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Impact of Microplastics Pollution on Aquatic Life: Bioaccumulation and Ecological Consequences

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ABSTRACT

Microplastics consisting of plastic particles smaller than 5 millimeters have been emerged as emerging pollutant worldwide due to their potential threat to life and environment. This article deals with an in-depth review of microplastics, including their origins, transport routes, bioaccumulation, and their impacts on fishes and aquatic invertebrates. Microplastics entered into aquatic environments through a variety of sources such as urban runoff, wastewater treatment plants, household items, industrial activities, and agricultural practices. Microplastics in the environment primarily originate from personal care products like microbeads and air blasting technologies. Secondary microplastics are generated from the breakdown of plastics through biological, chemical, and physical processes. The presence of microplastics in the aquatic ecosystems is controlled by their physical and chemical qualities and environmental interactions. Different analytical techniques like microscopy, spectroscopy, and chromatography are used for the detection and quantification of microplastics in the aqueous environment. The impact of microplastics on aquatic organisms like fishes and aquatic invertebrates has also been mentioned. The ingestion of microplastics causes physical harm, gastrointestinal blockage and abrasion, as well as chemical toxicity including oxidative stress. Microplastics also interfere with growth, reproduction, neurology, and behavior, posing serious effect to aquatic organisms and ecosystems.

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INTRODUCTION

In early 1900s, a revolutionary material ‘plastic’ was invented. The widespread usages of plastics in various fields have been since 1950 and first citations of plastic waste in marine ecosystems were reported in 1970 (Wootton *et al*., 2021). The amount of plastic production increased sharply from 230 million metric tons in 2005 to 442.56 million metric tons in 2023 (Thanigaivel et al., 2024). Plastics waste has become one of the major environment issue. With rise in the world population, the demand for plastics is expected predicted to reach double by the end of 2050. Due to exceptional durability and demand the plastic ends up in ecosystems (Alberghini *et al*., 2022). In the environment, plastics wastes have been degraded by mechanical and photochemical processes and microbes into smaller plastic particles (Bajt, 2021).

Microplastics (MPs) pollutions have become global challenging problem due to their numerous health and environmental consequences. The term “microplastics” was introduced by Thompson in 2004. Microplastics are defined as plastic particles ranging in size from 1 μm to 5 mm. Microplastics are further classified as primary or secondary depending on their origin. Primary MPs are generally intended for use in personal care products while secondary MPs are produced predominantly from the fragmentation or break down of larger plastics, during product

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use or due to weathering and degradation of plastic litter (Andrady, 2017). Microplastics can travel to long distances through runoff, river, ocean and atmospheric decomposition, resulting in wide spread dispersal in aquatic ecosystem (Du *et al.,* 2021). They exist in various forms like fibres, spheres, pellets, films or foam (Issac, 2021). MPs due to small size and large surface area absorb toxic substance like organic pollutants, heavy metals, bacteria and viruses most easily (Sharma et al., 2024).. Microplastics are characterized into six groups according to their chemical makeup; polyethylene, polystyrene, polypropylene, polyurethane, polyvinyl chloride, and polyethylene terephthalate (Osman et al., 2023). The International Union for Conservation of Nature (IUCN) identifies seven main origins of microplastics in marine ecosystems including synthetic fabrics, vehicle tires, road markings, personal care products and cosmetics, plastic pellets, marine coatings, city dust.

The identification of MPs in water system is a challenging due to their tiny size. MPs in water samples is characterized using Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR) and pyrolysis gas chromatography mass spectrometry (Pyro GC-MS), etc. (Du et al., 2021). MPs are found in all habitats worldwide including air, water sources, sediments, and soil (Makhdoumi et al., 2023). Therefore, MPs are ingested by a diverse array of species occupying different trophic levels, employing various feeding strategies, and inhabiting various habitats (Parker et al., 2021).

Numerous studies have been reported on the impact of ingested microplastics on physiological processes of various aquatic organisms. The negative impacts of MPs have been recorded for aquatic species, including fishes, penguins, sea turtles, mussels, clams and various crustaceans (Foley *et al.,* 2018). The ingestion of these MPs occur during feeding in water column or accidental as they resemble planktons in size, shape and colour, which makes it difficult to differentiate with food. MPs are ingested by aquatic organism by consuming prey that has previously ingested MPs (Makhdoumi et al., 2023; Thakur et al., 2022). Fisheries and aquaculture play vital roles in global food security by supplying significant amounts of dietary protein and supporting the livelihoods of millions of the people worldwide. As a result MPs are ingested by organism at different tropic level, allowing MPs to bioaccumulate through food chain (Béné et al., 2015). The fish exposed to polystyrene microplastics exhibited reduced hatching rate and embryo survival changes and change in lipid and energy metabolism (Bashirova, et al., 2023).

Microplastics (MPs) usually have negative or neutral effects on a variety of taxa. Positive impacts of MPs have never reported to understand the influence of MPs on various aquatic organisms. Some of the indirect impacts of MPs on fishes including altered feeding and predatory behaviour, lower feeding efficiency, immune system changes, physical blockage, and GIT oxidative stress have been reported. In aquatic invertebrates, harmful effects like accumulation of microplastics in various tissues like gills, gastrointestinal tract, impairment of feeding activity, neurotoxicity, genotoxicity, and reduced reproductive potential have been recorded (Costa, 2022).

Classification of microplastics

Microplastics are generally classified into different types based on their origin in the environment, particles shape, size, colour, composition, surface properties and buoyancy.

Class based on origin

MPs are classified into primary and secondary based on the origin. Primary microplastics are tiny plastics intentionally incorporated in products like microbeads, commonly found in skincare items (Song et al., 2024). Secondary microplastics are unintentionally produced from the breakdown of larger plastic waste already present in the environment (Enfrin *et al.,* 2019). They are formed from UV exposure, mechanical wear, temperature variations, and biodegradation. They are found much more abundant than primary microplastics (Hale et al., 2020). Due to the process of weathering the physical and chemical properties of microplastics change resulting in alterations to their environmental behaviour (Sun et al., 2020). The rate and mechanism of weathering of plastics depends on both the characteristics of plastics and environmental factors such as exposure to sunlight and temperature (Arp et al., 2021). Also, the impact of a specific environmental factor on the degradation rate is highly dependent on the type of plastic. The degradation rates of petrochemical-based polymers are slower in marine environments compared to landfills (Chamas et al., 2020).

Class based on shape

Microplastics classified based on their shape as beads, microspheres, films, irregular fragments, cylinders and fibres. The fibrous microplastics are found most dominant in the environment (Dris, et al., 2017). The toxicity and absorption ability of the MPs is affected by its shape and texture. Polyproplene microfibers were reported more toxic than spherical particles of polyethylene on amhipod, hyalella etc (Au et al., 2015). Fibers were stored in the gut for longer time causing serious harm to the organism.

Class based on size

Microplastics of different sizes including femto-size plastics (0.02–0.2 μm), pico-size plastics (0.2–2 μm), nano-size plastics (2–20 μm), micro-size plastics (20–200 μm), meso–size plastics (200–2000 μm), macro-size plastics (0.2–20 cm) and mega-size plastic (20–200 cm) are observed in environment. The size of MPs plays role in their ingestion, bioaccumulation and toxicity (Sieburth et al., 1978).

Class based on colour

Colour is an essential component that allows microplastics to penetrate the food chain through predators. They accidentally capture MPs due to resemblance with food items. MPs are observed in different colours ranged from transparent to opaque, light (white, green, and yellow) to dark (blue, black, brown, tan, and red) (Du et al., 2021).

Class based on composition

The type of polymer used to make microplastics determines their chemical composition. The most of materials are made up of synthetic polymers such as polyethylene and polypropylene, which are widely utilized in the textiles, cosmetics, and packaging sectors. Polyethylene terephthalate is another important polymer utilized in textile fibers and beverage bottles. This polymer is thicker in composition. The polymer such as polystyrene and polyvinyl chloride, which are mostly utilized in consumer items and building materials (Du et al., 2021).

Class based on surface properties

The positively charged polystyrene (PS) beads were absorbed by anionic character of the cellulose surface. Also the rough surface of the cellulose film provides additional binding sites, resulting in an excessive adsorption of positively charged PS beads (Nolte et al., 2017). The cell wall of the algae P. subcapitata had a higher affinity for neutral or positively charged PS than for negatively charged PS. The bacterial colonization is more common on eroded PP disks than on uneroded PP surfaces. The hydrophobic surface of plastic collects persistent organic pollutants (POPs) from marine water (Teuten, et al., 2007).

Class based on buoyancy

Microplastics with lower density than the surrounding water floats near the surface or suspended in sub-surface water, while MPs with high-density sink. MPs have dynamic density behavior, resulting in a cyclic distribution pattern in aquatic environments. Microorganisms

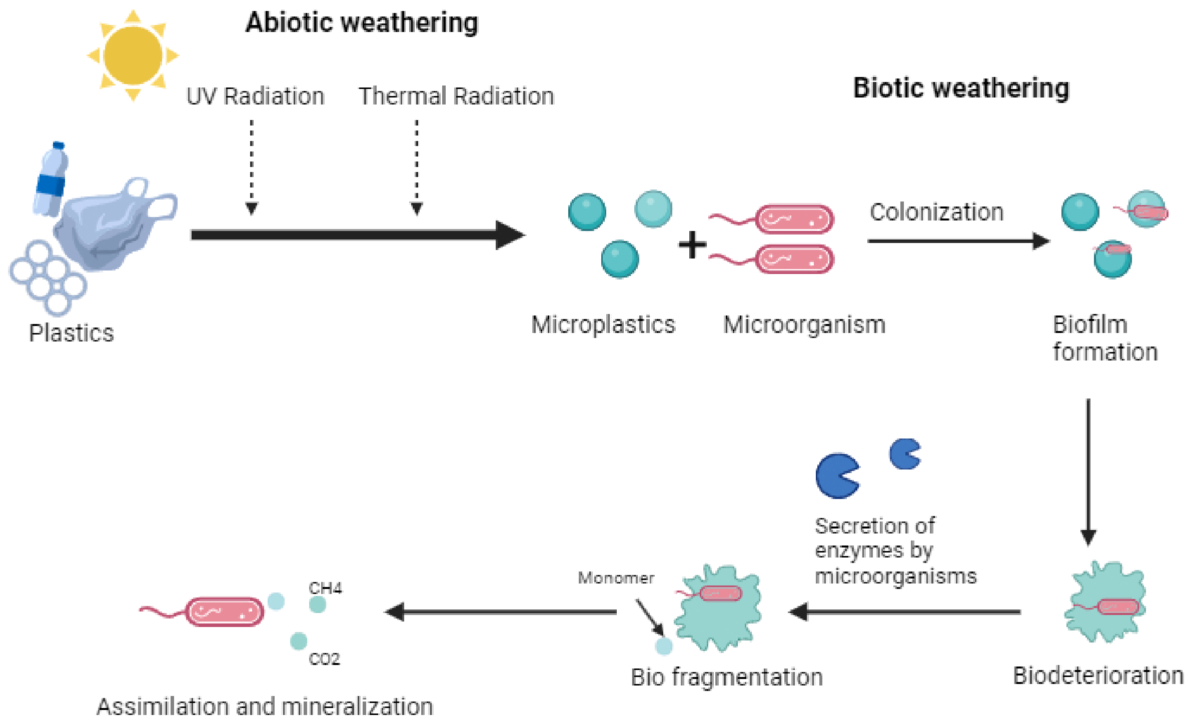

Fig. 1. Weathering of plastics (Abiotic weathering results in microplastics formation and simultaneous action by biotic agents leads to degradation of microplastics)

accumulate on the surface of MPs hence increase the density (Moore et al., 2001).

WEATHERING

Weathering is the process of formation of small size particles from large size plastic. Weathering process changes the physical and chemical properties of plastics. Figure 1 shows the weathering of plastics for generation of microplastics.

Abiotic weathering

In the aquatic environment, abiotic factors like tidal forces, waves, photooxidation altered the morphological and mechanical behaviour of plastics (Arp *et al.,* 2021). The molecular weight of polymers decreases during chemical fragmentation. Naturally, the effects of photo-oxidation and hydrolysis processes produce brittle materials, which promote mechanical degradation and resulted in the formation of micro and nano-plastic fragments. Abiotic weathering is of following types:

(i) Photodegradation

(ii) Thermal degradation

(i) Photodegradation

Photodegradation is considered as one of the most essential processes responsible for degradation of plastic in the environment. The mechanism of photodegradation of plastics typically involves free radical-mediated reactions triggered by solar irradiation. High energy ultraviolet (UV) irradiation, UV-B (290-315 nm) and medium-energy UV-A (315-400 nm), are responsible for degradation of plastic (Zhang *et al.,* 2020). UV radiation with wavelengths ranging from 290 to 400 nm, possesses sufficient energy (299–412 kJ/mol) to break the C–C bonds (284–368 kJ/mol) and C–H bonds (381–410 kJ/mol) in most of plastics (Duan *et al.,* 2021). Photo-oxidation weakens the plastic, making it more brittle and prone to fragmentation under mechanical pressures. Waves, sand abrasion, swelling and deswelling, and interactions with marine life contribute to the degradation of weak plastics (Andrady, 2017).

The process of plastic photodegradation involves three stages such as initiation, propagation, and termination. In the initiation stage, free radicals are created by breaking of polymer chain chemical bonds. During the propagation stage, radicals react with oxygen to form peroxyl radicals. Alongside the formation of hydroperoxides, additional complex radical reactions occur, resulting in auto-oxidation. The propagation eventually leads to either chain scission or crosslinking. The termination of the reaction occurs when two radicals combine to form inert products (Ali *et al.,* 2021).

(iii) Thermal degradation

Thermal degradation refers to the breakdown of plastics at high temperatures. At elevated temperatures, plastics can undergo thermo-oxidative reactions. The long polymer chains break down when enough heat is absorbed by the polymer due to overcoming of bond dissociation energy (Zhang et al., 2020). In aquatic environment, water dissolves heat more efficiently and lowers the temperature as compared to land. Moreover, toxic radicals produced during thermal degradation mostly ends up in landfills.

Biotic weathering

Plastics are also subjected to biotic weathering which occurs often simultaneously with abiotic processes (Arp et al., 2021).

(i) Biodegradation

Biodegradation is the process in which organic materials are degraded by living organisms. Microbes, including bacteria and fungi. The biodegradation process is influenced by various factors, such as the characteristics of the polymer, type of organism involved, and specifics of any pretreatment applied (Shah *et al.,* 2008). Effective biodegradation depends on the diversity of bacteria. Microbes often break down plastics into shorter chains known as monomers, which are subsequently ingested by microorganisms across semipermeable membranes and finally undergo mineralization within cells (Cai *et al.,* 2023). Initially, various physical and biological forces act upon the polymer. Physical forces such as heating, cooling, freezing, thawing, wetting, and drying cause mechanical damage like cracking of the polymer. Additionally, the growth of fungi on the polymer can lead to swelling and bursting, allowing the fungi to penetrate into polymer (Muthukumar *et al.,* 2015).

Degradation of plastic polymers by microorganisms involves three steps:

(a) Microorganisms attaching to the polymer's surface.

(b) Using the polymer as a carbon source, and

(c) Breaking down the polymer.

Microorganisms adhere to the surface of polymers and degrade by secreting enzymes to obtain energy for their growth (Elahi *et al.,* 2021). The breaking down of plastic polymers includes biodeterioration, bio fragmentation, mineralization and assimilation. Biodeterioration leads to the superficial breakdown of plastic surfaces, altering their physical, chemical, and mechanical properties. The formation of microbial biofilms on the plastic substrate significantly contributes to deterioration, causing severe chemical and physical degradation. The development of biofilms was influenced by the structure and composition of the plastic as well as by environmental conditions (Jaiswal *et al*., 2020). Following biodeterioration, the next phase is bio-fragmentation, characterized by enzymatic activity on plastic polymers (Cai et al., 2023). Plastic-degrading enzymes are broadly categorized into extracellular and intracellular types.

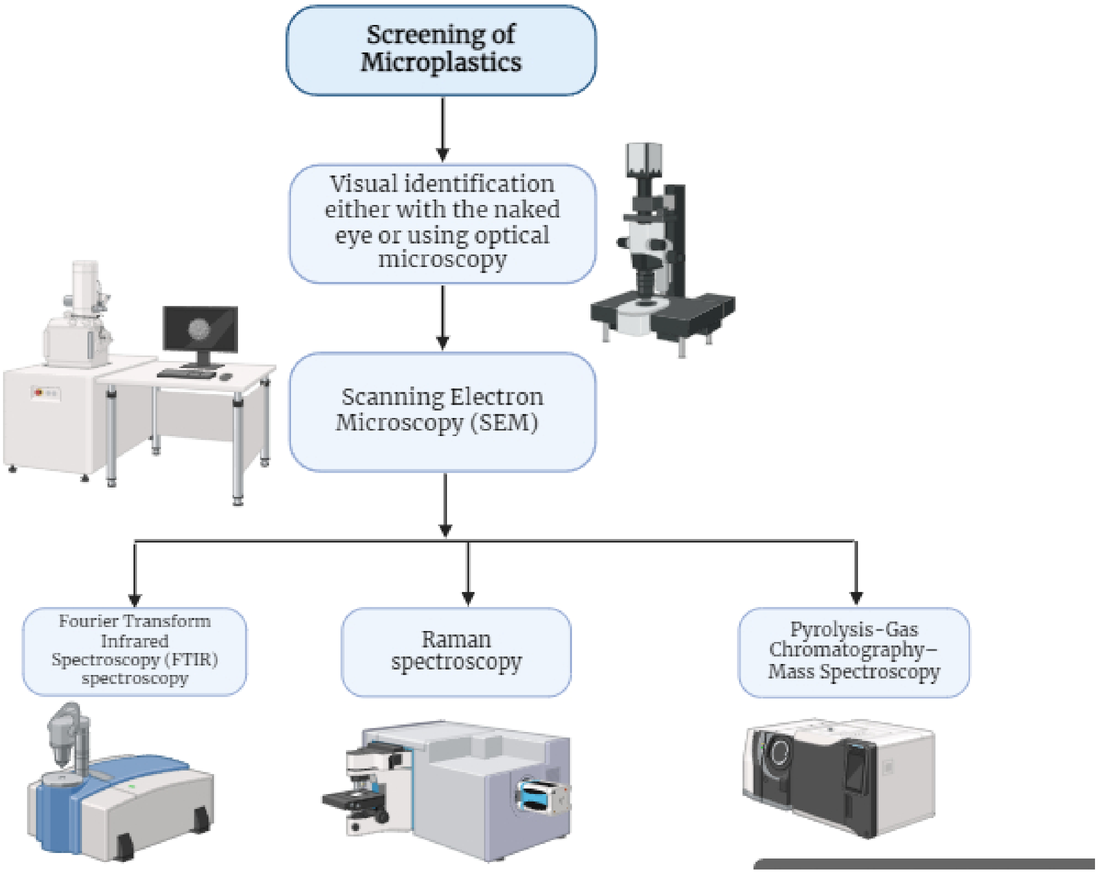

Fig. 2. Methods of detection of microplastics in environmental samples

Extracellular enzymes exhibit versatile reactivity from oxidative to hydrolytic functions. They primarily depolymerize long carbon chains of plastic into a mixture of oligomers, dimers, and occasionally monomers. Intracellular enzymes play a significant role in aerobic and anaerobic processes, converting intermediates into compounds, which can be absorbed by microbes (Amobonye *et al.,* 2021).

The final steps in biodegradation of plastics are mineralisation and assimilation. In mineralisation smaller monomers created by bio fragmentation pass through cell membrane, oxidised and used for biomass production (Cai *et al.,* 2023). Some monomers that cannot permeate through membranes remain outside and never assimilated. Assimilation involves incorporating atoms into microbial cells for complete degradation. Secondary metabolites resulting from assimilation are transported outside microbial cells and utilized for further degradation. The degradation of metabolites, both primary and secondary, releases oxidized products like CO_2, N_2, CH_4, and H_2O (Duan *et al*., 2021; Jaiswal *et al.,* 2020). Weathering influences the ingestion of particles by aquatic species, probably because, the particles resemble with natural food owing to their size (Arp *et al.,* 2021).

SCREENING OF MICROPLASTICS IN AQUATIC ENVIRONMENT

The most widely method used for identifying microplastics in aquatic system involves visual identification followed by confirmation of polymeric composition through chemical analysis. Mostly used methods of analysis of MPs include combination of optical and spectroscopic or thermo-analytical techniques. Different methods of detection of microplastics in environmental samples are shown in Figure 2.

Optical techniques

The initial analysis of the material is frequently performed by visual observation done through naked eye or optical microscope. The optical microscopy identifies indistinct particles by revealing surface texture and structural information (Silva et al., 2018). Shapes and colours are the primary criteria used for identifying potential microplastics. The shape of microplastics is essential for their classification and source identification. The particle size has a significant impact on migration of microplastics in the environment (Li at al., 2020). However, visual methods of analysis has numerous disadvantages; like accurateness of results are strongly impacted skill of examiner; microplastics smaller than 500 μm cannot be reliably distinguished; coloured particles are easier to be identified than white and transparent particles, easier to identify fibrous than other shapes. Stereomicroscopes cannot accurately distinguish between natural and synthetic particles. These disadvantages result in a significant error in visual identification findings. Therefore, it is essential to use both spectroscopic instruments and other analytical techniques for the identification of microplastics (Lv et al., 2021).

Scanning electron microscopy (SEM)

Scanning electron microscopy employs a high-intensity electron beam to scan the surfaces of polymer. This technique, combined with energy dispersive X-ray spectroscopy (EDS), effectively identifies microplastics (MPs), nanoparticles (NPs), and any organic pollutants attached to their surfaces (Adhikari et al., 2022). This combined technique is referred to as SEM/EDS or SEM/EDX analysis. SEM produces micrographs, while EDS determines the chemical composition of the sample (Wirnkor et al., 2019). Visualization of samples is possible when the surface conducts electricity, improved by coating the material targets with conductive metals such as palladium, platinum, tungsten, and gold. SEM has been used for effectively differentiating MPs varying in size from 1 μm to 1mm (Adhikari et al., 2022). SEM is employed to analyse the weathering progress of microplastics retrieved from natural environments by examining surface textures such as cracks and pits of particles. Although SEM is effectively used to investigate the surface of microplastics, it is unsuitable for handling large quantities of samples.

Fourier transforms infrared spectroscopy (FTIR)

FTIR spectroscopy is often used for the qualitative analysis of microplastics. By comparing the spectra of samples with those of known plastics, the polymer type can be quickly and directly identified (Silva et al., 2018). FTIR spectra is determined by measuring the absorption of infrared light, allowing for the identification of functional groups within microplastics and providing valuable information about the polymer (Sharma et al., 2024, Murugan et al., 2023). FTIR is capable of analyzing small particles, providing more reliable identification results. For instance, micro-FTIR spectroscopy is used to detect particles as small as 20 μm (Chen et al., 2020). FTIR to identify microplastics necessitates highly trained operators. This has limited the use of FTIR in characterizing large quantities of microplastics. Despite its limitations, FTIR is reliable and most commonly used technique for characterizing microplastics (Chen et al., 2020).

Raman spectroscopy

Raman spectroscopy is an advanced analytical technique utilized for detecting microplastics. The primary advantages of Raman spectroscopy are ability to examine small particles upto 1 μm size. It provides a superior response to non-polar plastic functional groups compared to other analytical methods (Mai et al., 2018). Raman spectroscopy depends on scattered light to study molecular vibrations, providing high specificity in identifying the chemical structure of microplastics (Sharma et al., 2024).

There are certain disadvantages to utilizing Raman spectroscopy to analyze microplastics. To reduce the fluorescence influence on the spectrum, environmental materials should be are purified before recording Raman spectra (Murugan et al., 2023). Choosing an appropriate wavelength for Raman laser spectroscopy is crucial to balance the enhancement of signal intensity and the suppression of sample fluorescence (Mai et al., 2018).

Pyrolysis-Gas Chromatography-Mass Spectroscopy

Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) has been significantly employed for the chemical identification of macromolecules that are too large to be characterized by liquid or gas chromatography (Picó et al., 2020). Pyrolysis involves controlled thermal degradation to decompose macromolecules into simpler volatile molecules. The simpler molecules are separated using gas chromatography and detected by mass spectrometry (Sharma *et al.,* 2024).

This technique has some advantages like it does not require sample pretreatment and simultaneous identification of the polymer type and organic plastic. However, there are certain limitations like it sometime generate incorrect results since different polymers create identical thermal breakdown products. Py-GC-MS causes harm to materials and cannot determine the sizes, shapes, or concentrations of microplastics (Wu et al., 2020). MP particles must be larger than 100 mm to be manually transferred to the pyrolysis tube for Pyr-GC/MS analysis. Furthermore, only one microplastic particle can be analyzed per run, with each analysis taking over 30 minutes (Chen et al., 2020). Table 1 show the advantages and limitations of various techniques used for analysis of MPs.

SOURCES AND PATHWAYS

The majority of plastics are produced and utilized on land, with the exception of its application in marine. According to various research studies, the highest proportion of microplastics identified in aquatic environments originates from textile washing. Additionally, personal care items, cosmetic products, tires, agricultural plastic films, artificial turf, road paints, landfills, litter, packaging, and the construction industry are also significant sources of microplastic pollution (Xu et al., 2020).

Primary microplastics enter aquatic ecosystems through household sewage discharge and the dumping of industrial effluents. Microplastics are present in facial cleansers, resin pellets, toothpaste, and cosmetics such as shower/bath gels, peelings, scrubs, deodorant, eyeshadow, makeup foundation, blush powders, mascara, baby products, shaving cream, bubble bath lotions, nail polish, hair colouring, insect repellents, and sunscreen. Microplastics are also utilized in air blasting technology, used to remove rust and paint from machinery, boat hulls, and engines (Auta et al., 2020). Large plastic items like fishing gear, plastic bags, plastic bottles, and food containers made of plastic, after breaking down, become sources of secondary microplastics in aquatic bodies (Osman et al., 2023).

Microplastics occurrence in freshwater ecosystems

Freshwater ecosystems include rivers, lakes, streams and ponds. Microplastic pollution has undoubtedly reached to fresh water from terrestrial sources and act as channels for transporting microplastics to seas andoceans. Microplastics also enter through the fragmentation of larger items and microplastics accumulate in sediments (Horton et al., 2018). Major sources of microplastics in the environment are shown in Figure 3.

The presence and distribution of microplastics in freshwater ecosystems is directly influenced by factors that include anthropogenic activities (agricultural practices, industrial operations, fishing), climatic patterns and hydrological conditions (Wu et al., 2020).

Table 1. Advantages and limitations of techniques used for analysis of MPs

Analysis technique	Advantages	Limitations
Optical technique	Ability to identify a large number of microplastic particles in a shorter amount of time. Cost-effective and can be performed without the need for specialized equipment.	The strong influence of examiner subjectivity on results. Microplastics smaller than 500 µm are difficult to distinguish. Coloured particles are more easily identified than white or transparent ones. Fibrous particles are also easier to recognize compared to other shapes. Cannot accurately differentiate between natural and synthetic particles. It has high costs and the need for specialized expertise.
Scanning electron microscopy (SEM)	Can effectively differentiate MPs varying in size from 1 µm to 1mm. Analyse the weathering progress of microplastics retrieved from natural environments. This method can investigate the surface of microplastics.	Can be performed only on solid samples which conduct electricity. Samples need to be well prepared thus unsuitable for handling large quantities and time consuming. It has high costs and the need for specialized expertise
Fourier transforms infrared spectroscopy (FTIR)	Qualitative analysis of microplastics in a non-destructive manner. Can reliably detect particles as small as 20 µm. Provides rapid results within a short time frame.	The equipment is expensive and requires specialized training to operate. Sample preparation can sometimes be challenging. Not reliable when the target particles are smaller than 20 mm. It has high costs and the need for specialized expertise
Raman spectroscopy	Ability to analyse particles as small as 1 µm. It offers a superior response to non-polar plastic functional groups compared to other analytical techniques. Raman spectroscopy provides high specificity in identifying the chemical structure of microplastics.	Laser-induced fluorescence can cause baseline variation and selecting appropriate wavelength for the Raman laser is essential. Requires extensive sample preparation before recording Raman spectra. It is a very expensive technique. It has high costs and the need for specialized expertise
Pyrolysis-Gas Chromatography–Mass Spectroscopy	It does not require sample pretreatment. Allows for the simultaneous identification of both the polymer type and associated organic plastic additives.	This technique may produce inaccurate results, as different polymers can generate identical thermal breakdown products. Destructive method and cannot determine the size, shape, or concentration of microplastics. Suitable for Microplastic particles which are larger than 100 mm. It has high costs and the need for specialized expertise

Microplastic contamination of freshwater ecosystems can occur through three primary pathways: 1) discharge of effluent from wastewater treatment plants, 2) flooding of wastewater sewers during periods of heavy rainfall, and 3) agricultural drainage and run-off from farm lands (Anderson et al., 2016).

Microplastics occurrence in marine ecosystems

Ocean is regarded as the largest global sink of MPs (Tang et al., 2023). The sources of marine microplastic pollution can arises from; 1) inland-based, 2) sea-based, and 3) air-based sources (Yang et al., 2021). 80% of marine debris originates on terrestrial environments (Coyle et al., 2020). Plastic litter being produced on land, from municipal drainage systems and sewage effluents, often finds its way into the sea through rivers or is blown offshore. Plastic waste generated by beach-related tourismis frequently discarded directly into the water system (Cole et al., 2011).

The fishing, shipping, and offshore industries such as petrochemical are major sea-based sources of plastic pollution. Discarded or lost fishing gear, emissions and leaks associated with large shipping operations, and illegal dumping of waste from ships, naval vessels and other

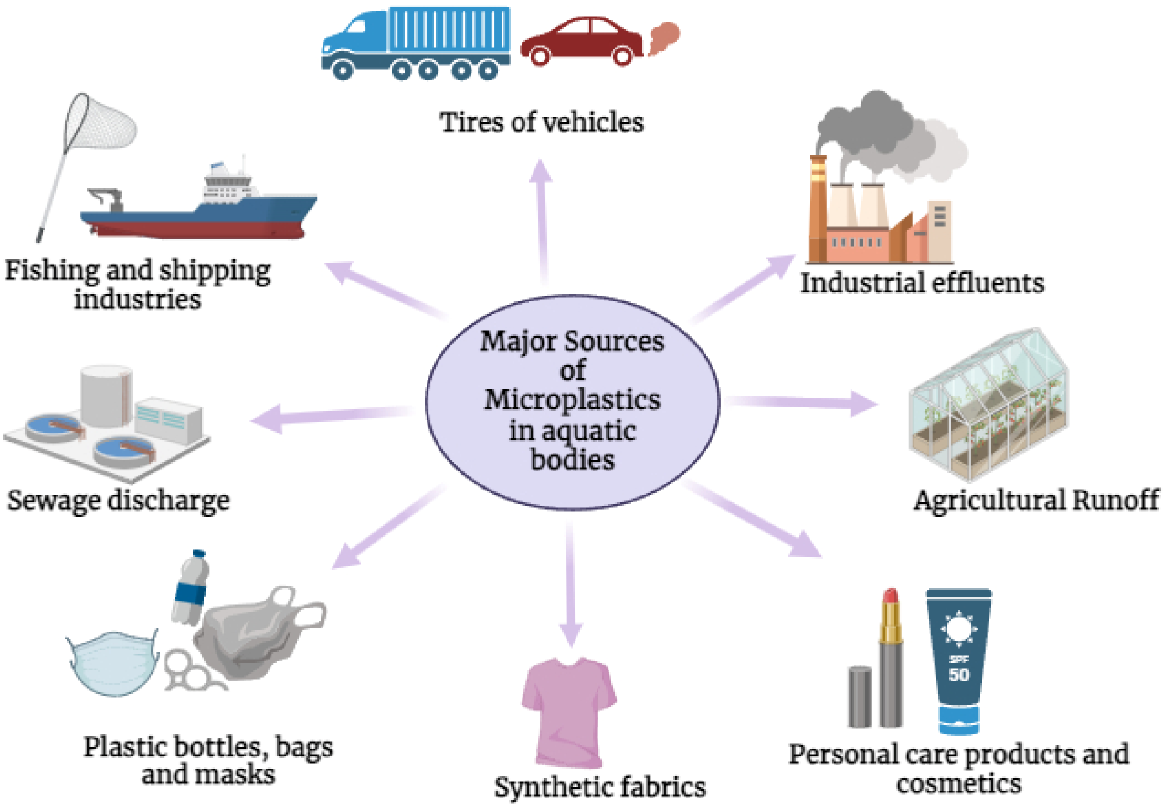

Fig. 3. Major sources of microplastics in the environment

offshore platforms, releasing effluents from offshore industries and lost containers are a major source of sea-based sources of plastic pollution. Air borne microplastics also contribute to microplastic pollution in marine ecosystems (Osma et al., 2023).

FATE OF MICROPLASTICS

Particle mobility and transport mechanisms play a significant role in the interactions between microplastics (MPs) and environment, hence influencing their continued existence and ultimate fate. Sizes, densities, and shapes further influence dispersion, resuspension, and sinking rates of microplastics (Mendoza et al., 2021).

The migration of microplastics in aquatic systems can be categorized into horizontal and vertical movements, which are closely related to flow velocity, flow variations, depth, bottom topography of the water, wind speed, and particle density. For horizontal transport, which is the primary mode of MPs movement, ocean currents significantly contribute to the migration, distribution, and accumulation of MPs in the open ocean. For vertical transport, density or buoyancy and the adsorption of MPs are some of the important factors. Wind force also plays a crucial role in vertical transportation. All these determine the sinking rate of MPs (Du et al., 2021). Microplastics enter water bodies and eventually reach the ocean. It is believed that 70% of marine debris sinks into the soil at the ocean floor. Of the remaining 30%, half floats on top of the saltwater (15%) and the other half is found in coastal regions (15%) (Wu et al., 2019). Microplastics enter and spread throughout the ocean leading to widespread distributionacross the globe, from major ocean gyres (e.g., the Pacific Ocean, the Atlantic Ocean, the Indian Ocean) to the polar regions and the equator, from densely populated areas to isolated islands, and from beaches to the deep sea.

Most microplastics are less dense than seawater and float on the surface, leading to their extensive accumulation in large subtropical oceanic whorls where convergent surface currents concentrate and retain debris for extended periods. The total plastic load on the ocean surface ranges from 7,000 to 35,000 tons globally (Cózar et al., 2014). However, surveys indicate that at least 4.8 million tonnes of plastic enter the marine environment annually, highlighting a significant discrepancy. This suggests that a substantial portion of plastics sinks to unknown depths (Wu et al., 2019; Yang et al., 2021).

Ingestion of MPs by aquatic organism is another fate of MPs in aquatic ecosystems resulting in different scenarios like elimination from organisms through excretion or the production of pseudo faeces or retention within the organism, translocation between tissues, or organisms that have ingested microplastics may be eaten by higher animals in the food web, transferring the microplastics to other animals at higher trophic levels (Auta et al., 2017).

The changing climate also has various effects on the fate of microplastics. Rising temperatures and increased UV radiation also results in degradation of plastics, leading to increased fragmentation and release of smaller microplastic particles. Climate change can modify ocean currents and circulation patterns, affecting the transport and distribution of microplastics. Extreme weather events like storms and floods, which are becoming more frequent and intense due to climate change, can also redistribute microplastics, increasing the potential for contamination (Haque et al., 2023).

MICROPLASTICS IN AQUATIC ORGANISMS

Aquatic foods are described as animals, plants and microorganisms which originate in aquatic bodies. Finfish, crustaceans (such as crabs and shrimp), cephalopods (octopus and squids), other molluscs (clams, cockles, and sea snails), aquatic plants (water spinach; Ipomoea aquatica), algae (seaweed) and other aquatic animals (mammals, insects and sea cucumbers) are included in aquatic foods (Golden et al., 2021). These are known for supplying nutrients and ensuring food security, emphasizing the pressing need to protect and manage this natural resource from pollution.

Ingestion of microplastics by fishes

Fish consume microplastics through three basic mechanisms. Firstly, the intakes of microplastics have occurred by mistaken with food. Second, microplastics are eaten unknowingly or accidentally while foraging. Third, they have been transported through the food chain, implying the possible transmission of microplastics from prey to predator. Fishes encounter microplastics primarily during active feeding (Parker et al., 2021). The type of feeding behaviour exhibited by a species has influence on the ingestion of microplastics. Generally, benthic feeders are expected to ingest more MPs compared to pelagic feeders. Additionally, the presence of MPs within the gastrointestinal tract of fish exhibits an inverse relationship with the quantity of plants or algae present, whereas it demonstrates a direct relationship with the occurrence of glass items or prevailing food items. Microplastics are also found in fish's gills and skin. Fish features such as gill surface area, structure, and habitat correlate with the passive buildup of microplastics on the gills. Thus, MPs are passively absorbed during swimming and breathing (Parker et al., 2021). Indirect ingestion, often referred to as "trophic transfer," happens when organisms consume preys that have previously ingested microplastics. Microplastic-contaminated feedstock poses a potential risk of microplastic exposure to fishes as the fishmeal, commonly utilized in fish feed production, which can transfer microplastics present within the fish to consumers (Walkinshaw et al., 2020).

Accumulation of microplastics in fishes

Fishes consume microplastics, which accumulate in their bodies due to the small size and poor biodegradability of the particles. The size of microplastics influences their accumulation in organisms. Smaller MPs particles are more easily absorbed and accumulated by organisms, leading to reduced growth rate, fecundity, and longevity (Du et al., 2021). Additionally, factors such as local human activity, contamination levels, and geographic location also accelerate the accumulation of MPs in fishes. MPs accumulate in different tissues of fish body (Makhdoumi et al., 2023). The most common techniques for detecting microplastics in various tissues and organs of fish include optical microscopy, scanning electron microscopy, fluorescence microscopy, Raman microscopy, and Fourier transform infrared spectroscopy (Xu et al., 2020).

Impact of microplastics on fishes

Microplastics have become widespread in nearly all aquatic environments. These particles are easily accessible to a diverse array of aquatic life, including fishes, sediments and certain planktonic creatures (Wang et al., 2020). The studies have documented the presence of microplastics in 728 fish species worldwide (Hossain et al., 2022). After consumption, microplastics impact fishes in three ways; (a) through accumulation of the microplastics in the body of fishleading to physical effects (obstruction of the gastrointestinal tract); (b) the release of plasticizers, additives, and other toxic chemicals from within the microplastics; and (c) by the release of harmful pollutants bound to the microplastics (Parker et al., 2020). Long term impacts of MPs in environmental matrices have been linked to a variety of health impacts, including oxidative stress, endocrine disruption, genotoxicity, immunotoxicity, cytotoxicity, neurotoxicity etc (Vaid et al., 2022). MPs can sorb microcontaminants such as POPs and HMs on surface for pathogen biofilm formation. Microplastics inhalation causes oxidative stress lungs, resulting in coughing, sneezing, shortness of breath, fatigue, and dizziness due to low blood oxygen levels. Microplastics can transport environmental pollutants, which harms human lung cells and increases the risk of chronic obstructive pulmonary disease. The impacts of MPs on the food chain and their transfer to humans are shown in scheme 1. The possible effects of microplastics on different organs of fishes are shown in Figure 4. Cumulative impacts of MPs on fishes are discussed as follow:

Gastrointestinal tracts

The gastrointestinal tract of fishes is the most studied organ for the accumulation of microplastics (Franzellitti et al., 2021). Microplastics cause obstruction in the intestine and alter the histopathological function of intestine. However, they have a low potential to accumulate in the fish digestive tract and translocated to the liver. The microplastics get absorbed through the intestinal lining, from where it enters the bloodstream, translocate to various organs, and threaten survival of the fish.

Microplastics in three commonly consumed fish species like leaping mullet (*Chelon saliens*), common carp (*Cyprinus carpio*), and Caspian kutum (*Rutilus caspicus*) from the southern Caspian Sea have been reported. A significant correlation was observed between MP concentration in the fish guts and growth environments of the fishes. MPs accumulation in gut is primarily influenced by the surrounding water, rather than biological factors like fish length, weight, and age (Nematollahi et al., 2021).

Immune responses

Exposure to microplastics resulted in intestinal damage in fishes, directly affecting their immune system through intestinal inflammation and cytokine expression. The fish's immune system comprises of innate immune system and adaptive immune system which protects them from foreign substances. MPs accumulation triggers the fish's innate immune system. Physical blockages and chemical toxicity from MPs buildup in fish tissues could induce immune response like increased neutrophil, lysozyme levels, decreased phagocytosis etc (Kim et al.,

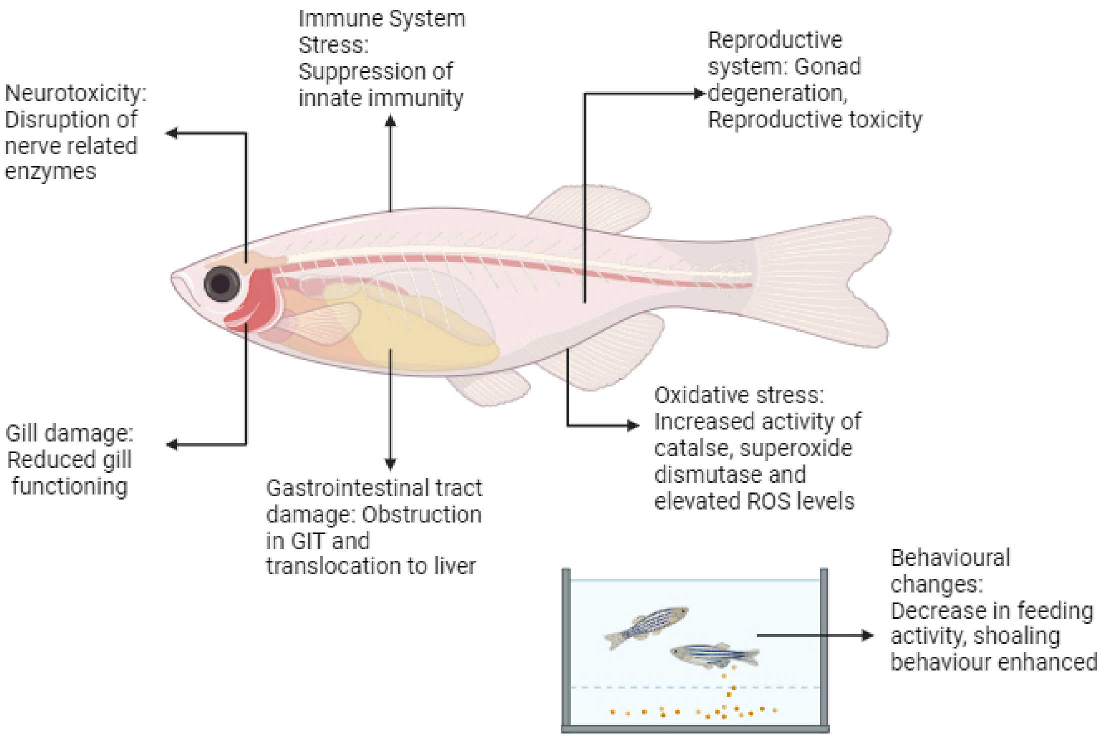

Fig. 4. Possible effects of microplastics on different organs of fishes

2021). Polycarbonate and polystyrene microparticles can suppress innate immunity in fish when neutrophils are exposed to microplastics. Microplastics can disrupt the natural defence mechanisms in fish and serve as stressors.

In yellow catfish and zebrafish, microplastics activated immune mechanisms through the NF-κB signalling pathway, resulting in increased expression of related signalling factors. MPs significantly increased the expressions of HIF-1α and TNF-α but inhibited the expression of IFN at high concentration under normal oxygen levels (Li et al., 2021).

Reduced gill functioning

Gills provide a route for uptake of microplastics in fishes (Santillo et al., 2017). Microplastics can damage the gills of fish. There are several histological evidences of gill damage like sloughing, hyperplasia, fusion. It can affect the permeability of gills, undermine the barrier function, result in increased ion losses, diminish active uptake rates and disturb electrochemical gradients (Zink et al., 2024).

Neurotoxicity

Exposure to microplastics cause neurotoxicity in fish by disrupting nerve-related enzymes and damaging lipid peroxidation. Various neurotransmitters, such as dopamine, gamma-aminobutyric acid, melatonin, vasopressin, serotonin, oxytocin, and kisspeptin are inhibited by exposureof microplastics in fish. Acetylcholinesterase (AchE) is especially used as a primary indicator of neurotoxicity among various neurotransmitters (Kim et al., 2021). AchE is a crucial enzyme in nerve conduction that degrades acetylcholine thus terminating the excitatory effect of neurotransmitters, and ensures normal nerve signal transmission. When acetylcholinesterase is inhibited, acetylcholine accumulates excessively, causing cholinergic nerves to become over-excited, leading to neurological disorders (Yin et al., 2021).

Barboza et al (2023) reported that microplastics were found in the brain of a fish species, European seabass (*Dicentrarchus labrax*) in which they observed major proportion (70%) of small microplastic particles (less than 50 μ m in size) in the brains of *D. labrax* specimens suggesting that smaller particles are more likely to penetrate the blood-brain barrier. The presence of microplastics in fish brains can lead to numerous adverse effects, including degeneration and necrosis of neurons (Barboza et al., 2023). The oxidative stress caused by microplastics in brain tissue leads to DNA damage, mitochondrial dysfunction, and ultimately cell death due to free radical attacks on neurons (Yin et al., 2021).

Impact on reproductions

Reproduction is a highly energy-demanding process, and insufficient nutritional intake can negatively affect an organism's fecundity. Reproductive toxicity causes harmful effects on various stages of the reproductive cycle, including gametogenesis, the quality of gametes and oocytes, egg production, fecundity, and sperm swimming speed.

It was demonstrated that the continuous exposure to waterborne polystyrene microplastic pollution can adversely affect the reproductive organs of fish. Exposure to high concentrations of microplastics increases ROS levels in the gonads of both male and female zebrafish. In male zebrafish, exposure of microplastics caused histological changes, such as basement membrane thinning in the testes, alongside increased apoptosis, which can further affect gamete production (Qiang & Cheng, 2021).

In another study on marine medaka fish microplastics delayed gonad maturation and reduced fecundity in female fish. The alterations in the hypothalamus-pituitary-gonadal (HPG) axis were observed as microplastic exposure had significantly negative regulatory effects on the female HPG axis. The transcription of genes involved in the steroidogenesis pathway in females was also downregulated. This disruption led to decreased concentrations of 17b-estradiol (E2) and testosterone (T) in female plasma. Additionally, parental exposure to 20 mg/L microplastics delayed incubation time and reduced the hatching rate, heart rate, and body length of the offspring (Wang et al., 2019). Microplastics impair the reproduction and development by disrupting hormone secretion. MPs cause endocrine disorders, damage the blood-testis barrier, lead to inflammation, atrophy, and degeneration of the testes, gamete malformations (Yin et al., 2021).

Change in behaviour

The behaviour is highly sensitive to environmental stimuli and chemical exposure. Behavioural changes related to feeding hold ecological significance as it impacts the ability to locate and obtain food, which can influence population dynamics. Fish's appetite is strongly impacted by their swimming and avoidance behaviours, which are essential for their survival (Sharma et al., 2019). It was found that after exposure of polystyrene microplastic the feeding time increased which confirmed the significant decrease in the feeding activity of fish exposed to microplastics. Additionally, the foraging time quickly decreased with exposure to polystyrene microplastics. Shortened foraging time and shoaling behaviour indicated an inhibited ability of fished to hunt after microplastics exposure (Yin et al., 2018).

Oxidative stress

Oxidative stress in fishes arises from exposure to pollutants, pathogens, and environmental stressors (Subaramaniyam et al., 2023). Upon absorption of microplastic particles, the alteration of the lipid bilayer and formation of pores and intracellular generation of reactive oxygen species (ROS) occured. Consequently, the elevated ROS levels lead to mitochondrial dysfunction, the release of pro-inflammatory cytokines, and cellular damage (Kadac-Czapska et al., 2024).

The activities of superoxide dismutase, catalase, as well as lipid peroxidation and DNA fragmentation in fishes increased with MPs exposure, indicating excessive reactive oxygen species (ROS) production (Hamed et al.,2020). Excessive ROS production or weakened antioxidant defences leads to oxidative stress, which is associated with several health issues, such as tissue damage, organ dysfunction, and compromised immune function (Subaramaniyam et al., 2023).

Mechanism of MPs on biological system

The intake of MPs causes anatomical and functional abnormalities in the digestive systems, resulting in nutritional and developmental difficulties in fish. MPs in the fishes, causing death before they reach maturity. The most prevalent impacts of MPs are oxidative stress, reduced mobility, gene expression disruption, and reproductive organ damage (Zhao et al., 2021). Growth suppression, dysbiosis of the fish gut, weight loss, disruption of the liver's anti-oxidative state, damage to reproductive organs, and growth retardation were reported in some fishes. Fishes also experienced stress, oxidative damage, survival, behavioral changes, and disruption to essential immune system processes (Li et al., 2021). The mechanisms of impact of microplastics on fishes are shown in scheme 2.

INGESTION OF MICROPLASTICS BY AQUATIC INVERTEBRATES

Besides fish, several other aquatic organisms have also affected by exposure to different types of microplastics (Badea et al., 2023). Invertebrates constitute an essential primary element of marine, brackish, and freshwater biodiversity (Pisani et al., 2022). Large numbers of aquatic invertebrates are highly susceptible to microplastics, resulting in both lethal and sub-lethal effects (Hodkovicova et al., 2022). The severity of impact varied with feeding strategies. Omnivores and deposit feeders are mostly greatly affected. Filter feeders experienced fewer impacts due to MPs. In many organisms ingested MPs cannot broken down enzymatically due to lack the specific enzymes needed to degrade polymers (Hodkovicova et al., 2022). The exposure of microplastics causes various harmful effects to aquatic invertebrates.

Mollusca

Mollusca is the second-largest phylum of invertebrate animals and an important food source for humans. Microplastics were found in commercially edible bivalves, such as mussels, oysters, and clams (Zhang et al., 2020). The size of plastic particles is similar to planktonic food, making filter-feeding organisms more susceptible for microplastics consumption. Once ingested, microplastics can be excreted as faces, accumulate in the gut, or be transferred to the circulatory systems through the intestinal wall (Khanjani et al., 2023). The effects of microplastics, including clogging or injuring gills and digestive tract, constitute the initial exposure to bivalves. Microplastics directly harm bivalves by hindering their filtration activity. In case of bivalves organs like digestive gland and gills are the most obstructed by microplastic exposure, exhibiting reduction in contacts between adjacent filaments, thickening and disorganization of the gill epithelium, infiltration of haemocytes (Sendra et al., 2021).

Microplastics entered into haemolymph through the intestinal wall and travel to other tissues (Hollerová et al., 2021). Polystyrene exhibited toxic effects on freshwater benthic clams, *Corbicula fluminea*. Various modifications were reported, including the activation of an innate immune response, the triggering of complement and coagulation cascades, and epithelial damage in the intestines.

Arthropoda

Aquatic insects spend at least one life stage in aquatic environments such as streams, rivers, lakes, estuaries, and oceans. Immature aquatic insects break down plastic large plastics particles into smaller meso, micro, and nano plastics (Ribeiro-Brasil et al., 2022). Among 70,000 species, Crustacea have prominent role for reduction of plastic pollution (Pisani et al., 2022). Copepod Calanus helgolandicus exposed to polystyrene microbeads have lower reproductive production, reduced food ingestion, energy depletion. The copepod *Calanus helgolandicus* on exposure to polystyrene microbeads, exhibited decreased reproductive output, diminished food consumption, energetic depletion and altered behaviour (Cole et al., 2015).

Gray and Weinstein (2017) examined the impact of polystyrene on the shrimp species *Palaemonetespaludosus*. On exposure to 75 µm particles, longer retention was observed in the gut with a subsequent increase in mortality rate (up to 55% compared to the control group). It was attributed due to gastrointestinal blockage, as clusters of microparticles found in the gastrointestinal tracts (Hollerová et al., 2021).

Annelida

Several studies have been reported on the impact of microplastics on annelids focusing on oxidative stress and energy reserves (Pires et al., 2022). The impact of MP on benthic, marine and freshwater invertebrates, including annelids, arthropods, ascidians, sea urchins, bivalve mollusks, and rotifers, significant changes were observed, with increased mortality in the polychaete *Perinereisaibuhitensis* (Zolotova et al., 2022).

The commercial plastic microspheres potentially causes neurotoxicity in *Hedistediversicolor*. The whole-body acetylcholinesterase (AChE) activity, a common marker for neurotoxic effects was found lower in polychaetes exposed to MPs as compared to unexposed polychaetes. Worms exposed to MPs also showed significantly reduced activities of antioxidant enzymes, indicated a suppression of the cellular antioxidative system in the worms (Urban-Malinga et al., 2022).

CONCLUSIONS

Microplastics contamination in aquatic environments has been reported. Major sources of mircoplatics in water includes sewage-contaminated water, industrial discharges, and fertilizers applied to crops, automobile tires, textiles, personal care products, cosmetics, and fishing gear. In the aquatic environment, abiotic factors such as tidal forces, waves, and photooxidation alter the morphological and mechanical properties of plastics. The presence of microplastics in the environment was detected using techniques like optical microscopy, electron microscopy, FTIR, and Raman spectroscopy. Microplastics have been reported in various fish species and aquatic invertebrates, with different concentrations. Microplastics cause detrimental effects, ranging from physical harm due to ingestion and entanglement to biochemical and physiological disruptions. Additionally, microplastics act as vectors for harmful chemical substances, including heavy metals, insecticides, pesticides, and other organic pollutants. Public awareness and policymaking on impact of microplastics pollution on human health and the environment should contribute to minimize the harms caused by microplastics. Moreover, the danger of microplastics exposure should be detected using health risk assessment models developed using machine learning and artificial intelligence in near future.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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