Histological observation	Gonçalves and Bebianno, (2021)
	Perna perna	2-days	PP	-	• dead embryos • Abnormal embryos	Wang et al. (2019)
	Mussels *(Mytilus galloprovincialis)*	2-days 7-days	PS PET	3μm 5-60μm 61–499μm	• Histological observation • AtCh • SOD	Gonçalves and Bebianno. (2021)

Table 3 Continued

			500–3000µm	• GPx • MDA	
	-	PS-NH2	50nm 1–50mg/L	• PS- NH2 may lessen the stabilisation of t he lysosomal membrane.	
	64-days	HDPE	1–50µm	• Gene expression (KEGG) • Shell length growth rate	Rist et al. (2019)
	48h	PS-NH	50nm	• test of Embryo toxicity • The yield of D.larvae, • Malformation rate • qRT-PCR • Histological observation	

Fig. 7 Micro-nanoplastic and Radioactive contaminants effects on Aquaculture. Statistics sourced from media reports, specifically from the Global Times, with editorial oversight and graphics by Wu Tiantong.

C. Bioaccumulation risks

Radioactive materials that adhere to microplastics can accumulate in the tissues of farmed species, raising food safety concerns as these contaminants may be transferred up the food chain to humans and other predators (Weis and Alava 2023).

D. Developmental delays

Combined exposure may result in developmental delays in juvenile organisms, which can long-term affect population dynamics and ecosystem stability.

E. Altered feeding behavior

The presence of microplastics may change aquatic organisms' feeding behavior, potentially leading to reduced food intake and further inhibiting growth and health (Zheng et al. 2023). Marine phytoplankton, which form the base of the food web, absorb radioactive materials from seawater. This uptake is crucial as it allows contaminants to move up the food chain when these organisms are consumed by zooplankton and larger fish.

Role of MNPs as vectors for radioactive contaminants in aquaculture

Micro- and nanoplastics (MNPs) play a critical role as vectors for radioactive contaminants in aquatic ecosystems, posing significant risks to aquatic organisms and raising concerns about food safety and ecosystem health. Their large surface area and chemical properties enable MNPs to absorb various pollutants, including radioactive isotopes, enhancing the bioavailability of these harmful materials in aquatic environments.

This vector role facilitates the transport of radioactive contaminants within aquatic ecosystems, leading to increased accumulation in aquatic organisms. Toxicological effects arise from the combined exposure to microplastics and radioactive contaminants, which can lead to increased toxicity in aquatic organisms. Research indicates that MNPs may exacerbate the harmful effects of radiation by altering cellular functions, increasing oxidative stress, and impairing immune responses (Li et al. 2023; Ashraf et al. 2014).

MNPs have a high surface area-to-volume ratio, allowing them to adsorb various contaminants, including radioactive isotopes. This sorption enhances the bioavailability of these contaminants in aquatic environments, making them more accessible to organisms. Acting as vectors, MNPs can transport radioactive contaminants across different aquatic habitats. This transport can lead to the accumulation of these contaminants in food webs, where they may bioaccumulate in higher trophic levels, including commercially important fish species. The sorption dynamics of radioactive contaminants onto MNPs are influenced by various physicochemical factors such as temperature, pH, and salinity. These factors can affect the stability and persistence of both the plastics and the contaminants in aquatic environments (Kim et al. 2019; Li et al. 2023)

Impacts on soil, living beings, and the environment

MNPs represent severe risks to health and the environment due to their high fragmentation, resistance to degradation, and global distribution. The influence of plastic additives on soil, living beings, and the environment is currently being studied. There is little knowledge of MP's effects on soil, biological creatures, and environmental contaminants. Furthermore, different plastic varieties include different compounds and possible toxins. Secondary microplastics, formed by the breakdown of bigger plastics, are ubiquitous in aquatic habitats. These tiny particles are absorbed by both marine species and animals, entering the food chain and eventually human bodies via seafood and other sources. MPs/NPs can enter human bodies by ingestion, inhalation, or biofouling. Due to their tiny size and massive surface area, MNPs can absorb pollutants, negatively impacting ecosystems and humans. Microplastics act as carriers of microbes and release harmful chemicals. They negatively impact the environment by damaging ships, causing animal injuries and deaths, and harming habitats. Research has found that persons in the UK may eat around 123 microplastic particles per year, while those in nations with higher shellfish consumption may ingest up to 4,620 particles per year (Catarino et al. 2018).

Detecting method

MPs fragments floating in aquatic environments are often collected using nets or trawls, and sample preparation-which typically includes density separation and sample digestion—comes next. Microplastics are often separated using sieves that may be used singly or in series and have mesh diameters ranging from 0.038 to 4.75 mm. Filters of small mesh sizes (e.g., 0.02 µm–5 µm) are also used to separate microscopic or nanoplastics. Chromatographic methods, including passive and active separation, are usually employed for plastic particles less than 1µm (Fu et al. 2020). Available quantitative and qualitative MP and NP detection methods include spectroscopic, chromatographic, and optical methods. Table 4 shows these techniques.

Mitigation strategies and reduction method

Micro- and nano-plastics are emerging contaminants of international concern that cannot be ignored as future environmental threats. New studies are being carried out to determine the critical challenges posed by the presence of these plastics in the ecosystem (Ali et al. 2023). Microplastics (MP) are difficult to remove from the environment; therefore, source reduction is critical for protecting the ecosystem and human well-being. Reducing consumption, promoting litter prevention through public awareness, and controlling single-use packaging materials are all important strategies. Minimizing dangerous chemicals in consumer items, decreasing plastic packaging, and restricting fertilizer and compost usage can all be supported. Additionally, mitigation efforts should focus on significant MP sources such as pigments, synthetic textile fibers, and tyre wear particles (Vivekanand et al. 2021).

Microplastics (MP) are made from paint, pellets, synthetic textile fibres, and tyre dust. They can persist in soil or seep into groundwater. They can accumulate in oceans and aquatic habitats through runoff, river transport, and direct discharge (Vivekanand et al. 2021). Wastewater treatment plants (WWTPs) are the principal entry pathways for MP, catching more than 90% of them through primary, secondary, and tertiary treatments; however, advanced techniques such as nanofiltration are required for highly tiny particles.

Table 4 Quantitative and qualitative methods of MP and NP detection

Methods	Types	Advantages	Limit of detection	Polymer type	Detection shape	Limitations	References
Visual method	Microscopic counting	• Low cost • Short detection time	>1 µm	PEG PCL Hybrid polymer	• Fibers • synthetic particles • Fragments • Textile fibers	sample cannot be determined and used in combination with other methods	Lorenzo-Navarro et al. (2021)
	Stereo microscopy	• Fast & easy • Identification of color, size & shape	<100 µm	PE PS PVC PCL PMMA	• Fibers • Fragments • Granules • Scale bar	Need for coupling with other Techniques Not feasible identification of particles	Adhikari (2022)
Spectro-scopic methods	FTIR	• Short analysis time • Chemical fingerprint	<20 µm	PA, PE, PET, PMMA, PP, PS and PVC	• Fibers • Fragments	Expensive Time consuming	Adhikari (2022)
	Raman microscopy	• Non destructive • Analysis of sample in gas, film, surface, solid, and single crystals is possible • Hyperspectral image • Automatic data acquisition & processing	MPs (1µm) NPs (<1µm)	LDPE	• Linear shape	Time-consuming Expensive instrument Interference with pigments	Kalaronis et al. (2022)
	Scanning electron spectro-scopy	• Clear and high resolution image of particles • Small particles detected in STEM mode	MPs (1 µm to 1 mm)	PE PS PP	• Synthetic particle • Fibers	Expensive Long time & effort for analysis Lack of information on the type of polymer	Bin et al. (2024)
	Transmission electron microscopy	• Very high resolution • Elemental analysis if coupled with EDS	<0.1 µm	PP PE PET PVC	/	Expensive Require sample preparation for particle size >100nm	Zhang et al. (2020)
Thermo analytical method	Pyro GC-MS	• Samples analyzed with organic plastic additives without solvent pretreatment	size larger than 500 µm	PVC PS PP PMMA PE	Not specific	selected MPs in the database can be analyzed	Adhikari (2022)
	TGA-MS	• Simple, fast, and easy method • Independent on MPs size and shape • Fully automated system	1 µm	PVC PA PS PE PP PET	/	No limitations on particle size	Mansa and Zou (2021)
Other methods	Tagging method	• Easy to operate • More effective and reliable • Can quickly screen out the required MPs • Identify fluorescent particles	MPs(1–5 mm)	PCL PNI PAAm PEI		The evaluation of the abundance of MPs is not accurate, and it is on the high side.	Issaka et al. (2023)
	Liquid chromate-graphy	• Recover high content of MPs. • Extensively used worldwide	/	PET, polycarbonate	/	sample size of evaluation analysis is small only specific MPs can be analyzed	Adhikari (2022)
	SEM dispersive X-ray spectro-meter	• Destructive technique • Applicable on a wide spectrum of particles • Identify Size, shape, number, and composition of MPs & NPs	< 100 nm	PCL PNIPAAm	• Fibers • Beads • Fragmens • Films	Time-consuming expensive, chemical characterization may be subject to a selection bias	Foetisch et al. (2022)

Landfills are another source, with MP entering WWTPs via landfill leachate and polluting soil and water using biosolids. Food waste, which frequently becomes contaminated with plastic, provides a pathway for MP into aquatic habitats and the human body. Other notable sources of MP include tyre wear, artificial grass, controlled-release fertilizers, and decaying macroplastics. Storm water runoff is a primary channel for MP into the environment. Recycling can help to prevent plastic waste from entering the environment or landfills, where more than 75% of non-biodegradable plastic garbage ends up. In the United States, plastic trash recycling rates fell from 9.0% in 2015 to 8.4% in 2017. In 2017, 5.6 million tons of plastic were burnt for energy recovery, whereas 26.8 million tons were landfilled. Practical rules are required to increase recycling rates; for example, 2019 Germany recycled more than 99.6% of plastic packaging trash, while California's State Bill 54 seeks to make all packaging recyclable or compostable by 2032 (USEPA 2021). Bioretention cells are excellent in removing microplastics (MP) from urban runoff. MP-sized 106–5000 µm decreased by 84% on average due to these ground depressions' collection and treatment of runoff. Microplastics (MP) are primarily removed by wastewater treatment plants (WWTPs), but sludge management needs to be performed efficiently to keep MP out of the environment again. Bioremediation, a treatment approach that breaks down MP-rich biosolids by hydrolyzing them with microorganisms such as bacteria or fungus, can be successful. Physical treatment methods such as filtration, coagulation, flocculation, and sedimentation efficiently eliminate microplastics (MP) from wastewater. Coagnants such as poly aluminium chloride and ferric chloride demonstrate high removal efficiencies, as do efficient techniques like electrocoagulation, magnetized nano-Fe3O4, biochar filtration, and zirconium metal foams. Photocatalytic titanium dioxide micromotors represent a potential new option (Krishnan et al. 2023).

Advanced oxidation processes (AOPs) that use hydroxyl radicals to break down microplastics (MP) are good at getting rid of them and could be used for further treatment in wastewater plants. Though eco-friendly and increasingly distributed, particularly in the United States and Europe, AOPs are costly due to the necessity for a steady supply of hydroxyl radicals (Rizwan and Bilal 2022). Microplastics (MP) can be efficiently broken down into ecologically benign carbon compounds by biological processes, including biodegradation and bioremediation. Actinomycetes, algae, bacteria, fungus, and their enzymes contribute to the decomposition of synthetic plastic. Using a consortium of microorganism's increases efficiency through synergistic interactions (Lee et al. 2023). Microplastic (MP) removal efficacy from water depends on several variables, including water turbidity, pH, and coagulant doses. The optimum pH for elimination is about 8, with varied coagulant requirements at different pH levels (Girish et al. 2023). Particle size affects removal efficiency; it is more challenging to remove smaller particles. MP size and shape also influence removal, with rougher and more elongated particles being removed more successfully. Nanoplastics (NP) studies are limited because current detection techniques primarily identify particles exceeding 1 millimeter. MP and NP remediation technologies that are both effective and broadly economically profitable need to be improved. Bio- and photodegradation, on the other hand, can function but is slow (Monira et al. 2021).

Challenges

Microplastics and nanoplastics (MNPs) present significant challenges due to their small size and the lack of practical detection tools. Current research focuses on understanding plastic additives' effects on aquatic organisms and the environment. Secondary microplastics, resulting from the breakdown of larger plastics, are prevalent in aquatic habitats, underscoring the urgent need to reduce plastic consumption. The lightweight, affordable, and durable nature of plastics complicates efforts to decrease their usage. Despite ongoing research, there remains limited knowledge about the effects of microplastics on soil health and living organisms. The diverse compounds in different types of plastics may introduce various toxins into the environment (Kershaw et al. 2011).

If plastic pollution is not effectively regulated, aquatic life and aquaculture industries may face severe consequences. Ingesting microplastics can lead to stunted growth, reproductive issues, or even death in marine species. This consumption risks human health as harmful compounds move up the food chain through seafood consumption. Additionally, plastic waste degrades ecosystems and diminishes biodiversity. The growing amount of plastic waste from aquaculture further exacerbates these environmental challenges. To tackle these challenges, strategies include prohibiting harmful chemicals, enhancing public education, improving waste management practices, and holding businesses accountable for reducing plastic packaging. Significant initiatives to combat these issues include minimizing plastic use, adopting biodegradable alternatives, and improving waste management systems. Public education is crucial for raising awareness about microplastic pollution. Holding firms responsible for reducing plastic packaging is also essential for driving change (Terepocki et al. 2017).

Policy and regulations

In order to use several federal laws for regulation, the essay emphasizes the importance of redefining MNPs as hazardous pollutants. It recommends that the Clean Water Act (CWA), the Safe Drinking Water Act (SDWA), and the Resource Conservation and Recovery Act (RCRA) be amended to clarify plastic polymer exclusions and categorize MPs as waste or hazardous pollutants. The FDA should categorize MPs as pollutants rather than food additives to ensure proper regulation. Precise definitions, methods, and international coordination are required to tackle plastic pollution. The main objective is to start controlling MPs immediately to decrease their negative environmental and human health effects.

Conclusion and future perspective

Microplastics and nanoplastics have emerged as significant environmental contaminants, threatening aquatic ecosystems and the broader food chain due to their widespread presence in marine and freshwater environments. These pollutants originate from the breakdown of larger plastic items and the shedding of synthetic materials, leading to detrimental effects on various aquatic organisms, including reduced reproduction rates, increased mortality, and physiological stress. The indirect impacts of MNP pollution on ecosystems remain underexplored, underscoring the need for further research into their ecological consequences and potential effects on human health. Addressing this issue requires raising public awareness about the dangers of microplastics and the importance of proper plastic disposal, alongside implementing effective policies and governance structures to limit MNP emissions. Governments play a crucial role in this effort by banning specific plastic products and establishing water treatment regulations. International cooperation is essential since plastic waste can cross borders and affect global water systems. Technological advancements, including improved filtration systems in wastewater treatment plants and the development of eco-friendly polymer alternatives, are vital for mitigating the effects of microplastics and nanoplastics.

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