Environmental Science and Pollution Research (2023) 30:114707–114721
https://doi.org/10.1007/s11356-023-30526-4

REVIEW ARTICLE

Microplastics in environment: a comprehension on sources, analytical detection, health concerns, and remediation

Tanish Goyal[1] · Sukhwinder Singh[1] · Ghanshyam Das Gupta[2] · Sant Kumar Verma[3]

Received: 8 March 2023 / Accepted: 12 October 2023 / Published online: 28 October 2023

Abstract
Contamination of ecosystems by microplastics (MPs) has been reported intensively worldwide in the recent decade. A trend of reports indicated their presence in the atmosphere; food items and soil ecosystems are rising continuously. Literature evidenced that MPs are abundant in seawater, beach sand, drinking water, agricultural soils, wastewater treatment plant (WWTP) effluent, and the atmosphere. The greater abundance of MPs in the environment has led to their invasion of seafood, human-consumed food items such as table salts, beverages, takeout food containers, and disposable cups, marine biological lives, and creating serious health hazards in humans. Moreover, the absence of guidelines and specifications for controlling MPs in the environment makes the situation alarming, and the human toxicity data of MPs is scarce. Thereby, the toxicity assessment of MPs in humans is of greater concern. This review compiles the updated information on the potential sources of MPs in different components of the environment (viz. soil, water, and air), their analysis methods, effects on human health, and remediation methods.

Keywords Ecosystem · Environmental pollution · Human health · Microplastics · Microplastic remediation · Plastic degradants · Soil pollution

Introduction

"Microplastic (MPs)" was coined in 2004 to address the recorded new smaller plastic particles in the range of 0.05–0.5 mm or could pass from the 500-µm sieve (Kumar et al. 2020; Magnusson et al. 2016), which are prevailing in the environment mainly due to littering and mismanaged waste. The upper size limit for microplastic was suggested as 5 mm in an international research workshop on "Occurrence, effects, and fate of microplastic marine debris" hosted by the National Oceanic and Atmospheric Administration (NOAA) in 2008. MPs have become a topic of serious concern for the environment and thus grabbed a particular focus of researchers. Accumulated data provided by further research led to an increased and sustained focus on the topic, which was not initially sustained in the first reports published in the early 1970s. "Plastics" in microplastics refers to a subclass of polymers that are a chemically long-chain arrangement of a particular chemical moiety. Because of the versatile properties of plastic, such as bio-inertness, lightweight, and moisture resistance, around one third of overall plastic resin is used solely for consumer packaging plastic (Chatterjee and Sharma 2019; Wan et al. 2019). Polymers used in plastics may be a homopolymer (composed of the same subunit throughout) or copolymers (different compositions with different sequences). Ethylene, propylene, vinyl chloride, and styrene are commonly used monomers for plastic manufacturing (Smith et al. 2018), which are present in microplastics.

Primary and secondary microplastics are the types of microplastics that are commonly found in the environment. Primary microplastics are plastic microparticulate directly released from plastic material, whereas secondary microplastics are generated via weathering or degradation of smaller fragments of plastics (Boucher and Friot 2017; Magnusson et al. 2016). Global data of mismanaged plastic

Responsible Editor: Philippe Garrigues

✉ Sant Kumar Verma
santkumarverma19@gmail.com

[1] Department of Pharmaceutical Analysis, ISF College of Pharmacy, Moga 142 001, Punjab, India

[2] Department of Pharmaceutics, ISF College of Pharmacy, Moga 142 001, Punjab, India

[3] Department of Pharmaceutical Chemistry, ISF College of Pharmacy, Moga 142 001, Punjab, India

waste was reported to be 99 million metric tonnes for 2015, projected to reach a tripled value of 155–265 metric tonnes by 2060 (Lebreton and Andrady 2019). Approximately 320 million tons of plastic are manufactured, and production is continuously rising, predicted to reach 33 billion tons by 2050 (Bhattacharya and Khare 2020; Chen et al. 2020). As one third of overall plastic resin is used to manufacture packaging plastic material, manufacturing at this huge level corresponds to the prevalence of microplastics in overall debris (Andrady 2011).

The aquatic ecosystem has been most intensively researched in the last few decades for microplastic contamination followed by terrestrial and atmosphere (Ng et al. 2018; Rillig et al. 2019), while data on the presence, accumulation, and significant effects in humans reported to date are significantly less (Tan et al. 2020; Yee et al. 2021). The microplastic study is vital to comprehend pollution sources, detect health risks, devise effective remediation, and protect ecosystems from plastic's pervasive and harmful influence. Therefore, this review includes the study of microplastics in the environment, *i.e.*, their sources, analytical detection, health concerns, and remediations.

Analysis of microplastics

Sampling and sample preparation

Microplastic content can be efficiently sampled from water, sand, soil, air, and living tissues using standard procedures, given that sampling is the most crucial step in the analysis. While developing a sample strategy, the distribution of MPs and the morphology of the site for MP sources are important factors to be considered. For soil sampling, ISO18400-102 prescribed various issues such as the types and sizes of samples required, the depth from which the samples must be taken, potential contaminants and their nature, sampling locations distribution, and other issues that must be taken into consideration (Lusher et al. 2014). Three methods have been reported for taking samples from marine sources: bulk sampling, selective sampling, and volume-reduced sampling (Hidalgo-Ruz et al. 2012). For the sampling of microplastics in air, passive atmospheric deposition and actively pumped samplers were used. Among these, actively pumped samplers are more efficient for estimating the number of microplastics inhaled by humans daily (Vianello et al. 2019). Apart from these methods, organic separation and density separation are two majorly used processes for the sampling. Sample preparation processes for MPs include drying, homogenization, sieving, sorting, dispersion of soil aggregates, density separation, removal of soil organic matter, and extraction with organic solvents. The digestion methods for sampling of marine environment comprise four methods: acid digestion (HCl, HNO_3), alkaline digestion (KOH, NaOH), enzymatic digestion (protease, lipase, cellulose, etc.), and oxidizing digestion (H_2O_2) (Stock et al. 2019).

Identification and quantification

Microplastics can be identified using a combination of physical and chemical characterization (Shim et al. 2017). Physical characterization defines various physical characteristics of the particles. It involves various types of microscopic techniques such as dissect microscopy (Setälä et al. 2014), polarized microscopy (Lusher et al. 2020), scanning electron microscopy (Fernández-González et al. 2021), atomic force microscopy (Julienne et al. 2019), and fluorescence microscopy (Scircle and Cizdziel 2019). However, chemical characterization involves describing particles based on their chemical characteristics. Various techniques used for the identification and quantification of microplastics include energy dispersive X-ray analysis (Kumar and Sharma 2021), differential scanning calorimetry (Liu et al. 2021a, b), FT-IR (Pico et al. 2018), Raman spectroscopy (Ragusa et al. 2021), and GC–MS (Shim et al. 2017). Table 1 summarizes the techniques used by different researchers to determine the presence of microplastics in different samples.

Remediation of microplastics from the environment

Physical methods

Physical methods to remove microplastics from wastewater include floatation, sedimentation, and filtration. Various experiments have been conducted to estimate the filtration capability of filters such as sand, membrane, and disk filters and screening (Table 2). Knoblock et al. (1994) experimented with the filtration capacity of porous membranes coupled with biological processes. This system proved to be efficient for the removal of microplastics from various industrial wastewater. An experiment was conducted to check the removal efficiencies of the disk filter, membrane bioreactor, dissolved air floating, and rapid sand filter. The results concluded that the membrane bioreactor was 99.9% efficient in removing microplastics from 6.9 to 0.005 microplastics per liter. It was also reported that membrane bioreactor, dissolved air floating, and rapid sand filtration efficiently removed microplastic irrespective of their size, even the smallest fraction of 20–100 µm (Talvitie et al. 2017).

Table 1 Techniques used for the determination of microplastic in different samples

Technique(s) used	Sample	Abundant microplastic type	Location	References
SEM and μ-FT-IR	Takeout food containers	Polystyrene	Shanghai, China	(Du et al. 2020)
Raman microspectroscopy	Human placenta	Polypropylene	Rome, Italy	(Ragusa et al. 2021)
ATR-FT-IR	Sediment and water samples	Nylon and polyethylene	Tamil Nadu, India	(Srinivasalu et al. 2021)
SP-ICP-MS ATR-FT-IR	Personal care products Teabags	Polystyrene, polylactic acid, polyethylene tetraphthalate	-	(Laborda et al. 2021)
ATR-FT-IR	Toothpaste, body, and facial scrub	Polyethylene	Selangor, Malaysia	(Suardy et al. 2020)
HPLC–ESI–MS/MS	Indoor dust samples	Polyethylene tetraphthalate, polycarbonate	China, Colombia, Greece, USA, Kuwait, India, Saudi Arabia, Pakistan, Japan, South Korea, and Vietnam	(Zhang et al. 2020a)
FT-IR	Road dust samples	Polyethylene, polypropylene	Da Nang, Vietnam; Shiga, Japan; Kathmandu, Nepal	(Yukioka et al. 2020)
FT-IR	Table salt samples	LDPE, nylon, PP, PET	Tamil Nadu, India	(Nithin et al. 2021)
Raman microscopy	Rainwater pipeline samples	Polypropylene, polyethylene, and polyester	Wuhan, China	(Sang et al. 2021)
μ FT-IR	Mulching farmland soil	Polyethylene	Xinjiang Uygur Autonomous Region, China	(Huang et al. 2020)
μ FT-IR	Sludge-applied soil samples	Polypropylene and polyvinyl chloride	Valencia, Spain	(van den Berg et al. 2020)
μ FT-IR	Agricultural soil and mulch samples	Polyethylene, ethylene-propylene copolymer, polypropylene	Shouguang City, China	(Yu et al. 2021)
ATR-FT-IR	Water samples	Polyethylene, polyester	Northeast Atlantic Ocean Portuguese	(Barboza et al. 2020)
Pyr-GC–MS	Road dust samples	PVC, PET	South-east Queensland, Australia	(O'Brien et al. 2021)
FT-IR and Raman spectroscopy	Eyeglass lens polish wastewater	Poly methyl methacrylate, PET	Busan, South Korea	(Lee et al. 2021)
SEM–EDS and μ FT-IR	Polycarbonate film	Polycarbonate	-	(Qin et al. 2021)
Raman spectroscopy	Beach sediment samples	PS, acrylonitrile, HDPE, PVC	Odisha, India	(Patchaiyappan et al. 2021)
ATR-FT-IR	Artificial soil samples	PET, LDPE	Victoria, Australia	(Ng et al. 2018)
μ FT-IR	Soil samples	PS, PE, PP, PVC, PET	Shaanxi Province, China	(Ding et al. 2018)
Fluorescence microscopy, SEM, AFM, and FT-IR	Disposable paper cups	HDPE	IIT Kharagpur, India	(Ranjan et al. 2021)
FT-IR	Treated wastewater samples	PS, PP, PE, and PET	Saudi Arabia	(Picó et al. 2018)

Filtration techniques

Wastewater from several sources is transferred to various wastewater treatment plants to remove microplastic (Saur 2020). Municipal wastewater treatment plants are only efficient in removing large plastics. However, the only drawback of municipal wastewater treatment plants is their inefficiency in removing micro- and nanoplastics (Lv et al. 2019). Various wastewater treatment plant processes are divided into four steps: preliminary, primary, secondary, and tertiary treatment (Table 3). In preliminary treatment, a sedimentation tank consisting of a screen removes large and large plastics. In primary treatment, aeration and sedimentation remove light and heavy plastics by skimming and sedimentation. Secondary treatment is referred to as biological treatment, which includes an aerobic tank, anaerobic tank, anoxic tank, and a settling tank that efficiently removes microplastic below 500 μm in size. Tertiary treatment is considered an optional step that is helpful in the removal of nitrogen and phosphorus with the help of various chemicals (Wu et al. 2021).

Table 2 Various physical filtration methods and their removal efficiency

Filtration methods	Microplastic removal efficiency	References
Membrane bioreactor (MBR)	79.01% 99.4%	Bayo et al. 2020 Li et al. 2021
Dynamic membrane	94%	Pizzichetti et al. 2021
Glass membrane	90.7%	Li et al. 2021
RO membrane	> 85%	
MF membrane	98%	Yahyanezhad et al. 2021
Disk filter	89.7%	Kim and Park 2021

Chemical methods

Commonly used chemical methods for removing microplastics are coagulation and sedimentation (Fig. 1), including iron and aluminum-based coagulants. The extent of removal of microplastics is based on the type and amount of coagulant used and the retention time of coagulation. Various experiments were conducted with aluminum and iron to check the better coagulation agent, and it was concluded that aluminum showed better coagulation than iron. The microplastic removal efficiency depends upon the pH, which decreases upon increasing the pH and increases upon decreasing the pH, especially for particles below 0.5 mm in diameter. Adding polyacrylamide, an enhancing coagulation agent, showed increased removal efficiency of microplastics with a diameter below 0.5 mm. However, no significant change in removal efficiency was observed for microplastic having a diameter of 5 mm or above. It showed an increase in removal efficiency from 25.83 to 61.19% for particles (diameter < 0.5 mm), while for microplastics (2–5 mm diameter), the removal efficiency increased from 4.27 to 18.34% (Ariza-Tarazona et al. 2019).

Biological methods

Biological methods for removing microplastics include aerobic and anaerobic digestion, lagoon, sludge treatment, and septic tank. Liu et al. (2019a) reported that virgin microplastics did not interfere with the activities of nitrite-oxidizing bacteria, ammonia-oxidizing bacteria, and phosphorus-accumulating microorganisms. It was reported that 10 mg/L of fresh Cyanothece sp. showed a 47% microplastic removal rate (Cunha et al. 2020). In another experiment, it was reported that the growth rate of *Daphnia magna* and the intake rate of PE increased as the exposure time and particle concentration were increased. Additionally, it was reported that *Raphidocelis subcapitata* exposed to PE showed more growth than those without exposure (Canniff and Hoang 2018). As such, the removal of microplastics by using a biological method is less efficient, and secondary contamination of microplastics in sedimentation or sludge can be increased (Liu et al. 2021a, b). Therefore, it was concluded that high microplastic removal efficiency by biological methods is not very optimistic.

Sources of microplastics in environments

Microplastics originates from plastic debris breakdown, synthetic fiber shedding, industrial processes, and improper waste disposal, entering water bodies and ecosystem (Fig. 2), posing environmental challenges. Mismanaged plastic waste degrades into microplastics through various methods, as shown in Fig. 3. The various plastic materials, their structure, and degraded microplastic from them are summarized in Table 4.

Sources of microplastics in water

Carpenter and Smith et al. reported the presence of plastic pellets on the surface of the North Atlantic Ocean in 1972.

Table 3 Various treatment procedures and their removal rate

Treatment method	Removal process	Microplastic removal rate (%)	Input conc. (MPs/L)	Output conc. (MPs/L)	References
Primary treatment	Primary sedimentation, grit removal, screening	76.5	183	43	Tagg et al. 2020
		76.9	35	8	Saur 2020
		80.6	1737	337	Saur 2020
		82	567.8	11.7	Ziajahromi et al. 2017
Secondary treatment	A_2O process	16.6	1.32	1.1	Lv et al. 2019
		90	128	12.8	Saur 2020
	Biofiltration	72.1	43	12	Ross 2020
	Membrane bioreactor	99.3	0.6	0.004	Talvitie et al. 2017; Lares et al. (2018)
Tertiary treatment	Denitrification and ultrafiltration	95	12.3	0.59	Yang et al. 2019

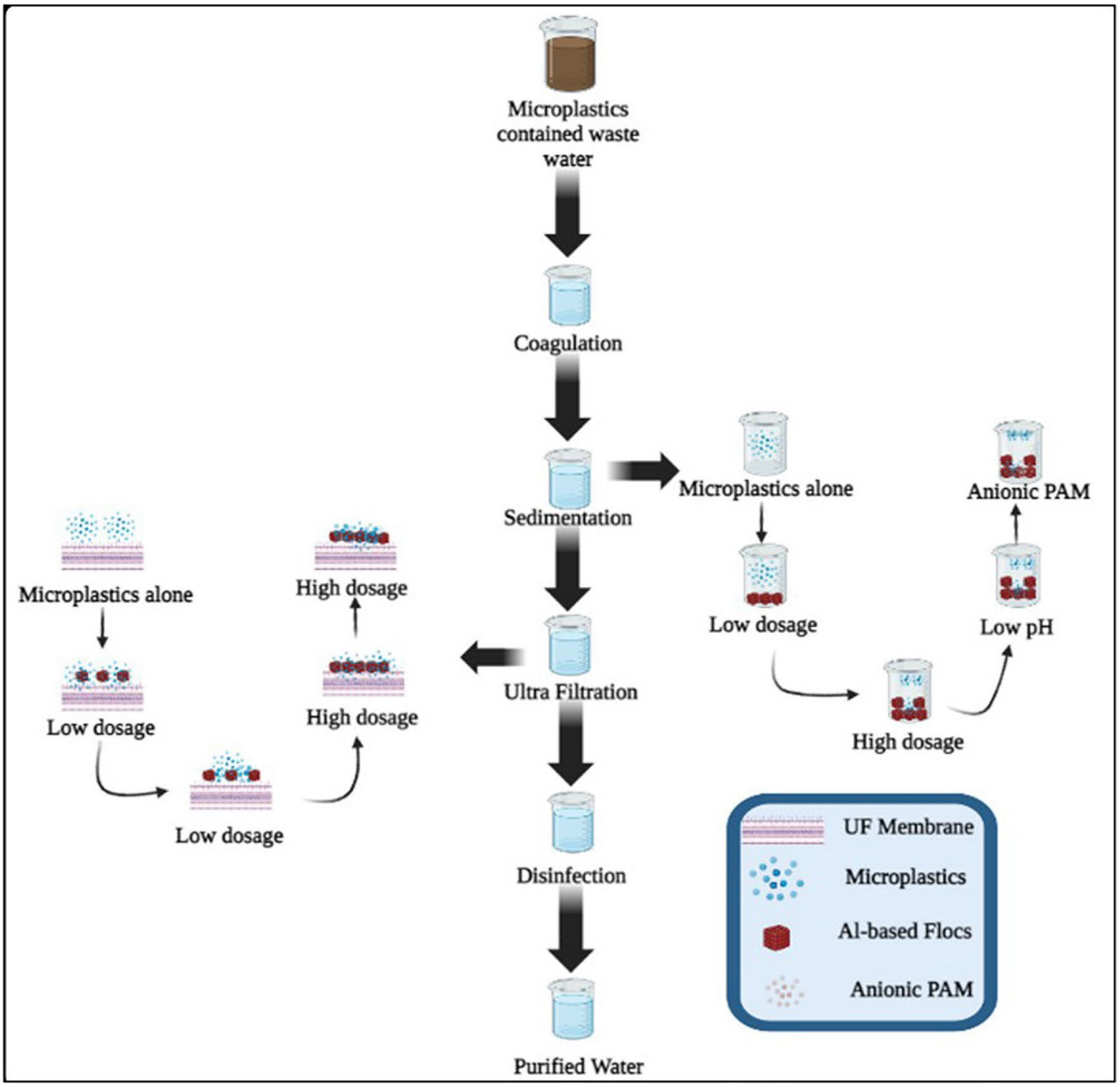


Fig. 1 Microplastic removal by coagulation, sedimentation, and ultrafiltration (UF) showing the effect of anionic polyacrylamide (PAM), pH, and the formation of Al-based flocs on the removal efficiency

They stated, "The increasing production of plastic, combined with present waste-disposal practices, will probably lead to greater concentrations on the sea surface. The only known biological effect of these particles is that they act as a surface for the growth of hydroids, diatoms and probably bacteria" (Carpenter et al. 1972). It was reported that near about 72.03 ± 19.16, particles of microplastics were present in 100 g of beach sediment (Dowarah and Devipriya 2019). The primary sources of marine pollution are fishing, domestic and industrial runoff, land plastic litter, tourism, ports, harbors, the shipping industry, and recreational activities (Fig. 4).

Plastic polymers are generally used to formulate personal care products such as liquid soaps, toothpaste, bubble wash, sunscreen, and hair cleaners for their specific functions such as exfoliators, hair fixatives, and volume bulking agents (Nizzetto et al. 2016). The most common type of personal care product is skincare. Polyethylene is the most often used material in skin cleansing products, accounting for around 92% of all consumption. Personal care items have been shown to contain 0.5 to 12% microplastic by weight (Magnusson et al. 2016). These plastic contents in the formulation are meant to be either rinsed off or retained on the skin's surface. The washed-away plastic content is the potential source of microplastics in water bodies. It was reported that 256–283 microplastic particles were present upon evaluating the sand samples with FT-IR spectroscopy from Tampico beach sediments at Tamaulipas State, southern Gulf of Mexico (Flores-Ocampo and Armstrong-Altrin 2023). Another

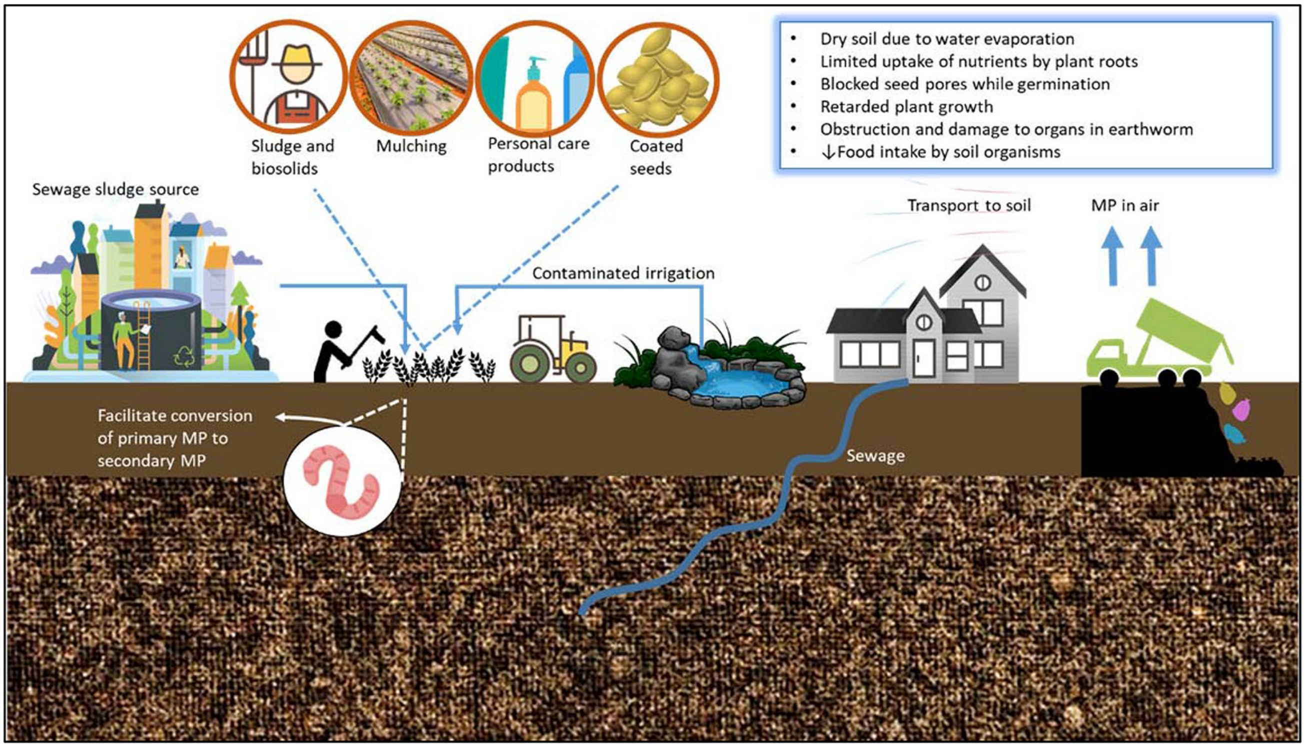


Fig. 2 Contamination of the ecosystem by microplastic (Wan et al. 2019; Khalid et al. 2020; Lönnstedt and Eklöv 2016; Song et al. 2019)

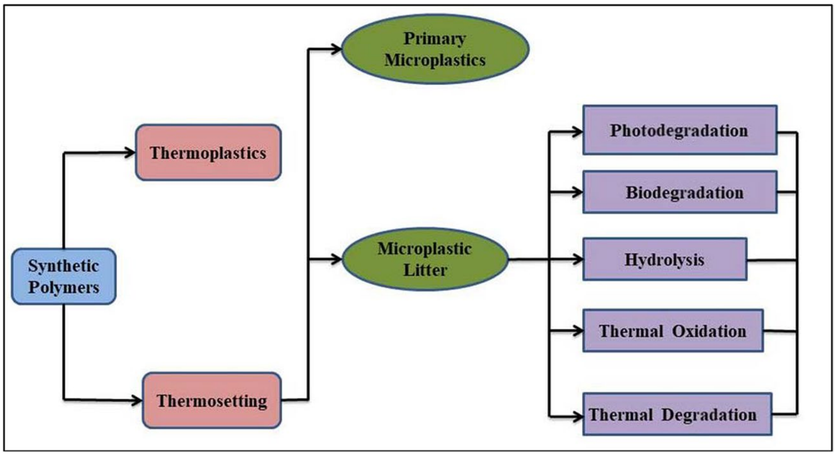
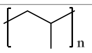
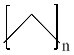
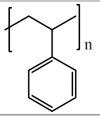
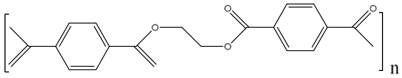
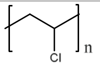
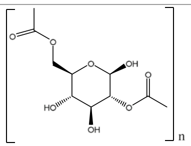
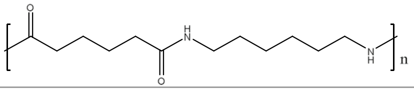
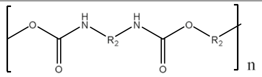


Fig. 3 Outline of the mismanaged plastic waste degradation cascade into microplastics (Sharma and Chatterjee 2017; Smith et al. 2018)

report showed that upon evaluating sand samples from Tecolutla beach sediment, the most abundant colored microplastic was black, followed by blue. These microplastics were in the form of fibers (Flores-Cortés and Armstrong-Altrin 2022).

Exfoliators used in cosmetics act as the primary source of microplastics in the water proved already (Liebezeit and Dubaish 2012; Piotrowska et al. 2020). Moreover, laundry-related activities also comprise a major part of sources of microplastic in sewage systems. Plastic fibers are rinsed out from the garments when they are washed. The proportion of acrylic and polyester fibers in sewage was comparable to that of ocean sediments. The report said a brand new fleece shirt with 100% polyester could lose 0.4% of its weight in the first four washes (Magnusson et al. 2016). Various reports showed that outdoor activities such as construction work, sports activities on school grounds, and rainwater pipelines are other sources

Table 4 The structure, use, and degradation products of the materials used to manufacture plastic materials

Plastic (Andrady 2011)	Monomer structure	Uses (Geyer 2020)	Degradation reactions (Gewert et al. 2015)	Degradation products (Robertson et al. 2012)
Polypropylene (PP)		Caps of bottles, ropes and packaging	Photo-oxidation and less susceptibility to microbial degradation	Pentane, methylpentane, ethane, hydroperoxides
Low-density polyethylene (LDPE)		Plastic bags, juice straws, and bottles	Photo-oxidation Biodegradation (molecular wt. less than 500 Da)	Ethane, ethene, propane, propene, butene, hexane, alcohols, aliphatic carboxylic acids
High-density polyethylene (HDPE)		Milk bottles		
Polystyrene (PS)		Food containers and utensils	Thermo-oxidation Photo-oxidation	Styrene, benzene, acetophenone, benzaldehyde, benzyl alcohol
Polyethylene tetraphthalate (PET)		Beverage bottles and clamshell containers	Photo-oxidation, hydrolytic, and photodegradation	Carboxylic acids
Polyvinyl chloride (PVC)		Cups, wire insulation, bottles, and door frames	Photo-oxidation Highly resistant to biodegradation	Polyene, hydrochloric acid
Cellulose acetate (CA)		Photographic films and playing cards	Enzymatic degradation	Acetic acid
Nylon		Nets, parachute, and seatbelt fiber	Thermal degradation, photochemical degradation	Butane, butylamine, ammonia
Polyurethane (PU)		Coatings and foam products (mattress, pillows)	Bio-degradation, photo-oxidation, and hydrolysis	Isocyanates, amines, hydrocarbons

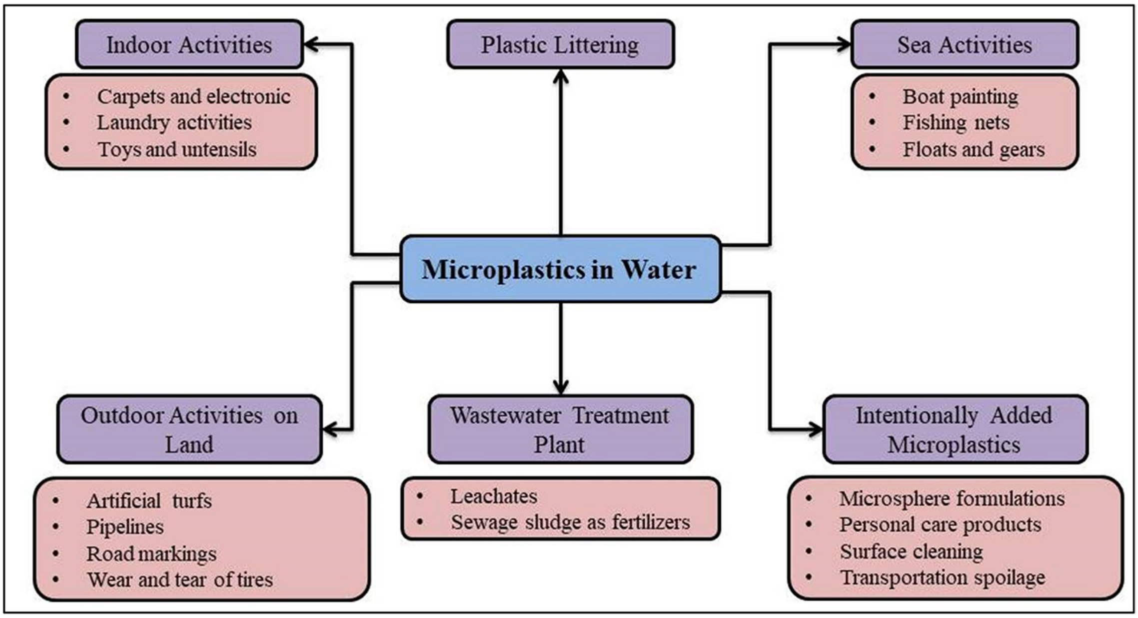


Fig. 4 Sources of microplastics in the aquatic environment

of microplastic reaching water matrices. It was reported that polystyrene (insulation foam), polyvinyl chloride (wall insulation), and polyethylene (cable insulation) are the major plastics commonly found at construction sites. Along with these sources, various other sources have been summarized in Fig. 5.

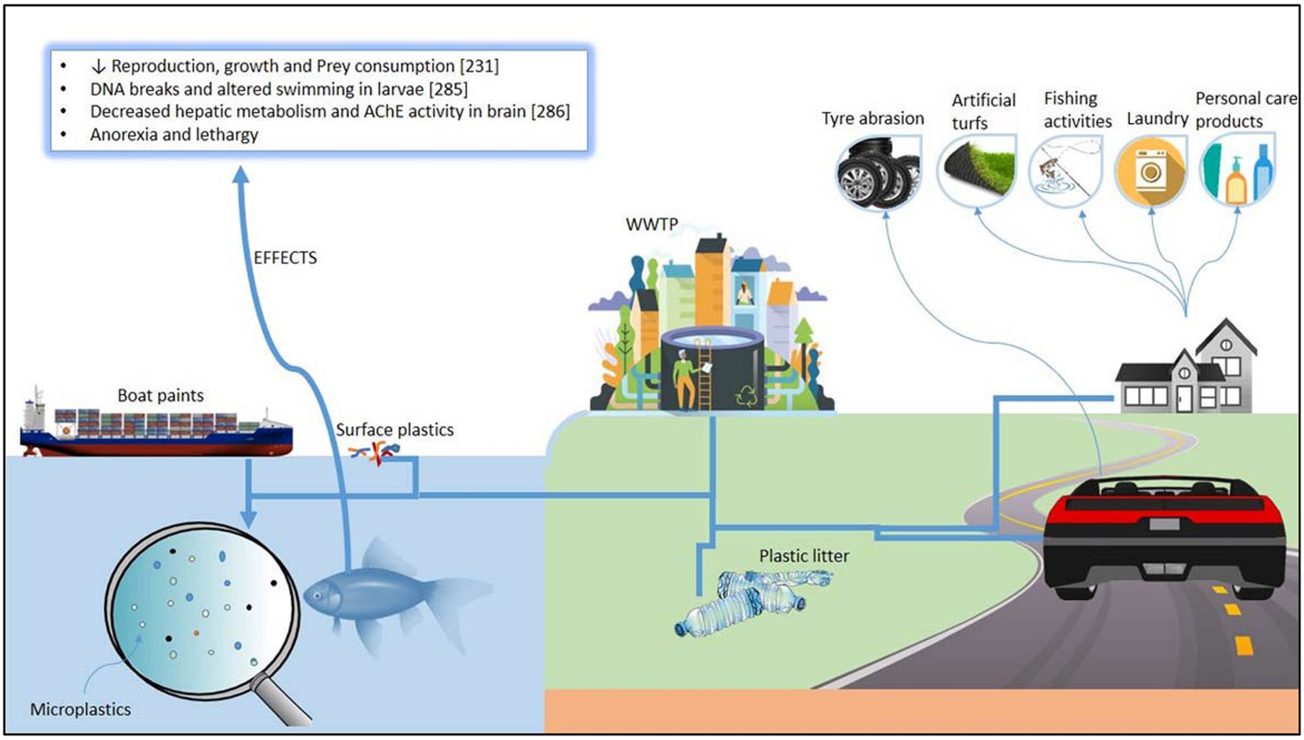


Fig. 5 Summarization of various possible sources of emission of microplastics in marine environments (Foley et al. 2018; Pannetier et al. 2020; Ding et al. 2018)

Effects of microplastics on the aquatic ecosystem

Microplastics consumed by biota could pose serious problems as they may act as a vehicle for transporting persistent organic pollutants (POPs) to the organisms which are adsorbed onto microplastics (Bowmer 2010). MPs are considered bioinert for the feeders in seawater due to the lack of metabolizing enzymes in them. The toxicity of any plastic can be considered because of the following vectors: the leachate content, toxicity due to the degradation products, and MPs with adsorbed POPs which could be ingested and bioavailable to organisms. The uptake of microplastics by marine organisms created harmful effects on their biological processes. Prevalent increased mortality was found in fishes before reaching maturity due to microplastic ingestion. Microplastics are proven to be a menace for the species by several studies. The mortality rate of the fish ingested with microplastics is reported to be more than the control (Auta et al. 2017; Jovanović 2017).

Harpadon nehereus, *H. translucens*, and *Sardinella gibbosa* collected from the North Bay of Bengal were reported to contain 443 MP items in intestines as total analyzed by micro-FT-IR (Hossain et al. 2019). Shore crab (*Carcinus maenus*) was reported for the uptake of microplastics by inspiration *via* gills along with ingestion which was found to be retained in the body for 21 days (inspirated) and 14 days (ingested). Hence, ventilation was concluded for the uptake of MPs in it (Watts et al. 2014). Uptake of MPs in gonads, digestive, and water vascular systems in sea urchins has been reported along with an increase in reactive oxygen and nitrogen species and increased immune cells as effects them (Murano et al. 2020). A concentration-dependent rise in bioaccumulation and reactive oxygen species during exposure to polystyrene microplastics was reported in shrimp (Suman et al. 2020). DNA damage and increased oxidative stress due to increased production of reactive oxygen species and altered antioxidant parameters after the microplastic ingestion are already reported (Hamed et al. 2020).

Sources of microplastics in soil

Various sources of microplastics reaching soil are plastic mulching, sewage sludge, and contaminated water resources. Plastic mulching is the practice of covering the soil with a polyethylene sheet to increase plant growth by maintaining high moisture content and temperature, reducing seed time and harvest time, and limiting weed growth (Espi et al. 2006). Plastic mulches are used due to their ability to transmit or reflect the selective wavelength of light. Approximately 20 million hectares of farmland use plastic mulching (Steinmetz et al. 2016). Polyethylene (low-density polyethylene, high-density polyethylene, linear low-density polyethylene) has become a significant foundation for manufacturing highly customizable mulch films with appropriate flexibility and ease of handling, life, and lack of toxicity and odor (Kara and Atar 2013). Different microplastic shapes negatively impacted soil aggregation, whereas root and shoot mass increased regardless of polymer type. Fibers, fragments, films, and foams were found to reduce soil aggregation by 29%, 27%, and 20%, respectively. Propylene was the most active in reducing microbial activity in soil (Lozano et al. 2021). Water employed in use for the irrigation of crops acts as a potential source of MPs in soil. The vegetables grown in greenhouses require heavy irrigation, proper fertilizers, and intensive cropping. Using wastewater due to its easy accessibility may lead to MPs in soil. Also, the runoff from streets directly from the fields provides soil with a heavy amount of microplastics (Zhang et al. 2020a, b). The water used in irrigation could contain microplastic contaminants, especially if it is street runoff or the effluent of textile, polymeric, or other industries. Water, due to its easy accessibility, contributes to soil contamination primarily. Factors like abundant availability of wastewater, heavy irrigation, and intense cropping practices for greenhouse vegetables or crops also affect the soil's microplastic content (Zhang et al. 2020a, b). Surface and landfill deposits contribute to the dispersion of microplastic particles into the atmosphere, which could be transported further to fields by atmospheric deposition. Rainfall potentially influences the fallout flux of atmospheric MP pollution.

Effects of agricultural microplastics on plant health

Macahdo et al. reported in their study that microplastic fibers in concentrations 0.05 to 0.40% affected soil physical properties much more than microplastic beads in concentrations 0.25 to 2.00% (de Souza Machado et al. 2018). The presence of microplastics in soil provides an altered structure to it by lowering the bulk density of soil, which results in decreased resistance of soil to the root and hence better aeration and root growth; on the other hand, it provides better conditions for the water evaporation from the soil, i.e., the soil would be dry. Yong Wan et al., in their study, reported that water evaporation of soil was increased due to microplastic particles due to increased water conductivity of soil, and the evaporation was dependent on the size and concentration of MPs. MPs with a diameter of 2 mm had a more pronounced effect than MPs with a diameter of 10 mm (Wan et al. 2019). Direct toxicity of microplastics could be mediated by blockage of seed pores, limiting uptake of nutrients and water through roots, and accumulation in roots, leaves, and other parts of the plant (Khalid et al. 2020). Previously, there was no evidence of microplastic uptake in plants; however, Lianzhen Li et al. recently reported on the uptake of microplastic beads in plants. Fluorescence methods were used to trace the absorption of polystyrene microplastic beads with diameters of 0.2 μm and 1.0 μm by the plant. The beads were also scattered about in the leaves (Li et al. 2019). Nanoplastics can be uptake as well as accumulate in plants. The surface charge on nanoplastics influences the amount of microplastic uptake and accumulation. Positively charged nanoplastics were reported to induce the accumulation of a higher amount of reactive oxygen species and inhibited plant growth and seedling development compared to negatively charged nanoplastics (Sun et al. 2019).

Sources of microplastics in air

Air pollution with microplastic as a pollutant is becoming a serious problem steadily. With the increasing production and usage of plastic items, the microplastics emitted from various sources enter the atmosphere, polluting it to a concentration above a significant level. The microplastics (mainly fibers) remain suspended in the air and can be transported to different places by the wind. These suspended microplastics could be inhaled directly by humans. The changes in respiratory and ventilator functions by the microplastic contaminants have been highlighted by Zuskin and Pimental (Mbachu et al. 2020). Various anthropogenic activities leading to MPs in the air are categorized into three main classes: industrial, agricultural, and domestic. The synthetic textile industry is considered the most contributing factor to MPs in the air (Chen et al. 2020; Mbachu et al. 2020). Production of synthetic textiles is increasing continuously due to their properties: strong and durable, resist wrinkles, resist chemicals, do not shrink on wash, low moisture absorbance, and resistant to fungal growth (Deopura and Padaki 2015). Polyethylene being very light is used in a wide range of products for different purposes. Atmospheric fallout comprises (as found to be) of polypropylene, polystyrene, polyethylene, and polyethylene tetraphthalate as dominant polymers in microplastics. Microplastics are released during abrasion, wear, or other activities like cleaning and drying (Napper and Thompson 2016). Catherine Stone et al. has thoroughly analyzed and concluded that synthetic textile has more fiber emission in usage but not in manufacturing. In comparison, woollen textiles produce more fiber emissions while manufacturing (Stone et al. 2020).

Kai Liu et al. analyzed the suspended atmospheric microplastic particles from the air samples from Shanghai using an active suspended particulate sampler. They estimated that around 270 kg of SAMS was transported via air from Shanghai. Textiles were concluded to be the primary source of MPs in the air (Liu et al. 2019b). Agricultural activities involving the incorporation of sewage sludge in soil for the renovation of organic content, plastic mulching for moisture retention and soil temperature maintenance, biocompost, and use of contaminated water for irrigation all act as potential microplastic contaminants to the soil. The microplastics from all these activities quickly spread and are suspended in the air, contaminating it. Domestic activities like unmanaged dustbins and landfill sites, plastic littering, and the use of plastic-made household items potentially cause the emission of microplastics into the air. Christian Ebere Enyoh et al. has reviewed the research on dust samples collected from different locations (mainly from Asia, Europe, and the West Pacific Ocean) analyzed for microplastics content (Enyoh et al. 2019). Transport, dispersion, and deposition are reported for moving microparticles in the air from one place to another.

Effects of suspended air microplastics

Microplastics can be inhaled easily into human lungs, but it depends upon the size of MP. Inhalable in the true sense refers to the ability to enter via mouth or nose and get deposited in upper respiratory airways. In contrast, those which could reach and deposit to the deeper lungs are generally referred to as respirable (Gasperi et al. 2018). Suspended air microplastics (SAMPs) adsorbed with microorganisms could source infections in the host organisms. Scarce research work has been done on investigating the effects of MPs on human tissues. In the first report of this type, Kerestin E. Goodman et al. investigated the toxicological effects of MPs on cultured human alveolar cells. They reported the changes in the cell proliferative and morphological changes as effects. An uptake of 1 µm microplastic, a dramatic decrease in metabolic activity, proliferative rate, and little cytotoxicity were the effects concluded, which proposes the consequence of microplastics to human lungs (Goodman et al. 2021). Alveoli, alveolar ducts, and terminal bronchioles are the sites in the lungs where fibers can accumulate and hence can cause chronic inflammation, granulomas, or fibrosis (Beckett 2000). Oxidative stress caused by MPs can lead to chronic inflammation and pave the way to lung diseases. The improper disposal of the items such as vinyl gloves, plastic ventilator components, visors, facemasks, gowns, and bags used in the COVID-19 pandemic could release many MPs into the environment (Amato-Lourenço et al. 2020; Aragaw 2020).

Sources of microplastics in humans

Microplastics can enter the human body through interrelated systems and activities. The air we breathe, the food we eat, the liquids we drink, and the human environment are the core broad categories that encompass all activities that expose humans to microplastics. Microplastics in marine water bodies are directly proportional to the microplastic content of seafood and other sea animals. Ana I. + Catarino and colleagues investigated the microplastic concentration of mussels. They reported the same concerning human microplastic ingestion through dust during meal consumption. Visual assessment of microplastic fibers using Nile red staining and FT-IR techniques yielded 48% and 50% accuracy, respectively (Catarino et al. 2018). It was reported that shellfish users might swallow 1358 microplastic particles every year. However, the extent is determined by the variety and quantity of shellfish consumed and the level of seafood removal by an individual's intestines (Daniel et al. 2021). It was found that salt derived from seawater or lake water also contains microplastics and can be backed by the known relation between the microplastic concentration in seawater and marine creatures. The content of microplastics in source water serves as a source of microplastics for salt production. A report showed that 21 Spanish table salt samples contained PET as the major polymer, near about 50–280 MPs/kg of sample (Iñiguez et al. 2017). M. Sivagami et al. studied different salt samples from Indian supermarkets, confirming the presence of microplastic content and evaluating the toxicity profile of MP content. The average abundance was 700 MPs/kg, with particle sizes ranging from 3.8 µM to 5.8 Mm.

Effects of microplastics on human health

Several reports provide evidence of the ingestion of microplastic in humans through diet. Based on the American diet, the annual human consumption of microplastics has been estimated to be 74,000 to 121,000 microparticles, while the persons using bottled waters to stay hydrated were estimated to consume an additional 90,000 MPs annually. The enhanced apoptosis rate of HEK-293 cells treated with MPs was used to prove MP's lethality (Sivagami et al. 2021). A variety of consumable items, including fish (Daniel et al. 2021), crabs (Watts et al. 2014), mussels (Catarino et al. 2018), table salt (Iñiguez et al. 2017; Lee et al. 2021), energy drinks and soft drinks (Shruti et al. 2020), white wine (Prata et al. 2020), mineral water bottles (Lee et al. 2021), milk products (Andrey et al. 2021), and tea bags have been reported widely as being the source of microplastics for humans. Microplastics may alter stored energy utilization and impair the body's defensive action against pathogens after ingestion and accumulation in the human body. The four hypothesized mechanisms by which microplastics may enter the human body through the respiratory system and gastrointestinal tract are passive diffusion, upper airways, lower airways, and endocytosis by M-cells (Ragusa et al. 2021). Lixin Wang et al. investigated and found the enhanced toxicity of polystyrene microplastics in the form of increased apoptosis and membrane alterations due to the degradation of MPs in the presence of simulated gastric fluid (Wang et al. 2021). The uptake of microplastics in mammalian testicles has been investigated and reported. Since spermatogenesis is such a delicate process, the presence of

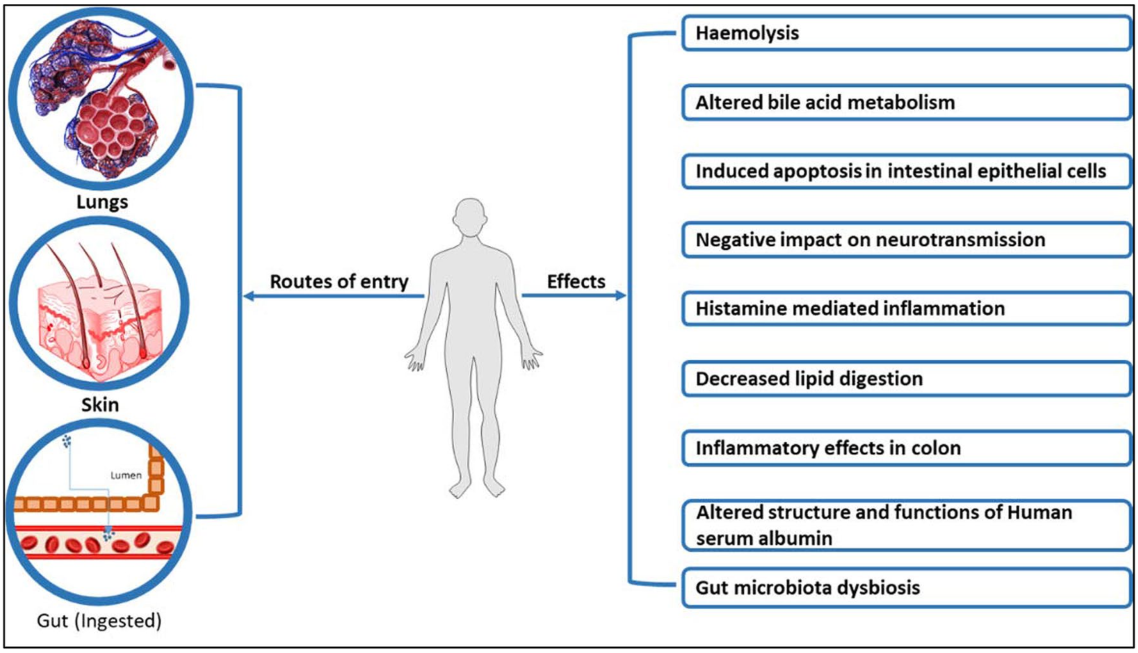


Fig. 6 Routes of entry and effect of microplastic on the human body

microplastics and chemical contaminants on it has a significant impact (decreased sperm quality) (D'Angelo and Meccariello 2021). Uptake of polystyrene nanoplastics in Caco-2 cells enhances the mitochondrial activity and hindered ABC transporter and toxicant effluent pump, resulting in increased arsenic toxicity (Fig. 6) (Wu et al. 2019).

Conclusion

Microplastics are defined as synthetic solid particles or polymeric matrices with sizes ranging from 0.05 to 5 mm, belong either to the primary or secondary origin, and are insoluble in water. Polymer science, one of the most revolutionary fields, has come up with indispensable compounds such as PVC, PE, and many polymers with numerous applications in everyday life. Despite this, rising production, consumption, and incorrect disposal contribute to rising global environmental concerns. Microplastics are being continuously investigated to explore the sources, safety, sophisticated techniques or analysis, and potential hazards concerning human and environmental health, as both are interconnected. The number of reports on the presence of MPs in human dietary food items is continuously increasing. Emerging evidences are available for the presence of MPs in human-consumed seafood, beverages, and other food items. Human ingestion and inhalation of MPs and their substantial risks to human health have already been suggested.

In this review, an efficient approach has been executed to compile the recent research and reported knowledge on the issue. The sources of MPs in context to marine, agriculture, atmosphere, and humans, the potential hazards to different ecosystems and humans are adequately covered. Emerging sources of microplastics like textiles and cosmetics are discussed. Advanced techniques detection and quantification of microplastics, including spectroscopic methods, offer more comprehensive insight. The effects of MPs on humans and their mechanisms have been briefed. In addition, the sampling, processing, and analytical methods employed so far have been described. Physical, chemical, and biological remediation approaches used for removing microplastics from water bodies have been discussed for their appropriate future implementation. The absence of guidelines and specifications for controlling MPs in the environment makes it a trending field for the researcher and the regulatory agencies for future research.

Acknowledgements Sant Kumar Verma is grateful to the Science Engineering Research Board (SERB), Dept. of Science and Technology, Govt. of India, for the Startup Research Grant (SRG, Project No.: SRG/2021/001496). We are thankful to Yogita for her contribution in the revision of the manuscript.

Author contribution SKV suggested the original idea, and the concept of this review was developed in discussion with GDG. TG and SS performed the data curation and wrote the final draft of the manuscript. The final version of the manuscript was read and approved by SKV.

Data availability Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Amato-Lourenço LF, dos Santos GL, de Weger LA, Hiemstra PS, Vijver MG, Mauad T (2020) An emerging class of air pollutants: potential effects of microplastics to respiratory human health. Sci Total Environ 749:141676. https://doi.org/10.1016/j.scitotenv.2020.141676

Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62(8):1596–1605

Andrey D, Ericksen B, Peixoto R, Carreres B, Ambühl M, Descarrega J, Poitevin E (2021) Detection and characterization of small-sized microplastics (≥ 4 µm) in milk products. Res Sq 1–19. https://doi.org/10.21203/rs.3.rs-257514/v1

Aragaw TA (2020) Surgical face masks as a potential source for microplastic pollution in the COVID-19 scenario. Mar Pollut Bull 159:111517. https://doi.org/10.1016/j.marpolbul.2020.111517

Ariza-Tarazona MC, Villarreal-Chiu JF, Barbieri V, Siligardi C, Cedillo-González EI (2019) New strategy for microplastic degradation: green photocatalysis using a protein-based porous N-TiO2 semiconductor. Ceram Int 45(7):9618–9624. https://doi.org/10.1016/j.ceramint.2018.10.208

Auta HS, Emenike C, Fauziah S (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ Int 102:165–176. https://doi.org/10.1016/j.envint.2017.02.013

Barboza LGA, Lopes C, Oliveira P, Bessa F, Otero V, Henriques B, Raimundo J, Caetano M, Vale C, Guilhermino L (2020) Microplastics in wild fish from North East Atlantic Ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. Sci Total Environ 717:134625. https://doi.org/10.1016/j.scitotenv.2019.134625

Bayo J, Lopez-Castellanos J, Olmos S (2020) Abatement of microplastics from municipal effluents by two different wastewater treatment technologies. Trans Ecol Environ 242:15–26

Beckett WS (2000) Occupational respiratory diseases. N Engl J Med 342(6):406–413. https://doi.org/10.1056/NEJM200002103420607

Bhattacharya A, Khare S (2020) Ecological and toxicological manifestations of microplastics: current scenario, research gaps, and possible alleviation measures. J Environ Sci Health, Part C 38(1):1–20. https://doi.org/10.1080/10590501.2019.1699379

Boucher J, Friot D (2017) Primary microplastics in the oceans: a global evaluation of sources (Vol. 10). Iucn Gland, Switzerland

Bowmer T (2010) KP 2010. Bowmer T, Kershaw P (Eds): Proceedings of the GESAMP international workshop on micro-plastic particles as a vector in transporting persistent, bioaccumulating and toxic substances in the oceans In GESAMP Reports & Studies. UNESCO-IOC, Paris 68:68

Canniff PM, Hoang TC (2018) Microplastic ingestion by Daphina magna and its enhancement on algal growth. Sci Total Environ 633:500–507. https://doi.org/10.1016/j.scitotenv.2018.03.176

Carpenter EJ, Anderson SJ, Harvey GR, Miklas HP, Peck BB (1972) Polystyrene spherules in coastal waters. Science 178(4062):749–750. https://doi.org/10.1126/science.178.4062.749

Catarino AI, Macchia V, Sanderson WG, Thompson RC, Henry TB (2018) Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. Environ Pollut 237:675–684. https://doi.org/10.1016/j.envpol.2018.02.069

Chatterjee S, Sharma S (2019) Microplastics in our oceans and marine health. Field Actions Science Reports. J Field Actions(Special Issue 19):54–61

Chen G, Feng Q, Wang J (2020) Mini-review of microplastics in the atmosphere and their risks to humans. Sci Total Environ 703:135504. https://doi.org/10.1016/j.scitotenv.2019.135504

Cunha C, Silva L, Paulo J, Faria M, Nogueira N, Cordeiro N (2020) Microalgal-based biopolymer for nano- and microplastic removal: a possible biosolution for wastewater treatment. Environ Pollut 263:114385. https://doi.org/10.1016/j.envpol.2020.114385

D'Angelo S, Meccariello R (2021) Microplastics: a threat for male fertility. Int J Environ Res Public Health 18(5):2392. https://doi.org/10.3390/ijerph18052392

Daniel DB, Ashraf PM, Thomas SN, Thomson K (2021) Microplastics in the edible tissues of shellfishes sold for human consumption. Chemosphere 264:128554. https://doi.org/10.1016/j.chemosphere.2020.128554

de Souza Machado AA, Lau CW, Till J, Kloas W, Lehmann A, Becker R, Rillig MC (2018) Impacts of microplastics on the soil biophysical environment. Environ Sci Technol 52(17):9656–9665. https://doi.org/10.1021/acs.est.8b02212

Deopura B, Padaki N (2015) Synthetic textile fibres: polyamide, polyester and aramid fibres Textiles and Fashion. Elsevier, pp 97–114. https://doi.org/10.1016/B978-1-84569-931-4.00005-2

Ding J, Zhang S, Razanajatovo RM, Zou H, Zhu W (2018) Accumulation, tissue distribution, and biochemical effects of polystyrene microplastics in the freshwater fish red tilapia (Oreochromis niloticus). Environ Pollut 238:1–9. https://doi.org/10.1016/j.envpol.2018.03.001

Dowarah K, Devipriya SP (2019) Microplastic prevalence in the beaches of Puducherry, India and its correlation with fishing and tourism/recreational activities. Mar Pollut Bull 148:123–133. https://doi.org/10.1016/j.marpolbul.2019.07.066

Du F, Cai H, Zhang Q, Chen Q, Shi H (2020) Microplastics in takeout food containers. J Hazard Mater 399:122969. https://doi.org/10.1016/j.jhazmat.2020.122969

Enyoh CE, Verla AW, Verla EN, Ibe FC, Amaobi CE (2019) Airborne microplastics: a review study on method for analysis, occurrence, movement and risks. Environ Monit Assess 191(11):1–17. https://doi.org/10.1007/s10661-019-7842-0

Espi E, Salmeron A, Fontecha A, García Y, Real A (2006) Plastic films for agricultural applications. J Plast Film Sheeting 22(2):85–102. https://doi.org/10.1177/8756087906064220

Fernández-González V, Andrade-Garda J, López-Mahía P, Muniategui-Lorenzo S (2021) Impact of weathering on the chemical identification of microplastics from usual packaging polymers in the marine environment. Anal Chim Acta 1142:179–188. https://doi.org/10.1016/j.aca.2020.11.002

Flores-Cortés M, Armstrong-Altrin JS (2022) Textural characteristics and abundance of microplastics in Tecolutla beach sediments, Gulf of Mexico. Environ Monit Assess 194(10):752. https://doi.org/10.1007/s10661-022-10447-4

Flores-Ocampo IZ, Armstrong-Altrin JS (2023) Abundance and composition of microplastics in Tampico beach sediments, Tamaulipas State, southern Gulf of Mexico. Mar Pollut Bull 191:114891. https://doi.org/10.1016/j.marpolbul.2023.114891

Foley CJ, Feiner ZS, Malinich TD, Höök TO (2018) A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci Total Environ 631:550–559. https://doi.org/10.1016/j.scitotenv.2018.03.046

Gasperi J, Wright SL, Dris R, Collard F, Mandin C, Guerrouache M, Langlois V, Kelly FJ, Tassin B (2018) Microplastics in air: are we breathing it in? Curr Opin Environ Sci Health 1:1–5. https://doi.org/10.1016/j.coesh.2017.10.002

Gewert B, Plassmann MM, MacLeod M (2015) Pathways for degradation of plastic polymers floating in the marine environment. Environ Sci: Processes Impacts 17(9):1513–1521. https://doi.org/10.1039/C5EM00207A

Geyer R (2020) Production, use, and fate of synthetic polymers plastic waste and recycling. Elsevier, pp 13–32. https://doi.org/10.1016/B978-0-12-817880-5.00002-5

Goodman KE, Hare JT, Khamis ZI, Hua T, Sang QXA (2021) Exposure of human lung cells to polystyrene microplastics significantly retards cell proliferation and triggers morphological changes. Chem Res Toxicol 34(4):1069–1081. https://doi.org/10.1021/acs.chemrestox.0c00486

Hamed M, Soliman HA, Osman AG, Sayed AEDH (2020) Antioxidants and molecular damage in Nile Tilapia (Oreochromis niloticus) after exposure to microplastics. Environ Sci Pollut Res 27:14581–14588. https://doi.org/10.1007/s11356-020-07898-y

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 46(6):3060–3075. https://doi.org/10.1021/es2031505

Hossain MS, Sobhan F, Uddin MN, Sharifuzzaman S, Chowdhury SR, Sarker S, Chowdhury MSN (2019) Microplastics in fishes from the Northern Bay of Bengal. Sci Total Environ 690:821–830. https://doi.org/10.1016/j.scitotenv.2019.07.065

Huang Y, Liu Q, Jia W, Yan C, Wang J (2020) Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ Pollut 260:114096. https://doi.org/10.1016/j.envpol.2020.114096

Iñiguez ME, Conesa JA, Fullana A (2017) Microplastics in Spanish table salt. Sci Rep 7(1):1–7. https://doi.org/10.1038/s41598-017-09128-x

Jovanović B (2017) Ingestion of microplastics by fish and its potential consequences from a physical perspective. Integr Environ Assess Manage 13(3):510–515. https://doi.org/10.1002/ieam.1913

Julienne F, Delorme N, Lagarde F (2019) From macroplastics to microplastics: role of water in the fragmentation of polyethylene. Chemosphere 236:1–8. https://doi.org/10.1016/j.chemosphere.2019.124409

Kara B, Atar B (2013) Effects of mulch practices on fresh ear yield and yield components of sweet corn. Turk J Agric for 37(3):281–287. https://doi.org/10.3906/tar-1206-48

Khalid N, Aqeel M, Noman A (2020) Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environ Pollut 115653. https://doi.org/10.1016/j.envpol.2020.115653

Kim KT, Park SH (2021) Enhancing microplastics removal from wastewater using electro-coagulation and granule-activated carbon with thermal regeneration. Processes 9:617. https://doi.org/10.3390/pr9040617

Knoblock M, Sutton P, Mishra P, Gupta K, Janson A (1994) Membrane biological reactor system for treatment of oily wastewaters. Water Environ Res 66(2):133–139. https://doi.org/10.2175/WER.66.2.6

Kumar R, Sharma P (2021) Microplastics pollution pathways to groundwater in India. Curr Sci 120(2):249

Kumar M, Xiong X, He M, Tsang DC, Gupta J, Khan E, Harrad S, Hou D, Ok YS, Bolan NS (2020) Microplastics as pollutants in agricultural soils. Environ Pollut 265:114980. https://doi.org/10.1016/j.envpol.2020.114980

Laborda F, Trujillo C, Lobinski R (2021) Analysis of microplastics in consumer products by single particle-inductively coupled plasma mass spectrometry using the carbon-13 isotope. Talanta 221:121486. https://doi.org/10.1016/j.talanta.2020.121486

Lares M, Ncibi MC, Sillanpää M, Sillanpää M (2018) Occurrence, identification and removal of microplastic particles and fibres in conventional activated sludge process and advanced MBR technology. Water Res 133:236–246. https://doi.org/10.1016/j.watres.2018.01.049

Lebreton L, Andrady A (2019) Future scenarios of global plastic waste generation and disposal. Palgrave Commun 5(1):1–11. https://doi.org/10.1057/s41599-018-0212-7

Lee HJ, Song NS, Kim JS, Kim SK (2021) Variation and uncertainty of microplastics in commercial table salts: critical review and validation. J Hazard Mater 402:123743. https://doi.org/10.1016/j.jhazmat.2020.123743

Li L, Zhou Q, Yin N, Tu C, Luo Y (2019) Uptake and accumulation of microplastics in an edible plant. Chin Sci Bull 64(9):928–934

Li Q-C, Lai Y-J, Yu S-J, Li P, Zhou X-X, Dong L-J, Liu X, Yao Z-W, Liu J-F (2021) Sequential isolation of microplastics and nanoplastics in environmental waters by membrane filtration, followed by cloud-point extraction. Anal Chem 93:4559–4566. https://doi.org/10.1021/acs.analchem.0c04996

Liebezeit G, Dubaish F (2012) Microplastics in beaches of the East Frisian islands Spiekeroog and Kachelotplate. Bull Environ Contam Toxicol 89(1):213–217. https://doi.org/10.1007/s00128-012-0642-7

Liu H, Zhou X, Ding WQ, Nghiem LD, Sun J, Wang QL (2019a) Do microplastics affect biological wastewater treatment performance? Implications from bacterial activity experiments. ACS Sustain Chem Eng 7:20097–20101. https://doi.org/10.1021/acssuschemeng.9b05960

Liu K, Wang X, Fang T, Xu P, Zhu L, Li D (2019b) Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci Total Environ 675:462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110

Liu W, Zhang J, Liu H, Guo X, Zhang X, Yao X, Cao Z, Zhang T (2021a) A review of the removal of microplastics in global wastewater treatment plants: characteristics and mechanisms. Environ Int 146:106277. https://doi.org/10.1016/j.envint.2020.106277

Liu X, Sun P, Qu G, Jing J, Zhang T, Shi H, Zhao Y (2021b) Insight into the characteristics and sorption behaviors of aged polystyrene microplastics through three type of accelerated oxidation processes. J Hazard Mater 407:124836. https://doi.org/10.1016/j.jhazmat.2020.124836

Lönnstedt OM, Eklöv P (2016) Environmentally relevant concentrations of microplastic particles influence larval fish ecology. Science 352(6290):1213–1216. https://doi.org/10.1126/science.aad8828

Lozano YM, Aguilar-Trigueros CA, Onandia G, Maaß S, Zhao T, Rillig MC (2021) Effects of microplastics and drought on soil ecosystem functions and multifunctionality. J Appl Ecol 58(5):988–996. https://doi.org/10.1111/1365-2664.13839

Lusher AL, Burke A, O'Connor I, Officer R (2014) Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar Pollut Bull 88(1–2):325–333. https://doi.org/10.1016/j.marpolbul.2014.08.023

Lusher A, Welden N, Sobral P, Cole M (2020) Sampling, isolating and identifying microplastics ingested by fish and invertebrates. Anal Nanoplast Microplast Food 9:1346–1360

Lv X, Dong Q, Zuo Z, Liu Y, Huang X, Wu WM (2019) Microplastics in a municipal wastewater treatment plant: fate, dynamic distribution, removal efficiencies, and control strategies. J Clean Prod 225:579–586. https://doi.org/10.1016/j.jclepro.2019.03.321

Magnusson K, Eliaeson K, Fråne A, Haikonen K, Olshammar M, Stadmark J, Hultén J (2016) Swedish sources and pathways for microplastics to the marine environment: IVL Svenska Miljöinstitutet

Mbachu O, Jenkins G, Pratt C, Kaparaju P (2020) A new contaminant superhighway? A review of sources, measurement techniques and fate of atmospheric microplastics. Water Air Soil Pollut 231(2):1–27. https://doi.org/10.1007/s11270-020-4459-4

Murano C, Agnisola C, Caramiello D, Castellano I, Casotti R, Corsi I, Palumbo A (2020) How sea urchins face microplastics: uptake, tissue distribution and immune system response. Environ Pollut 264:114685. https://doi.org/10.1016/j.envpol.2020.114685

Napper IE, Thompson RC (2016) Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar Pollut Bull 112(1–2):39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025

Ng EL, Lwanga EH, Eldridge SM, Johnston P, Hu HW, Geissen V, Chen D (2018) An overview of microplastic and nanoplastic pollution in agroecosystems. Sci Total Environ 627:1377–1388. https://doi.org/10.1016/j.scitotenv.2018.01.341

Nithin A, Sundaramanickam A, Surya P, Sathish M, Soundharapandiyan B, Balachandar K (2021) Microplastic contamination in salt pans and commercial salts—a baseline study on the salt pans of Marakkanam and Parangipettai, Tamil Nadu, India. Mar Pollut Bull 165:112101. https://doi.org/10.1016/j.marpolbul.2021.112101

Nizzetto L, Futter M, Langaas S (2016) Are agricultural soils dumps for microplastics of urban origin? ACS Publications. https://doi.org/10.1021/acs.est.6b04140

O'Brien S, Okoffo ED, Rauert C, O'Brien JW, Ribeiro F, Burrows SD, Toapanta T, Wang X, Thomas KV (2021) Quantification of selected microplastics in Australian urban road dust. J Hazard Mater 416:125811

Pannetier P, Morin B, Le Bihanic F, Dubreil L, Clérandeau C, Chouvellon F, Van Arkel K, Danion M, Cachot J (2020) Environmental samples of microplastics induce significant toxic effects in fish larvae. Environ Int 134:105047. https://doi.org/10.1016/j.envint.2019.105047

Patchaiyappan A, ZakiAhmed S, Dowarah K, Khadanga SS, Singh T, Jayakumar S, Thirunavukkarasu C, Devipriya SP (2021) Prevalence of microplastics in the sediments of Odisha beaches, southeastern coast of India. Mar Pollut Bull 167:112265. https://doi.org/10.1016/j.marpolbul.2021.112265

Pico Y, Alfarhan A, Barcelo D (2018) Nano and microplastic analysis: focus on remediation technologies and occurrence in freshwater ecosystems. Trends Anal Chem 2018:1–57

Piotrowska A, Czerwińska-Ledwig O, Serdiuk M, Serdiuk K, Pilch W (2020) Composition of scrub-type cosmetics from the perspective of product ecology and microplastic content. J Toxicol Environ Health Sci 1–7. https://doi.org/10.1007/s13530-020-00051-9

Pizzichetti ARP, Pablos C, Álvarez-Fernández C, Reynolds K, Stanley S, Marugán J (2021) Evaluation of membranes performance for microplastic removal in a simple and low-cost filtration system. Case Stud Chem Environ Eng 3:100075. https://doi.org/10.1016/j.cscee.2020.100075

Prata JC, Paço A, Reis V, da Costa JP, Fernandes AJS, da Costa FM, Duarte AC, Rocha-Santos T (2020) Identification of microplastics in white wines capped with polyethylene stoppers using micro-Raman spectroscopy. Food Chem 331:127323. https://doi.org/10.1016/j.foodchem.2020.127323

Qin J, Liang B, Peng Z, Lin C (2021) Generation of microplastic particles during degradation of polycarbonate films in various aqueous media and their characterization. J Hazard Mater 415:125640. https://doi.org/10.1016/j.jhazmat.2021.125640

Ragusa A, Svelato A, Santacroce C, Catalano P, Notarstefano V, Carnevali O, Papa F, Rongioletti MC, Baiocco F, Draghi S, D'Amore E (2021) Plasticenta: first evidence of microplastics in human placenta. Environ Int 146:106274. https://doi.org/10.1016/j.envint.2020.106274

Ranjan VP, Joseph A, Goel S (2021) Microplastics and other harmful substances released from disposable paper cups into hot water. J Hazard Mater 404:124118. https://doi.org/10.1016/j.jhazmat.2020.124118

Rillig MC, Lehmann A, de Souza Machado AA, Yang G (2019) Microplastic effects on plants. New Phytol 223(3):1066–1070. https://doi.org/10.1111/nph.15794

Robertson RM, Thomas WC, Suthar JN, Brown DM (2012) Accelerated degradation of cellulose acetate cigarette filters using controlled-release acid catalysis. Green Chem 14(8):2266–2272. https://doi.org/10.1039/C2GC16635F

Ross PS (2020) Tackling microfiber pollution at source a solution-oriented partnership across public and private sectors. OECD Workshop on Microplastics from Synthetic Textiles in the Environment: Knowledge, Mitigation and Policy. Available online: https://www.oecd.org/water/Draft_Agenda_Public_OECD_Workshop_MP_Textile.pdf. Accessed on 12 Jan 2023

Sang W, Chen Z, Mei L, Hao S, Zhan C, bin Zhang W, Li M, Liu J (2021) The abundance and characteristics of microplastics in rainwater pipelines in Wuhan, China. Sci Total Environ 755:142606. https://doi.org/10.1016/j.scitotenv.2020.142606

Saur T (2020) Global assessment of microplastic pollution in wastewater treatment plants. OECD Workshop on Microplastics from Synthetic Textiles in the Environment: Knowledge, Mitigation and Policy. Available online: https://www.oecd.org/water/Draft_Agenda_Public_OECD_Workshop_MP_Textile.pdf. Accessed on 11 Feb 2023

Scircle A, Cizdziel JV (2019) Detecting and quantifying microplastics in bottled water using fluorescence microscopy: a new experiment for instrumental analysis and environmental chemistry courses. J Chem Educ 97(1):234–238. https://doi.org/10.1021/acs.jchemed.9b00593

Setälä O, Fleming-Lehtinen V, Lehtiniemi M (2014) Ingestion and transfer of microplastics in the planktonic food web. Environ Pollut 185:77–83. https://doi.org/10.1016/j.envpol.2013.10.013

Sharma S, Chatterjee S (2017) Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environ Sci Pollut Res 24(27):21530–21547. https://doi.org/10.1007/s11356-017-9910-8

Shim WJ, Hong SH, Eo SE (2017) Identification methods in microplastic analysis: a review. Anal Methods 9(9):1384–1391. https://doi.org/10.1039/C6AY02558G

Shruti V, Pérez-Guevara F, Elizalde-Martínez I, Kutralam-Muniasamy G (2020) First study of its kind on the microplastic contamination of soft drinks, cold tea and energy drinks—future research and environmental considerations. Sci Total Environ 726:138580. https://doi.org/10.1016/j.scitotenv.2020.138580

Sivagami M, Selvambigai M, Devan U, Velangani AAJ, Karmegam N, Biruntha M, Arun A, Kim W, Govarthanan M, Kumar P (2021) Extraction of microplastics from commonly used sea salts in India and their toxicological evaluation. Chemosphere 263:128181. https://doi.org/10.1016/j.chemosphere.2020.128181

Smith M, Love DC, Rochman CM, Neff RA (2018) Microplastics in seafood and the implications for human health. Curr Environ Health Rep 5(3):375–386. https://doi.org/10.1007/s40572-018-0206-z

Song Y, Cao C, Qiu R, Hu J, Liu M, Lu S, Shi H, Raley-Susman KM, He D (2019) Uptake and adverse effects of polyethylene terephthalate microplastics fibres on terrestrial snails (Achatina fulica) after soil exposure. Environ Pollut 250:447–455. https://doi.org/10.1016/j.envpol.2019.04.066

Srinivasalu S, Natesan U, Ayyamperumal R, Kalam N, Anbalagan S, Sujatha K, Alagarasan C (2021) Microplastics as an emerging threat to the freshwater ecosystems of Veeranam lake in south India: a multidimensional approach. Chemosphere 264:128502. https://doi.org/10.1016/j.chemosphere.2020.128502

Steinmetz Z, Wollmann C, Schaefer M, Buchmann C, David J, Tröger J, Muñoz K, Frör O, Schaumann GE (2016) Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci Total Environ 550:690–705. https://doi.org/10.1016/j.scitotenv.2016.01.153

Stock F, Kochleus C, Bänsch-Baltruschat B, Brennholt N, Reifferscheid G (2019) Sampling techniques and preparation methods for microplastic analyses in the aquatic environment—a review. Trends Anal Chem 113:84–92. https://doi.org/10.1016/j.trac.2019.01.014

Stone C, Windsor FM, Munday M, Durance I (2020) Natural or synthetic—how global trends in textile usage threaten freshwater environments. Sci Total Environ 718:134689. https://doi.org/10.1016/j.scitotenv.2019.134689

Suardy NH, Tahrim NA, Ramli S (2020) Analysis and characterization of microplastic from personal care products and surface water in Bangi, Selangor. Sains Malays 49(9):2237–2249. https://doi.org/10.17576/jsm-2020-4909-21

Suman TY, Jia PP, Li WG, Junaid M, Xin GY, Wang Y, Pei DS (2020) Acute and chronic effects of polystyrene microplastics on brine shrimp: first evidence highlighting the molecular mechanism through transcriptome analysis. J Hazard Mater 400:123220. https://doi.org/10.1016/j.jhazmat.2020.123220

Sun J, Dai X, Wang Q, van Loosdrecht MC, Ni BJ (2019) Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Res 152:21–37. https://doi.org/10.1016/j.watres.2018.12.050

Tagg AS, Sapp M, Harrion JP, Sinclair CJ, Bradley E, Nam YJ, Ojeda JJ (2020) Microplastic monitoring at different stages in a wastewater treatment plant using reflectance micro-FTIR imaging. Front Environ Sci 8:145. https://doi.org/10.3389/fenvs.2020.00145

Talvitie J, Mikola A, Koistinen A, Setälä O (2017) Solutions to microplastic pollution—removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res 123:401–407. https://doi.org/10.1016/j.watres.2017.07.005

Tan H, Yue T, Xu Y, Zhao J, Xing B (2020) Microplastics reduce lipid digestion in simulated human gastrointestinal system. Environ Sci Technol 54(19):12285–12294. https://doi.org/10.1021/acs.est.0c02608

van den Berg P, Huerta-Lwanga E, Corradini F, Geissen V (2020) Sewage sludge application as a vehicle for microplastics in eastern Spanish agricultural soils. Environ Pollut 261:114198. https://doi.org/10.1016/j.envpol.2020.114198

Vianello A, Jensen RL, Liu L, Vollertsen J (2019) Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin. Sci Rep 9(1):1–11. https://doi.org/10.1038/s41598-019-45054-w

Wan Y, Wu C, Xue Q, Hui X (2019) Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci Total Environ 654:576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123

Wang L, Wang Y, Xu M, Ma J, Zhang S, Liu S, Wang K, Tian H, Cui J (2021) Enhanced hepatic cytotoxicity of chemically transformed polystyrene microplastics by simulated gastric fluid. J Hazard Mater 410:124536. https://doi.org/10.1016/j.jhazmat.2020.124536

Watts AJ, Lewis C, Goodhead RM, Beckett SJ, Moger J, Tyler CR, Galloway TS (2014) Uptake and retention of microplastics by the shore crab Carcinus maenas. Environ Sci Technol 48(15):8823–8830. https://doi.org/10.1021/es501090e

Wu B, Wu X, Liu S, Wang Z, Chen L (2019) Size-dependent effects of polystyrene microplastics on cytotoxicity and efflux pump inhibition in human Caco-2 cells. Chemosphere 221:333–341. https://doi.org/10.1016/j.chemosphere.2019.01.056

Wu M, Tang W, Wu S, Liu H, Yang C (2021) Fate and effects of microplastics in wastewater treatment processes. Sci Total Environ 757:143902. https://doi.org/10.1016/j.scitotenv.2020.143902

Yahyanezhad N, Bardi MJ, Aminirad H (2021) An evaluation of microplastics fate in the wastewater treatment plants: frequency and removal of microplastics by microfiltration membrane. Water Pract Technol 16:782–792. https://doi.org/10.2166/wpt.2021.036

Yang L, Li K, Cui S, Kang Y, An L, Lei K (2019) Removal of microplastics in municipal sewage from China's largest water reclamation plant. Water Res 155:175–181. https://doi.org/10.1016/j.watres.2019.02.046

Yee MSL, Hii LW, Looi CK, Lim WM, Wong SF, Kok YY, Tan BK, Wong CY, Leong CO (2021) Impact of microplastics and nanoplastics on human health. Nanomaterials 11(2):496. https://doi.org/10.3390/nano11020496

Yu L, Zhang J, Liu Y, Chen L, Tao S, Liu W (2021) Distribution characteristics of microplastics in agricultural soils from the largest vegetable production base in China. Sci Total Environ 756:143860. https://doi.org/10.1016/j.scitotenv.2020.143860

Yukioka S, Tanaka S, Nabetani Y, Suzuki Y, Ushijima T, Fujii S, Takada H, Van Tran Q, Singh S (2020) Occurrence and characteristics of microplastics in surface road dust in Kusatsu (Japan), Da Nang (Vietnam), and Kathmandu (Nepal). Environ Pollut 256:113447. https://doi.org/10.1016/j.envpol.2019.113447

Zhang J, Wang L, Kannan K (2020a) Microplastics in house dust from 12 countries and associated human exposure. Environ Int 134:105314. https://doi.org/10.1016/j.envint.2019.105314

Zhang L, Xie Y, Liu J, Zhong S, Qian Y, Gao P (2020b) An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environ Sci Technol 54(7):4248–4255. https://doi.org/10.1021/acs.est.9b07905

Ziajahromi S, Neale PA, Rintoul L, Leusch FDL (2017) Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Res 112:93–99. https://doi.org/10.1016/j.watres.2017.01.042