

Review

Microplastics influencing aquatic environment and human health: A review of source, determination, distribution, removal, degradation, management strategy and future perspective

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ABSTRACT

Microplastics (MPs) are produced from various primary and secondary sources and pose multifaceted environmental problems. They are of non-biodegradable nature and may stay in aquatic environments for a long time period. The present review has covered novel aspects pertaining to MPs that were not covered in earlier studies. It has been observed that several methods are being employed for samples collection, extraction and identification of MPs and polymer types using various equipment, chemicals and instrumental techniques. Aquatic species mistakenly ingest MPs, considering them prey and through food-chain, and then suffer from various metabolic disorders. The consumption of seafood and fish may consequently cause health implications in humans. Certain plasticizers are added during manufacturing to provide colour, durability, flexibility, and strength to plastics, but they leach out during usage, storage, and transport, as well as after entering the bodies of aquatic species and human beings. The leached chemicals (bisphenol-A, triclosan, phthalates, etc.) act as endocrine disrupting chemicals (EDCs), which effect on homeostasis; thereby causing neurotoxicity, cytotoxicity, reproductive problems, adverse behaviour and autism. Negative influence of MPs on carbon sequestration potential of water bodies is also observed, however more studies are required to understand it with a detail mechanism under natural conditions. The wastewater treatment plants are found to remove a large amount of MPs, but in turn, also act as significant sources of their release in sludge and effluents. Further, it is covered that how advanced oxidation processes, thermal- and photo-oxidation, fungi, algae and microbes degrade the plastics and increase their numbers in the surrounding environment. The management strategy comprising recovery of energy and other valuable by-products from plastic wastes, recycling and regulatory framework; are also

Abbreviation: Acrylonitrile butadiene styrene, ABS; bentonite, BT; bisphenol-A, BPA; butyl-benzyl phthalate, BBP; Bis(hydroxyethyl)terephthalate, BHET; cellophane, CP; cellulose acetate, CA; cellulose acetate butyrate, CAB; di-butyl phthalate, DBP; dichloro-diphenyl-trichloroethane, DDT; diethyl phthalate, DEP; di-2-ethylhexyl phthalate, DEHP; di-iso-decyl phthalate, DiDP; di-isononyl phthalate, DiNP; dimethyl terephthalate, DMT; endocrine disrupting chemicals, EDCs; environmental stress cracking, ESC; ethylene glycol, EG; ethylene vinyl acetate, EVA; hexachlorocyclohexanes, HCHs; high-density polyethylene, HDPE; high modulus and low shrinkage PET, HMLS-PET; linear low-density polyethylene, LLDPE; low-density polyethylene, LDPE; monoethylene glycol, MEG; microplastics, MPs; mono-2-hydroxyethyl terephthalate, MHET; nanoplastics, NPs; persistent organic pollutants, POPs; polyacrylamide, PAM; polyacrylonitrile, PAN; polyamide, PA; polybrominated diphenyl ethers, PBDE; polybutadiene, PB; polybutylene terephthalate polycarbonate, PBT; PC, polychlorinated biphenyls, PCBs, polychloroprene, PCP, polycyclic aromatic hydrocarbons, PAHs, polydimethylsiloxane, PDMS, polyester, PES, polyethylene, PE, polyethylene chlorinated, PEC, polyethylene terephthalate, PET, polyethylene oxide, PEO, polyimide, PI, polymethyl methacrylate, PMM, polyolefin, PO, polypropylene, PP, polystyrene, PS, polystyrene acrylonitrile, PSA, polytetrafluoroethylene, PTFE, polyurethane, PU, polyvinyl acetate, PVA, polyvinyl acetate ethylene, PVAE, polyvinyl chloride, PVC, polyvinyl stearate, PVS, styrene acrylate, PO, propylene oxide, SA, tetrabromobisphenol-A, TPA, teraphthlic acid TBBPA; vinyl acetate copolymer, VAC; wastewater treatment plants, WWTPs.

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described in detail. The future perspectives can be of paramount importance to control MPs generation and their abundance in the aquatic and other types of environments. The studies in future need to focus on advanced filtration techniques, advanced oxidation processes, energy recovery from plastic wastes and influences of MPs on carbon sequestration in aquatic environment and human health.

1. Introduction

The plastics have a low-cost, durability, strength and light resistant properties; therefore are being used in a wide range of applications (Bujaczek et al., 2021; Sharma et al., 2023; Razaviarani et al., 2024). They contain a high molecular weight and on being exposed to wind, flowing water, heat and microorganisms, get changed to MPs (≤ 5 mm); followed by NPs (≤ 1 μ m; Thacharodi et al., 2024). The global production of plastics was reached about 1.7 million tons in 1950, 355 million tons in 2016, and 367 million tons in 2020. Its production is expected to cross 1,000 million tons by 2050 (Hale et al., 2020; UNEP, 2021; Bhatia et al., 2024). The MPs have been found in almost all aquatic habitats, ranging from rivers to deep oceans. The estuaries, lakes, rivers, and oceans receive MPs from surrounding regions and anthropogenic activities (Galgani et al., 2021). Plastics in aquatic environments may increase to 53 million metric tons by 2030, with the potential for further growth in the future (Borrelle et al., 2020).

The accumulation of MPs in aquatic environments is becoming a global issue, with potentially irreversible impacts. Mani et al. (2015) in their study at Rhine River observed 8,92,777 MPs particles km^{-2} . The sediments and water from Chiuse and Bolsena Lake (Central Italy) indicated 234 and 112 MP kg^{-1} in dry sediments and 0.82–4.42 and 2.68–3.36 particles m^{-3} in water, respectively (Fischer et al., 2016). The sub-glacial debris of Forni Glacier at Italian Alps also revealed PE, PES, PP and PA polymers (74.4 ± 28.3 particles kg^{-1} ; Ambrosini et al., 2019). Different cities in China, in a study shown 440 ± 275 MPs particles L^{-1} in the tap water, and majority of samples were containing PP and PE particles of < 50 μ m size (Tong et al., 2020). Bakir et al. (2020) in their study covered the South Pacific oceanic region and defined 33,000 MPs particles kg^{-1} from deep sediments, which was higher than observed from the sediments of Belgian coastal zone comprising 390 particles kg^{-1} . Recently, fibres (38 %) and fragment (41%) of PET (11.8%), PP (18.7%) and PE (30.3%) polymers are observed from 2068 different locations of five major oceans (Kakade et al., 2024).

The aquatic species may directly ingest MPs particles by mistake as a prey, along with their natural food and via trophic transfer (Costa et al., 2020). The small size, buoyancy and different colours of MPs particles increase their potential to be ingested as food by aquatic species (Hamed et al., 2023). The MPs on entering in food-chain pose serious threats to the aquatic (phytoplankton, zooplankton, mammals, fishes, seals, turtles, birds, etc.) and terrestrial lives (animals, birds, reptiles, etc.; Renzo et al., 2021). MPs impact on body movement and behaviour and can block the digestive tracts of aquatic species, thus reduce their feeding rate (Santos et al., 2015). They accumulate in the stomachs of species and prevent them from ingesting food. MPs may also contain heavy metals and other toxins, enhancing their toxicity upon consumption (Hamed et al., 2023). However, the MPs in aquatic environment are affecting proliferation and health of aquatic species; thereby accelerating suspense, also for human health (Jaikumar et al., 2022).

The consumption of seafood and fish provide protein, minerals, trace elements, vitamins, fibres, amino acids, carotenoids, phospholipids and other nutrients essential for human health. The average consumption of seafood and fish all over the world in the duration of 1960–2019 was increased from 9.9 to 20.5 kg per capita, which may further rise to 21.4 kg per capita up to 2030 (FAO, 2020). The aquatic species used for food are mainly derived from freshwater/marine environment and aquaculture sector, and their demand is continuously increasing with time (Karbalaei et al., 2021; Laine et al., 2023). The MPs are consumed by aquatic species and are transported to humans through the consumption

of seafood. The humans are also exposed to microplastics through inhalation and dermal contact, and that also depend on age, culture, food habits, lifestyle and their nearby surroundings (Bhatia et al., 2024). The earlier studies have also reported MPs from certain drinks and eatables (Ambrosini et al., 2019; Lestari et al., 2021; Villegas et al., 2021; Sharma et al., 2023; Razaviarani et al., 2024). Microplastics (MPs) and Nanoplastics (NPs) are the emerging contaminants and their presence in aquatic environments poses a serious risk to aquatic life and human health.

The density of MPs particles due to formation of biofilm gets increased and results their downward movement in water bodies. Further, the bio-fouling on MPs particles reduces the photosynthesis rate of phytoplankton, causing them to sink toward the bottom. In both these cases, the zooplankton from the surface layers get less carbon (Cole et al., 2016). Moreover, the faecal pellets containing MPs, rather than sinking at the bottom; mainly float at surface, wherefrom the carbon again is released to the atmosphere and combination of all such factors results less sequestration of the carbon in water bodies (Sunil et al., 2024). The wastewater treatment plants (WWTPs) are also found to be effective for their removal, but rather than a huge amount of MPs are released in the environment through sludge and effluent (Gangula et al., 2023; Miino et al., 2024). The plastics are generally non-degradable based on physico-chemical properties, therefore may stay in all types of environments for the long time duration. The degradation and removal of MPs require proper attention to get ride from their problems (Conley et al., 2019). The physical, biological and chemical agents gradually degrade them in their environment of existence (Gewert et al., 2015; Kumar and Maiti, 2016; Atanasova et al., 2021). Energy can also be recovered from the plastic wastes and that can be a feasible solution of the MPs problems (Praveenkumar et al., 2024).

The earlier studies have mainly focused on determination of MPs from different biotic and abiotic environment for understanding their abundance, density, size, types and harmful impacts, etc. However, the studies confirming detailed mechanism after MPs consumption by aquatic species in food chain including human health are inadequate (Gammaro et al., 2020). Further, the influence of MPs on carbon sequestration capacity of water bodies, removal and degradation, energy recovery from plastic wastes and their recycling are still emerging topics in present context. Certainly, large numbers of review articles are available so far, but a sound approach to cover above topics pertaining to MPs in aquatic environment is lacking and very essential. Therefore, objective of present review is to understand influences of MPs in aquatic environments; their sources, determination, abundance and implications on aquatic species. Further, to address new data and perspectives related to carbon sequestration potential, human health, removal and degradation, energy recovery and recycling processes. This study will also be helpful for the researchers to find and fill the research gaps in future.

The introduction section of this review explores the existing knowledge, addresses research gaps of earlier studies and defines objectives of the study. The methodology describes the strategy adopted to collect required information from different sources and selection as well as rejection of earlier downloaded studies using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. The source, determination, and distribution of MPs in different freshwater sources and marine environment are well defined. In its continuation, the implications of MPs on aquatic species such as phytoplankton, zooplankton, crustacean, molluscs, turtle, fish, mammals, aquatic birds, coral, etc., are presented. Thereafter, the impact of

MPs on carbon sequestration potential of aquatic environment and human health are exposed. Removal and degradation part covers WWTPs, Advanced Oxidation Processes (AOPs), thermal- and photo-oxidation, and fungal, algal and microbial degradation of MPs. The management strategy marks energy recovery from plastic using different treatment techniques and recycling, etc. Future perspectives before conclusion part are also given with suggestions need to be implemented for controlling MPs and their problems. The tables and figures are also provided in appropriate sections for effective presentation of the data and understanding of readers.

2. Methodology

The information available in literature has been categorically compiled using peer-reviewed research/review articles mainly published during the year 2014–2024. The studies published before this time period were not found significant for the present review as the studies related to MPs in aquatic environment are mainly emerged only from a decade. The articles were downloaded online through Google, Google Scholar, Science Direct, Web of Science, PubMed, Research gate, etc. These platforms were selected due to their wide range of publications pertaining to the MPs and environmental science. Certain keywords as well as the combination of keywords like MPs and toxicity, sources and transportation, determination, distribution, impacts on freshwater (river, lake/wetland, drinking water), estuary, glaciers, marine environment and aquatic species (phytoplankton, zooplankton, crustacean, shrimps, prawn, molluscs, lobster, crab, turtle, corals, fish, sea and freshwater birds, etc.) were used for the literature search. In addition, the MPs and food-chain, seafood, carbon sequestration, human health, removal, degradation, WWTPs, energy recovery, recycling, etc., were also searched according to the requirement of various sections.

The science citation indexed (SCI) as well as web of science journals of top rank publishers such as Elsevier, Springer, Wiley, etc., were given

due emphasis while downloading the research/review articles. The PRISMA guidelines were followed to find, select, evaluate and synthesize earlier studies (Page et al., 2021; Kumar et al., 2021). A total of 1463 articles were downloaded and amongst 44 showed duplication and were initially removed from the record. Thereafter, 629 were excluded during screening for not having required information related to topics and sub-topics. Further, 370 articles did not have sufficient data, proper validation, methodology quality and scientific standpoint, and were also excluded (Fig. 1; Fialek et al., 2022). The excluded articles were also not containing sufficient sample size, experimental design and statistical rigour. Apart from, non-relevant objectives, unsatisfactorily results, non-refereed nature; were also the main reason behind exclusion of the downloaded articles. Finally, 420 articles containing relevant and scientific information close to the MPs in aquatic environment as well as according to the above requirements are considered in this review. Figure-3 and 4 are created using online software 'BioRender.com'.

3. Microplastics source and transportation

The plastics are derived from petrochemicals and comprise monomers, oligomers and polymers, which generally bound in a chain like structure through polymerization (Chen et al., 2022a). The MPs may have different sources and means of transportation (Fig. 2). During production of plastic polymers, several chemicals extracted from crude-oil are added. The additives (plasticizers) such as dyes, phthalates, brominated flame-retardants, fillers, lubricants, BPA, antioxidants, stabilizers, etc., are mixed for providing colour, strength, flexibility, stability, protection from multifaceted environmental stressors, softness, etc., to the plastics (Hahladakis et al., 2018). The plastics are heterogeneous due to their shape, size, colour and polymer types. They have also replaced the use of metals, fibres, rubber, backed-clay, papers and glass in manufacturing of different products like instruments, electrical appliances, computers, cell-phones, vehicles, utensils, items of medical

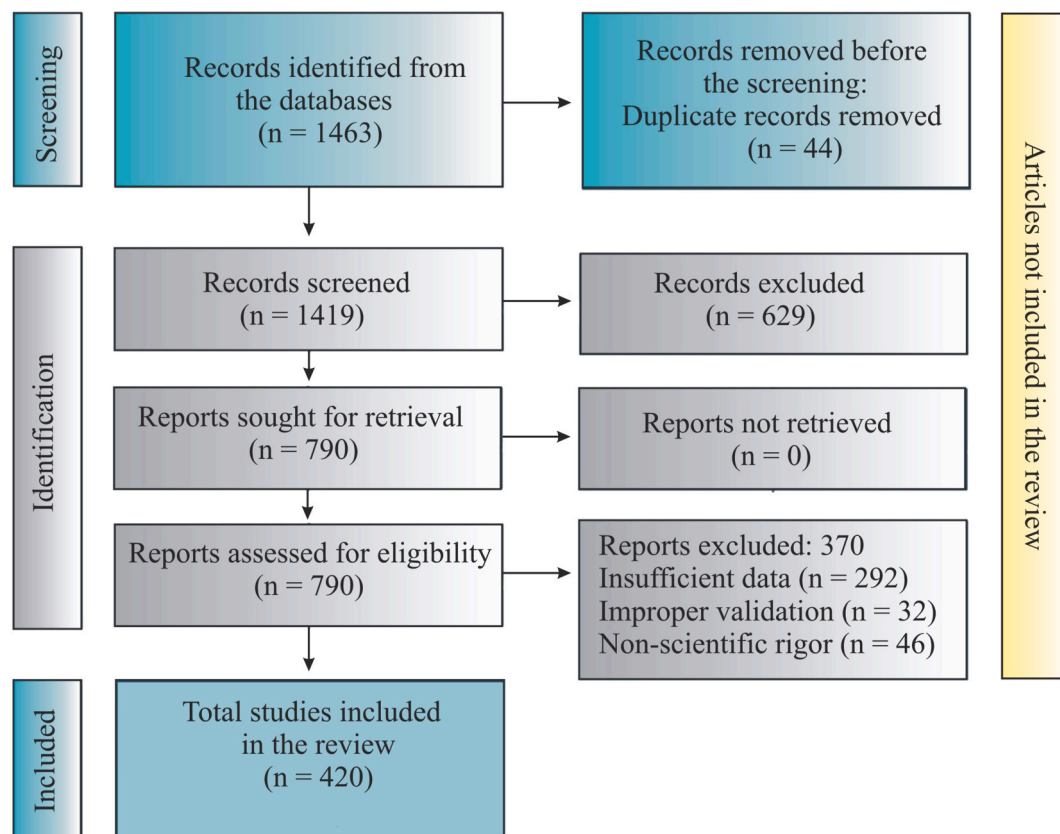


Fig. 1. PRISMA guidelines followed to select and synthesize earlier studies.

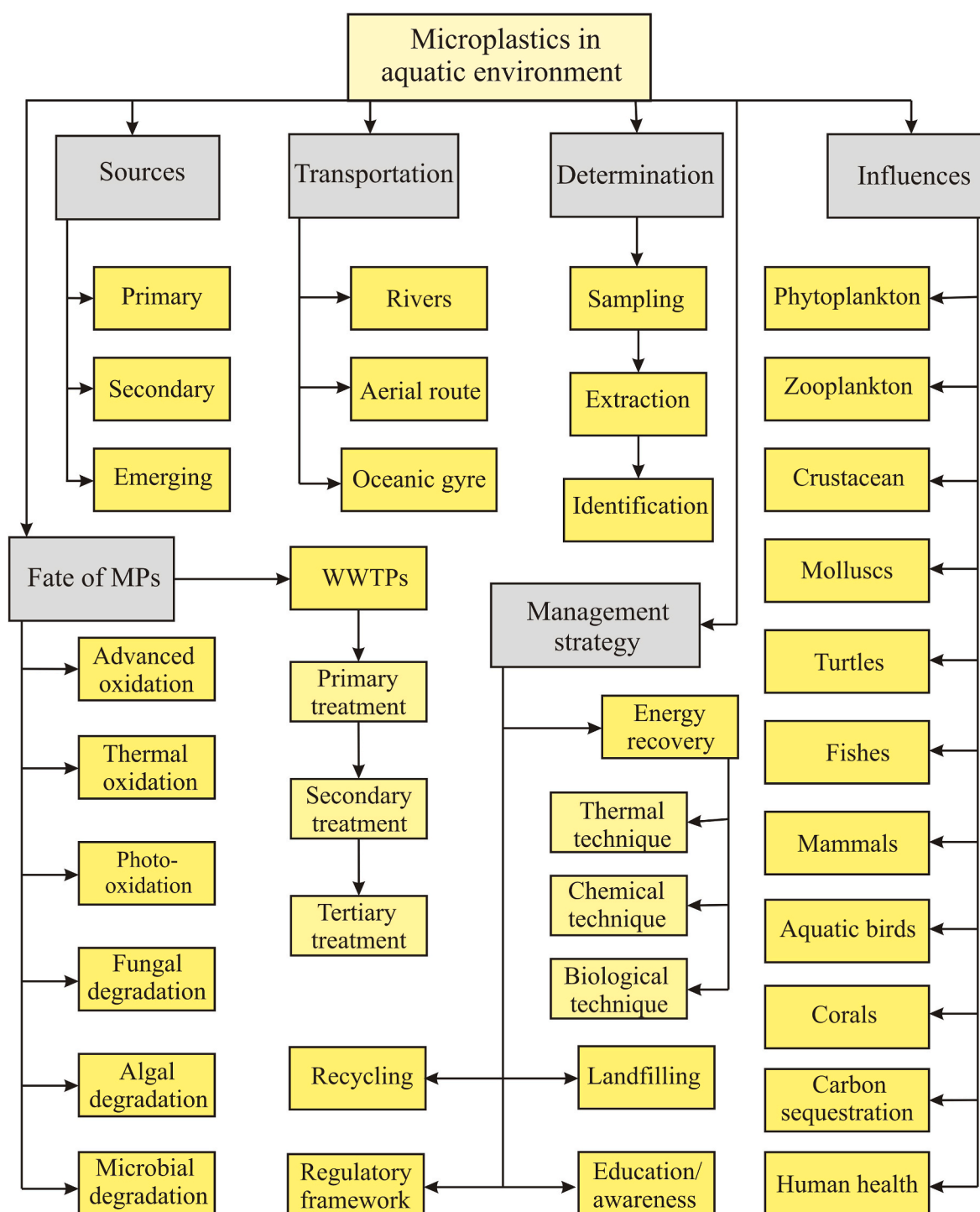


Fig. 2. Various stages of MPs comprising source, transportation, determination, influences, fate and management strategy.

sector, personal care products, cleaners, sports items, packaging, etc. (Emenike et al., 2023; Sharma et al., 2023). The sources and transportation of MPs may vary from one region to another based on industrialization and environmental conditions.

3.1. Sources of microplastics

3.1.1. Primary source

The source, which generates MPs particles (pellets, fibres, sphere and fragments) directly in the environment, is termed as primary source (Stenger et al., 2021; Fig. 3). Xu et al. (2022) collected soil samples from

Mauerpark, Germany and observed MPs in the range of 1.1×10^5 to 2.9×10^5 MP kg⁻¹ dry soil. The MPs were found to be originated from the spray painting, which may contain harmful additives such as phthalate esters, brominated flame retardants, cadmium, lead, pigments, catalysts, etc. (Turner, 2021). Initially, the natural exfoliants such as walnut husks, oatmeal, pumice and apricot were used in cosmetics and personal care products, but are mostly neglected at present owing to increasing use of MPs. These are also considered as emulsifiers, exfoliants, film-forming, binding and anti-static agents. The uses of MPs are increasing with time in toothpastes, sunscreen, body scrubs, deodorants, hair dyes, blush-powder, hand and face wash, nail-polish, road marking,

shampoos, shower-gels, lips-sticks, bar soap, insect killers, pharmaceutical, etc. (Anderson et al., 2016a).

Napper et al. (2015) suggested a release of 4,594–94,500 micro-beads from single use of exfoliants. Hintersteiner et al. (2015) also observed PO polymer (MPs) from the personal care products. The MPs such as PS, PES, PU, PE, PVC, PES, nylon, melamine, acrylic, etc., are used in personal care products, textiles, construction and as abrasives in industries for metal surface cleaning (Blair et al., 2017). The MPs are observed in higher concentration toward the production and recycling industrial units; hence mark their origin from primary sources (Duis and Coors, 2016). The industrial units ($2.76 \text{ items L}^{-1}$) in a study are found to release more MPs than the domestic sector (1.29 item L^{-1} ; Long et al., 2021). In industries, the WWTPs comprising primary, secondary and tertiary treatments generally release a huge concentration of MPs in the sludge and effluents; henceforth to the surrounding environment (Tang and Hadibarata, 2021; Gkika et al., 2023). The developed countries may generate more MPs due to industrial activities as compared to the developing one.

3.1.2. Secondary source

A huge amount of large sized plastic (macro-plastic) wastes is produced everywhere and act as secondary source of MPs (Fig. 3; Esposito et al., 2022). The fragmentation of plastics may occur via physical, chemical and biological processes, which result in discoloration, erosion, delamination, cracking, etc. Environmental Stress Cracking (ESC) plays a role in disintegration of plastic to MPs or NPs. The roles of pH, ultraviolet (UV) rays, moisture, temperature, microbes and enzymes in plastic degradation are also discussed in an earlier study by Atanasova et al. (2021). The UV rays under natural conditions during the day disintegrate the C-H group of polymers due to absorption of heat. The rise in temperature promotes chemical transformation and chain branching in plastics and thus final degradation occurs (Gewert et al., 2015). In addition, fungi, algae and microbes also aid in plastic degradation; although it is a very slow process (Atanasova et al., 2021; Nava et al., 2022; Solanki et al., 2022). The disintegration of polymers such as PVC, PA, PET, PE, PP, ABS, PU, PS, PVS, EVA, nylon, etc., produces pellets, fibres, fragments, foam, debris, film, etc., of various colours and sizes (McGoran et al., 2020; Atanasova et al., 2021; Jitkaew et al., 2023).

The recycling process is also found to produce MPs in an earlier study by Staplevan and Hai (2024). Sobhani et al. (2020) observed release of MPs during cutting, tearing, twisting and scissoring of plastic containers. They observed $0.46\text{--}250 \text{ MP cm}^{-1}$ depending on size, density, thickness, anisotropy and stiffness of plastic. The land based sources account 80–90% MPs from the plastic containers, bottles, bags and clothes as compared to the oceanic sources such as fishing gear/nets, tourism, naval vessel, etc. (Osman et al., 2023). The improper waste management in developing and under-developed countries may have greater possibility of MPs generation rather than the developed nations.

3.1.3. Emerging source

The emerging sources of MPs are the 3D printing, biodegradable plastics and textiles, which may increase the global load of MPs, further in future (Amato-Lourenço et al., 2020). Zhang et al. (2019) in their study observed $106 \text{ particles cm}^{-3}$ from the chamber having a 3D printer, which used the ABS filament. Henry et al. (2019) identified MPs originating from the textile industry due to washing and tearing the clothes. Such industries require an enormous quantity of water and discharged water as an effluent from them contain MPs. Deng et al. (2020) from the surrounding of the textile industries located at Shaoxing city, China, observed $2.1\text{--}71.0 \text{ items L}^{-1}$ and $16.7 \text{ to } 1323.3 \text{ items kg}^{-1}$ in water and sediments, respectively. Biodegradable plastic is considered as an alternate of the conventional plastic, but does not undergo complete degradation and leave behind MPs, which result severe consequences (Wang et al., 2021d; Fan et al., 2022). The influences of biodegradable MPs on fish have also been defined by Malafeev et al. (2023). The MPs formation rate of biodegradable plastic is found to be

more than their degradation rate (Liao and Chen, 2021). The negative consequences of COVID-19 also has increased the demand of facemasks, gloves, gowns, bags and visors made of polymeric materials, which in turn are also increasing the MPs load in the environment (Fadare and Okoffo, 2020).

3.2. Transportation

The rivers are the main channels of MPs transportation to the other freshwater resources and marine environment (De Arbeloa and Marzadri, 2024). An earlier study covering a 2575 km stretch of Ganga River, India, during different seasons exposed the fragments (9%) and fibres (91%) shaped MPs in a range of 1–3 billion; transported to Bay of Bengal, every day (Napper et al., 2021). Another study at the Ganga River also shown the presence of $131.5 \pm 53.60 \text{ particles kg}^{-1}$ dry weight and $118.5 \pm 49.65 \text{ particles } 1000 \text{ L}^{-1}$ in sediment and water, respectively (Badola et al., 2023). The Amazon River (South America) and its tributaries also marked the presence of 5 and 152 MP m^{-3} , respectively, which might further be transported to the oceans (Rico et al., 2023). Similarly, midstream and upstream of Yangtze River, China, also showed 3226.8 and 3598.6 particles m^{-3} , respectively, carried from surrounding regions (Huang et al., 2023). The ships, boats and fishing-nets may also release plastics directly to the water column (Turner, 2021; Fig. 3). The MPs may be escaped from wastewater treatments plants to the effluents and sludge and thereafter reach in water bodies (Murphy et al., 2016; Conley et al., 2019). The MPs after reaching the aquatic environment may circulate via action of wind, ocean current and human activities (Anderson et al., 2016b).

The prevailing wind driven oceanic gyres circulate the plastic wastes and accumulate it in the garbage patch. The plastics remain in gyre until they turns into MPs due to mechanical forces, aquatic life and ultraviolet rays. The atmospheric deposition is also identified a source of MPs to the aquatic environment. The MPs from the soil are lifted by wind based on their sizes and density and transported to other region including water bodies (Bhardwaj et al., 2024). The MPs in water bodies generally floats on surface and in water column based on their density. They may either be ingested by aquatic species mistakenly as a prey or via trophic transfer and get deposit at the bottom as a sedimentary component. In aquatic environment, they may persist for a long time as compared to the earth surface, because in soil the degradation of MPs particles occurs faster due to exposure of direct ultraviolet and infrared radiations including human activities and different other mechanical forces (Hale et al., 2020).

4. Microplastics determination

4.1. Microplastics sampling

The MPs can be sampled from water column using different filtration devices and equipment (Table-1). The manta trawl is most suitable for filtration of huge amount of water from the desired depths to remove MPs, and similarly, stainless sieve is mainly used for the sediment samples. Lenaker et al. (2019) in their study used a net size of $333 \mu\text{m}$ during samples collection from surface and sub-surface of the Milwaukee, Kinnickinnic and Menomonee River and Michigan Lake. Likewise, Jiang et al. (2018) collected 30 L water from 22 locations and filtered with a filtration unit of $45 \mu\text{m}$ size, which is also different than $53 \mu\text{m}$ size fixed by Bujacsek et al. (2021) in their study at North Saskatchewan River. Desforges et al. (2014) in their study at sea-surface of northeast Pacific Ocean had fixed manta trawl net at a depth of 4.5 m.

Enders et al. (2015) in Atlantic Ocean considered a depth of 3 m and filtered water with a filtration unit mounted with the mesh sizes of 10 and $300 \mu\text{m}$ and having a flow rate of 2.5 m^3 per hour. The authors have sampled the MPs from various depths using different net and sieve sizes (Choy et al., 2019; Alfaro-Nunez et al., 2021). The mesh size in earlier studies is found to be different; however the most appropriate size that

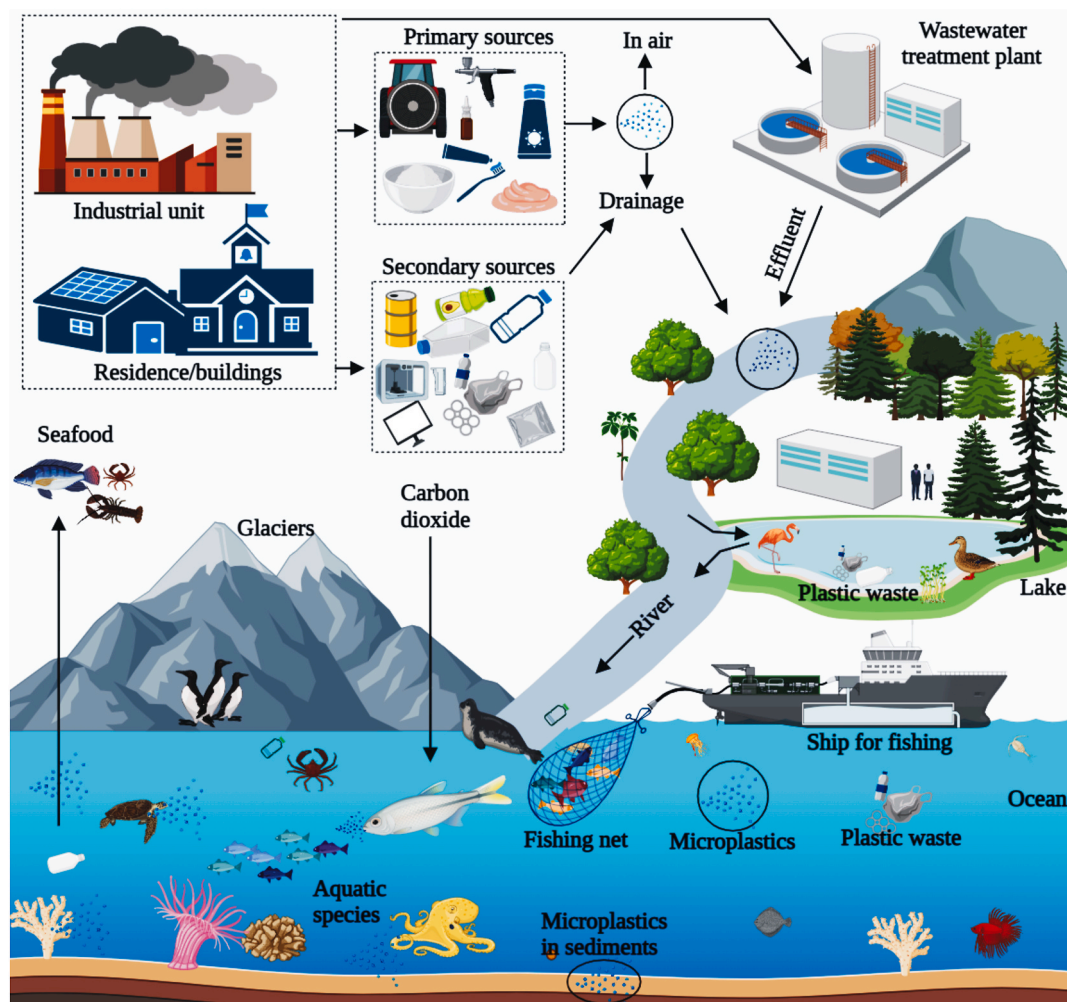


Fig. 3. Sources, transportation and entry pathway of MPs in aquatic environments via different means (created using BioRender.com).

could extract the MPs particles from water is selected in the range of 100–500 μm . There is a need of a standardized technique for sampling of MPs of different sizes at various depths. The freshwater bodies and marine sediments samples collected from bottom, coasts and beaches are also used for MPs determination from different locations in the world (Table-1; Liu et al., 2019; Ji et al., 2024).

4.2. Extraction of microplastics

The density separation is a most common and widely accepted method for the extraction of MPs from sediment samples (Crutchett and Bornt, 2024; Table-1). It extracts MPs based on their densities and undergoes treatment of samples, floatation, settling and filtration. The original colour, shape and size of MPs must be retained after the treatment/digestion to understand MPs polymer types (Wang et al., 2018). The studies have indicated a very high feasibility of ZnCl_2 ($>1.7 \text{ g cm}^{-3}$) to extract MPs particles having higher density (Crutchett and Bornt, 2024). Saturated NaCl is also considered most appropriate due to its non-hazardous nature and suitable for MPs having low density (1.20 g cm^{-3}). Likewise, NaI (1.5 g cm^{-3}) during density separation has also indicated greater recovery of MPs (99.8%) from sediments as compared to NaCl (1.15 g cm^{-3}) and KOH (1.2 g cm^{-3} ; Murphy et al., 2022). Horton et al. (2017) in their study prepared ZnCl_2 solution ($1.7\text{--}1.8 \text{ kg L}^{-1}$) in a beaker for extraction of PVC particles (1.5 g cm^{-3}). Then the samples were mixed and content was kept undisturbed. The MPs started to float at surface due to low density and further addition of ZnCl_2 solution in the beaker caused overflow of floating particles. The

overflowed content from the beaker contained the MPs particles, which were extracted using glass fibre filter of $1.2 \mu\text{m}$ pore sized.

However, Nuelle et al. (2014) primarily utilized NaCl (1.5 g cm^{-3}) and thereafter NaI (1.8 g cm^{-3}) solution for more floatation of MPs was used. The nitrocellulose filters of 0.45 mm pore sized were used for filtration of the content. Lenaker et al. (2019) treated the samples with ZnCl_2 (1.6 g mL^{-1}) solution and content in beaker was stirred for 10 min and kept that undisturbed for 1 h. The overflowed liquid was then filtered with $125 \mu\text{m}$ sized steel mess to extract MPs particles. The organic material and calcite minerals were removed using H_2O_2 (30%) and HCl (5%), respectively. The samples from water column and aquatic species somehow don't undergo density separation likewise the sediments, although, wet-digestion is equally imperative here too for separating MPs and organic matter. Enders et al. (2015) initially dried the samples collected from Atlantic Ocean at 60°C for 24 h and then to remove organic matter; were placed in the solution of sodium dodecylsulfate (150 g L^{-1}) and micro-water. Thereafter, solution was sonicated (20 min) and kept overnight; followed by vacuum filtration using polycarbonate/polyamide filters having pore sizes and diameters of $10 \mu\text{m}$ and 25 mm , respectively. Jiang et al. (2018) treated samples with hydrogen peroxide (H_2O_2 ; 30 %) to eliminate phytoplankton. Further, ZnCl_2 solution (1.5 g cm^{-3}) was also used to remove minerals and soil particles. The supernatants were filtered using glass fibre filter papers of $0.22 \mu\text{m}$ pore size.

The samples are also treated with H_2SO_4 and HNO_3 to remove animal tissues, but their higher concentration may alter composition of MPs particles (Blair et al., 2017). The apparatus, equipment and filter papers

used during extraction process may retain MPs and should be rinsed with the deionized water in collecting vessel. The selection of pore size of filters also influences the MPs extraction. Visibility of MPs on the filter papers after filtration can be enhanced using biological stain Rose Bengal and Nile Red solution (Mason et al., 2018). The microfluidic system is also used for the separation of the MPs (Ece et al., 2023). In an earlier study, Chen et al. (2022b) used PDMS-based chip having a height and width of 220 and 500 μm , respectively, for detection of MPs from the sea-water and sediments. The optical photo-thermal infrared (O-PTIR) spectroscopy was combined with the chip and achieved 90% of the MPs separation.

4.3. Identification of polymers type

The visual inspection of MPs according to their shapes, sizes and colours may be possible in certain cases, otherwise digital microscopy comprises stereo-, optical-, light- and compound-microscope, can be utilized to isolate them from other impurities (Table-1; Gupta et al., 2021). Identification of polymer types can be done using Micro-Fourier transform-infrared spectroscopy (μ -FTIR), Micro-Raman Spectroscopy, etc. (Liu et al., 2024). The Scanning Electron Microscope (SEM) is also used to observe surface characteristics of the MPs and based on that, PS, PP, PE, etc., types of MPs particles can be identified. The same technique was also followed by Corcoran et al. (2015) in their study at Lake Ontario, Canada.

Table 1
Sample collection, extraction and identification of polymer type from different regions.

Location	Sample type	Sampling device	Extraction method	Chemical used	Isolation	Polymer identification	Polymer type	Reference
Lake Ontario, Canada	Sediments	Mini box corer	Density separation	Sodium polytungstate solution	–	μ -FTIR Spectroscopy	PP, PE	Corcoran et al. (2015)
Super markets, China	Table salts	Collected from super market	Filtration, floatation	30% H_2O_2	Stereo Microscope	μ -FTIR Spectroscopy	PP, PE, PES, CP, BT	Yang et al. (2015)
Lake Ontario, Canada	Sediments	Petite ponar grab, Glew gravity corer, etc.	Density separation	Sodium polytungstate solution	Stereo Microscope	XRF, Raman Spectroscopy	PVC, PE, PP, PS, PU, PSS, PET	Ballent et al. (2016)
Vembanad Lake, Kerala, India	Sediments	Van Veen grab and 5 mm mesh	Wet peroxide oxidation	30% H_2O_2	–	Micro-Raman Spectroscopy	PS, LDPE, PP, PS, HDPE	Sruthy and Ramasamy (2017)
River Thames basin (UK)	Sediments	Stainless steel scoop	Floatation, density separation	Concentrated ZnCl_2 solution	Binocular Light Microscope	Raman Spectroscopy	PP, PES, PET, PE, PS, PVC	Horton et al. (2017)
Shanghai, China	River sediments	Metal shovel	Density separation	Concentrated saline solution (NaCl)	Stereo Microscope	μ -FTIR Spectroscopy	PP, PES, rayon, PVS	Peng et al., 2017
Qinghai Lake, China	Water and sediments	Trawl net-112 μm , Steel shovel	Flotation/ Density separation	Potassium formate solution, 30% H_2O_2	Stereo Microscope	Micro-Raman Spectroscopy	PE, PP, PET, PS	Xiong et al. (2018)
Monterey Bay	Water	Detritus samplers	Filtration	–	Stereo Microscope	Raman Spectroscopy	PET, PA, PC, PVC	Choy et al. (2019)
Pearl River catchment, China	Water and sediments	Plankton net-160 μm , Grasp bucket and Gravity corer	Density separation	Potassium formate solution, 30% H_2O_2	Stereo Microscope	FTIR Spectroscopy	LDPE, PP, PE, PET, EVA, PVC, PS, PA, PU, PAN	Fan et al. (2019)
Pacific Ocean	Sediments	Lander box corer	Density separation	Saturated sodium iodide solution (NaI)	Stereo Microscope	FTIR Spectroscopy	PET, nylon, PES, PP	Peng et al., 2020
Pearl River- and estuary, China	Water	Stainless steel sieve-50 μm	Filtration	30% H_2O_2	Stereo Microscope	Micro-Raman Spectroscopy	PA, PP, PE, PVC, VACs, cellophane	Yan et al. (2019)
Vila and Mele Bay, Vanuatu	Surface waters	Manta trawl Net-335 μm	Filtration, visual inspection	30% KOH:NaClO solution	–	ATR-FTIR	PE, PS, PP, PVAE	Bakir et al. (2020)
Antarctica and southern ocean	Sediments core	Oktopus multicores	Density separation	HCl, Sodium polytungstate, 30% H_2O_2	Stereo Microscope	μ -FTIR Spectroscopy	PES, PU, PE, PS,	Cunningham et al. (2020)
Western Pacific Ocean	Sediments	Stainless-steel box corer	Centrifuge method	NaCl, KOH, Potassium iodide (KI)	Optical Microscope	μ -FTIR Spectroscopy	PP, PE, PET, PES	Zhang et al. (2020a)
Edmonton, Alberta, Canada	River water	Plankton net-53 μm	Wet peroxide oxidation	ZnCl_2 solution, FeSO_4 , 30% H_2O_2	Compound Microscope	Micro-Raman Spectroscopy	PP, PE, PVC, PVA, PES, PET	Bujaczek et al. (2021)
Mandovi and Zuari estuary, India	Water	Plankton net-300 μm , steel sieve	Visual inspection	NaCl, 30% H_2O_2	Stereo Microscope	μ -FTIR Spectroscopy	PI, PAM, PVC, PA	Gupta et al. (2021)
Kiel Fjord, Western Baltic Sea	Sediments	Metal shovel	Density separation	Calcium chloride (CaCl_2),	Stereo Microscope	Micro-Raman Spectroscopy	PE, PS, PP, PA	Schroder et al. (2021)
Vatnajökull ice cap, Iceland	Snow core	Auger, Filtration	Melting and filtration	–	Optical Microscope	μ -Raman Spectroscopy	PU, PVC, PU, PA,	Stefansson et al. (2021)
Thames River, UK	Water	Lamotte horizontal water sampler, Bucket	Filtration	–	Light Microscope	FTIR Spectroscopy	PS, PEC, PP, PVC, PCP	Devereux et al. (2023)
Huguangyan Maar Lake, China	Lake core	Sediment corer	Density separation	ZnCl_2 solution, 30% H_2O_2	Agilent 8700 LDIR	Agilent 8700 LDIR	PU, PE, PP, PVT, PET, ABS, PC, etc.	Ji et al. (2024)

The pyrolysis-gas chromatography mass spectrometry (Pyr-GC/MS) can also be used to understand the macromolecules structural information of the MPs (Brits et al., 2024). The machine-learning is a type of the artificial intelligence (AI) and uses data set and can detect and classify MPs with a high precision; however it is an emerging field and requires more research in future (Weber et al., 2023; Withana et al., 2024). Raman spectroscopy is also considered very convenient for determination of MPs presence in the environment. Chen et al. (2022b) used Raman Spectroscopy and O-PTIR and observed MPs having a size of 19 μm from the sea-water and sediments. The image can be analysed using software to measure a minute difference in shapes of MPs particles. Valente et al. (2023) pre- and post-treated the PVC, PP, PS, nylon and PET polymers using $\text{H}_2\text{O}_2 + \text{HNO}_3$ (40 °C; 15 and 5%), H_2O_2 (50 °C; 30 %) and KOH (60 °C; 10 %) and incubated them for 12 h. They observed small differences in sizes and shapes of polymers due to digestive chemicals that could not be possible via any other technique.

4.4. Challenges associated with MPs determination

The determination of MPs may also be influenced during sampling, extraction and identification. During extraction, a net size in a range of 100–500 μm is most commonly used, and that cannot retain particles below this size; leading to underestimation. It is a limitation of this method as it impacts on actual measurement of smaller MPs and NPs. Likewise, the density separation is a cost effective and very easy method; however, the MPs particles having huge difference of densities in same sample may affect the process of extraction. Apart from, the mixing time, floatation solution mass relative to mass of samples, composition of solution used in floatation, etc., may also influence the extraction of MPs from sediments (Han et al., 2019). The current techniques either overlook or underestimate the MPs and that is an issue to consider. The quality control, blank testing and cross-validation can also be of paramount importance to avoid errors and improve the results, but rather than a cent per cent reliability may not be achieved. The advancement in instrumentation techniques such as electron microscope, machine learning, etc., may address this issue and future-oriented view of the problem concerned with MPs in aquatic environment.

5. Distribution of MPs in aquatic environment

The MPs are having a potential to reach in all types of aquatic environments through various means of transportations (Lestari et al., 2021; Table-2; Fig. 2). The quantification of MPs distribution is very essential to understand the risk level of their ingestion and trophic transfer among various species of freshwater resources and marine environment (Devereux et al., 2023).

5.1. Freshwater resources

5.1.1. River

The rivers receive a heavy load of plastic wastes from surroundings and act as transport pathway of MPs to the lakes and oceans (Besseling et al., 2017; Bhan et al., 2024). Earlier study at Austrian Danube, the second largest river in Europe, revealed 17,349 plastics particles with a density of 1,000 m^{-3} . That river carries a huge load of plastics (4.2 tons per day) to the Black Sea (Lechner et al., 2014). The North Saskatchewan River, which is the fifth largest river of Canada, indicated 4.6–88.3 MPs particles m^{-3} , mainly PP and PE (Bujacsek et al., 2021). The Surabaya River, a main part of Brantas, is one among the top 20 global rivers contaminated with plastics debris, indicated MPs in the range of 9.66–21.16 particles m^{-3} (Lestari et al., 2021).

An earlier study covered 820 km long stretch of Rhine River from Basel to Rotterdam. The study observed 8,92,777 MPs particles km^{-2} from the river, however a part of this river, specifically in a metropolitan city, Rhine-Ruhr, revealed 3.9 million particles km^{-2} (Mani et al., 2015). The mangrove sediments from Singapore coast were found to contain

12–62.7 MPs particles kg^{-1} dry sediments (Nor and Obbard, 2014), which might be transported by the rivers or tides from oceans. The Ganga River, India, in a study by Napper et al. (2021) marked the presence of 1–3 billion MPs fibres and fragments. The sediments of the same river in another study by Badola et al. (2023) also showed 131.5 ± 53.60 particles kg^{-1} dry weight and 118.5 ± 49.65 particles 1000 L^{-1} in sediment and water, respectively. Bhaduri et al. (2024) in their study at the Beas River, Himachal Pradesh, India, observed 112.27 items L^{-1} and 319.47 items kg^{-1} of MPs from water and sediments, respectively. The MPs sequestered in the sediments may stay for a long time period and reintroduce in water column through disturbances.

5.1.2. Lake/wetland

The standing water of the lakes favors more settling of MPs at bottom; therefore their concentration gets increased (Jimenez-Contreras et al., 2024). The Winnipeg Lake, Canada, in a study revealed around 1, 93,420 MPs particles km^{-2} ; more than the Erie (1,05,503 particles km^{-2}), Superior (5,391 particles km^{-2}) and Huron Lake (2,779 particles km^{-2}) (Anderson et al., 2016b). The MPs settle down and mix with bottom sediments as confirmed from the Toronto Harbour and Humber Bay (Lake Ontario), which marked >500 particles kg^{-1} in dry sediments (Ballent et al., 2016). The sediments generally contain higher concentration of MPs as compared to the water column like observed from Chiusei and Bolsena Lake (Central Italy) with a concentration of 0.82–4.42 and 2.68–3.36 particles m^{-3} in water, while 234 and 112 MP kg^{-1} in dry sediments, respectively (Fischer et al., 2016).

The MPs are also observed from the Hovsgol Lake (Mongolia), with a density of 20,264 MPs particles km^{-2} , which is very high as compared to most of the Laurentian Great Lakes (Free et al., 2014). Several other studies also indicated MPs density different in the water and sediments of the lakes such as Vembanad Lake, India (252.80 particles m^{-2} ; Sruthy and Ramasamy, 2017), UK urban lake (25–30 MPs particles 100 g^{-1} dry sediments; Vaughan et al., 2017), Tibet plateau remote lakes, China (8–563 particles m^{-2} dry sediments; Zhang et al., 2016) and Poyang Lake, China (11–3,153 particles kg^{-1} ; Liu et al., 2019). The MPs in lake sediments may lie for a long time and when the bottom is disturbed, they eventually reintroduce in above water column and show ecological impacts. The lakes pass through different stages from oligotrophic to eutrophic or even hyper-eutrophic, therefore the biofilm formation may occur on MPs surface very fast (Long et al., 2015; Kumar et al., 2019; Kumar and Mahajan 2020).

5.1.3. Glacier

The glaciers and Polar Regions are also found to contain MPs, although limited studies are still carried out there (Gonzalez-Pleiter et al., 2021; Rosso et al., 2024). The presence of MPs in glaciers may cause their melting and retreating at a fast rate, owing to the greater UV radiation absorption efficiency of the MPs particles rather than the glaciers, snow and ice, which have higher albedo and reflect most of solar radiation back to the atmosphere (De-Vrese et al., 2021). Further, the MPs surface may also contain microbes, which also induce melting of the glaciers. Ambrosini et al. (2019) in their study observed PE, PES, PP and PA (74.4 ± 28.3 particles kg^{-1}) MPs types from the sub-glacial debris of Forni Glacier at Italian Alps. The MPs may reach there from the higher elevation zones, ocean currents, atmospheric deposition and anthropogenic activities (Mishra et al., 2021). The scats from penguin and seals, which consume MPs via food-chain, may also transport MPs from oceans to the glaciers (Garcia-Garin et al., 2020; Bourdages et al., 2021).

5.1.4. Estuary

The MPs content in the estuaries may vary according to weather conditions as observed by Gupta et al. (2021) from Mandovi-Zuari Estuary, India. The MPs in the water column during a wet period (September) were observed 0.107 particles m^{-3} , while 7,314 particles kg^{-1} from the sediments. Similarly, during the dry period (April), the

water column indicated 0.99 MPs particles m^{-3} and 4,873 particles kg^{-1} were observed from the dry sediments. The higher concentration was related to high transportation of plastics as well as MPs from surrounding regions by the river during the rainy season, and in the dry season, that transportation became low. Bailey et al. (2021) indicated water of Raritan Hudson Estuary, having 400–600 MPs particles m^{-3} at the mouth, while this concentration throughout the estuary was 1–2.75 particles m^{-3} . The water of Solent Estuarine Complex (UK), which comprises Hamble, Itchen, Southampton water and Test estuary, revealed 296, 1,155, 960, and 348 MPs particles, respectively (Gallagher et al., 2016). Peng et al. (2017) monitored Changjiang Estuary, China, and found 20–340 MPs particles kg^{-1} dry sediments. Some more estuaries such as Oujiang Minjiang, Jiajiang and Bohai Bay, China (Zhao et al., 2015; Wu et al., 2019), Northern Gulf, Mexico (Wessel et al., 2016) and Kayamkulam, India (Radhakrishnan et al., 2021), also revealed different concentration of MPs particles in water and sediments.

5.1.5. Drinking water

The drinking water must cover quality assurance aspects to avoid health implications (Koelmans et al., 2019). The drinking water from tap, bottles, etc., is also assessed in earlier studies and found to contain MPs (Danopoulos et al., 2020). The presence of MPs in drinking water could harm human health and cause long-term consequences. A study in Hong Kong (China) used tap water and indicated 78.2 % of the total samples containing fibres and microplastics (<1 mm) with a mean density of 2.181 ± 0.165 particles L^{-1} (Lam et al., 2020). However, different other cities in China revealed 440 ± 275 MPs particles L^{-1} in the tap water and majority of samples had contained PP and PE particles of <50 μm size (Tong et al., 2020). A study comprised 259 bottles of 11 brands from 9 different countries and showed that 93 % of the total observed MPs particles from inside the bottles were present before packaging. The study further confirmed MPs size in the range of 6.5–100 μm and with a density of 0–1,000 particles L^{-1} in drinking water (Mason et al., 2018).

Schymanski et al. (2018) observed MPs such as PP, PO, PET and PE in the returnable and single-use plastics bottles with a density of 118 and 14 particles L^{-1} , respectively. Similarly, the beverage cartoons and glass bottles also showed MPs in the range of 11 and 0–253 particles L^{-1} , respectively. The drinking water bottles in a recent study found to contain pellets, fibres, films and fragments types of PS, PC, PMM, PP, etc., MPs in a range of 9 ± 1.00 to 3 ± 1.73 MP L^{-1} and posed a risk to the consumers (Sarlin et al., 2024). The cleaning of plastics bottles, age, opening and closing the lid and bottle-filler also enhance such risks of MPs contamination in drinking water (Weisser et al., 2021).

5.2. Marine environment

Around 10% of total plastics and 60–88% of the world's plastic litter are reaching the marine environment (Avio et al., 2017). The marine environment comprises MPs in surface water and at beaches, shores, seabed sediments in various concentrations (Oztekin et al., 2024). It is having a greater content of MPs as compared to the freshwater resources (Osman et al., 2023). The deep oceanic zones contain 99% of the total plastics budget, whereas the rest 1% may be toward the surface (Wang et al., 2021a). MPs entering oceans and seas from rivers can travel long distances via ocean currents and due to hydrodynamic effect. There is a probability of higher occurrence of MPs toward points of generation, industries and big coastal cities. A study estimated that out of 275 million metric tons plastic wastes generated from 192 different countries, 4.8–12.7 million metric tons reached to the ocean during 2010 (Amelia et al., 2021). The MPs in sediments may lie for long time periods and also forever. Thus the sediments act as a major sink of MPs, which may also reintroduce in water due to disturbance of sediments.

A study at Saudi Red Sea confirmed an availability of PET, PP and PS in different concentrations (Al-Lihaibi et al., 2019). Desforges et al.

(2014) observed that MPs are abundant everywhere in the NE Pacific Ocean with a density of 8–9,200 particles m^{-3} , which is greater as compared to the Bering Sea, US west coast, North Pacific gyre, etc. The beaches of Mediterranean Sea in a study marked 5–85 MPs particles kg^{-1} of different shapes, colours and sizes. The distribution was found to be mainly influenced by the wind direction (Piperagkas et al., 2019).

Similarly, Eriksen et al. (2014) further quantified MPs from Indian Ocean, North Atlantic, South Atlantic, North Pacific, South Pacific as well as Mediterranean Sea, Australian coasts and the Bay of Bengal. They covered 1,571 sites and estimated plastics particles weighted around 2, 68,940 tons, and amongst, 35,540 tons were MPs (Kosore et al., 2018). The presence of MPs in oceans has contributed to the decline in water quality. Pham et al. (2014) inferred to pay attention on increasing concentration of marine litter including plastics, after their finding from Arctic and Atlantic Ocean as well as the Mediterranean Sea. Enders et al. (2015) also given similar suggestion after they observed MPs from the Atlantic transect in the range of 13–501 particles m^{-3} with a concentration highest at the European coast; followed by decreasing content toward the mid-Atlantic. The concentration again found to be increased on the way toward the North Atlantic Subtropical gyre. Sutton et al. (2016) from the water of San Francisco Bay observed MPs in a range of 15,000–2,000,000 particles km^{-2} .

The MPs are also reported from the deep-sea sediments and beaches having greater chances of interaction with various aquatic species (Zhang et al., 2020a). Bakir et al. (2020) in their study covering the South Pacific region, observed 33,000 plastic particles kg^{-1} from deep sediments. Even the Polar Regions are also found to contain MPs as a result of transportation by ocean currents and several anthropogenic activities (Mishra et al., 2021). Kanhai et al. (2020) in their study at the Arctic Ocean showed MPs in the ice cores and its underlying water with a density of 2–17 particles L^{-1} and 0–18 particles m^{-3} , respectively. Galgani et al. (2021) inferred that concentrations of MPs is increasing in the oceans worldwide, and going to be a huge problem for future.

Globally, the MPs are observed in various concentrations from water and sediments of marine environment. Earlier study at Antarctica, Atlantic Ocean and Arctic Ocean, indicated MPs concentration 0.17 ± 0.34 , 1.15 ± 1.45 and 38–234 items m^{-3} , respectively, in water column (Obbard et al., 2014; Cincinelli et al., 2017; Kanhai et al., 2017). However, the abundance of MPs from Asia (Bohai Sea, China), Europe (Lagoon of Venice, Italy), North America (Canaveral National Seashore, USA), Africa (South Africa) and Mediterranean Sea are observed as 0.33 ± 0.34 items m^{-3} , 672–2175 item kg^{-1} , 123–196 item kg^{-1} , 340.7–4757 items m^{-2} and 13000 items km^{-2} , respectively (Hamid et al., 2018). The global contribution of plastics to the oceans by various rivers of Asia, Africa, Europe, South America, Central and North America and Australia-Pacific is estimated 86, 7.8, 0.28, 4.8, 0.95 and 0.02%, respectively (Kibria et al., 2023).

The MPs in ocean may be distributed in higher concentration at the densely populated coastal regions and may also be influenced by the urban runoff, agricultural practices using plastic mulching and industrial activities. The floods and storms also influence the distribution and accumulation of MPs in the marine environment. The north pacific gyre in the northern Pacific Ocean also accumulates the marine debris and that is termed as great pacific garbage patch (GPGP). It contains plastics, which disintegrate to MPs due to mechanical forces. An earlier study used aircraft surveys and multi-vessel and observed 45–129 thousand tons plastics in an area of 1.6 million km^{-2} between Hawaii and California, i.e. a zone of plastic accumulation. The observed plastics was 4–6 times more than was previously recorded and contained 8% MPs of total mass of GPGP. This difference was also due to use of robust technique in the measurement of large debris, but rather than the plastic accumulation was found to be increased within GPGP as compared to water in the surrounding (Lebreton et al., 2018).

Table 2

Distribution, characteristics and abundance of MPs in different regions.

Sample type	Country	Shape of MPs	Color	Size	Abundance	Polymer type	Reference
Rhine and Main River sediments	Germany	Fibers, pellets, fragments, sphere	Transparent, whitish	<5 mm	4000 particles kg ⁻¹	PP, PS, PE, PVC, PET, PA	Klein et al. (2015)
Bohai Sea beach sediments	China	Fragments, sheets, film	Dark-blue, brown, purple, light, green, pink, black	1 µm to 5 mm	102.9–163.3 particles kg ⁻¹	PE, PVA, PS, PP, PET, LDPE	Yu et al. (2016)
Alpine glacier supra-glacial debris	Italy	Fibers, fragments	Violet, black, light-blue, transparent, red	<5 mm	74.4 ± 28.3 particles kg ⁻¹	PA, PES, PE, PP, PS	Ambrosini et al. (2019)
Lake and pond sediments	Finland	Fibers, fragments	Red, green, blue, yellow	<5 mm	395.8 ± 90.7 particles kg ⁻¹	PA, PS, PU-PET, cellulose	Scopetani et al. (2019)
Jiaozhou Bay surface water	China	Fragments, fibers, granules	Green, red, black, grey, blue	1200 ± 780 µm	15 ± 6 particles kg ⁻¹	PP, PE, PET, PA, PVA, LDPE	Zheng et al. (2019)
Hangzhou Bay surface sediments	China	Micro-beads, film, fiber, fragment	Transparent, blue, red, black, green	50–5,000 µm	130–280 particles average: 180 ± 50 kg ⁻¹	PS, PP, PE, PET, PO, cellulose	Fraser et al. (2020)
Sediments	Oman sea	Film, fragments, fibers, pellets	Blue, red, white, black, green	100–5,000 µm	138.3 ± 4.5 to 930.3 ± 49.1 particles kg ⁻¹	PE, PP, nylon, PET, PVC	Kor et al. (2020)
Water samples	Persian Gulf, Middle East Asia	Pellets, film, fragments, fibers	Blue, yellow, red, white, black, green, colorless	100–5,000 µm	1.8 × 10 ⁴ particles km ⁻²	PE, PP, PS	Kor and Mehdinia (2020)
Sea water	Southern ocean (around Antarctic continent)	Fragments, film, pellets, filaments	Black, transparent, yellow, grey, green, blue	<5 mm	188 ± 589 particles km ⁻²	PE, PP, PS, PVC, PMM, nylon	Suaria et al. (2020)
Sediments	Western Pacific Ocean	Fragments, film, fibers	White, red transparent, blue, yellow, –	<5 mm	240 particles kg ⁻¹	PES, PET, PP, PE, CP	Zhang et al. (2020a)
Raritan river water	New Jersey, USA	pellets, fragments, sheets	–	500–2000 µm	400–600 particles m ³	PP, PE, PS, PES, PVS	Bailey et al. (2021)
Kayamkulam Estuary sediments	India	Filaments, fibers, pellets, fragments	White, colored	<5 mm	438.8 particles kg ⁻¹	PES, PE, PP	Radhakrishnan et al. (2021)
Sediments	Kiel Fjord (Baltic Sea), Germany	Fibers, fragments	Orange, blue, red, yellow, pink	0.2–5.0 mm	1.8 to 4.5 particles kg ⁻¹	PS, PE, PP, PA	Schroder et al. (2021)
Barrow River sediments	Ireland	Fibers, fragments	White, red, black, blue	100 µm- to 5 mm	155 particles kg ⁻¹	PE, PP, PET, CA, nylon	Murphy et al. (2022)
Thames River surface water	United Kingdom	Pellets, fragments, fibers, glitter, foam	White, blue, red, black, yellow, gold, brown, pink, green, transparent, orange, purple	<5 mm	12.27 particles L ⁻¹	PS, PVC, PCP, PE, PP	Devereux et al. (2023)
Estuarine sediments	Penang, Malaysia	Fragments, pellets, film, fibers, foam	Transparent, red, black, green	500 µm–5 mm	430 ± 7.2 to 4000 ± 29.17 particles kg ⁻¹	PE, PP, PS, PVC, PA, PEO, PCP	Tan and Zanuri (2023)
Water and sediments	Akmola Region, Kazakhstan	Film, fibre, fragments	–	100–500 µm	1.2 × 10 ⁻¹ to 4.5 × 10 ⁻¹ particles/dm ³	PET, PE, PS, PP, PA	Salikova et al. (2024)

6. Microplastics influence on aquatic species

The influences of MPs can be observed right after their ingestion and trophic transfer in food-chain species. Earlier studies indicated MPs in gastrointestinal tracts and other body parts of aquatic species suffering from metabolic disorders (Hale et al., 2020; Wang and Chen, 2023; Table-3; Fig. 2). The additives used during polymerization get released from the MPs and create toxicity in living organisms.

6.1. Phytoplankton

The diatoms, green algae, cyanobacteria, etc., mainly float as phytoplankton on water surface. Badylak et al. (2021) in their study at the Florida Keys observed an equal abundance of MPs particles and algal cells and hence confirmed a greater chance of interaction between them. The high abundance of microalgae and bacteria in water is found to play a positive role in their aggregation and colonization on the MPs surface. The density of MPs particles get increased due to adherence of phytoplankton. Peller et al. (2021) in their study comprising *Cladophora* algae in the Michigan and Erie Lake, found the physical entanglement and adsorptive forces responsible for the interaction among the algae and MPs particles. However, the interaction and aggregation of MPs with phytoplankton may be harmful to the growth of phytoplankton like as observed in case of microalgae *Scenedesmus obliquus* exposed to polystyrene. The reduction in growth of this species was based on polymer size only; not the type (Liu et al., 2020).

The toxic effect of MPs on marine algae *Skeletonema costatum* by selecting photosynthetic parameters and algal growth has also been defined by Zhang et al. (2016). The exposures of 1 µm sized PVC particles for 90 days on this species reduced growth up to 39.7%, but on increasing the particle size to 1 mm, no impact on growth was observed. Instead, the photosynthesis rate was affected due to reduction of photosynthetic efficiency and chlorophyll. The MPs with bigger sizes generally impact on photosynthesis, while the smaller ones generally penetrate through the cell wall and cause further damage (Liu et al., 2020).

The phytoplankton on surface of MPs particles causes formation of biofilm, which contain protein and carbohydrate to a major extent (Galgani et al., 2019). It is proved for PS, which generally has more biofilm formation characteristics as compared to other polymers (Li et al., 2019). The biofilm also may promote adsorption of harmful contaminants such as heavy metals (Kadac-Czapska et al., 2022). Certain types of MPs have been shown to carry more heavy metals than others. The bio-fouling may also develop due to biofilm as well as adherence of phytoplankton, pathogenic bacteria, etc., on MPs surface. The increased density causes shifting of the MPs particles toward deep bottom layers. The diatoms are considered as omnipresent residents of the MPs particles and are observed in Spain, Greece, Mediterranean coasts and Italy (Nava and Leoni, 2021).

6.2. Zooplankton

The consumption of MPs by zooplankton depends on their abundance, shapes and sizes (Botterell et al., 2019). Desforges et al. (2015) collected zooplankton from northeast Pacific Ocean, and under laboratory conditions, the MPs ingestion rate (PS) was recorded as 1 particle by each among 34 copepods (*Neocalanus cristatus*) and 17 euphausiids (*Euphausia pacifica*). It was unexpected that out of 149 MPs, the zooplankton (copepods) ingested 129 particles. The trophic transfer of MPs particles has also been justified by Costa et al. (2020) using *Tigriopus fulvus* as a prey contaminated with MPs and *Aurelia* sp. as a predator in controlled conditions. After 24 h, the MPs along with copepod were found to be transferred in the predator body. The weathered and aged MPs become more susceptible to ingestion by the zooplankton; mistakenly from the aquatic environment, because of their appearance similar to the phytoplankton (Vroom et al., 2017). The toxic effects of MPs have also been observed on zooplankton development, reproduction and swimming behaviour (Shen et al. 2020a, 2020b; Suwaki et al., 2020). The zooplanktons ingest the MPs and also get ingested themselves as a prey due to their small size in food-chain.

6.3. Crustacean

6.3.1. Shrimp

The shrimp comprises mouth parts for chopping the ingested materials, thereafter stomach for food breakdown by enzymes, the intestine for absorption and retention of food/materials; followed by the anus at its posterior end to expel faecal pellets (Devriese et al., 2017). The connection between MPs and shrimps is observed from the southern part of the North Sea and channel regions. The MPs having 200–1,000 μm size and average density of $0.68 \pm 0.55 \text{ MP g}^{-1}$ wet weight were found in 63 % of the total monitored shrimps (Devriese et al., 2015). The shrimp species *Parapeneopsis stylifera*, *Penaeus indicus* and *Metapenaeus monoceros* in the northern region of the Arabian Sea were found to contain 1,220 MPs particles in gastrointestinal tracts. The northern part of the Bay of Bengal (Bangladesh) containing *Penaeus monodon* (tiger shrimp) and *Metapenaeus monoceros* (brown shrimp) also indicated the MPs particles in the range of 3.87 ± 1.05 and 3.40 ± 1.23 items g^{-1} , respectively, in their digestive tracts (Hossain et al., 2020).

Similarly, MPs are also observed from northwest Persian Gulf (*Metapenaeus affinis*; Keshavarzifard et al., 2021) and even from a flagship species *Aristeus antennatus*; averaging 1.66 ± 0.1 MPs particles individual⁻¹ (Cau et al., 2019). Earlier, *Artemia parthenogenetica* (brine shrimp larva) was exposed to 10 μm sized PS for 14 days and confirmed no impact on growth, development and survival. However, the mitochondrion was increased to some extent and microvilli became disordered (Wang et al., 2018). The MPs are also observed from hepatopancreas, exoskeleton, gastrointestinal tract and muscles of *Litopenaeus vannamei*, (white leg shrimp), in a range of 16.31 ± 1.87 , 4.37 ± 0.27 , 137.78 ± 16.48 and 1.69 ± 0.13 particles, respectively. The MPs in these organs might result various metabolic disorders in the shrimps (Vitheepradit and Prommi, 2023). The experimental studies pertaining to influence of MPs on shrimp are still limited and should cover more observation regarding impact of MPs on shrimps with detailed mechanism.

6.3.2. Prawn

The prawn is consumed as seafood in whole world and found to have MPs particles in their body. The tiger prawn (*Penaeus semisulcatus*) from different sites of Musa Sanctuary of Persian Gulf showed MPs (1.5 g^{-1}) in muscle and exoskeleton (Abbasi et al., 2018). The presence of MPs in muscle increases threats of trophic transfer rather than the gastrointestinal tract, because from there, the MPs can easily be expelled outside. The impact of PE (0.5–1.0 μm) and PS (30–150 μm) has also been determined in several individuals of giant river prawn (*Macrobrachium rosenbergii*). The MPs exposure in their diet created changes in weight,

length and survival rate; hence the entire biology of the species was affected (Jaikumar et al., 2021). The gastrointestinal tract of *Macrobrachium rosenbergii* (freshwater prawn) in a study marked an average of 33.43 ± 19.07 items individual⁻¹ (Reunura and Prommi, 2022). The head, middle part and tail tissues of 60 prawns of similar freshwater species revealed PP type of MPs in a size range of 101–500 μm , which may be harmful for these species and consumers in food-chain (Tee-hor et al., 2024).

6.3.3. Lobster

The risk of MPs ingestion in lobsters starts right from larval stage as plankton larvae, which generally float on top water layer up to 30 m and face a very high MPs concentration (Woods et al., 2020). During their post-larval period, they shift again to deep water column having higher abundance of MPs particles. In an earlier study, 89 individuals of a Norwegian lobster species, *Nephrops norvegicus*, were collected from a depth of 270–660 m of Mediterranean Sea. Amongst, 83 % of the total individuals were found to contain PP, PE, etc., in their stomach with a density of 5.5 ± 0.8 particles individual⁻¹ (Cau et al., 2019). The same species was also found to contain MPs in gastrointestinal tract and potentially creates problems for the food-chain and seafood consumers (Hara et al., 2020).

Devriese et al. (2017) in their study observed that MPs contaminated with toxic chemicals do not have any impact on the nutritional state of lobster (*Nephrops norvegicus*). However, PCBs applied on MPs (PS) surface reached in tail tissues after 21 days of exposure. The lobster may also retain MPs in their gills including guts; thus suffer from the respiratory and gastrointestinal troubles (Taylor et al., 2016). In a recent study, *Cephalothorax carapace* and *Homarus americanus* were exposed to higher concentrations of MPs with an adequate food supply. These species ingested MP particles and ultimately perished due to a reduction in their oxygen consumption capacity (Woods et al., 2020).

6.3.4. Crab

The crabs have a capability to survive both inside and outside of the water, but mostly prefer aquatic habitats. The crabs in an earlier study were exposed to PS, i.e. the most abundant MPs in the marine environment, for 14 days and indicated MPs in hepatopancreas, stomach and gills. The PP particles were found to lay impact on embryo development and reproduction, including enhancement of mortality in adult mole crabs, *Emerita analoga* (Pacific beach; Horn et al., 2020). The MPs in crabs may also impact on the cognitive behaviour as observed in *Pagurus bernhardus* (European crab), which was exposed to PE for 5 days (Crump et al., 2020). The MPs in intestine, gills and gastrointestinal tract of *Carcinus maenas* and *Eriocheir sinensis* (Thames Estuary) highlighted the risk of digestive and respiratory problems, which may also cause further complaints in their body (McGoran et al., 2020).

The Guayas River Estuary (Ecuador) also indicated MPs in digestive tracts, hepatopancreas, gills and tissues of *Minuca ecuadoriensis* and *Leptuca festae* (Villegas et al., 2021). A long intestinal tract and gills in the crabs allow long retention of MPs in body and result in osmoregulatory and respiratory problems (Watts et al., 2016). Another study by Watts et al. (2015) also marked the impact of MPs on energy balance and food consumption in *Carcinus maenas*. The MPs are also reported from different other crabs species such as *Parasesarma bidens*, *Paraleptuca splendida*, *Metopograpsus frontalis*, *Thalamita crenata*, *Callinectes sapidus*, *Carcinus maenas*, etc. (McGoran et al., 2020; Waddell et al., 2020). The MPs in crustaceans may also influence feeding, swimming, defence and reproductive habits including physiological functions comprising oxidative damage, neuromodulation, immunomodulation, metabolic regulation, etc. (Zhang et al., 2023).

6.4. Molluscs

The Molluscs comprises a large numbers of species such as snail, oyster, octopus, clam, unio, pila, squid, gastropod, etc., and most of

them are consumed as seafood (Walkinshaw et al., 2020). Abidli et al. (2019) from northern Tunisia (Lagoon of Bizerte) observed films, fragments and fibrous shaped MPs particles in a range of 703.95–1,482.82 kg⁻¹ wet weight, inside the soft tissues of *Mytilus galloprovincialis* (Mediterranean mussel), *Crassostrea gigas* (oyster), *Bolinus brandaris* (sea-snail), *Ruditapes decussatus* (grooved carpet shell) and *Hexaplex trunculus* (sea-snail of medium size). The *dosidicus gigas* (squid) revealed 93% of the exposed MPs with a size of 200 µm in the digestive tract (Alfaro-Nunez et al., 2021).

The MPs are also observed in the wild oysters *Saccostrea cucullata*, collected from Pearl River Estuary, China. The study indicated 1.5–7.2 MPs particles g⁻¹ wet weight of the body tissues and ranged 1.4–7 particles individual⁻¹ (Li et al., 2018a). Another study revealed 10.5 and 57.2 MPs particles g⁻¹ from *Scapharca subcrenata* and *Patinopecten yesoensis* (bivalve), respectively (Li et al., 2015). From the coastal region of Taiwan, 6,630 MPs particles were observed from 660 oysters with an average concentration of 3.24 particles g⁻¹ wet weight and in the range of 0.63–37.94 particles g⁻¹ (Liao et al., 2021). These species are vulnerable to ingest MPs of various shapes such as pellets, fibres, films and fragments, which are confirmed from individuals of *Ruditapes philippinarum* (Manila clam/Japanese carpet shell) ranging 4.3–36.6 particles (Liu et al., 2021a).

Different types of MPs particles such as nylon, PET and PE are also reported from other species such as *Thais mutabilis* (snail), *Amiantis purpuratus* (clam), *Pinctada radiata* (pearl-oyster), *Cerithidea cingulate* (horn-snail) and *Amiantis umbonella* (clam), in the range of 0.2–21 particles g⁻¹ wet weight and 3.7–17.7 MPs per individual species (Naji et al., 2018). These species may ingest MPs directly from freshwater, marine environment and via food-chain, and thus pose major threats.

6.5. Turtle

Turtles are found to be abundantly present in freshwater and marine environment and may contain a huge concentration of MPs particles (Clause et al., 2021). Abreo et al. (2016) recovered a dead turtle from the Lapu-Lapu, agdao (Philippines) and found plastic debris and stomach blockage. It indicates that a small quantity of debris may easily block the gastrointestinal tract and cause death of the turtle (Santos et al., 2015). A recent study highlighted different nesting sites of *Chelonia mydas* (green turtle) and *Caretta caretta* (loggerhead) with MPs particles density of 45,497 ± 11,456 particles m⁻³ in the top 2 cm. However, the MPs were deposited up to 60 cm; equal to depth of a turtles nest, but the density was found to be decreased with depth (Duncan et al., 2018). Therefore, the risk of MPs consumption by turtles is not only due to the abundance of MPs in the water column, but also from the superficial sediments. Both PP and PE are abundantly present in the marine environment and their impact has been observed in *Caretta caretta* (15.83 ± 6.09 individual⁻¹) from sub-tropical gyre (North Atlantic; Pham et al., 2017). Renzo et al. (2021) observed PET, PP, PES, and HDPE from the liver tissues and fat of *Caretta caretta*. The turtles consider translucent and flexible MPs particles as a prey and mistakenly ingest them; thus suffer from certain health issues including death (Schuyler et al., 2014).

6.6. Fish

Both of the MPs and fish larvae are found to be abundantly present in surface water column and hence the risk of MPs transfer as a prey starts rightly therefrom in the larvae (Whitney et al., 2021). Fish that ingest microplastics show disrupted physiological functions. The sizes of MPs play an imperative role during ingestion by fishes; likewise observed in juvenile of *Acanthochromis polyacanthus* (planktivorous reef fish). Initial treatment of plastic particle having 2 mm diameter remained in gut for 6 weeks, but did not cause any impact on behaviour and growth. However, when size was reduced to <300 µm, 2,102 particles were observed in fish after a week and laid a toxic effect on body growth (Critchell and Hoogenboom, 2018). The MPs may be accumulated in digestive tract of

fish with time and the higher content also blocks the digestive tract. The false satiation of food also avoids ingestion of food thus feeding rate and nutrients absorption are reduced. The intestinal obstruction result oxidative stress; followed by more metabolic disorders including death (Jovanovic, 2017).

During filtration of water, the MPs may enter the gills based on sizes and break filaments, damage gills, reduce efficiency of respiration and cause hypoxia (Jabeen et al., 2017). They may also enter the fish through skin and reach the internal organ; however it may be possible for MPs having small size and fish containing any lesion (Barboza et al., 2020a). An earlier study indicated direct entry of MPs in muscle; tissues and kidney from gastrointestinal tract of fish (Vignardi et al., 2015). The MPs from the gastrointestinal tract may undergo pinocytosis; followed by phagocytosis as well as endocytosis and reach inside the tissues. The MPs containing toxic chemicals also enter the bloodstream of fish and become a part of cardiovascular system; thus increase blood pressure and results blood cells toxicity (Bhuyan, 2022). The MPs of small size may enter the muscle tissues, whereas the large sized to the interstitial tissues. The small MPs may also reach to the brain and cause neurological toxicity; followed by other metabolic disorders (Barboza et al., 2020a). The MPs may enter the body tissue and shows biomagnification; thus transfer in food-chain. The bioaccumulation of plastic particles in gills, intestine and liver has been observed from the *Pseudobagrus fulvidraco*, which was exposed to PE particles (Lee et al., 2023). The EDCs are also observed from the aquatic environment and hence the susceptibility of their direct entry or via trophic transfer in fish is very high. These chemicals in fish may impact on homeostasis and result long term chronic effects such as behavioural changes, reproductive toxicity and endocrine disruption (Pironti et al., 2021). However, the detail mechanism behind the process is lacking in literature still so far (Handy and Al-Bairuty, 2019).

A study comprising 26 fishes from freshwater and sea coast in China, revealed MPs in intestine and stomach, with a density (0.5–1.9 items individual⁻¹) higher in sea benthopelagic fishes as compared to those were from freshwater (Jabeen et al., 2017). The virgin plastics generally do not cause health hazards as observed by Jovanovic et al. (2018) in *Sparus aurata* (gilt-head seabream), which was exposed to MPs for 45 days. The retention of MPs in gastro-intestine was observed very low and did not cause any body disorder. However under natural condition, the biofilm formation may contain harmful microbes, PCBs and heavy metals and on ingestion may accumulate in organisms and increase toxicity through synergistic effects. The Atlantic Ocean contains around 1,100 fish species including 600 pelagic with more than 2 billion annual catches. An earlier study there comprised 76 fishes and observed 11% of the species containing MPs in digestive tracts (Lusher et al., 2016).

Further, the fishes from northeast Atlantic Ocean in a study showed the presence of BPA in liver and muscles. The liver from *Scomber colias* indicated greater concentration of BPA (302 ng g⁻¹ dry weight) as compared to *Trachurus trachurus* (5 ng g⁻¹ dry weight), while muscle of *Scomber colias* showed a high concentration of bisphenol-E (272 ng g⁻¹ dry weight). The fishes having greater content of MPs particles confirmed more contamination as compared to those having lower MPs content (Barboza et al., 2020b). The zebra-fish in a study when exposed to PS particles for 21 days specified the impacts on physiology and cellular function as well as a decline in heart rate and other metabolic activities (Dimitriadis et al., 2021). The impact of MPs on reproductive system of female zebra-fish has been observed by Gupta et al. (2023). Those fish species were exposed with PS in a concentration range of 20–500 µg L⁻¹ and revealed major change in gonadosomatic index, and the change was also found to be dose dependent. The steroid hormone level also caused a significant imbalance in the hormonal homeostasis.

The fishes on being exposed to microplastics show oxidative stress, which may or may not be controlled by enzymatic (catalase, superoxide dismutase and glutathione) and non-enzymatic antioxidants (glutathione and thiol). The fishes then may also suffer from cytotoxic and neurological disorders (Guimaraes et al., 2021). The toxicity concerning

Table 3

Polymer type, shape, colour and mode of transfer of MPs in various aquatic species.

Species	Location	Polymer type	Shape	Colour	Mode of transfer	Observed from	Reference
<i>Acartia tonsa</i> (Zooplankton)	Hudson-Raritan estuary, USA	PE, PP, PS, PET, PES, PU, PS	Fragments, beads, film	Orange, blue, red, purple, green	Ingestion	Body (after organic matter digestion)	Sipps et al. (2022)
<i>Calanus hyperboreus</i> (Zooplankton)	Fram Strait, Arctic	PU, PS	Fragments	–	Ingestion	Body (after organic matter digestion)	Botterell et al. (2022)
<i>Dosidicus gigas</i> (Jumbo squid)	Eastern tropical Pacific Ocean	PA, PS, PET, PC, PAN, PP, PVC	Fibre, film, fragments	Blue, red, transparent, black, yellow	Ingestion	Stomach content	Wang and Chen (2023)
<i>Saccostrea cucullata</i> (Oysters)	Pearl River Estuary, China	PP, PET, PE, PA, PVC, PS	Fragments, fibres, sheets, pellets	White, yellow, blue, red, brown, black, green	Trophic transfer/ ingestion	Soft tissues	Li et al. (2018a)
<i>Mytilus galloprovincialis</i> (Molluscs)	Bizerte, Northern Tunisia	PP, PE	Film, fragments, fibres	Blue, red, black, yellow, green, white	Ingestion	Soft tissues	Abidli et al. (2019)
<i>Penaeid shrimp</i> (Penaeid shrimp)	Northern Bay, Bengal	PA, rayon	Fibres, filaments	Green, blue, black, red, transparent, white	Trophic transfer/ ingestion	Gastrointestinal tract	Hossain et al. (2020)
<i>Carcinus maenas</i> (Brachyuran crab)	Thames Estuary	PES, PP, PE, PA,	Film, fragments, fibres	Blue, pink, yellow, red, brown, grey, green, silver orange	Ingestion	Gastrointestinal tract and gills chamber	McGoran et al. (2020)
<i>Callinectes sapidus</i> (Blue crab)	Corpus Christi Bay, Texas	PET, PS, PES, PC	Fibres, fragments	White- yellow, red, black, blue	Ingestion	Stomach tissues	Waddell et al. (2020)
<i>Metapenaeus affinis</i> (White shrimp)	Northwest, Persian Gulf	PS, PET, PP	Film, spheres, fragments, fibres	Black, blue, red, green, white	Trophic transfer/ ingestion	Digestive tissues	Keshavarzifard et al. (2021)
<i>Crassostrea angulata</i> (Portuguese oysters)	Taiwan coastline	PET, PP, PE, PS, PVC, PA, PC	Spheres, fibres, flakes	Orange, black, yellow, transparent	Ingestion	Soft tissues	Liao et al. (2021)
<i>Nephrops norvegicus</i> (Norway lobster)	Marine water, Iran	PP, PA, PS, PES	Fibres, fragments	Blue, red, black, grey, yellow, purple, pink, green, white	Ingestion	Digestive tract	Joyce et al. (2022)
<i>Macrobrachium rosenbergii</i> (Freshwater prawn)	Central region, Thailand	PE, ABS, PCL	Fragments, fibre, sphere, film	Red, blue, green, black, white, yellow, transparent	Ingestion	Gastrointestinal tract	Reunura and Prommi (2022)
<i>Ruditapes philippinarum</i> (Bivalve)	Yantai, China	PET, CP, PU, PE, PP, PES, PVA	Film, fragments, pellets, fibres	–	Ingestion	Soft tissues	Liu et al. (2021a)
<i>Filopaludina sumatrensis speciosa</i> (Gastropod)	Southern Thailand	PET, PP, PE, PA, rayon	Fibres, fragments	Dark-blue, red, brown, transparent, black, green, pink, purple, yellow	Ingestion	Body tissues	Jitkaew et al. (2023)
<i>Chelonia mydas</i> (Green turtle)	Great Barrier Reef, Australia	HDPE, PES, PVC, nylon, rayon	Debris, film, fabric	Dark-green, transparent, white, black	Ingestion	Chyme samples	Caron et al. (2018)
<i>Caretta caretta</i> (Loggerhead turtle)	Adriatic coast, Molise, Italy	PES, HDPE, PP	Film, fragments, fibres, pellets	White, blue, black, yellow, transparent, brown	Ingestion	Liver and abdominal fat tissues	Renzo et al. (2021)
<i>Lutra lutra</i> (otter)	Ticino River, Italy	PET, PA	Fibres	–	Ingestion/ trophic transfer	Faecal material	Smiroldo et al. (2019)
<i>Galeus melastomus</i> (Demersal shark)	Western Mediterranean Sea	PP, PET, PE, PAN, PA, CP	Fragments, film	Blue, black, transparent, red, white,	Ingestion/ trophic transfer	Stomach content	Alomar and Deudero (2017)
<i>Delphinapterus leucas</i> (Beluga whale)	Eastern Beaufort Sea, Canada	PES, PE, PS, PP, PVC, nylon	Fibres, fragments	–	Trophic transfer/ ingestion	Intestine, stomach, and faeces	Moore et al. (2020)
<i>Dicentrarchus labrax</i> (Wild fish)	NE Atlantic Ocean, Portugal	PE, PES, cellulose	Pellets, fibres, fragments	White, blue, black, yellow, red/pink	Ingestion/ trophic transfer	Dorsal muscle, gills and gastrointestinal tract	Barboza et al. (2020a)
<i>(Neogobius melanostomus)</i> (Round goby)	Muskegon, St. Joseph and Milwaukee River, USA	–	Film, fragments, foam, fibres, beads	Blue, red, purple	Ingestion/ trophic transfer	Digestive tract, body tissues	McNeish et al. (2018)
<i>Thamnaconus septentrionalis</i> (Greenfin horse-faced filefish)	Yangtze estuary, East and South, China Sea	PET, PES, CP	Fragments, sheets, fibres	Transparent, black, blue	Ingestion	Intestine, stomach	Jabeen et al. (2017)
<i>Delphinus delphis</i> (Dolphin fish)	Galician coasts, Spain	–	Beads, fibres, fragments	Black, red, blue, yellow, green	Ingestion	Stomach content	Hernandez-Gonzalez et al. (2018)
<i>Katsuwonus pelamis</i> (Tuna fish)	Ternate city, North Maluku, Indonesia	–	Film, fibres, fragments	Green, blue, black, brown, red, white	Ingestion	Gastrointestinal tract	Lessy and Sabar (2021)
<i>Scyliorhinus canicula</i> (Shark fish)	North-East Atlantic	PAM, CP, PP, PES	Fibres, beads, fragments	White, yellow, red, black, green, orange, clear, blue	Ingestion	Stomachs and digestive tract	Parton et al. (2020)

(continued on next page)

Table 3 (continued)

Species	Location	Polymer type	Shape	Colour	Mode of transfer	Observed from	Reference
<i>Rhizoprionodon acutus</i> (Shark fish)	Bay of Bengal, India	PP, PAM, PE	Granules, fragments, film, foam, fibres	Pale white, black, blue, red, black	Trophic transfer/ ingestion	Digestive tract	Janardhanam et al. (2022)
<i>Oreochromis mossambicus</i> (Tilapia fish)	Dhanmondi Lake, Bangladesh	PP, PVC, PC, LDPE, HDPE	Foam, Fibres, film, pellets, fragments	Red, black, yellow, white, blue, green, transparent	Ingestion	Gastrointestinal tract	Mercy et al. (2023)
<i>Nemipterus japonicus</i> (Kurisi fish)	Jeneponto Regency, South Sulawesi Province	PVC, CA, CAB, PBT, PB	Line form, fragment	Green, black, transparent, blue, red	Ingestion	Body tissues	Basri et al. (2024)

PVC and PE in fishes has also been proved from Zebra-fish and Medaka, respectively. These species after MPs exposure did not reveal any change in the genotoxicity, lipid peroxidation and classical biomarkers; however their growth was significantly reduced after 2 months. Further, the reproduction was also altered due to the presence of PVC rather than PE particles (Cormier et al., 2021). Wang et al. (2021b) observed enhanced sexual maturity in female fishes (*Oryzias melastigma*) after exposure of PS for 150 days.

The pristine and chlorpyrifos loaded PS particles in another study revealed toxicity and adversative effect on *Oncorhynchus mykiss* (rainbow trout); particularly on gill tissues (Karbalaei et al., 2021). The accumulation, adsorption and toxicity of triclosan in zebra-fish has also been found to be enhanced due to ingestion of PVC, PP and PE, which caused oxidative stress and neurotoxicity in the brain and lipid peroxidation related to liver (Sheng et al., 2021). Thus, MPs cause oxidative stress, cytotoxicity, neurotoxicity and other metabolic disorders, although the greater impact of MPs may be at the larval stage in fishes. The MPs contamination is also confirmed in tuna, shark, etc. Around the Balearic Islands, 125 individuals of black-mouth cat-shark (*Galeus melastomus*) were monitored, and out of them, 16.80 % were found to contain MPs (Alomar and Deudero, 2017).

The trophic transfer of MPs has also been recorded from the tuna fish (*Thunnus albacares*), which had ingested a fish containing MPs in the stomach. However, some MPs were also recovered from the stomach of tuna itself (Chagnon et al., 2018). Another study indicated 137 MPs particles at an average, each from the whale sharks (*Rhincodon typus*), manta ray (*Mobula alfredi*) and tuna (*Katsuwonus pelamis*; Lessy and Sabar, 2021). The fish species porbeagle shark (*Lamna nasus*), which is categorised as a critically endangered, even found to contained MPs in northeast Atlantic Ocean (Maes et al., 2020). The PAM (10%), synthetic cellulose (33.3%), PES (8.3%) and PP (25%) are also observed from the demersal sharks (Parton et al., 2020). Fishes are consumed as food by a large mass of population all over the world and thus pose a greater risk to the human health (Schmid et al., 2018).

6.7. Marine mammal

The marine mammals mainly feed on small fishes, crustacean, molluscs, aquatic birds, etc., and thus are the indicators of the MPs trophic transfer (Nelms et al., 2019). The zooplanktons also play an important role in transfer of MPs toward higher trophic levels. Earlier study also confirmed presence of 137 MPs particles on an average, each from beluga whales (*Delphinapterus leucas*) and dolphins (*Delphinus delphis*; Moore et al., 2020; Lessy and Sabar, 2021). The scats of 44 *Callorhinus ursinus* (northern fur seal) were collected from eastern Pacific Range, and out of that, 41% of scat samples revealed an average density of 16.6 ± 19.1 MPs fibres scat⁻¹ (Donohue et al., 2019). However, 42 scats of *Arctocephalus gazelle*, i.e. Antarctic fur seals, were examined by Garcia-Garin et al. (2020), but no MPs were observed, which infers low risk of MPs in food-chain at Bransfield Strait and that may increase further in future.

The grey seal *Halichoerus grypus* in an earlier study comprised 13 individuals (Ireland, south coast) and indicated a total of 363 MPs

particles such as films (1%), fragments (14%) and fibres (85%). Further 12 seals also marked the presence of *Acantocephala* parasites (74.5 ± 67.7 parasites seal⁻¹), which might be reached with contaminated MPs floating in parasitic zones (Hernandez-Milian et al., 2019). The necropsy of *Halichoerus grypus* (grey seal) and *Phoca vitulina* (harbour seal) in a study (Germany) utilized gastrointestinal tracts, and in addition, the scat samples were also collected from sandbank. Thus, a total of 255 MPs particles such as PE, PET, EVA, PP and nylon fibres were observed from 10 intestines and 9 scat samples (Philipp et al., 2020). Although, there are limited number of studies related to seals, which may suffer from various disorders after exposure to MPs particles (Zantis et al., 2021).

6.8. Aquatic bird

Aquatic birds are mainly carnivorous and feed on zooplankton, small fishes, insects, etc., therefore are at a risk of MPs consumption (Nicastro et al., 2018).

6.8.1. Freshwater bird

The MPs particles in freshwater birds are evidenced in earlier studies of different regions. The *Cygnus olor* (mute swan), *Anas platyrhynchos* (mallards) and *Ardea cinerea* (grey heron) from the Geneva Lake again confirmed 4.3 ± 2.6 MPs particle bird⁻¹ in digestive tracts (Faure et al., 2015). The aquatic birds such as geese, loons and ducks from all across the Canada are found to contain different plastics debris and that is a very serious issue as these birds are consumed as food by the Canadian aboriginal people at a large scale (Holland et al., 2016). Reynolds and Ryan (2018) observed 283 MPs particles from faecal samples and 408 from feather brushing of Yellow-billed duck, Spur-winged goose, Cape shoveler, Egyptian goose, Red-billed teal, White-faced duck and Cape teal, which is of serious concern.

Different types of MPs such as PP, PVC and PES are also recovered by D'Souza et al. (2020) from the faecal pellets (44.6%) and regurgitant (50.1%) of the riverine predator *Cinclus cinclus* (Eurasian dippers). The river kingfisher *Alcedo atthis* in a study indicated PP, PU and PE types of MPs fibres (63 µm–3.09 mm) in 7.5% of 133 regurgitated pellets. This bird usually feeds and lives along the watercourse of the Ticino River, Italy (Winkler et al., 2020). A study at 30 chicks of *Phalacrocorax auratus* (double-crested cormorants) from different sites of Laurentian Great Lakes indicated 5.8 MPs particle bird⁻¹ such as PP and PE in their gastrointestinal tracts (Brookson et al., 2019). The studies are very limited and only confined to the availability, but toxicity imposed on birds also needs to be explored.

6.8.2. Seabird

Seabirds are the indicators of trophic transfer of MPs in food-chain of aquatic environment. An earlier study revealed 439 plastics and amongst 73.2% were MPs sheets and fragments (yellow, white and clear) in the regurgitant and digestive tracts of two chicks and adult gull species *Larus marinus* (Great Black-backed) and *Larus argentatus* (Herring gull) of Maine and North Hampshire, USA (Caldwell et al., 2020). The necropsy of 30 coastal and marine birds (*Morus serrator*, *Phalacrocorax varius*, *Anhinga novahollandiae*, etc.) of South-eastern Australia,

confirmed dark and blue colored 49 MPs particles inside the stomach of 9 birds. Internal organelles damage and blockage of the intestine are some of health hazards observed in birds, which is of serious concern (Gilbert et al., 2016). The dropping of migratory birds such as *Larus michahellis* (Yellow-legged gull), *Chroicocephalus ridibundus* (Black-headed gull) and *Phalacrocorax aristotelis* (European shag) from 10 different sites confirmed 114 MPs particles, which is greater than that found in sand at beaches (Masia et al., 2019). It shows that the seabirds are very susceptible to MPs ingestion in the food-chain (Wilcox et al., 2015).

In Southern Portugal, the intestine, stomach and gastrointestinal tracts of eight different species were found to contain PDMS, PS, PE, PTFE and PAM. A total of 22.5% from 160 individuals of *Phalacrocorax carbo* (great cormorant), *Alca torda* (razorbills), *Ciconia ciconia* (white storks), *Larus fuscus* (black-backed), *Ardea cinerea* (grey heron), *Morus bassanus* (northern gannets), *Phoenicopterus roseus* (greater flamingos) and *L. michahellis* (yellow-legged gull) were containing MPs particles (Nicastro et al., 2018). The impacts of MPs on seabirds are also observed from different other regions, worldwide (Thiel et al., 2018). The MPs ingestion creates deleterious impacts and a study by Roman et al. (2019) inferred that MPs are the main cause of death in seabirds; considering a total of 1,733 birds from 51 different species. Most of the birds were found to be suffered from impaction, perforation and gut blockage after the ingestion of MPs particles and other marine debris. The data related to MPs stress in water-birds is very important to make a conservational strategy (Nicastro et al., 2018). The MPs in Flesh-footed Shearwater are found to lay impact on reproductive output and also may results delayed ovulation, reduction of feeding, kidney and liver problems, lethal impacts, etc. (Fossi et al., 2018; Wang et al., 2021c).

The penguins at the Polar Regions are also suffering from the same problem of plastic pollution as confirmed in *Pygoscelis papua* (gentoo penguin) from the South Orkney, South Georgia, Signy and Bird Island of Antarctic region. A total of 20% depositions from 80 penguins were found to contain fragments and fibres of PP, PAN, PE, PES and rayon with an average concentration of 0.23 ± 0.53 MPs penguin deposition⁻¹ (Bessa et al., 2019). Similarly, Mirny Island of East Antarctica also revealed MPs in *Pygoscelis adeliae*, *Aptenodytes forsteri* and *Catharacta maccormicki* (Golubev, 2020). The faecal samples of *Aptenodytes patagonicus* (king penguin) in South Gorgia, marked 77% of the samples containing an average concentration of 21.9 ± 5.8 MPs particles g⁻¹ (Guen et al., 2020). The MPs in penguins may be transferred from the lower level in the food-chain and pose further risks for the species of higher trophic levels, such as seals and large fishes, etc. In addition, the risk is also associated with the abundance of MPs in surface and sub-surface water of the polar region as a result of anthropogenic effects or ocean gyre (see Lusher et al., 2015).

6.9. Coral

The corals are very sensitive and ingest MPs incidentally, even when enough food is available for them (Axworthy and Padilla-Gamino, 2019). A recent study on 34 corallimorph (*Discosoma nummiforme*) revealed that 55 % (19) MPs particles were ingested at the rate of 0.7 and 1.5 particle polyp⁻¹ with time exposures of 84 and 108 h, respectively (Connors, 2017). The corals of Xisha Island (China Sea) are also found to have MPs particles in a range of 0.02–1.3 particles g⁻¹ (i.e. 1–45 particles individual⁻¹); in addition, PET and rayon fibres were the dominant types of MPs (Ding et al., 2019). After MPs are ingested by corals; assert impact on certain metabolic functions. Berry et al. (2019) after 15 treatments of PE micro-beads and PP particles on *Acropora tenuis* (reef-building coral) found a significant impact on fertilization rather than the development of the embryo and larva settlement were having no any remarkable influence.

Grillo et al. (2021) in their study at *Porites porites* gave treatments of PS MPs particles in a concentration range of 1–1,000 mg L⁻¹ for 96 h. The MPs were found to be clustered inside filaments (mesenterial) and

gastro-vascular tissues, but did not exert any toxic effect during the said time duration. Hall et al. (2015) in their study observed impact of MPs exposure at scleractinian corals (Australia) and found MPs in mesenterial tissues inside the gastro-vascular cavity. Similar results were also observed by Rotjan et al. (2019) on *Astrangia poculata*, which is a temperate coral species. Instead, Hierl et al. (2021) in their study applied a high dose (i.e. 0.5 g L⁻¹) of PET to 4 species of Hermatypic coral and observed skeletal growth and entire corals were survived. However, the coral species are found to behave differently under the influence of varying temperatures and types of MPs particles, which may impact on the photosynthetic activities as observed in *Seriatopora hystrix* and *Acropora* sp. under laboratory conditions (Mendrik et al., 2021).

Harmful impacts of microplastic contamination have also been noted under controlled conditions at *Stylophora pistillata*, *Montipora digitata*, *Pocillopora verrucosa*, *Acropora muricata*, and *Porites lutea* corals species. The MPs generally have negative consequences on thermal tolerance of the corals; however the heat stress mainly impact photosynthetic capacity of the algal symbionts, coral health and physiology. In addition, heat stress in presence of MPs may also enhance the tissues necrosis and breaching including death of the corals (Reichert et al., 2021). The corals also remove MPs from surrounding water through ingestion or adhesion and the removal rates generally get increased due to bio-fouling on MPs surface. Corona et al. (2020) found increased ingestion and adhesion rate of MPs particles by *Danafungia scruposa* (mushroom coral) after the MPs surface was covered with *Artemia salina*.

The MPs particles settled at sea bottom with time and mix in the coral reef sediments (Zhang et al., 2019), thus become the sedimentary components and continue to create problems thereafter for burrowing and bottom dwelling species (Utami et al., 2021). The earlier studies have shown MPs in the crustacean, molluscs, turtles, fish, aquatic birds, coral, etc., with some metabolic disorders and strengthen that MPs are entered in food-chain of the aquatic environment. Although, the studies are still confined to expose the presence of MPs in the body and lacking the detail mechanism, which need to be explored in future.

7. Microplastics influencing carbon sequestration potential

The freshwater bodies and oceans are the major sinks of carbon dioxide and as a rough estimate; the amount of dissolved inorganic carbon in the oceans alone is around 50 times more than the atmospheric level (Laws and Maiti, 2019). However, the carbon fixation capacity of the water bodies is seriously affected by the availability of the MPs particles via different means (Shen et al., 2020b; Fig. 4). The negative influences of MPs on aquatic biota including phytoplankton are noticed in terms of growth, development and other metabolic disorders (Liu et al., 2020). The MPs surface generally colonizes the microalgae and plankton in the form of biofilm, which in turn increases the MPs density.

The aggregation of microbial population on biofilm after bio-fouling in the aquatic environment transports carbon formed via photosynthesis, from the upper euphotic zone to the deep bottom and this is also known as biological pump (Galgani et al., 2019). That carbon may stay at the bottom in sediments for decades, centuries and millions of years; thus freshwater bodies including oceans are considered as the major sinks of carbon. The biofilm formation and its shift from surface layers to the bottom after association with MPs mainly inhibit phytoplankton to carry on photosynthesis in the euphotic zone and thus the primary production is affected (Fig. 4).

In an earlier study, Sjollem et al. (2016) inferred that the growth rate of microalgae in presence of MPs with a concentration of 250 mg L⁻¹ may decline up to 45%, which is enough to alter natural carbon sequestration efficiency of aquatic environment all over the world. It also has a direct impact on zooplankton, which get less carbon via consuming phytoplankton and in addition suffer from various metabolic disorders, thus their capability to absorb carbon further get reduced (Cole et al., 2016; Shen et al., 2020a). Plastic particles in the water column also block sunlight, preventing photosynthesis in marine plants.

The copepods are also found to consume MPs in the freshwater and marine environment (Desforges et al., 2015). Their faecal pellets containing MPs; rather than sinking at the bottom, move toward the surface and due to degradation of such pellets, the carbon is escaped to the atmosphere (Wieczorek et al., 2019; Fig. 4). The reduction in the sinking of gelatinous zooplankton faecal pellets has also been confirmed by Wieczorek et al. (2019) for PS and PE at the rate of 1.47 and 1.35 times, respectively. Although, there are very few studies claiming MPs particle and their impact on carbon sequestration, but the available studies clearly define that the presence of MPs has negative impacts on the natural process of carbon sequestration (Shen et al. 2020a, 2020b). It is a matter of great concern as the level of carbon dioxide in the atmosphere is increasing rapidly and ability of water bodies to sequester carbon is being affected negatively due to MPs particles. The MPs thus are affecting the carbon sequestration potential of freshwater and marine ecosystems (Sharma et al., 2023).

8. Microplastics influence on human health

The most prominent pathways of MPs entry in human beings are the ingestion; inhalation and dermal absorption (Domenech and Marcos, 2021). However, MPs implications on human health via consumption of aquatic species containing MPs are considered in the present study (Gamarro et al., 2020; Sheng et al., 2021; Hamed et al., 2023). The MPs are observed from body tissues of aquatic species; therefore the risk of their transfer to human beings persists even after removal of gastrointestinal tracts (Barboza et al., 2020a). The entry of MPs in human beings may also occur through mineral water (Mason et al., 2018; Welle and Franz, 2018), groundwater (Panno et al., 2019), plastic food container (Fadare et al., 2020), beers (Bergmann et al., 2017), table-salt (Yang et al., 2015), tea-bags (Hernandez et al., 2019), energy drinks (Shruti et al., 2020), honey (Diaz-Basantes et al., 2020), sugar (Makhdoumi et al., 2023), packaged food (Siddiqui et al., 2023), etc. Therefore, susceptibility of human beings to intake MPs inside the body is very high.

The plastics production requires plasticizers in huge quantity; may be up to 70–80%. The most of chemicals get leached out from plastics under influence of light, heat and other environmental conditions during their storage, utilization, recycling and disposal, etc. (Hahladakis et al., 2018). Leaching of chemicals from plastics is mainly due to their low molecular weight and loose bonding with polymer matrix. The additives/chemicals firstly be leached on the MPs surface lying in any medium; followed by the surrounding environment. Inside the body of human being, the MPs may transfer from one organ to another via different means. After endocytosis and persorption of MPs from lumen of gastrointestinal tracts, the chemicals get leached in tissues and body fluids (Bhuyan, 2022). The leaching may continue for a long time and also depends on polymers types and characteristics (Lestido-Cardama et al., 2022). The leached out chemicals such as BPA, phthalates, bisphenone, triclosan, flame retardants, styrene, organotins, etc., are the endocrine disruptors (Fig. 5).

Leaching of BPA has also been observed in tissues of fishes containing polycarbonate polymer (Koelmans, 2015). There are several factors such as shape, size, types, additives used, structure of energy band, surface charge and reactivity, etc., of the MPs that defines the toxicity imposed on cells inside the body. The BPA, phthalates and flame retardants are the most prominent EDCs and specifically used in the production of PC and PVC, TBBPA and PBDE, respectively. In addition, the BPA is also used in food packaging, coating of food and cans, etc. (Lestido-Cardama et al., 2022). The EDCs impact on endocrine system and loose self-response and resistance capacity in living beings pertaining to changing environmental conditions (Lauretta et al., 2019). The ability of self-response is referred as homeostasis, which is a self-regulating mechanism provided by endocrine system; and balances the body temperature, glucose level, blood pH and different electrolytes essential for survival.

The EDCs act as hormonal disruptors and inhibit natural hormone function through mimicking and modifying actions and expressions of the hormones receptor in the cells of human beings. The EDCs primarily attack on single cell, tissues or any organ; followed by damage of kidney,

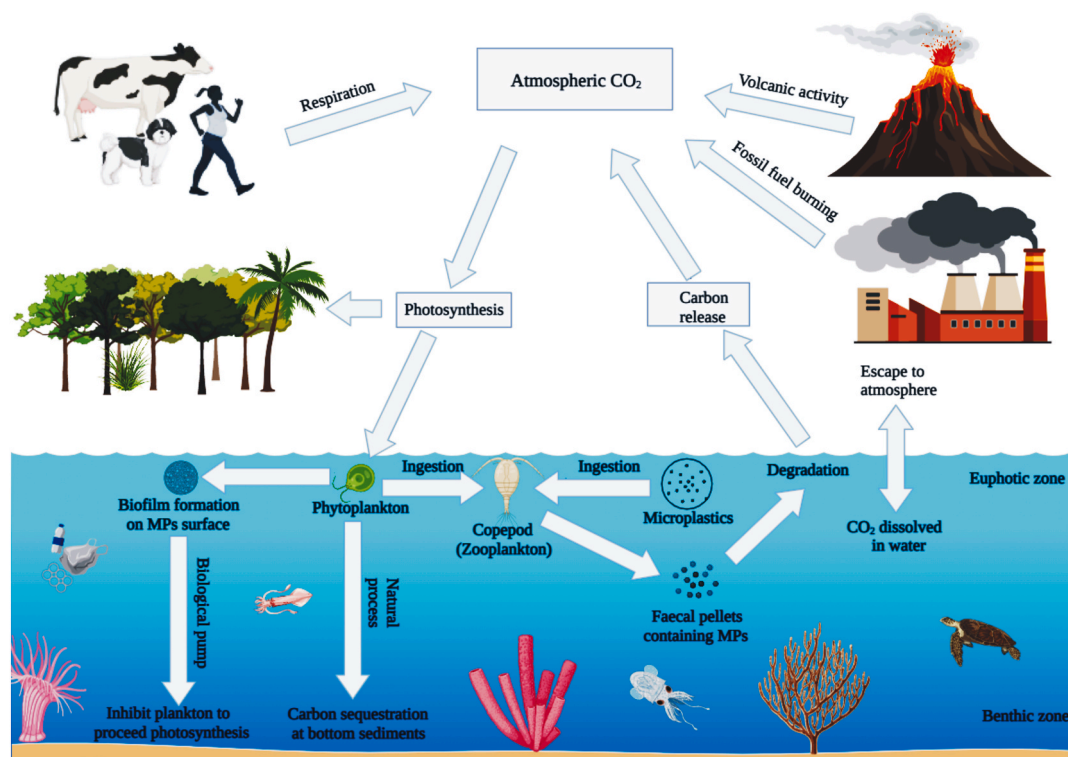


Fig. 4. Impacts of MPs on carbon sequestration potential of aquatic environment.

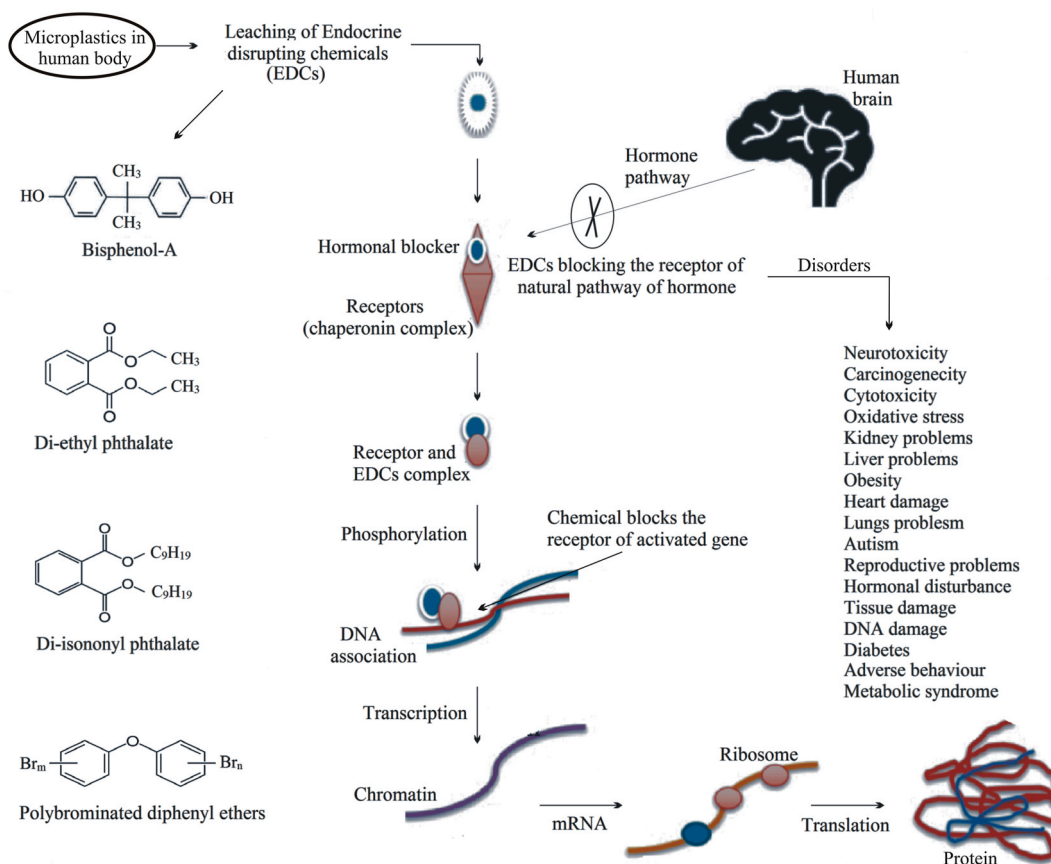


Fig. 5. EDCs leached out from MPs block the receptor of natural pathway of hormones and cause different disorders in human beings.

DNA, liver, heart, brain, lungs and digestive system (Campanale et al., 2020). They cause obesity, autism, cardiovascular diseases, urethra development, metabolic syndrome, early sex maturity in girls and adverse behaviour and disrupt thyroid hormones (Galloway, 2015; Lauretta et al., 2019). The BPA increases the prostate size and prostate androgen receptor level and decreases daily sperm production in the human body. It is also found to be an ovarian toxicant and lay impact on reproduction in women (Peretz et al., 2014; Blackburn and Green, 2022).

The phthalates such as DEHP, DEP, DBP, BBP, DiDP, DiNP, etc., are used as additive during PVC production and easily leached outside from the polymer surface (Wang and Qian, 2021). They increase the quinolinic acid formation and may subsequently cause hippocampal and neuronal damage in human beings. The brominated flame retardants are resistant to heat and delay the fire catch and added in the production of PS and ABS polymers. Most of flame retardants do not undergo polymerization and hence never participate in polymeric chain and become a part thereof. They negatively influence the thyroid hormones, pituitary weight, hearing and reproductive system in living beings.

The hydrophobic nature of MPs polymers helps in absorption of harmful chemicals, which also enter in aquatic food-chain and thereafter in human body through seafood items (Nava and Leoni, 2021). There is also a need of major concern on HCHs, DDT, PCBs, PAHs, POPs, heavy metals, etc., which persist in oceans water and are detrimental to health of aquatic species and human health (Rochman, 2015; Gamarro et al., 2020). The earlier studies have warned that the MPs may reach the human beings through food-chain and create serious health issues. Some studies have also marked MPs in blood, lungs, body tissues, etc. of human beings (Ragusa et al., 2021; Zhang et al., 2021a; Bhuyan, 2022; Leslie et al., 2022).

Certain additives and chemicals, which are used in plastics production, are also observed from the human beings in different

concentrations (Bhuyan, 2022). Zhang et al. (2021a) determined MPs in faeces of young people that might be transported through food, water and surroundings. The MPs in the sputum of patients having respiratory disease were observed as 565 particles 10 ml^{-1} (Huang et al., 2022a). Schirinzi et al. (2017) carried out a study to observe the effect of MPs on cerebral and epithelial human cells. They found an increase in oxidative stress levels in both the cell lines. In contrast, Jin et al. (2022) carried out a long term study to reveal the effects of PS and observed changes in testicles morphology along with decreasing level of testosterone, LH (Luteinizing Hormone) and FSH (Follicle Stimulating Hormone) in serum and a decline in viability of sperms.

The human lung cells exposed to PS MPs in a study found to reduce the cell proliferation and enhance morphological changes (Goodman et al., 2021). The lung tissue of 13 autopsied decedents of 48–94 years aged in a study indicated the presence of 87.5 % fragments ($3.92 \mu\text{m}$) and 12.5 fibres ($11.23 \mu\text{m}$) of PU, PE, PS, PVC, PA, etc., polymers (Amato-Lourenço et al., 2021). Likewise, Jenner et al. (2022) in their study considered 13 lung tissues and observed PP (23%), PET (18%) and resin (15%) as the most abundant MPs particle having an average density of $1.42 \pm 1.50 \text{ particle g}^{-1}$ tissue. The patients of cirrhosis disease earlier marked the presence of 3–29.5 μm (avg. $9.8 \mu\text{m}$) sized MPs ranging 4.6–11.9 particle g^{-1} liver tissue (Horvatits et al., 2022). The breast milk of 26 women in a study also marked a presence of PP, PVC and PE dominant types of MPs in the size range of 2–12 μm and having spherical and fragment shape (Ragusa et al., 2022). There are several studies, which confirmed the presence of MPs in human body. However, the studies confirming direct impact of MPs contaminated sea-food consumption on human beings under controlled conditions are still lacking so far.

9. Removal and degradation of microplastics

Abundance of MPs in aquatic environment is continuously increasing and may cross billion tones in this century (Geyer et al., 2017). The use of plastics in wide ranges of applications and lack of proper management strategies are the main causal factors behind MPs problems. Therefore, the removal and degradation of microplastics is very essential and certain techniques are used worldwide to avoid their distribution in different environments (Table 4). The MPs are even left after different treatment techniques and thereafter reach to the aquatic environments (Murphy et al., 2016; Conley et al., 2019). The removal techniques remove a large percentage of MPs from the water, while the degradation breakdown them to harmless compounds or the smaller fragments, which may still be harmful in nature. Further, the secondary pollutants such as di-phthalate, bisphenol-A, etc., may also be formed due to chemical and thermal degradation of MPs.

9.1. Wastewater treatment plants

Initially, the purpose of WWTPs was to purify water from microbial contaminations and thereafter, the removal of dyes, heavy metals, nutrients, persistent organic pollutants, etc., was started with certain modification in treatment plants' processing parts and designs (Kroiss et al., 2021). The WWTPs from recent past are also being used for removal of MPs reaching therein from domestic and non-domestic sources including agricultural and industrial discharge, etc. (Bayo et al., 2020b). Keeping in view deleterious impacts, the target of maximum removal of MPs from wastewater has gained an attention of the scientific community to strengthen every step involved in the process of WWTPs (Michielssen et al., 2016; Lee and Kim, 2018; Liu et al., 2021a; Parashar and Hait, 2023).

The wastewater in treatment plants undergoes through the preliminary as well as primary, secondary and tertiary phase to ensure no MPs particles left in discharged effluents and sludge (Gangula et al., 2023). It is observed that majority of MPs are removed during primary and secondary stages, although the shape, size, colour, density, polymeric chemistry and plant designs including operational technique also matter a lot (Gies et al., 2018; Lares et al., 2018). Conley et al. (2019) observed removal efficiency of WWTPs in the range of 85.2 ± 6.0 – $97.6 \pm 1.2\%$ and leaving behind 500 to 1,000 million MPs particles per day in the effluents discharged in the environment.

9.1.1. Preliminary and primary treatment

The preliminary treatment comprises coarse and fine screening, which may remove particles in the range of 6–150 mm and <1.5–6 mm, respectively, such as rags, plastics, paper, sticks, etc. Thereafter, grit chamber (aerated/vortex) removes sand, silt, stones, cinder, etc.; leaving behind suspended and floating particles, which are then removed via primary treatment using settling tank (primary clarifier) based on sedimentation and skimming. The screen mesh size in preliminary treatment play an important role in MPs removal. Liu et al. (2019) considered the screen mesh size of 6 mm and after the primary treatment, the effluent contained <1.6 mm sized MPs particles. In an earlier study, the MPs with size >500 μm showed a higher retention in settling tank as compared to those MPs having size in a range of 37–300 μm (Petroody et al., 2020).

Collective use of preliminary and primary treatment is found to be more effective in MPs particles removal. The preliminary technique alone in a study retained only 69–79% MPs (Ziajahromi et al., 2021). However, Michielssen et al. (2016) utilized both techniques and observed such retention in a range of 84–88% MPs. Even, 98.3% retention of PES, PP, PA and PE types of MPs particles has also been achieved through simultaneous use of both these techniques (Lares et al., 2018). Various phases of preliminary and primary technique are found to be capable of removing MPs in the range of 16.5–98.4 %. The studies confirmed that most of impurities are retained, but discharged

primary sludge and wastewater are found to contain large content of MPs; thus require further as well as the next categories of treatments (Iyare et al., 2020; Gangula et al., 2023).

9.1.2. Secondary treatment

The secondary treatment is a biological process and uses microbes for removal of organic impurities left in wastewater after the primary treatment technique. Its basic components are the aeration chamber for mixing sewage and air, and trickling filter, which is a bed of gravels, stones, etc., to pass the sewage. Bacteria loaded activated sludge is also used to aid faster degradation of sewage and other organic materials. Murphy et al. (2016) inferred that biological treatment for MPs removal is not as effective as that of the primary treatment. However, earlier studies have shown a good efficacy of secondary technique in MPs removal (Acarer, 2023). This technique is more efficient to remove large particles rather than the smaller sized, owing to their retention in bio-film or any other microbial aggregates (Lee and Kim, 2018).

Magni et al. (2019) from Italian WWTPs observed 84% MPs particles of PA and PES types from the activated sludge and outlet that pose a huge risk for the receiving environment. Iyare et al. (2020) indicated 7, 16 and 19% MPs retention capacity of trickling filter, activated sludge process and bio-filtration. Liu et al. (2019) inferred that smaller sized MPs are mainly removed by activated sludge. Pittura et al. (2021) revealed that settling tank plus activated sludge collectively can remove up to 60% MPs particles. The sludge line in a drinking water treatment plant found to retain 98.3% film, fragments and fibres types of MPs (Dronjak et al., 2022). Although, the removal of MPs content by activated sludge also depends on inputs, treatment plants capacity, settling tank, operating process and plastic degradation stage (Harley-Nyang et al., 2022; Acarer, 2023).

9.1.3. Tertiary treatment

Advanced and modern techniques showing a higher efficiency of MPs removal, are placed under tertiary treatment. An earlier study indicated 75 and 91.9% MPs removal during primary and secondary treatment stages, respectively, however during tertiary stage, their removal increased to >98% (Hidayatullah and Lee, 2019). The MPs removal during tertiary treatment is based on the use of operating system such as disc filter, membrane bioreactor, sequential batch reactor, rapid sand filter, reverse osmosis, flocculation, etc. The adhesions of microbes on activated carbon coated filter plate in a bioreactor revealed 91.04 % MPs removal efficiency, which is more as compared to those, were removed using disc filter (Kwon et al., 2022). The membrane bioreactor comprising membrane filtration and biological treatment is found to remove 99% MPs by Lares et al. (2018), while Bayo et al. (2020b) via same technique observed 79.01% removal only.

The main causes behind MPs removal difference are the material used in membranes fabrication and their pore sizes, polymer types and availability of other contaminants in wastewater, etc. (Acarer, 2023). The removal of PVC and PET polymers fragments through collective use of micro-filtration, ion-exchange and granular activated carbon has been observed in a range of 78–86 and 94–100%, respectively. However, combination of ion exchange and activated carbon marked less removal efficiency and it strengthens that micro-filtration may also retain small sized particles (Cherian et al., 2023). Dalmau-Soler et al. (2021) observed 78% MPs removal through sand filtration and thereafter a total of 93% in the discharged water using a combination of various stages. They inferred that reverse osmosis and ultrafiltration techniques are more efficient rather than the granular activated carbon filtration and zonation stage.

The membrane bioreactor, which is being used extensively in wastewater treatment may be aerobic and anaerobic and comprises both biological and advanced filtration techniques (Al-Asheh et al., 2021). The MPs removal rate of membrane bioreactor in a study was observed more (79.01%) than rapid sand filter (75.49%). Their removal efficiency was found to be 57.61 and 53.83% for fibres and 98.83 and 95.53% for

particulate MPs, respectively (Bayo et al., 2020a). However, the ultra-filtration technique and coagulation are not so efficient for MPs removal, but generally used for drinking water purification. Large pore sizes and their irregularity may not allow retention and promote escape of the MPs in above filtration systems (Tang and Hadibarata, 2021). Dynamic membrane is also being used in treatment of municipal, industrial, surface and oily water and sludge; mostly the organic wastes (Poerio et al., 2019). Its efficiency for micro-particles removal from synthetic wastewater has been observed by Li et al. (2018b).

The biochar, a carbonaceous material, is also found to remove MPs with significant results. There are certain techniques employed in biochar production such as pyrolysis, torrefaction, electro-modification, hydrothermal carbonization, gasification, etc. (Gabhane et al., 2020). The surface area and porosity of biochar plays an important role beside other characteristics such as positive surface charge and functional groups. However, the treatment of biochar may modify these characteristics according to requirements and increase the adsorption rate during removal process (Kumar et al., 2022). Further, Magid et al. (2021) increased the pyrolysis temperature from 500 to 700 °C and thereafter 900 °C and observed an increase of aromaticity, surface area and hydrophobicity of the biochar.

In an earlier study, the efficiency of biochar in combination of sand filtration unit for PS removal in WWTPs was observed 95%; however, without biochar the sand filtration system had achieved only 60–80% MPs removal (Wang et al., 2020). The biochar may be modified to increase the surface area, porosity as well as removal efficiency. The oxidising, magnetising and activating biochar are some of the modified version of the pristine biochar for organic and inorganic impurities removal from wastewater (Cairns et al., 2024). The activating biochar is produced by steam activation and has large pore sizes and shows significant removal of MPs. The oxidising biochar is the resultant of biochar treatment with $\text{HNO}_3/\text{H}_2\text{SO}_4$ to improve oxygenated functional group and the sorption efficiency (de la Rosa et al., 2018).

Similarly, the magnetising biochar is formed due to metals (iron and magnesium) incorporation in the biochar. The main emphasis behind is to increase the positive charges, which attract the MPs having negative charges due to their functional group. Li et al. (2023) in their study used pristine biochar and MPs (PA) removal was observed only about 25%. However, use of magnetized biochar achieved the MPs removal efficiency up to 97%. Tang and Hadibarata (2021) observed MPs removal after the primary, secondary and tertiary treatments in the range of 16.5–98.4, 78.1–100 and 87.3–99.9%, respectively. Although, the MPs removal per cent of WWTPs is satisfactorily, but rather than effluents and sludge contain a large amount of particles. Hence, there is a need to focus on removal efficiency of WWTPs via advanced filtration technique and modification of plant design, processing parts, etc.

9.2. Advanced oxidation processes

Advanced oxidation processes (AOPs) are followed in earlier studies to increase the degradation kinetics of MPs particles (Sanchez-Montes et al., 2022). An earlier study by Liu et al. (2021b) observed an impact of $\text{UV}/\text{H}_2\text{O}_2$ on PS particles, which showed changes in various characteristics including surface morphology, carbonyl index, molecular weight and hydrophobicity. However, there was a requirement of long time for complete degradation of the PS particles. Na et al. (2021) used $\text{UV}/\text{H}_2\text{O}_2$ for 6 h to treat drinking water containing PS polymers. Initially, sand filtration and coagulation removed $\text{PS} > 20 \mu\text{m}$ and then $\text{UV}/\text{H}_2\text{O}_2$ was used to treat PS having $10 \mu\text{m}$ size. After 1 h, the increased concentration of PS particles of 1–2.5 μm size was observed as a result of fragmentation due to $\text{UV}/\text{H}_2\text{O}_2$ exposure.

Hidayatullah and Lee (2019) in their study of wastewater treatment applied ozone (O_3) with coagulation and achieved MPs removal 99.2% and without coagulation, it was 89.9%. The AOPs has indicated 50–99 % removal of desired pollutants, but limited studies are available still so far in literature (Dos Santos et al., 2023; Kim et al.,

2022). Fenton and sulphate radicals are also found to be effective in degradation of the plastic wastes in earlier studies (Wang and Wang, 2017; Du et al., 2021). The sulphate radicals-AOPs in a study found to mark a significant contribution in the degradation of PE MPs polymers with the help of peroxymonosulphate as well as activation of catalyst to generate free radicals. The end product obtained after PE degradation was not harmful for the aquatic microorganism (Kang et al., 2019).

9.3. Thermal and photo-oxidation

Thermal-oxidation is mainly caused by infrared radiations (760–2,500 nm), whereas solar radiations in the UV-A (~315–400 nm) and UV-B (~295–315 nm) ranges cause photo-oxidation. The plastics exclusively are made up of carbon chain and under natural conditions during the day; the earth surface as well as water bodies receive ultra-violet solar radiations, which enhance brittleness and result colour loss of the plastics. That is further followed by disintegration of the polymers and degradation of plastics. During photo-oxidation, the free radicals are produced due to absorption of ultraviolet light as heat by unsaturated chromophoric group and thus the C–H bonds of the polymer are broken down (Gewert et al., 2015). The UV radiations stimulate formation of hydroxyl and carbonyl groups, which promotes degradation of MPs (Ghatge et al., 2020). The photo-oxidation of the plastics as well as MPs particles increases the cross-linking, chemical transformation, chain scission and branching; thereafter the molecular weight of the polymer gets reduced. It increases brittleness as well as the discolouration and then the surface area becomes susceptible to further reaction. Finally, the polymers changes to the oligomers or monomers (Gewert et al., 2015).

The ESC result the plastic degradation at room temperature due to interaction of polymer and chemicals present in the surroundings; thereby cracks formation occurs on the surface after a certain period of time. The use of nanoparticles is also increasing during plastics production from the recent past to enhance physical and chemical degradation of plastics (Kumar and Maiti, 2016). The presence of impurities during plastic manufacturing also supports faster breakdown of the plastic particles. The wind action, rainwater, waves, hydrodynamic effect as well as oceanic gyre result MPs disintegration. The smaller and fragmented parts produced by mechanical degradation also become vulnerable to other types of natural degradation (Mohan et al., 2020).

The natural degradation of polymers in environment is a very slow process and results incomplete degradation. Further, it may release harmful chemicals in the environment. The photocatalytic degradation based on semiconductor devices is also used at present for MPs degradation. Jiang et al. (2021) inferred that the reactive oxygen species (ROS) can degrade the plastic particles efficiently. Most of the plastics particles can be partially degraded only under the influence of UV-illumination; suggest that ROS are not capable to degrade them in the presence of the visible light (Du et al., 2021). The degradation of MPs is also found to be excellent using TiO_2 - and ZnO -based materials in earlier studies by Yuan et al. (2017) and Qi et al. (2017), respectively. Such a technology may partially degrade the MPs, but rather than there is a need to work for achieving more feasibility.

9.4. Fungal degradation

The intra- and extra-cellular enzymes such as hydrolase, cutinase, polyesterase, laccase, peroxidase, lipase cutinase, esterase, etc., present in fungi are involved in degradation of plastics such as PE, PVA, PP, PU and PET (Solanki et al., 2022; Temporetti et al., 2022). The fungi colonize and result biofilm formation on MPs surface and release extracellular matrix and degrade them (Andreu and Olmo, 2023). The fungi fulfil their energy requirement from MPs and decrease their resistance and strength. The MPs are mostly hydrophobic in nature and to increase the adhesion of fungi, hydrophilic functional groups may be added (Varshney et al., 2023). Kettner et al. (2017) observed attraction and

adhesion of fungi at MPs particles (PE and PS) in their study comprising Warnow River, Baltic Sea and a wastewater treatment plant.

The isolates of *Aspergillus flavus* in a study degraded HDPE on the basis of ether and carbonyl groups and presence of enzymes (Zhang et al., 2020b). The fungi, *Aspergillus sydowii* and *Aspergillus terreus*, isolated from a dumping site, have also been found effective for degradation of polythene exposed for 60 days (Sangale et al., 2019). Some more studies have also shown degradation of MPs using *Fusarium solani pisi*, *Chaetomium globosum*, *Trichoderma harzianum*, *Pichia pastoris*, *Penicillium citrinum*, etc. (Temporiti et al., 2022). The enzyme laccase isolated from *Bjerkandera* spp. in a study was observed to degrade BPA, which is used as an additive during plastic production and acts as endocrine disruptor (Kang et al., 2021). The fungi may persist in all types of environments and can play important roles in MPs degradation; however take a long time in the process.

9.5. Algal degradation

The algae derive energy from MPs and in turn also act as a catalyst for their degradation. The carbon requirement of algae is not so much and that makes their adaptability in the environment containing the MPs (Yan et al., 2016). They colonize on MPs surface and release extracellular polysaccharide and ligninolytic enzymes, which aid in degradation of polymer chain (Long et al., 2015; Kumar and Chandra, 2020). The microalgae *Scenedesmus abundans* in a study was found to remove PMM, PS and polylactide particles with 70–98% efficiency (Cheng and Wang, 2022). The development of biomass (microalgae) and polymer composition in the biofilm formed on the surface of PET and HDPE were observed in the lentic mesocosms of Iberian Peninsula. The study revealed development of the biomass in a greater extent on the PET rather than HDPE. The adhesion was due to energy requirement of microalgae, which might degrade the MPs particles (Nava et al., 2022). The enzyme, PETase, produced by *Chlamydomonas reinhardtii* (green algae) in a study indicated degradation of PET polymers. The cell lysate and PET in the study were incubated for 4 weeks at 30 °C. Thereafter, the morphology and terephthalic acid produced due to degradation of PET were observed and analysed using SEM and High Performance Liquid Chromatography, respectively. The catalytic activities of hydrolysing enzyme PETase was thus proved for the degradation of PET polymers

(Kim et al., 2020).

9.6. Microbial degradation

The bio-degradable plastics show a faster degradation as compared to the non-biodegradable. The microbes colonize and adhere on the polymer surface, which provides nutrients (carbon) and supports their growth. Bacterial species such as *Arthrobacter*, *Bacillus*, *Streptomyces*, *Corynebacterium*, *Rhodococcus*, *Pseudomonas*, *Micrococcus*, etc., and certain enzymes like cutinases, proteases, dehydrogenases, laccases and esterases are found to be involved in the degradation of the natural and synthetic plastics (Atanasova et al., 2021). The aerobic environment in the presence of O₂ results production of water and CO₂, whereas absence of O₂ under anaerobic conditions produces CH₄, H₂O and CO₂.

The microorganisms attacks on polymers for energy requirements and secrete extra cellulose enzymes, which breakdown the plastic smaller in size. The smaller fragments of polymers also cross the cellular membrane and further degradation occurs within microbial cells (Dey et al., 2021). Firstly, the chemicals and enzymes attack on the surface of plastic, which becomes rugged and then the cracks are developed, which further increase degradation and it is applicable for all types of plastics (Gewert et al., 2015). However, bio-degradation also depends on density, long- and side-chains, molecular weight, hardness, functional groups, pre-treatment, physical forms, types of degrading organisms and more (Thakur et al., 2023). Instead, moisture content and the temperature also play a prominent role in this context (Iram et al., 2019; Table-5).

10. Management strategy

10.1. Energy recovery

Microplastics persist in the environment and continue to accumulate without proper management. The use of MPs for harvesting energy is one of the key movements in reducing the MPs accumulation and dependency on fossil fuels. The conventional practices for energy extraction from plastics release the toxic gases. Hence to curb this problem, there is a need to focus on some emerging technologies that lead to sustainable management of microplastics along with harvesting some

Table 4
Comparison of various removal and degradation techniques.

Technique used	Removal efficiency (%)	Advantage	Disadvantage	Reference
Membrane bioreactor	99	Low cost, effective removal	Membrane fouling, high cost	Lares et al. (2018)
Dynamic membrane	90	Low cost, no extra chemical requirement, energy efficient	Suitable for low density particles	Li et al. (2018b)
Ozonation	90	High removal efficiency, energy saving, lost cost	Harmful for health of people	Hidayaturrahman and Lee (2019)
Microbial degradation	12	Eco-friendly, low cost	It is a very slow process	Park and Kim (2019)
Biochar	100	High efficiency, low cost, stable in nature	Harmful chemicals may leach at biochar	Siipola et al. (2020)
Adsorption	92.2	Low cost, energy saving, simple to use	Low selectivity	Sun et al. (2020)
Rapid sand filter	75.49	Effective removal, low cost operation, reduce foul smelling	Cleansing of filter is a tedious process	Bayo et al. (2020a)
Reverse osmosis	54	Low energy requirement, no chemical needed	Basically used for drinking water treatment	Dalmau-Soler et al. (2021)
Fungal degradation	60.1	Easy to use, versatile in nature, low cost	Slow rate, low efficiency	Ghosh and Pal (2021)
Flocculation	93.4	Simple operation, easily remove small particles, low cost, energy efficient	Water quality control requirement	Peydayesh et al. (2021)
Ultrafiltration	95	Compact plant size, high efficiency, low consumption of energy	Efficient to remove particles of 1–100 nm	Poerio et al., 2019
Photo-catalytic degradation	98.4	Eco-friendly in nature, durable in use	High cost, low selectivity	Uheida et al. (2021)
Algal degradation	84	Easy to handle, low cost, easy availability	High retention time	Cheng and Wang (2022)
Magnetic separation	97	Low energy requirement, fast removal, low cost and high efficiency	Addition of magnetic seeds and their separation	Li et al. (2023)
Electrochemical oxidation	70	Very efficient, contain easy process	High cost of electrodes	Mais et al. (2024)

valuable products for efficient energy production.

10.1.1. Thermal technique

Thermal technique takes place at a higher temperature for breaking bonds and synthesis of valuable bio-oil, biochar as well as gas. Pyrolysis and gasification are the two efficient energy harvesting methods, which can utilize plastics waste in a sustainable way. The process of gasification comprises heating in the presence of a catalyst and under oxygen controlled conditions. It is carried out at a temperature ranging from 500 to 1,200 °C, which results the formation of valuable products like syngas (mixture of different gases, i.e. carbon dioxide, carbon monoxide, hydrogen, methane, nitrogen, etc.). This syngas can be utilized to produce synthetic liquid fuel using Fischer-Tropsch process. Further, the thermal energy from syngas can be employed in steam boilers, dryers, cement kilns, and other heat generating devices (Mallick et al., 2023). An earlier study designed a hybrid bio-thermal system for the anoxic degradation of plastic wastes comprising PS, PP and PE. The syngas was produced (395.6–504.2 ml of CH₄/g) from CO₂ gasification of plastic wastes (Zhang et al., 2022). It has also been observed that the production cost of syngas (\$ 0.02 kWh; ~\$5.9/MMBtu) is much less as compared to that of the woody biomass (\$0.056 kWh; ~\$191.08/MMBtu; Indrawan et al., 2020).

The plastic waste due to high carbon content can be converted to the oil at higher temperature (Praveenkumar et al., 2024). Pyrolysis is a thermal degradation process that can be operated at a temperature range of 350–550 °C under an oxygen free environment and synthesizes various valuable products including bio-oil, pyro-gas as well as pyro-char. Among the different types of plastic wastes, the major contributors are PVC, PO, PS and PET (Miandad et al. 2017a, 2017b). In a study, the heating of HDPE at an oxygen deficient temperature ranging 300–400 °C and a rate of 5–10C/min generated 80.88 wt% of liquid oil. The study further utilized a semi batch reactor at 550 °C and synthesized liquid oil of 79.08 wt% and gaseous product of 24.75 wt%. The synthesized oil comprised kerosene, diesel and gasoline, which were compatible to the petroleum (Ahmad et al., 2015).

10.1.2. Chemical technique

It is one of the most appropriate techniques for the extraction of valuable by-products from different categories of plastic wastes. The chemical technique may include chemolysis, ozonolysis, catalytic degradation, etc. Chow et al. (2021) developed a novel mechano-chemical process for the conversion of plastic wastes polymers (PE, PVC, PP, etc.) utilizing ball milling with KMnO₄. They observed synthesis of alkene intermediates at ambient temperature and valuable gases like methane, hydrogen, carbon monoxide as well as carbonate ions on further oxidation. Another study by Jie et al. (2020) utilized a microwave to transform heterogeneous plastic wastes into valuable by-product using FeAlOx as a catalyst. More than 98% theoretical mass of hydrogen was extracted with ~56.5 mmol/g plastic and in addition, 620 mg/g plastic content of the carbon was also produced after 10 repeated cycles.

Jiang et al. (2022) carried out a study on methanolysis of PET and using poly ionic liquids (PIL-Zn²⁺) as a catalyst found 100% transformation of PET as well as synthesis of 89.2% of dimethyl terephthalate (DMT) at 107.62 kJ mol⁻¹ of activation energy. Whereas, Pham and Cho (2021) earlier adopted a low energy catalytic pathway for PET resin methanolysis to synthesize 93.1% DMT by utilizing activation energy of 66.5 kJ mol⁻¹. However, the energy consumed by different available processes for depolymerisation of PET in hydrolytic process was found to be 22–35 and 45–65 MJ kg⁻¹ during methanolysis (Mallick et al., 2023).

10.1.3. Biological technique

Biological methods could be a sustainable solution for combating MPs wastes to extract energy and valuable products after screening of selective resistant microorganisms. Algae, bacteria, fungi and viruses are

among the microbial species that have a potential to degrade the heterogeneous MPs wastes and recovery of valuable by-products as well as organic compounds (see Table-5). It is observed that earlier studies have employed different techniques to manage plastic wastes through energy recovery, etc. However, more focus should be given on energy harvesting techniques at different temperature ranges, and using suitable catalysts and microbial species, which may aid in more energy recovery and other valuable by-products from plastic wastes.

10.2. Recycling

Recycling is the best way to reduce plastic wastes in the environment and it may be primary, secondary, tertiary and so on, based on quality of the discarded plastics materials (Shanker et al., 2023). The primary method of recycling is practiced for the scraped plastics in their manufacturing industrial units. The plastics to be recycled generally retain original qualitative characteristics, and therefore having no requirement of any pre-treatment disinfection and depolymerisation, etc., before sending in manufacturing line (Chen et al., 2022a). The secondary method is also known as mechanical recycling and mainly undergoes collection, sorting, washing, grinding and manufacturing. The sorting can be manual and also based on FT-IR, X-ray, electrostatic, density, hydro-cyclone, etc. (Schyns and Shaver, 2021).

All polymers do not have similar melting temperature; therefore a high temperature may degrade chemistry of that requires low temperature. Therefore, the quality of some polymers is reduced to some extent as observed for the plastic containing PET and PVC polymers (Ragaert et al., 2017). Polymer bends may also be developed from the plastic wastes comprising mixed polymers during the process (Manias and Utracki, 2014). The tertiary recycling comprises solvolysis and biotechnological and engineering techniques. These techniques use chemicals, enzymes and high temperature, respectively, and aid in splitting of polymers bonds and providing monomers of best quality (see Fig. 6). The monomers recycling reverse the plastic chemicals and further utilized for obtaining high quality monomers and value added products. Likewise, the quaternary recycling technique utilizes the plastic wastes for energy and fuel production via pyrolysis and photo-reforming, respectively (Chen et al., 2022a).

10.3. Landfilling

The landfilling could be a better and feasible option for the management of plastic wastes at a large scale. The plastic wastes in open environment as a natural mounds or pits can be reduced through landfills (Huang et al., 2022b). Almost 50% of the globally load of plastic wastes is disposed of in landfills, thereby it is considered as a most preferred among other management practices. Canada landfills around 82% of plastic wastes in comparison to other countries, whereas USA (73%) ranks second; followed by European and Asian countries (Macheca et al., 2024). The biodegradable wastes may be degraded easily inside landfills, while the plastic wastes take 10–100 years to decompose and that also depend on chemical composition of plastics and environmental conditions (Thiounn and Smith, 2020). The landfills may also be a source of energy due to methane gas production during decomposition of wastes. Landfills allow a large amount of plastic wastes disposal, but still has a lot of drawbacks, such as slow degradation, generation of MPs and leaching of secondary pollutants, such as additives, plasticizers, pigments, etc. (Huang et al., 2022b). However, safety measures can be applied in the landfills to avoid MPs generation and chemicals leaching, which may cause groundwater contamination, air pollution, etc. (Evode et al., 2021).

10.4. Regulatory framework

The plastic wastes management rules and policies have been framed at local level in most of countries all over the world, and some of them

Table 5

Plastic/MPs biodegradation using different microorganisms.

Microorganism	Plastic/MPs polymer	Temperature	Degradation product	Reference
<i>A. beijerinckii</i> HM121	PS	30 °C	Organic compounds	Chandra and Singh, 2020
<i>T. molitor</i> and <i>T. obscurus</i>	HDPE, LDPE, and LLDPE	28.58 ± 0.15 and 27.01 ± 0.14	–	Yang et al. (2022)
<i>Alternaria alternata</i> FB1	PE Films	–	Carbonyl bonds, diglycolamine, CO ₂ and H ₂ O	Gao et al. (2022)
<i>Candida antarctica</i> and <i>Humicola insolens</i>	Amorphous PET bottle	37 °C to 50 and 60 °C	TPA, MHET, BHET, MEG	Carniel et al. (2017)
Genus <i>Defluviitoga</i> and Phylum <i>Thermotogae</i>	HDPE, PS, PP, PET	–	Acetic, butyric and propionic acid	Zhang et al. (2021b)
<i>Zalerion maritimum</i>	PE	25 °C	Carbonyl groups	Paco et al. (2017)
<i>Chlorella vulgaris</i>	PET films	UV, 100 °C for 48 h	Alkanes, ester, fatty acids, benzoic acid, aromatics, and Bis (2-Ethyl) hexyl phthalate	Falah et al. (2020)
<i>Clostridium botulinum</i>	PET film	50 °C	TPA, MHET	Biundo et al. (2018)
<i>Thermobifida cellulosilytica</i>	HMLS-PET	60 °C; 72 h	BHET, TPA, MHET	Vecchiato et al. (2017)
<i>Humicola insolens</i>	PET	50 °C; 6 h	TPA, Ethyl glycol	Quartinello et al. (2017)
<i>Sphingobacterium</i> sp. and <i>Bacillus</i> sp.	LDPE	30 °C, Four weeks	Ethers, alcohol, esters, carboxylic acid	Khampratueng et al., 2024

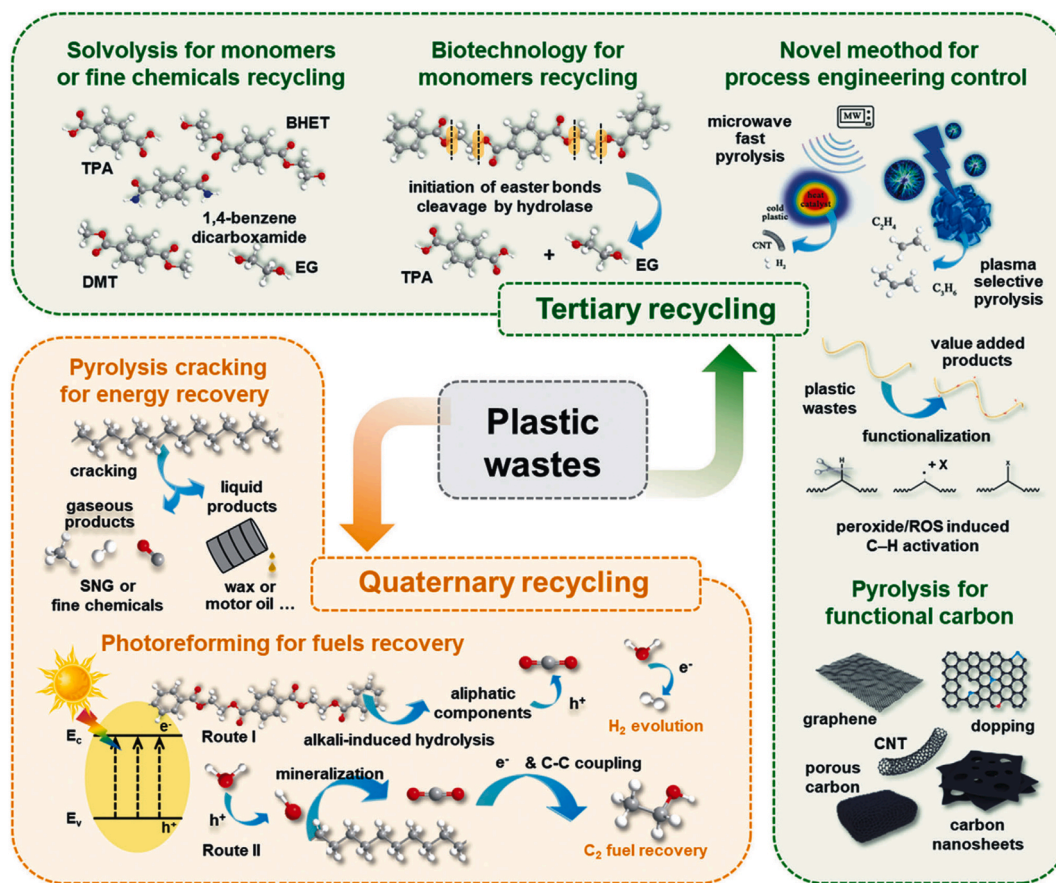


Fig. 6. Tertiary and quaternary recycling of plastic wastes for producing good quality monomers and fuel recovery, respectively (Reproduced with permission from Chen et al. (2022a), their all rights are preserved).

directly emphasize on MPs and their problems. The United States have constituted the Microbead-Free Water Act (2015), to avoid microbeads use in personal care products. The Sustainable Development Goal-14 is concerned with prevention of pollution of marine ecosystem until 2025. A resolution passed by 200 plus nations at Nairobi, during 2017 also guarantees the control of marine pollution. Global Plastic Action Partnership (GPAP) further emphasizes to initiate evidence based actions for controlling plastic wastes of various coastal countries through fast-track circular economy. It aims to strengthen a network through political

commitment and involving stakeholders, communities, trusts, business, NGOs and governments to tackle problems of plastics pollution. Plastic tax may be imposed on people generating plastic wastes and that can be utilized for its management practices as observed in the countries such as Spain, Italy and United Kingdom (Desalegn and Tangl, 2022). The London convention 1972 also emphasized to prevent marine pollution from dumping the wastes and to ensure effective control of pollution influencing the marine environment all over the world. However, the international agreements may vary from local initiatives due to

differences of economic level, pollution sources and regulatory frameworks. The local strategies target the regional pollution sources, such as river clean-up programs or local plastic bans. Due to lack of global standards, insufficient comprehensive data, inadequate coordination and regular monitoring, the efficiency of all approaches and strategies to curb the plastic wastes and MPs problems may be diminished (Schandl et al., 2020).

India has framed the Environmental Protection Act, 1986, and more specifically, the Plastic Waste Management Rules, 2016, to control plastic wastes effectively. The plastic management index marked the India at 20th rank for implementing the regulations and policies related to plastic wastes management. From the different types of wastes generated in India, plastic wastes cover approximately 8%, i.e. around 6173 tons as an uncontrolled waste on daily basis. Roughly, 1 million tons of plastic wastes are incinerated, 2.5 million tons dumped in landfills sites, and 0.25 is used in cement industries as a fuel (Rafey and Siddiqui, 2021). The country is facing plastic wastes problem due to its generation in huge amount and lack of proper space for disposal. The country has a capacity to recycle 47% of plastic wastes in its 20,000 industries and 1000 tons of wastes are being recycled daily at present. A huge content of plastic wastes is also being mixed with bitumen in road construction to get ride from its problem. A slogan '*Savachh Bharat Abhiyan*' is also given to create awareness among civilians to pay attention and participate in cleanliness campaign to control generation and manage wastes in their locality. The state of Himachal Pradesh (India) has control the generation of plastic wastes from single use carry bags, which are completely ban from last years. It has been possible in the state due to government initiatives, NGOs and local people cooperation. The other states in the country are also working to control plastic wastes, but the target is yet to be achieved.

The government can set up various regulations, and likewise, more sustainable practices can be developed by the industries. The stakeholders, NGOs and trusts may advocate for essential change in the system, whereas the communities can participate in wastes reduction and recycling initiatives. Considering emerging threats of MPs on global scale, the countries like Thailand, South Korea and European Commission have framed the use of bio-based plastics instead of polymer based. The countries like France, Australia, New York, etc., also have initiated to control single-use plastics, however there is a need of ban on manufacturing too. The local level and community driven initiatives to clean up coastal regions including beaches and rivers may aid in management of single-use plastic very well.

To control the growth of MPs pollution, the design improvement to reduce MPs shedding and replacement of plastic products with bio-plastics may play an important role. The circular economic model can also be applied to extend the life of plastic products and reduce generation of plastic wastes at the source. The plastic products life can be enhanced through refurbishing, repairing, reducing, reusing, recycle, remanufacturing, rethinking, recovering and refusing. The social and economic challenges may also impose restrictions in implementing management strategies pertaining to the control of MPs generation from their sources and further management. It is due to the reason that a large mass of population worldwide is reliant on the industries and plastics products for their economy and livelihood. The up-gradation of WWTPs and other industrial processing units is very costly, which is a big challenge and cannot be ignored. Education and awareness programs can foster behaviour change of the people regarding plastic uses and management. The non-compliance with bans on certain plastic products and illegal dumping should impose fines on people and industries. In addition, the MPs concentration in water bodies and ecosystems can be tracked through environmental monitoring programs for their proper management.

11. Future perspective

The plastics require a modified version of production techniques, without use of harmful chemicals/plasticizers, which on leaching act as EDCs. Hot spots of MPs sources and discharging points in rivers, lakes and oceans must be identified and organized. The documentation of MPs abundance and concentration from water bodies, sediments, species, etc., is not so enough for future and the direct risk assessment techniques pertaining to MPs and aquatic habitats is the need of time. The long-term effects of MPs on human health need to be studied well to make the people conscious toward their harmful impacts. The removal technologies at present are unable to achieve 100 % feasibility and demand some innovative techniques. The AI-driven MPs detection techniques, advanced filtration systems, AOPs and use of bio-plastics instead of synthetic one could shape the future of MPs management. Apart from, the cutting-edge technologies such as nanotechnology and advanced recycling method could potential reduce the MPs pollution. These techniques are at their initial phases and require more research and development to get scalable solutions.

Most of studies pertaining to aquatic environments are confined to beaches and surface water; however there is a need to understand the impact of MPs on deep-sea ecosystems. Interdisciplinary task forces combining experts from various fields such as environmental science, chemistry, public health along with policies should be developed to find a comprehensive solution of MPs problem. Keeping in view the global spread of MPs, the international policies may overcome this problem. The United Nations Environment Assembly recently has approved a resolution to initiate an intergovernmental negotiation having legal foundation at the international community to end the plastic pollution from the environment all over the world. However, it requires more work at the ground and international level to achieve the target. The basal convention and its amendment in 2019 also favour the plastic wastes management. China also had imposed a ban on production and handling of ultra-thin plastic bags in 2008.

Similarly, the European Union and Canada also have declared a ban on some plastic items of single-use (Syberg et al., 2021). Most of other countries including India have also ban on the use and store of single-use plastic carry bags. The Extended Producer Responsibility (EPR) policy fixes the responsibility of producers pertaining to end of life of their items. It may strengthen industries to develop and produce sustainable products. In this regard, the Resource Sustainability Act (RSA) in Singapore was framed and that confined to the management of packaging waste (Sin and Tueen, 2023). It was an inspiring and ambitious move to combat the long-lasting plastic issues at the worldwide level. The low-income countries are unable to manage and control plastic wastes; therefore capacity building through international aid programs may improve their waste management infrastructure. Technological transfer agreement is also the need of the time to ensure that the entire regions worldwide can access the solution. Further, the interdisciplinary collaboration of experts from all over the world in different fields can help to develop critical thinking and skills, which are essential to get solutions of complex problems pertaining to plastic wastes.

Test-design based mechanistic studies at every stage of MPs interaction with aquatic species in food-chain and human health need to be carried out in future. The standard permissible limits of MPs content and various polymers need to be defined for aquatic ecosystems and human beings. It must be ensured before consumption as the drinks and eatables are free from MPs contamination, to avoid human health implications. The use of MPs as exfoliants needs to be controlled at all. Earlier studies have marked negative influence on the carbon sequestration potential of aquatic environment, although the studies are very limited. There is also a need of more work in filtration systems and plant design of WWTPs for minimizing MPs release in sludge and effluents; thenceforth to the

environment. The bacterial species, fungi and plastic degrading enzymes can be incorporated via more scientific approaches to achieve feasible solution concerning plastic wastes at large scales.

There is a need of more experimental works to enhance the feasibility of using plastic wastes for energy recovery including much more valuable by-products. The use of nanoparticles as additives in plastic production process to support faster degradation can be of paramount importance and it requires more work to bring it to the ground level. Apart from, the “reduce, reuse and recycle” strategy should be incorporated in every sector for plastics and their products. Participatory approach of the local people as well as indigenous communities nearby coastal regions may also coordinate in strengthening policies pertaining to control the MPs and management of aquatic environments. There is also a need of societal behaviour change and it may require awareness campaigns. In addition, the education may also encourage consumers to reduce the use of plastics and recycle it properly. Sustainable alternatives such as jute bags instead of that made up of plastic and many more similar regular habits may reduce a huge amount of plastic wastes. The people doing excellent work for management of plastic wastes and reduce plastic consumption may be given some rewards as incentives, which will also attract more people to achieve sustainability.

12. Conclusions

The present review has explored that MPs are reached in aquatic environments in a huge concentration. The studies have also indicated MPs at glaciers (74.4 ± 28.3 particles kg^{-1}) and even in eatables and drinking water ($0\text{--}1,000$ particles L^{-1}). Emerging technologies such as 3D printing, bio-plastics and textiles may also add a huge to the global load of plastic wastes and require more attention. The MPs are also observed from surface water and beaches of oceans; however deep-sea ecosystem should be studied in detail. The entry of MPs in human blood, faeces, lungs and placenta is confirmed, but the long-term impacts of MPs on human health still need to be explored. The carbon sequestration potential of aquatic environment due to MPs is also found to be influenced, which is a serious issue as it may impact the global climate in future. The WWTPs are huge sinks and sources of MPs generation in the environment and their feasibility may be achieved by innovative technology as well as modification in plant design and using advanced filtration system. The advanced oxidation processes (AOPs), biodegradable plastics, plastic degrading enzymes, nanotechnology and circular economy could shape the MPs management in future. Interdisciplinary studies should be carried out by involving experts from various fields to find comprehensive and innovative solutions of MPs generation and spread in the environment. The use of Artificial Intelligence (AI) in detection, identification and quantification of MPs can generate a huge data with very high accuracy. The entry of MPs in food-chain is harmful for human health and environment, therefore, some policies need to be developed and enforced with aims to reduce MPs pollution. The stakeholders and NGOs need to engage themselves in the fight against MPs pollution. Industries can play an important role in controlling this problem using the sustainable practices. The researchers should also prioritize studies on MPs control via advanced recycling and removal techniques from the environment. Energy recovery from plastic wastes with high efficiency and without release of harmful chemicals or pollutants also participates in curbing plastic problems. Local communities also need to be motivated through awareness programs and incentives to participate in clean-up efforts of water bodies and surrounding environment. The MPs pollution disproportionately affects vulnerable communities as compared to the advanced one, because that influences their food sources, water bodies and health. The dumping and burning of plastic wastes also release dioxins that may affect reproductive, immune, respiratory and hormonal systems in human beings. The economic cost associated with plastic control is very high and requires equitable solutions that consider the social implications of plastic wastes and its management. There is a need of collective actions to make

a change, which is cent per cent possible. The entire nations should work together with a collaborative approach and participation of local people to tackle MPs pollution. The immediate global cooperation and implementation of strict regulations are urgently required to control plastic wastes and achieve environmental sustainability. The policymakers may consider present review's finding to craft legislation to promote better wastes management, plastic reduction strategies and public awareness initiatives.

CRediT authorship contribution statement

Pawan Kumar: Writing – review & editing, Writing – original draft, Conceptualization. **Anil Kumar:** Writing – review & editing. **Deepak Kumar:** Writing – review & editing. **Kalp Bhusan Prajapati:** Writing – review & editing. **Ambrish Kumar Mahajan:** Writing – review & editing. **Deepak Pant:** Writing – review & editing. **Anoop Yadav:** Writing – review & editing. **Anand Giri:** Writing – review & editing. **Satish Manda:** Writing – review & editing. **Soniya Bhandari:** Writing – review & editing. **Richa Panjla:** Writing – review & editing.

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