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Microplastic contamination, an emerging threat to the freshwater environment: a systematic review

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Abstract

Microplastics have been noticed as widespread in an aquatic environment at the microscale. They have nonstop increased due to the increase in the production of synthetic plastics, population and poor waste management. They are ubiquitous in nature and slowly degrade in water and soil. They are emerging pollutants that have received interest from public audiences and research communities. They have great stability and can adsorb various other pollutants like pesticides, heavy metals, etc. After entering the freshwater environment, microplastics can be stored in the tissue of organisms and stay for a long time. They can generate a serious threat to freshwater ecosystems and can cause physical damage to organisms. Visual identification, Raman spectroscopy, pyrolysis–gas chromatography–mass spectrometry (Pyro–GC–MS), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and combined methods are the commonly known methods for the quantification and identification of microplastics. The detected concentration of microplastics depends on the sampling method, locations and identification techniques. The authors assessed the sources, transport, impacts, identification and characterization, and treatment of microplastics in freshwater environments in detail. The authors are also giving some recommendations for the minimization of the MPs from the freshwater environment. This review article will provide the baseline facts for the investigators to do more research on microplastic pollution in the future.

Keywords Plastics, Microplastics, Freshwater environment, Pollution, Treatment, Identification and characterization techniques

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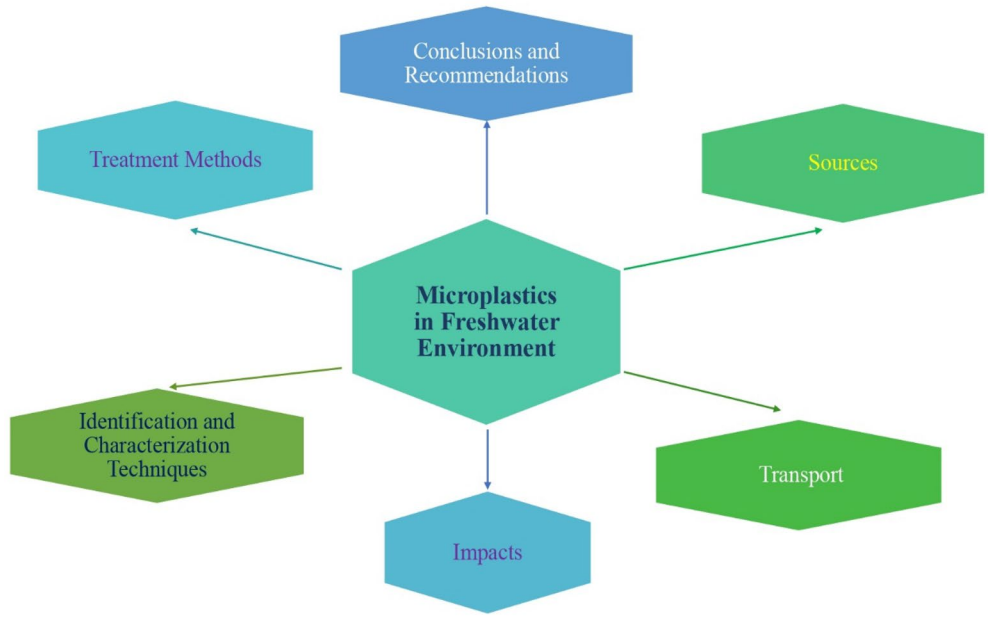
Graphical Abstract



Introduction

Plastic pollution is a big environmental problem. Plastics are made up of long polymer chains. Polymers are designed by the polymerization and condensation reaction, such as polyethylene is designed by the reaction of polymerization, while the reaction of condensation designs nylon. Plastics can be flexible, inexpensive, lightweight, robust and waterproof and act as insulators. They are not biodegradable, but some are biodegradable and can be decomposed by hydrolysis or by the action of microbes or in the occurrence of ultraviolet (UV) light (Bhardwaj and Sharma 2021; Bhardwaj 2022a). They can be classified as microplastics (1×10^{-3} m to $<5\times10^{-3}$ m), mesoplastics (5×10^{-3} m to $<25\times10^{-3}$ m) and macroplastics ($\geq25\times10^{-3}$ m) (Lee et al. 2013).

The use of plastic is increasing with the increase in the population and is regularly used in different types of industries like packaging, electrical, sports, automotive, construction, cosmetics, water treatment plants, etc. Plastics are of two types: thermoset and thermoplastics. Thermoset plastics cannot be recycled, for example, polyurethane (used in pillows, insulating foams, building insulation, etc.); some polyesters; epoxy resins and some acrylic resins. Thermoplastics can be recycled, for example, polypropylene (used in auto parts, snack wrappers, food packaging, bottle caps, etc.); polyethylene (used in shampoo bottles, toys, plastic bags, pipes, milk bottles, bottle caps, etc.) (Miloloza et al. 2020); polyvinyl chloride (used in frames, pipes, cable insulation, etc.); polyethylene terephthalate (used in water bottles); polystyrene (used in building insulation, eyeglasses, etc.); polycarbonates and polyamides (Fig. 1).

Some plastics comprise pro-oxidants that encourage fragmentation and have the potential to form microplastics (Thompson et al. 2004; Kershaw 2015). Microplastics have largely been an overlooked part of plastic pollution (Hartmann et al. 2019). Microplastics are naturally hydrophobic and can go into the freshwater environment through treated and untreated sewage effluent, surface run-off, air deposition, industrial effluent and tainted plastic trash. They are in synthetic clothing, cosmetics and even plastic shopping bags. They have been reported in food, air, beer and tap water. They have been pervasive in the environment for an extensive time and can be swallowed by biota due to their utility, stability and degradation resistance (Peiponen et al. 2019; Bhardwaj 2023).

Microplastics can enter tap and bottled water from the water distribution systems. They are present in dust particles and may be a source of air pollution (Bhardwaj and Vikram 2023; Bhardwaj et al. 2023). They differ in size, type, color and density and their physical appearances are strongly related to their fate, toxicity and source (Bhutto and You 2022). The length of these particles is smaller than 5×10^{-3} m. If the length is less than 1×10^{-6} m then they are termed nanoplastics. They have been categorized

into six groups: fragments, pellets, microbeads, fibers, films and foam (Anderson et al. 2017). The occurrence of different types of microplastics in freshwater environments worldwide is presented very well in Table 1.

Microplastics are classified as primary and secondary microplastics based on their sources (Bhardwaj 2022b). Primary microplastics are manufactured at the microscale and include plastic fibers, plastic pellets and microbeads. Plastic fibers are used in the textile industry, plastic pellets are used in the industry and microbeads are used in particular care products. Primary microplastics originate from leakage during the production of plastics and micro-cleansing elements in particular care items (Anderson et al. 2017). Primary microplastics enter the atmosphere through abrasion during washing, unintentional loss from falls during transport or manufacturing and the presence of personal care products in the effluent of households.

While secondary microplastics are formed from the bigger plastics products after fragmentation (e.g. bottles, clothes, marine litter, bags, tyres, industrial and agricultural sources, etc.) and this fragmentation occur when larger plastics get exposed to waves, wind and UV radiation (Choudhury et al. 2022). Zhao et al. (2015) described that secondary microplastics are formed by the destruction of bigger plastic particles through photolysis, mechanical forces, thermo-oxidation, thermo-degradation and biodegradation processes.

Very little research is available on macroplastic disintegration and deprivation in the freshwater ecosystem. Andrady (2007) and Dai et al. (2023) studied the disintegration and deprivation process of macroplastic debris in the aquatic environment. They stated that in the existence of high temperatures and UV light, macroplastics fragmented into microplastics. Zbyszewski and Corcoran (2011) described the degradation of microplastics in freshwater systems by using a microscopic technique. Microplastics can further be split into nanoplastics. The environmental stages of nanoplastics are yet to be measured (Alimi et al. 2018).

The existence of microplastics in the freshwater environment is an emerging risk that can affect the capability of organisms (Auta et al. 2017a). Several researchers reported the occurrence of different types of microplastics in aquatic environments by using different techniques. For examples: 0.0043 particles/m^2 were reported by Eriksen et al. (2013) in Great Lakes, USA; 0.020 particles/m^2 were reported by Free et al. (2014) in Hoysgol Lake, Mongolia; 0.028 particles/m^3 were reported by Sadri and Thompson (2014) in Tamar Estuary, England; 4137.3 ± 2461.5 and 0.167 ± 0.138 numbers/m^3 were reported by Zhao et al. (2014) in Yangtze Estuary System, China; 3.0 to 108.0 particles/m^3 were reported by Dris et al. (2015) in Seine River and Marne River, Paris, France; 0.89 particles/m^2 were reported by Mani et al. (2015) in Rhine River, Switzerland, France, Germany, Netherlands; 0.05 to 32.0 particles/m^3 were reported by Baldwin et al. (2016) in Great Lake, USA; 0.19 particles/m^2 were reported by Anderson et al. (2017) in Winnipeg Lake, Canada; 2.0 fragments/m^2 were reported by Cable et al. (2017) in Superior Lake, USA; 48.0 to 187.0 particles/L were reported by Leslie et al. (2017) in Amsterdam Canal, Netherlands; 252.80 ± 25.76 particles/m^2 were reported by Sruthy and Ramasamy (2017) in Vembanad Lake, Kerala, India; 0.0 to $110{,}000.0 \times 10^{-6}$ particles/m^2 were reported by Hendrickson et al. (2018) in Western Lake Superior, USA; $25{,}000.0 \times 10^{-6}$ to $40{,}000.0 \times 10^{-6}$ particles/m^2 were reported by Sighicelli et al. (2018) in Italian Subalpine Lakes, Italy and $492{,}000.0 \times 10^{-6}$ microplastic/m^2 were reported by Xiong et al. (2019) in Yangtze River, China.

Microplastics in freshwater and oceans exhibit some differences in terms of distribution, sources and potential impacts. In freshwater systems like rivers and lakes, microplastics primarily come from urban runoff, industrial discharges and the fragmentation of larger plastic debris. The smaller water volumes and lower turbulence in freshwater bodies may lead to the accumulation of microplastics in specific areas. On the other hand, in the oceans, microplastics can originate from similar sources but are also influenced by marine activities, such as shipping and fishing. Ocean currents play a significant role in dispersing microplastics across vast distances, leading to widespread contamination of marine environments. Ocean serve as the final basins for the world's plastic waste. Additionally, the salty nature of seawater may affect the physical and chemical properties of microplastics, potentially influencing their behavior and interactions with marine organisms. Both freshwater and marine ecosystems face environmental challenges due to the ingestion of microplastics by aquatic organisms, leading to potential bioaccumulation and biomagnification in the food web. The impacts on biodiversity, ecosystem health, and human well-being make the study and mitigation of microplastic pollution crucial in both freshwater and marine environments. Understanding these differences can help tailor effective strategies for monitoring, management, and prevention in diverse aquatic ecosystems (Eerkes-Medrano et al. 2015).

More than 60 countries have banned single-use plastics and microbeads (UNEP 2018). In 2015, the United States of America (USA) approved an act "Microbead-Free Water Act" which prohibited the manufacture and distribution of cosmetic goods that contain plastic microbeads (Kershaw 2015). However, the information related to the microplastics in the freshwater environment is still in

Table 1 Occurrence of different types of microplastics in freshwater environment

S. No.	Locations	Detection methods	Concentration of microplastics	Type/color/size of microplastics	References
1	Effluent from West Hornsby, NSW, Australia	FTIR spectroscopy	1.0 particle/L	PEST, PMMA and PA	(Browne et al. 2011)
2	Huron Lake, Canada	FTIR spectroscopy and SEM	408.0 items/m^2	PE and PP	(Zbyszewski and Corcoran 2011)
3	Laurentian Great Lakes, USA	Visual identification and SEM	0.0043 particles/m^2	Microbeads; blue, white and gold; $< 1.0 \times 10^{-3}$ m	(Eriksen et al. 2013)
4	Hovsgol Lake, Mongolia	Sieving and light microscopy	0.020 particles/m^2	Fragments, films, foams and pellets	(Free et al. 2014)
5	Tamar Estuary, Southwest England	Sieving and FTIR spectroscopy	0.028 particles/m^3	Fragments and debris; PE, PS and PP; $< 1.0 \times 10^{-3}$ m to 3.0×10^{-3} m	(Sadri and Thompson 2014)
6	Yangtze Estuary System, China	Floatation and stereo microscopy	4137.3 ± 2461.5 and 0.167 ± 0.138 numbers/m^3	Fibers, granules and films; transparent and colored	(Zhao et al. 2014)
7	Seine River and Marne River, Paris, France	Stereo microscopy	3.0 to 108.0 particles/m^3	Fibre; 100.0×10^{-6} m to 5000.0×10^{-6} m	(Dris et al. 2015)
8	Various Lake, Switzerland	Visual identification	2.0×10^3 particles/m^3	Fragments, pellets, cosmetic beads, fibers, films, and foams; PP, PE and PS	(Faure et al. 2015)
9	Pearl River Estuary, Hong Kong	Visual identification and sieving	5595.0 items/m^2	Fragments; EPS	(Fok and Cheung 2015)
10	Rhine River, Switzerland, France, Germany, Netherlands	Microscopy and FTIR spectroscopy	0.89 particles/m^2	Fragments, fibers and spherules; PS, PP, PEST, PMMA and PVC	(Mani et al. 2015)
11	Urban Estuaries of KwaZulu-Natal, South Africa	Visual identification	$745.4 \pm 129.7 \times 10^{-3}$ particles/500L	Fragments and fibres	(Naidoo et al. 2015)
12	Urban Estuaries, China	Micro-Raman spectroscopy	100.0 to 4100.0 numbers/m^3	Fibers and granules; PP, PE, PVC and PTFE	(Zhao et al. 2015)
13	Great Lake, USA	Visual identification, FTIR spectroscopy and Raman spectroscopy	0.05 to 32.0 particles/m^3	Fragments, beads, fibers, films and foam	(Baldwin et al. 2016)
14	WWTPs, Los Angeles, USA	Microscopy and FTIR spectroscopy	$\sim 0.93 \times 10^6$ microplastics	Fragments; PET; blue; 90.0×10^{-6} m to 300.0×10^{-6} m in width and 100.0×10^{-6} m to 600.0×10^{-6} m in length	(Carr et al. 2016)
15	Jurujuba Cove, Brazil	Sieving, microscopy and ATR-FTIR spectroscopy	16.4 items/m^3	Fragments; blue, green, red, yellow and orange; PP and PE; 1.0×10^{-3} m	(Castro et al. 2016)
16	Chiusi and Bolsena Lake, Italy	Visual identification and microscopy	2.68 to 3.36 particles/m^3 in Chiusi Lake and 0.82 to 4.42 particles/m^3 in Bolsena Lake	Fragments and fibers; PE, PP and PET; $< 5.0 \times 10^{-3}$ m	(Fischer et al. 2016)
17	Taihu Lake, China	Micro-FTIR spectroscopy, SEM/EDS	11.0 to 234.6 items/kg in sediment and 3.4 to 25.8 items/L in surface water	Fibers; cellophane, PET, PEST and PP; blue, white and transparent; 100.0×10^{-6} m	(Su et al. 2016)
18	Tibet Plateau Lake, China	SEM and Raman spectroscopy	8.0 ± 14.0 to 563.0 ± 1219.0 items/m^2	Fragments, foams, sheets and lines; PS, PP, PVC, PET and PE	(Zhang et al. 2016)

Table 1 (continued)

S. No.	Locations	Detection methods	Concentration of microplastics	Type/color/size of microplastics	References
19	Lagoon-Channel of Bizerte, Northern Tunisia	Stereo microscopy	3000.0 to18,000.0 items/kg in sediment	Fragments, fibers and pellets; red, white, black, green and blue; 0.3×10^{-3} m to 5.0×10^{-3} m	(Abidli et al. 2017)
20	Winnipeg Lake, Canada	SEM/EDS	0.19 particles/m^2	Fibers, film and foam	(Anderson et al. 2017)
21	Superior Lake, Huron Lake and Erie Lake USA	SEM/EDS	2.0 fragments/m^2	Fragments, films, foams, spheres and fibers; $>106.0\times10^{-6}$ m	(Cable et al. 2017)
22	North Shore Channel, Michigan Lake, USA	Pyrolysis-GCMS	3.36 to 6.42 particles/m^3	Foams, films, fragments and pellets; PP, PS and PE	(Hoellein et al. 2017)
23	Thames River Basin, UK	Visual identification, flotation and Raman spectroscopy	660.0 particles/kg in sediment	Fragments and fibers; PP, PEST and polyarylsulphone; 1.0×10^{-3} m to 4.0×10^{-3} m	(Horton et al. 2017a)
24	Yarra and Maribyrnong Rivers, Australia	Visual identification	79% microplastics in Yarra River and 66% microplastics in Maribyrnong River	PS; $<2.0\times10^{-3}$ m	(Kowalczyk et al. 2017)
25	Amsterdam Canal, Netherlands	Microscopy and FTIR spectroscopy	48.0 to 187.0 particles/L	Fibers and spheres; 10.0×10^{-6} m to 5000.0×10^{-6} m	(Leslie et al. 2017)
26	South Africa, Thailand, Japan and Malaysia	Density separation and FTIR spectroscopy	100.0 to 1900.0 pieces/kg in sediment	PEP, PS, PET, PP, PAK and PE	(Matsuguma et al. 2017)
27	Hudson River, USA	Micro-FTIR spectroscopy	0.98 microfibers/L	Cotton, PET, PP, fluoro-polymer/teflon and nitrocellulose/clay; blue, black, transparent and red	(Miller et al. 2017)
28	Vembanad Lake, Kerala, India	Density separation and micro-Raman spectroscopy	252.80 ± 25.76 particles/m^2	PE	(Sruthy and Ramasamy 2017)
29	Beijiang River, China	SEM/EDS and micro-FTIR spectroscopy	178.0 ± 69.0 to 544.0 ± 107.0 items/kg sediment	PP and PE; blue and brown	(Wang et al. 2017a, b)
30	20 Urban Lakes, Hanjiang River and Yangtze River, Wuhan, China	Stereoscopic microscopy, SEM and FTIR spectroscopy	1660.0 ± 639.1 to 8925.0 ± 1591.0 numbers/m^3	Fiber; PP and PET; $<2.0\times10^{-3}$ m	(Wang et al. 2017a, b)
31	Three Gorges Reservoir (TGR), China	Micro-Raman spectroscopy	25.0 to 300.0 numbers/kg in the sediments and 1597.0 to 12,611.0 numbers/m^3 in surface water	Fibers; PP, PE and PS; transparent	(Di and Wang 2018)
32	Seine River and Marne River, Paris France	Stereo microscopy and FTIR spectroscopy	100.6 ± 99.9 fibers/m^{-3} in the Marne River and 48.5 ± 98.5, 27.9 ± 26.3, 27.9 ± 40.3 and 22.1 ± 25.3 fibers/m^{-3} in the Seine River	Fibers; PET, PP, PA and PUR; blue	(Dris et al. 2018)
33	Charleston Harbor and Winyah Bay Estuaries, South Carolina, USA	SEM and FTIR spectroscopy	221.0 ± 25.6 particles/m^2 in sediment samples of Winyah Bay and 413.8 ± 76.7 particles/m^2 in sediment samples of Charleston Harbor	Fragments, fibers, foams and spheres; white, green, grey, blue, black and red	(Gray et al. 2018)
34	Western Superior Lake, USA	Microscopy, ATR-FTIR spectroscopy and pyrolysis GC–MS	0.0 to 110 000.0 $\times10^{-6}$ particles/m^2	Fragments, fibers, and films; PVC, PP, PE, PET, PS and PDMS	(Hendrickson et al. 2018)

Table 1 (continued)

S. No.	Locations	Detection methods	Concentration of microplastics	Type/color/size of microplastics	References
35	River sediments, Shanghai, China	Density separation, microscopy and micro-FTIR spectroscopy	802.0 items/kg dry weight	Spheres, fibers and fragments; PP, PEST, rayon; red, white, transparent and blue	(Peng et al. 2018)
36	Maggiore Lake, Iseo Lake and Garda Lake, Italy	Visual identification, stereomicroscope and FTIR spectroscopy	$40{,}000.0 \times 10^{-6}$ particles/m^2 in Iseo Lake, $39{,}000.0 \times 10^{-6}$ particles/m^2 in Maggiore Lake and $25{,}000.0 \times 10^{-6}$ particles/m^2 in Garda Lake	Fragments, pellets, fibers and films; PP, EPS and PE; 1.0×10^{-3} m to 5.0×10^{-3} m	(Sighicelli et al. 2018)
37	Wind Farm in the Yellow Sea, China	Sieving and micro-FTIR spectroscopy	$2.58 \pm 1.14 \times 10^3$ items/kg in the sediment and 0.330 ± 0.278 items/m^3 in the surface water	Fibers, granules and films; PET, cellophane, PE and PVC; black and transparent	(Wang et al. 2018)
38	Danjiangkou Reservoir, China	Micro-Raman spectroscopy	0.47 to 15.02×10^3 microplastic/m^3 in surface water and 15.0 to 40.0 microplastic/kg in wastewater	Fibers; PP	(Di et al. 2019)
39	Wei River Basin, China	FTIR spectroscopy	3.67 to 10.7 items /L	Fibers; PE, PVC and PS	(Ding et al. 2019)
40	Suzhou River, Huangpu River and Yangtze Estuary, China	Stereo microscopy and micro-FTIR spectroscopy	0.08 to 7.4 items/L	Fibers; PES, rayon and PP; blue, red	(Luo et al. 2019)
41	Flemish River, Belgium	Microscopy and spectroscopy		Foam, film, fiber and fragment; blue, green, red and yellow; EVA, PP, PET, PVC, cellophane, PVA and PA	(Slootmaekers et al. 2019)
42	Feilaixia Reservoir in the Beijiang River, China	Visual identification, micro-FTIR spectroscopy and GC–MS	0.56 ± 0.45 items/m^3	Foams, films, fragments and fibres; PP, PS, EPS, PVC, PE and PET	(Tan et al. 2019)
43	Pearl River along Guangzhou city and Pearl River Estuary, China	Stereomicroscopy, micro-Raman spectroscopy and SEM	19,860.0 items/m^3 in urban and 8902.0 items/m^3 in the estuary	Films, fragments and fibers; PA and cellophane	(Yan et al. 2019)
44	Poyang Lake, China	Visual identification, stereomicroscope and micro-Raman spectroscopy	5.0 to 34.0 items/L for surface water and 54.0 to 506.0 items/kg for sediments	Fibers, films, pellets and fragments; PP and PE; white, black and transparent; $< 0.5 \times 10^{-3}$ m	(Yuan et al. 2019)
45	Yangtze River, China	Stereo microscopy, Raman spectroscopy	$492{,}000.0 \times 10^{-6}$ microplastic/m^2	PP, PE, PS, nylon, POM, cellulose and EVA	(Xiong et al. 2019)
46	Eight WTWs in England and Wales (UK)	FTIR spectroscopy	4.9 particles/L in raw water and 0.00011 particles/L in potable water	PE, PET, PP in raw water and PS and acrylonitrile butadiene styrene in potable water	(Johnson et al. 2020)
47	Yongjiang River, China	Raman spectroscopy	500.0 to 7700.0 items/m^3 in surface water and from 90.0 to 550.0 items/kg in sediments	PP and PE	(Zhang et al. 2020)
48	Vistula River, Poland	Raman spectroscopy		PE, PP, PA and PC; white, blue and red	(Rytelewska and Dąbrowska 2022)

PE polyethylene, *PP* polypropylene, *PET* polyethylene terephthalate, *PS* polystyrene, *EPS* expanded polystyrene, *PVC* polyvinylchloride, *PA* polyamides, *PC* polycarbonates, *PEST* polyester, *PMMA* poly (methyl methacrylate), *PUR* polyurethane, *PDMS* polydimethylsiloxane, *EVA* ethylene–vinyl acetate, *PVA* polyvinyl acetate, *PTFE* polytetrafluoroethylene, *PEP* polyethylene-polypropylene, *PAK* polyacrylates, *POM* polyoxymethylene, *FTIR* Fourier transform infrared, *ATR-FTIR* attenuated total reflectance-Fourier transform infrared, *SEM* scanning electron microscope, *EDS* energy dispersive X-ray spectroscopy, *WWTPs* wastewater treatment plants, *WTWs* water treatment works, *NSW* New South Wales, *USA* United States of America, *UK* United Kingdom

its initial state as compared to the marine environment. The authors considered approximately 150 research/review articles for this review and searched these articles from Google Scholar and Research Gate after inputting keywords like plastics, microplastics, freshwater environment, Fourier-transform infrared spectroscopy and Raman spectroscopy. Most of the articles were written from 2000 to 2023 and were from different locations like the United States of America, Australia, England, China, India, France, Netherlands, Hong Kong, Tunisia, South Africa, Thailand, Japan, Switzerland, Germany, Canada, Malaysia, Italy, Mongolia, Brazil, Belgium and Poland. This review article aims to focus on the sources, transport, impacts, identification and characterization and treatment of microplastics in freshwater environments.

Sources of microplastics

Microplastic pollution is a complex environmental issue with multiple mechanisms contributing to its presence in water bodies. Microplastics are distributed in the water column and the distribution is dependent on their properties, such as size, shape, density and adsorption of chemicals. The distribution of microplastics is also dependent on environmental conditions such as water density, wind, currents and waves. Polymeric elements from cleaning and cosmetic goods, feedstocks used in the production of plastic goods and plastic powders used for air blasting are the principal sources of microplastics (Jiang 2018). According to Morritt et al. (2014), microplastics are mostly produced after the destruction of macroplastics and can enter the freshwater system. Drinking water production, distribution and wastewater effluent, atmospheric deposition, industrial effluent and run-off from land-based sources are the different major sources of microplastics in freshwater environments (Cesa et al. 2017).

In addition to this, diverse elements have emerged from diverse foundations like road superficial marking made up of thermoplastic paints, packaging materials, trash of plastic bottles and fibers resulting from textiles (Horton et al. 2017a). The color of microplastics confirms the numerous sources of microplastics and indicates that microplastics originated from synthetic (Rezania et al. 2018). Floating macroplastics play the chief source of microplastics in the marine atmosphere.

Drinking water production, distribution and wastewater effluent

The treatment of drinking water delivers a wall to microplastics. Some constituents of the treatment plants are fabricated by plastics and their deprivation formed the microplastic particles in drinking water (Mintenig et al. 2019). The bottles and their caps are other sources of microplastic particles in drinking water (Oßmann et al. 2018). Wastewater effluent is a vital collection point of microplastics that are free in daily life and is an extensively recognized cause of microplastics in freshwater (Horton 2017). Effluents from sewage treatment plants can be a significant source of microplastics in rivers and coastal areas. Microbeads from cosmetic products and synthetic fibers from clothes are the main local inputs into sewage systems. Horton (2017) described that the barrier of wastewater treatment is temporarily bypassed through heavy rainfall, and it is the straight source of microplastics in freshwater.

A wastewater treatment plant (WWTP) could act as a pathway for microplastics. There are two paths, direct and indirect by which the microplastics are out from the WWTPs. By the direct pathway, microplastics are released directly through the effluent of WWTPs and carry high numbers of microplastics. While by the indirect pathway, microplastics are released from the WWTPs into sludge (Gatidou et al. 2019) and this sludge is used as a fertilizer in agricultural lands (Sun et al. 2019). Wastewater treatment plants may not effectively capture all microplastics, allowing some particles to be discharged into receiving water bodies. Murphy et al. (2016) reported that 65 million particles of microplastic were out each day from the effluent of WWTPs. Maritime activities contribute to microplastic pollution through the release of particles from paints, fishing gear and the disposal of plastic waste at sea.

Atmospheric deposition, industrial effluent and run-off from land-based sources

Atmospheric deposition has been recognized as an extra possible supplier of microplastics in the freshwater environment through wet and dry deposition and precipitation (Wright and Kelly 2017). It brings microplastic particles to remote areas, including mountainous regions and polar environments, where they settle and contribute to contamination. Microplastics that are created from industrial and urban dust can enter in freshwater ecosystems from the atmosphere (Abbasi et al. 2019) and it is an indirect source of microplastics in freshwater. Urban areas contribute significantly to microplastic pollution as rainfall washes plastic debris from streets, sidewalks and urban surfaces into stormwater drains. The airborne microplastics originate from waste incineration, buildings, industrial emissions, landfills, fertilizer usage and traffic. Microplastics in street dust are rich in heavy metals and have a toxic effect on the freshwater environment.

The involvement of effluents from industries for microplastics in wastewater has yet to be examined (Kooi et al. 2018). However, industrial microplastics have been conveyed in freshwater. Eerkes-Medrano

et al. (2015) described the microplastic pollution near the Great Lakes, USA which is situated near the industrial area. Fibers that are out from the textile industries due to tear and washing of clothes can be another important source of microplastics (Henry et al. 2019). Microplastics can create from terrestrial practices, infrastructure, road run-off and tyre debris (Verschoor et al. 2016). City dust is the finest example of a land-based cause of microplastics (Boucher and Friot 2017). Rainstorms and agricultural run-off or farming activities have been recognized as potential causes of microplastics in the freshwater environment (Horton et al. 2017b).

Transport of microplastics

The primary pathways through which microplastics enter aquatic environments include fragmentation of larger plastics, abrasion from products, runoff from urban areas, shipping and fishing activities, wastewater treatment plant effluents and atmospheric deposition (Mao et al. 2022). The transport pathway of microplastic pollution in the air is not known yet (Horton and Dixon 2018) and the pathway is not separate from terrestrial and aquatic pollution. The route of exposure to microplastics for animals and humans is food (Wright and Kelly 2017). Lau and Wong (2000) reported the presence of polystyrene residual and epoxy resins in food materials having the possibility to enter the body of living organisms through food. The diagrammatic representation of the sources, transformation and transport of microplastics is shown in Fig. 1.

Impacts of microplastics on the freshwater environment

The use of plastics is a major threat to the freshwater environment (Sarijan et al. 2021). The existence of microplastics in freshwater environments is harmful to the health of organisms. This threat exists due to the size, surface characteristics and adsorption of chemicals on the surface of microplastics. The health impacts, fate and transport of microplastics are not being studied thoroughly yet. However, the presence of microplastics in bottled water, tap water and the digestive system of the various invertebrates of freshwater have been reported (Kosuth et al. 2018; Mintenig et al. 2019). Microplastics with low density ($< 1.0 \times 10^3$ kg/m^3) keep floating on the water surface and are consumed by filter-feeding invertebrates (e.g. *Daphnia magna*) and carnivorous fish (e.g. *Culter dabryi* and *Culter alburnus*) (Zhu et al. 2022) while microplastics with high density ($> 1.0 \times 10^3$ kg/m^3) may suspend in the water column and are consumed by omnivorous fish (e.g. *Sinibrama wui*) (Zhang et al. 2017).

After exposure to polyvinylchloride or polyethylene, the immune system of fish can be destroyed due to oxidative stress in the leukocytes (Espinosa et al. 2018). Local human activities are the major causes of the accumulation of microplastics in the muscles of fish (Akhbarizadeh et al. 2018). Reduced growth, variation in oxygen (O_2) consumption, a limited feeding capability, a decreased lifespan and amplified antioxidant-related enzyme action have been reported after the ingestion of microplastics (Windsor et al. 2019). Due to the low feeding capacity of food, less energy is produced to carry out life functions resulting in reproductive and neurological toxicity.

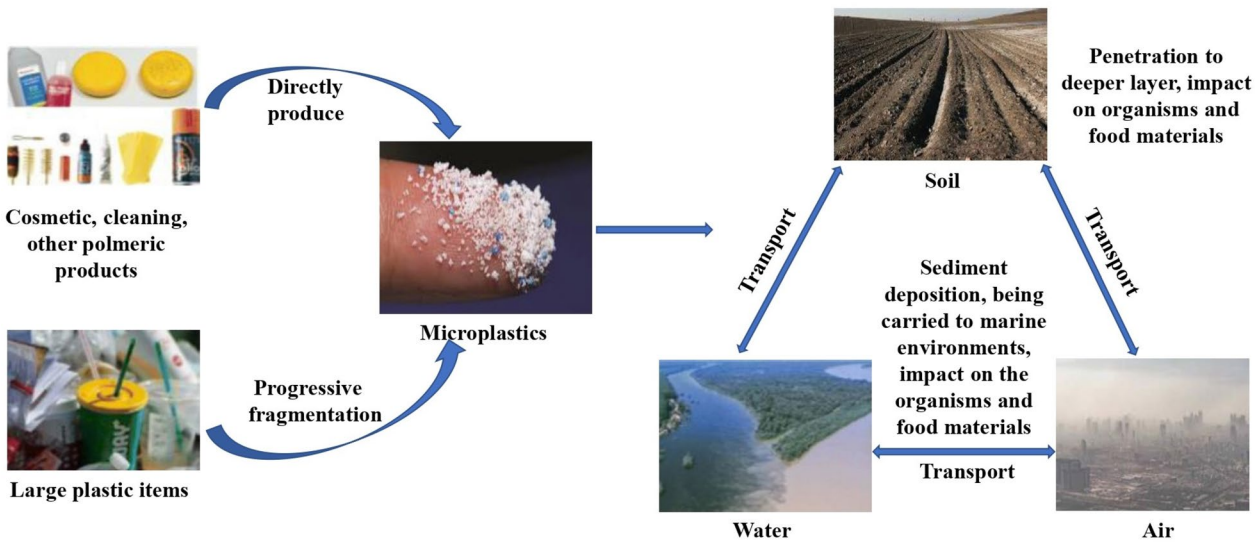


Fig. 1 Sources, transformation and transport of microplastics

Microplastics affect aquatic organisms for several generations due to their slow degradation and stability and also affect the photodegradation of organic mixtures and the poisonousness of metal ions.

Due to size and surface characteristics

The harmfulness of microplastics depends on the shape, size, surface area and surface characteristics. Microplastics greater than 150×10^{-6} m are not absorbed by organisms. The distribution and absorption of small particles of microplastic may be higher. Lu et al. (2016) studied the exposure properties of polystyrene in Zebrafish and confirmed that the poisonousness of microplastics depends on their size. Au et al. (2015) stated that fibers of polypropylene are more poisonous than the spherical elements of polyethylene for the lake's amphipod, *Hyalella azteca*. Li et al. (2020) stated that fibers are the major type of microplastics in freshwater. Biofilm is developed in the water supply when microorganisms start to colonize on the surfaces of microplastics (He et al. 2023). These microbes are harmless and stick to hydrophobic nonpolar surfaces more quickly than they do to hydrophilic ones.

Due to toxic chemicals

This impact exists in the form of polymers such as vinyl chloride, 1,3-butadiene and ethylene oxide. Tetrabromobisphenol A (TBBPA), polybrominated diphenyl ether (PBDEs) and phthalate esters exist in microplastics while they are not bound to the polymer. This chemical threat can simply travel into the atmosphere and the migration rate depends upon the molecular weight of the mixtures. Larger molecular weight particles travel at a slower rate than the smaller particles. Toxic chemicals such as PBDEs, bisphenol A and phthalates get stuck on the microplastics and may encourage their noxious effects after absorption by living organisms (Padervand et al. 2020). These chemicals are endocrinal disruptors and may exhibit their toxic effects on release. After interaction with different types of heavy metals, microplastics can give rise to a serious issue on the freshwater environment (Vedolin et al. 2018). Volatile complexes such as methylene chloride, ethylbenzene, benzene and toluene are released from plastics and can also contribute to long-lasting health effects (Andrady 2017). Microplastics can act as a contaminant transporter for toxic chemicals such as hexachlorobenzene (HCB) and dichlorodiphenyltrichloroethane (DDT) (Bhardwaj et al. 2018, 2019; Laskar and Kumar 2019; Bhardwaj and Jindal 2020, 2022).

Identification and characterization of microplastics

There are several methods/techniques for the identification and characterization of microplastics such as visual identification, spectroscopic, pyrolysis–gas chromatography-mass spectrometry (Pyro-GCMS), scanning electron microscope (SEM) and combined method (Fig. 2). Stolte et al. (2015) stated that the identification of secondary microplastics is tough due to the large diversity of pathways and sources. If the biofilm is not removed from the surface of the microplastics then it can interfere in the identification and detection of microplastics.

Visual Identification:

It is an obligatory method for the parting of microplastics from additional inorganic and organic materials in the residues of samples. It can help in the identification of microplastics that originate from laboratory contamination and field samples (Mathalon and Hill 2014). It allows the classification of microplastics based on physical appearances, observed directly or using a microscope. It also allows the classification of microplastics by shape, size and color. It is one of the most used and widely available methods but is not reliable. It is a time time-consuming method. Large microplastics can be detected by this method (Doyle et al. 2011) and particles lesser than 1×10^{-3} m cannot be recognized (Lee et al. 2013). Transparent particles of size 20×10^{-6} m can be identified by this method (Mintenig et al. 2017).

Spectroscopic techniques

These techniques are reliable and well-established and are used to recognize the structure of polymers. In these techniques, the emission or absorption spectra of the particles are matched with reference spectra. These techniques are non-destructible and highly accurate.

Raman spectroscopy

It is an appropriate technique for the chemical characterization of microplastics in the aquatic ecosystem (Lenz et al. 2015). It presents a molecular fingerprint spectrum that is based on the polarity of the chemical bonds (Elert et al. 2017). By using micro-Raman spectroscopy, very small particles of size $<20\times10^{-6}$ m have been detected (Schymanski et al. 2018). The sample (500×10^{-9} m to 800×10^{-9} m) is irradiated with a monochromatic wavelength and the result is compared with polymer spectra libraries to identify the plastic particles (Young and Elliott 2016).

Fourier Transform Infrared Spectroscopy (FTIR)

It is a highly recommended technique for the chemical characterization of microplastics. It depends on the material, configuration and wavelength (Lusher et al. 2014). Microplastics can be detected by stimulating molecular vibrations with the infrared spectrum and this spectrum is the result of the change in

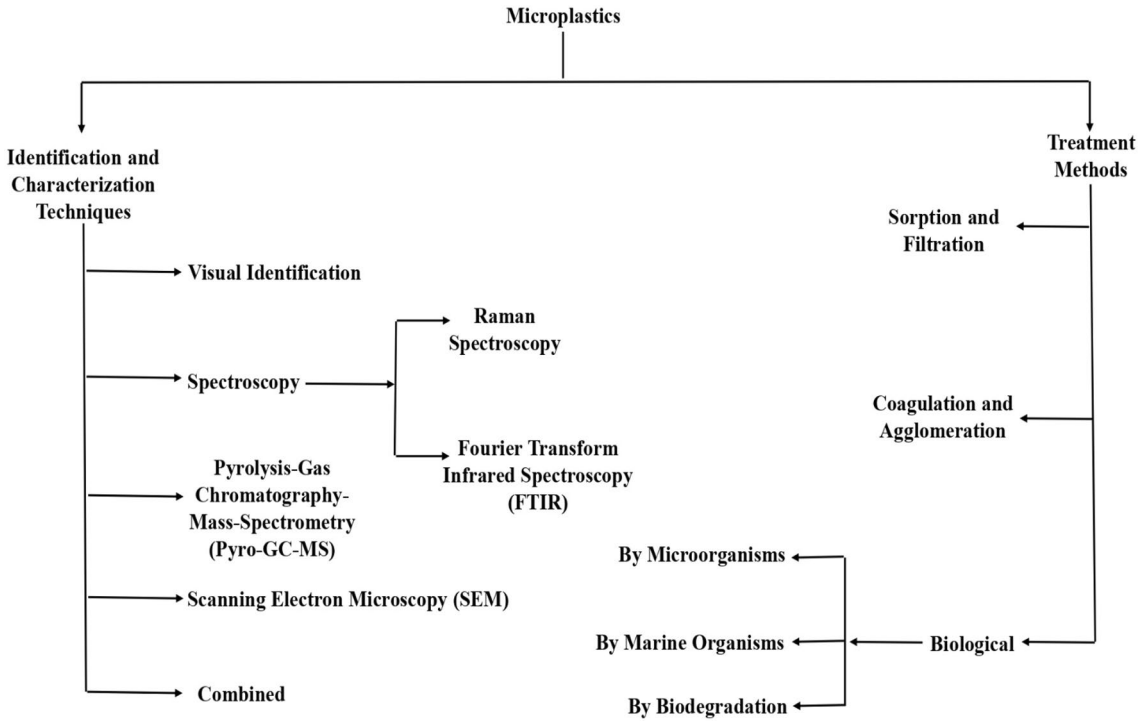


Fig. 2 Different techniques/methods for the identification, characterization and treatment of microplastics

dipole moment. Van der Hal et al. (2017) studied the presence of microplastics in aquatic environments and stated that microplastics can be detected at a particular unique infrared spectrum. Diverse FTIR techniques such as attenuated total reflection FTIR (ATR-FTIR) improve the knowledge of irregular microplastics while transmission FTIR applies to thick or opaque samples (Courtene-Jones et al. 2017). Micro-FTIR produces a great-resolution map of the sample without a pre-selection step (Wesch et al. 2016). Löder and Gerdts (2015) used micro-FTIR spectroscopy for the characterization of microplastics of size $< 500 \times 10^{-6}$ m.

Pyrolysis–gas chromatography-mass spectrometry (Pyro-GC–MS)

In this technique, the polymer sample is pyrolyzed (decomposed) under an inert condition and the decomposed sample is analyzed by GC–MS (Shim et al. 2017). This technique is used to identify polymer types and requires large mass particles compared to the spectroscopic technique. Hence this technique is not suggested for handling huge sample sizes. In this technique, only one particle is analyzed in a single run (Nuelle et al. 2014). This technique is detrimental and does not provide information on the number, size or shape of particles.

Scanning electron microscopy (SEM)

This technique imagines the surface characteristics of microplastics and delivers high-resolution images of a sample by examining the surface with a focused electron beam (Kalčíková et al. 2017). The sample images $> 0.5 \times 10^{-9}$ m allow the difference between microplastics (Wang and Wang 2018). This technique does not detect the composition of the polymer. SEM with energy-dispersive X-ray spectroscopy (EDS) has also been used to gather knowledge on the chemical composition and morphology of microplastics (Fries et al. 2013).

Combined method

A combined method can improve the quantification and identification of microplastics in freshwater because a single method is not sufficient for the investigation of microplastics. Both spectroscopic and microscopic techniques are used to analyze a large quantity of microplastics in water samples (Song et al. 2015). First, the spectroscopy technique is applied for the chemical characterization of microplastics and then the stereo microscope technique is used to count the microplastic particles. Song et al. (2015) reported the microplastic of size $< 1.0 \times 10^{-3}$ m by using this method. Collard et al. (2015) used a new procedure for the identification and quantification of microplastics and it was based on the

digestion of hypochlorite. First, the separation of microplastics from the film was done by sonication after that the analysis was done by Raman spectroscopy.

Treatment of microplastics

There are several methods for the removal/degradation of microplastics such as sorption and filtration methods, coagulation and agglomeration methods and biological methods (Fig. 2). SEM and FTIR are widely used techniques for the study of morphology and structural changes during the degradation of microplastics.

Sorption and filtration methods

In the filtration process, the solid particles are separated from the liquids/fluids based on the size of the plastics. Filtration encompasses granular filtration and membrane filtration based on filter types. Granular filtration engages the retention of solid particles through attachment and transport steps, facilitated by granular media such as glass beads, quartz sands and activated carbon. In the membrane filtration technique, the membrane assists as a selective barrier and allows certain ions and small molecules to pass through it. Microplastic removal efficiency depends on membrane durability, concentration and the size of the microplastics.

Membranes are categorized based on pore size, including ultrafiltration, nanofiltration, microfiltration and reverse osmosis membranes. Ultrafiltration, nanofiltration and microfiltration are capable of efficiently excluding particles $> 0.08 \times 10^{-6}$ m to 2.0×10^{-6} m, 0.005×10^{-6} m to 0.02×10^{-6} m and 0.002×10^{-6} m, respectively. Reverse osmosis is primarily employed for desalination purposes (Zhang et al. 2021). Li et al. (2018) used membrane technology for the removal of microplastics from polluted water. Horton and Dixon (2018) obtained the filtrate of microplastics within 1200 s by decreasing the turbidity of effluent. Ward (2015) designed a device based on polymer coverings as an extended mesh screen for the removal of microplastics. Membrane bioreactors are suitable for the exclusion of microplastics, and these bioreactors can eliminate ~ 99.9% of microplastic particles/m^3 (Lares et al. 2018).

Microplastic fragments show the devotion behavior on the surface of edible algae and seaweed (Sundbaek et al. 2018). Alginate is a gelatinous substance that is released from the cell walls of the seaweed. Alginate is responsible for the devotion behavior of polystyrene fragments on the surface of seaweed (Martins et al. 2013) and ~ 94.5% of microplastics are adsorbed by the alginate. The sorption of microplastic particles on the surface of algae differs from the surface charge of particles. Positively charged microplastic particles are more effectively adsorbed on the algae than negative charge microplastic particles (Nolte et al. 2017).

Microplastic adsorption on green algae can be considered a viable treatment methodology due to the natural affinity of algae for particle adsorption. Green algae possess cell surfaces and extracellular polymeric substances that can effectively attract and bind microplastics. This process aids in the removal of microplastics from water bodies. Additionally, green algae's ability to photosynthesize can contribute to the overall purification of water by utilizing sunlight and producing O_2. This environmentally friendly approach provides a sustainable and potentially cost-effective method for mitigating microplastic pollution in aquatic environments (Priyadharshini et al. 2021).

Coagulation and agglomeration methods

Several researchers used this method for the elimination of microplastics and stated that the efficiency of the microplastic removal and degradation depends on pH, concentration, composition of media and type of coagulant. Zhang et al. (2021) stated about the coagulation and agglomeration method that the surface properties of microplastics should be the primary consideration for colloidal stability. Coagulants employed in the removal of microplastics encompass synthetic organic coagulants, aluminum-based coagulants, natural organic coagulants and iron-based coagulants.

Shirasaki et al. (2016) used coagulation and agglomeration methods for the elimination of microplastics from wastewater. Ariza-Tarazona et al. (2019) used iron and aluminum salt coagulants for the elimination of polyethylene particles and stated that high aluminum doses can increase the elimination efficiency of microplastics. Perren et al. (2018) used the electrocoagulation method for the removal of polyethylene particles from a stirred-tank batch reactor and stated that it is a cost-effective method.

Akbal and Camcl (2011) used metal hydroxide coagulants for the removal of microplastics and reported that these coagulants destroy the colloids and then stabilize the floating microparticles. Polyethylene and polystyrene were degraded by a photocatalyst based on titanium dioxide (TiO_2) (Wang et al. 2019). The aging of polystyrene and polyethylene was investigated by Liu et al. (2019) while chemical structure degradation of polyethylene and polypropylene was investigated by Brandon et al. (2016). The photocatalytic destruction of low-density polyethylene with the help of zinc oxide (ZnO) nanoparticles was investigated by Tofa et al. (2019) in aquatic environments.

Biological methods

There are several popular biological approaches for the removal and degradation of microplastics from aquatic environments such as by microorganisms, marine organisms and biodegradation. The differences in the removal of microplastics can be attributed to (i) variations in microbial populations, (ii) characteristics of the microplastics in the wastewater (such as size, shape, taste and surface structure) and (iii) abiotic factors like temperature and pH. Among the biological treatment processes, methods such as microbial treatments (utilizing the activated sludge method and biofilm-related processes), membrane bioreactor (MBR) technology, aerobic digestion, anaerobic digestion and constructed wetlands have been recognized as the most widely employed and effective approaches for the removal of microplastics (Ahmed et al. 2021).

Within the activated sludge process, the sludge undergoes thorough mixing with O_2 in a reactor, prompting microorganisms to utilize the sludge as their source of nourishment. The removal of microplastics in this process takes place through adsorption, degradation or aggregation. Microorganisms release extracellular polymeric substances (EPS) to absorb available contaminants, including microplastics and subsequently break them down to generate desired products. Whereas within the biofilm process, biofilms undergo a cyclic sequence of three stages (i) a growth phase, (ii) a stationary phase and (iii) a peeling period.

Following the peeling phase of one layer of the biofilm, a new film begins to develop, actively participating in the removal of additional microplastics and other contaminants present in the wastewater. Similar to the activated sludge process, microorganisms initially adsorb microplastics using the EPS they secrete. Microplastics serve as attachable carriers, aiding the microorganisms in their growth. Following a stationary phase, biofilms begin to detach from the carrier's surface, gathering contaminants and eventually contributing to the treated water.

By microorganisms

Microorganisms such as fungi, zooplankton and bacteria were found suitable for the removal of microplastics at minimal concentrations. However, the mechanism of the removal and degradation of microplastics through microorganisms is not well understood yet and needs to be explored further. Urbanek et al. (2018) studied the removal of microplastics from the aquatic environment and reported that fungi and algae catalyze the reactions of the degradation of microplastics. *Zalerion maritimum* is a naturally occurring fungus that uses microplastics as a nutrient source (Paço et al. 2017). Auta et al. (2017b) studied the degradation of polystyrene, polypropylene, polyethylene and polyethylene terephthalate by using bacterial strains such as *Bacillus gottheilii* and *Bacillus cereus*. They reported that *Bacillus gottheilii* is a better microplastic degrader.

By marine organisms

Due to their small size and lightweight, microplastics are quickly distributed over the ocean surface after traveling a long distance by wind. Ahmed et al. (2018) studied the degradation of natural and artificial microplastics by marine organisms. Dawson et al. (2018) investigated the fragmentation of polyethylene by Antarctic Krill (*Euphausiasuperba*) in Australia. Cocca et al. (2020) described the harvesting of high-density polyethylene with the help of two marine communities such as Agios and the Souda consortium.

Hall et al. (2015) studied the consumption of microplastic particles in the scleractinian corals and reported polypropylene particles in their gut cavity. They stated that the ingesting rate was 50×10^{-6} m plastic 3600×10^{4} m^{-2}/s^{-1}. Arossa et al. (2019) studied the ingestion of microplastics in the Red Sea giant clam and reported that larger clams ingest higher concentrations of microplastics.

By biodegradation

Biodegradation is an environmentally friendly procedure when compared to other treatment approaches, as it transforms organic materials into fragments and ultimately into carbon dioxide (CO_2). This process involves two key steps: depolymerization and mineralization. Depolymerization is the breakdown of polymers into monomers, dimers and short chains of oligomers. These smaller molecules can pass across bacterial membranes, serving as a source of carbon and energy. Mineralization, on the other hand, is the process where the last products are methane, water and CO_2. Microplastics go through microbial breakdown over the activity of exoenzymes, promoting depolymerization by microbial species, ultimately leading to mineralization. This biodegradative process is crucial in converting microplastics into environmentally benign end products (Ahmed et al. 2021).

Conclusions and recommendations

Microplastic pollution is a life-threatening environmental problem. The presence of microplastics threatens the entire freshwater environment. From the previous literature, it can be concluded that different types of microplastics have been detected in freshwater environments by using different methods such as scanning electron microscopy, Raman spectroscopy, pyrolysis gas chromatography-mass spectrometry, FTIR spectroscopy, etc. There is limited study available on the presence of microplastics in aquatic environments. The intensity of

microplastic pollution was excessive due to the activity of the inhabitants and industries situated near the freshwater environment. Regarding color transparency, white and blue microplastics were dominant, while polypropylene and polyethylene were the chief microplastics. Microplastic particles whose size was less than 100×10^{-6} m proved to be most hazardous for the health of humans.

Several research gaps exist in our understanding of microplastic pollution in water bodies, hindering the development of comprehensive mitigation strategies. There is a need for standardized and harmonized methods for microplastic sampling, analysis and quantification. The lack of consistency in methodologies hampers comparisons between studies and regions. The long-term consequences and potential synergistic effects with other pollutants are not fully understood. The role of microplastics in facilitating the transport of other contaminants and pathogens in water bodies is another understudied area. Improved knowledge in this regard would enhance our understanding of the broader environmental implications of microplastic pollution.

Additionally, more research is required to elucidate the sources, pathways and fate of microplastics in freshwater ecosystems, with a focus on understanding how different environments influence their transport and distribution. Addressing these research gaps is essential for developing effective policies and management strategies to mitigate the impact of microplastics on aquatic ecosystems and human health. Mitigating microplastic pollution in water bodies requires a comprehensive approach that addresses both the sources of microplastics and their impact on ecosystems.

Establishing the standards to determine the ecological risk posed by microplastics is very significant. Researchers believe that the issue of microplastic pollution can be solved through the combined efforts of community enrolment, legislation, and biotechnological and engineering tools. The government and non-government organizations can play an important role in minimizing microplastic pollution by encouraging the recycling of plastics, to use of biodegradable bags and non-plastic resources and to conduct of awareness programs of plastic pollution.

We suggest several recommendations for the minimization of the microplastic pollution. These are:

- Reduce single-use plastics: Policies to reduce the production and consumption of single-use plastics should be encouraged and implemented. This includes promoting alternatives, such as reusable containers and bags, and implementing plastic bag bans or fees. People who use items made from plastic waste should be encouraged.
- Improve waste management: The waste management infrastructure to prevent plastic litter from entering water bodies should be improved. Effective recycling programs, waste collection systems, and waste disposal facilities to reduce the likelihood of plastic waste reaching aquatic environments should be implemented.
- Promote sustainable practices: Sustainable production and consumption of plastics practices in industries should be encouraged. This involves promoting eco-friendly packaging, reducing unnecessary packaging, and adopting circular economy principles to minimize the generation of plastic waste.
- Storm-water management: Storm-water management to reduce the transport of microplastics from urban areas to water bodies should be improved. Green infrastructure solutions and filtration systems to capture and prevent the runoff of plastic particles should be implemented.
- Raise awareness: The government bodies should conduct awareness programs like conferences and field activities to educate the public, industries, and policymakers about the impacts of microplastic pollution. Increased awareness can lead to more responsible behaviour, support for policies addressing plastic pollution, and changes in consumption patterns.
- Research and monitoring: Invest in research to better understand the sources, distribution and effects of microplastics. In future research, continuous monitoring of the microplastics should be done in regions from where less data has been published like Africa, Asia, and South America to track the levels of microplastics in different water bodies and identify emerging hotspots. New policies should be made worldwide by the authorities for the regular monitoring of plastic pollution in freshwater environment.
- Innovative technologies: Innovative and cost-effective technologies to capture and remove microplastics from water bodies should be explored and implemented. This includes the development of filtration systems, skimmers, and other advanced analytical techniques for both freshwater and marine environments.
- International cooperation: Industries, non-governmental bodies (NGOs) and government bodies can work together for the reduction/elimination of microplastics from the freshwater environment. There is a need to foster international collaboration to address the global nature of microplastic pollution. The standards and regulations should be developed and implemented to control plastic production and disposal globally.

- Clean-up initiatives: The community-based clean-up initiatives to remove plastic debris from water bodies should be supported and participated. These efforts can help raise awareness and directly contribute to reducing the amount of microplastics in the environment.

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