



Effect of microplastics in water and aquatic systems

Merlin N Issac¹ · Balasubramanian Kandasubramanian²

Received: 9 June 2020 / Accepted: 22 February 2021 / Published online: 2 March 2021

© The Author(s), under exclusive licence to Springer-Verlag GmbH, DE part of Springer Nature 2021

Abstract

Surging dismissal of plastics into water resources results in the splintered debris generating microscopic particles called microplastics. The reduced size of microplastic makes it easier for intake by aquatic organisms resulting in amassing of noxious wastes, thereby disturbing their physiological functions. Microplastics are abundantly available and exhibit high propensity for interrelating with the ecosystem thereby disrupting the biogenic flora and fauna. About 71% of the earth surface is occupied by oceans, which holds 97% of the earth's water. The remaining 3% is present as water in ponds, streams, glaciers, ice caps, and as water vapor in the atmosphere. Microplastics can accumulate harmful pollutants from the surroundings thereby acting as transport vectors; and simultaneously can leach out chemicals (additives). Plastics in marine undergo splintering and shriveling to form micro/nanoparticles owing to the mechanical and photochemical processes accelerated by waves and sunlight, respectively. Microplastics differ in color and density, considering the type of polymers, and are generally classified according to their origins, i.e., primary and secondary. About 54.5% of microplastics floating in the ocean are polyethylene, and 16.5% are polypropylene, and the rest includes polyvinyl chloride, polystyrene, polyester, and polyamides. Polyethylene and polypropylene due to its lower density in comparison with marine water floats and affect the oceanic surfaces while materials having higher density sink affecting seafloor. The effects of plastic debris in the water and aquatic systems from various literature and on how COVID-19 has become a reason for microplastic pollution are reviewed in this paper.

Keywords Plastic debris · Microplastics · Marine system · Aquatic organisms

Introduction

Increased productivity and slow biotic decomposition of plastic led to its cumulation in the environment leading to adverse effects in aquatics. The plastics entering into the marine environment may remain for hundreds and thousands of years, during which they get fragmented due to the mechanical and photochemical processes resulting in the formation of microplastics (< 5 mm) or nanoplastics (< 1 µm) (Espinosa et al. 2016). Plastics are organic polymers emanating from petroleum that

includes polyethylene, polypropylene, polyvinylchloride, and polyester, out of which PE and PP are standard, holding first and second positions respectively in the global market, followed by PET (Leng et al. 2018) accounting for around 18% in global production, making it the third most manufactured plastic. Albeit not as prevalent as polyethylene and polypropylene, PET due to its safe nature, light weight, affordability, and low manufacturing cost is primarily used as packaging material. With its 1.37–1.45 g cm⁻³ density, PET sinks rapidly and is particularly accessible for benthic species (Weber et al. 2018). While PET show resistance to weathering, fragmentation mechanisms are not immune to it and abiotic weathering is likely to occur by photooxidation and hydrolysis in marine environments. The pH variance in ocean may possibly alter the chemical balance of microplastics by raising or lowering the rate of chemical leach from their surface, so PET, which is commonly understood to be safe, may become dangerous in the near future (Piccardo et al. 2020).

The leverage of tailoring of properties of polymers has led to their wide utilization in various household, and industrial applications (Inamdar et al. 2018; Gore and Kandasubramanian 2018a; Jayalakshmi et al. 2018, 2020; Kumar et al. 2020;

Responsible Editor: Philipp Gariguess

✉ Balasubramanian Kandasubramanian
meetkbs@gmail.com

¹ CIPET: Institute of Plastics Technology (IPT), HIL Colony, Edayar Road, Pathalam, Eloor, Udyogamandal P.O., Kochi, Kerala 683501, India

² Nano-Surface Texturing Laboratory, Department of Metallurgical and Materials Engineering, Defence Institute of Advanced Technology (DU), Ministry of Defence, Girinagar, Pune, Maharashtra 411025, India

Cherukattu Gopinathanicker et al. 2020). The production and apportioning of plastic debris in marine endure to upswing over time, thus escalating its accretion on oceanic surface and seabed (Sahetya et al. 2015; Sharma et al. 2016; Gupta et al. 2016; Gupta and Kandasubramanian 2017; Rastogi and Kandasubramanian 2020a; Kavitha and Kandasubramanian 2020). The average size of plastic in atmosphere appears to dwindle resulting a surge in profusion and allocation of microplastic flotsam and jetsam observed during recent decades. The presence of plastics in the aquatic environment dispenses with a crucial condition that adversely affects the socio-economic facets of tourism industry, shipping, trawling, and fish farming (Thushari and Senevirathna 2020). Floatable and incessant characteristics of microplastics make them prevalent in the aquatic environment as a marine contaminant, acting as a carrier for the transfer of pollutants (Rodrigues et al. 2019) to organisms present in water. The small size of microplastics results in their uptake by a wide range of aquatic species disturbing their physiological functions, which then go through the food web creating adverse health issues in humans (shown in Fig. 1). They are uptaken and mostly excreted rapidly by numerous marine species, and so conclusive proof on biomagnification is not obtained (Cozar et al. 2014). However, effects of MP uptakes result in reduced food intake, developmental disorders, and behavioral changes.

Almost 700 aquatic species in the world were adversely affected by the introduction of microplastics, including sea turtles, penguins, and other crustaceans (Mam et al. 2020). However, the predicament due to microplastic depreciates as most sufferers go unexplored over the vast oceans (Pabortsava and Lampitt 2020). Ingression of plastics into the ecosystem is mainly due to the erroneous human actions or unrestrained wastes from water or sewage treatment plants and textile industries (Ayalew et al. 2012; Nitesh Singh and Balasubramanian 2014; Gonte et al. 2014; Sharma and Balasubramanian 2015; Rastogi and Kandasubramanian

2020b; Rastogi et al. 2020). The terrestrial plastic accretion ultimately flows into the water systems due to inadequate landfill interment systems (Anbumani and Kakkar 2018).

Continuous massive production and dispersal of plastics into the marine ecosystem further aggravate the contamination of previously polluted medium (Thushari and Senevirathna 2020). Microplastics provide habitat for growing microorganisms, due to their size and varying effects (Yang et al. 2020). Microplastics can readily accrue and release hazardous organic pollutants like DDT, polybrominated diphenyl ethers, and other additives that incorporate during manufacture present in water, thereby elevating their concentration (Gonte and Balasubramanian 2012; Gore et al. 2017, 2018a,b, 2019a,b,c, 2020; Thakur and Kandasubramanian 2019; Rajhans et al. 2019; Campanale et al. 2020). As the particle size reduces, it reverberates in the elevation of potential harms of microplastics, but its adverse effects in marine organisms are not well defined (Law and Thompson 2014).

Additive-free microplastics are not chemically hazardous to aquatic organisms, but they create problems in physical conditions such as bowel obstructions (Udayakumar et al. 2021). Depending on the demand of products, certain additives are added to the virgin microplastics resulting in additional property of adsorption of pollutants present in water and thereby impersonate as vectors. Researches reveal the harmful threats plastic poses to human health at any point of the plastic lifecycle, from the extraction of fossil fuels to consumer use to disposal and furthermore (Gore et al. 2016; Gore and Kandasubramanian 2018b; Gharde and Kandasubramanian 2019; Issac and Kandasubramanian 2020). A summarised picture of recent impacts on human health is shown in Fig. 2. Since microplastics can adversely impact various organisms, so the risk of humans to get affected by microplastics cannot be overlooked. As humans are the ultimate consumers of sea

Fig 1 Microplastic pathway in organisms

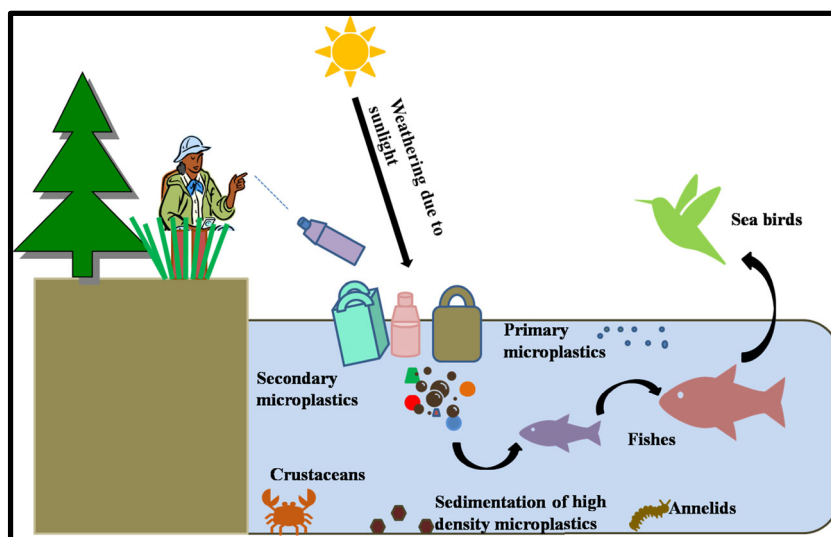
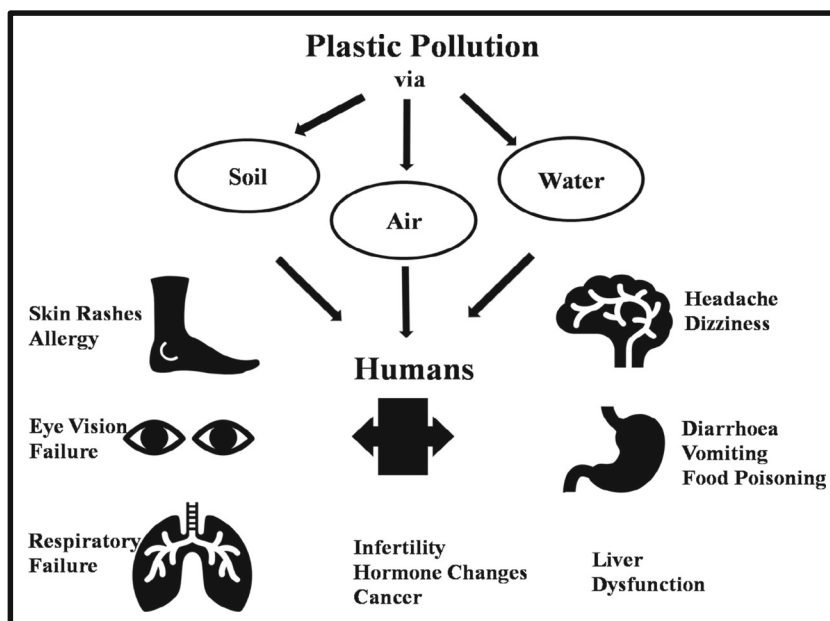


Fig 2 Pollution impacts on human



foods (Saha et al. 2021) which are highly affected by microplastics, there is a high chance of microplastic transfer to humans (Smith et al. 2018). Presence of microplastics in tap water (Tong et al. 2020), sea salt (Selvam et al. 2020), and bottled water (Mason et al. 2018) are proven studies on how many ways they can reach the human body. Recent studies of microplastics in human stool (Zhang et al. 2021) and placenta (Ragusa et al. 2021) are examples of its presence in humans. If plastics can harm humans so badly, then what happens when we consume such minute particles which are even more dangerous still needs to be studied.

This paper discusses one of the increasing concerns of the present world, i.e., Microplastics. Plastic debris with varying sizes consisting of macro, meso, micro, and nano that are plenty in numbers get transported all over the oceans with waves and winds and found floating on the surface. The floating microplastics mistook as food get ingested, resulting in massive impacts on the health of aquatic organisms. Critical issues faced in plastic pollution depend on the nature of the debris and the pathways they follow to reach the marine ecosystem. Waste dismissal from treatment plants, overrun of sewerages during heavy rains, biosolid runoff from agricultural fields were the methods by which aquatic systems get contaminated by microplastics. Due to the challenges in identification and sorting, studies on microplastics are limited. This review describes the source, distribution, plastics in microplastics, effects of microplastics in marine water and fresh water systems, impact of COVID-19 in microplastic pollution, and the extent to which they affect the aquatic organisms thereby aiming to raise consciousness about the adverse effects of microplastics.

Microplastics—a boon or bane

Potentially harmful and obnoxious contamination caused by plastics has been troubling people for centuries. Nevertheless, a lot of research is being conducted over the past few decades on less visible plastic debris of size less than 5 mm, i.e., microplastics (Weis 2020). Microplastics are synthetic solid particles or polymer matrixes, of regular or irregular form with size range 1 μm –5 mm, of primary or secondary origin, insoluble in water (Frias and Nash 2019). Microplastics can be seen in the form of fiber, film, foam, sphere, and pellet (Cowger et al. 2020). Thompson et al. in 2004 described the accretion of micro-sized particles ranging in size 20 μm in aquatic systems as microplastics.

The origin of microplastics comes from two main sources: one is primary, developed to be smaller in size like nurdles or powders, and the other is secondary, resulting from the fragmentation of larger particles (Thompson 2015). The dwindling size of microplastics makes them bioavailable throughout the food chain. Particles of different sizes assuredly have varying effects, i.e., finer particles have intrinsically different implications from large particles, as the particles amass in the tissue themselves and cause physical processes to disrupt (Campanale et al. 2020). Floatable and incessant properties of microplastics make them widely dispersed in the aquatic environment as a marine contaminant via ocean currents (Lusher 2015), acting as a carrier for the transfer of pollutants to organisms present in water. Microplastics are prevalent in aquatic environments covering poles to the equator, from the surface to the deepness of sea (Thompson 2015).

Several researchers studied impact of MPs on various marine organisms such as mussels (Paul-Pont et al. 2016;

Gandara e Silva et al. 2016; Wang et al. 2020b), oysters (Green 2016; Gardon et al. 2018), copepods (Jeong et al. 2017; Choi et al. 2020), and so on and continued unabated (Seltenrich 2015). The deleterious effects of microplastics are even passed on to high tropic levels (Avio et al. 2017) indirectly through consumption of microplastic injected organisms.

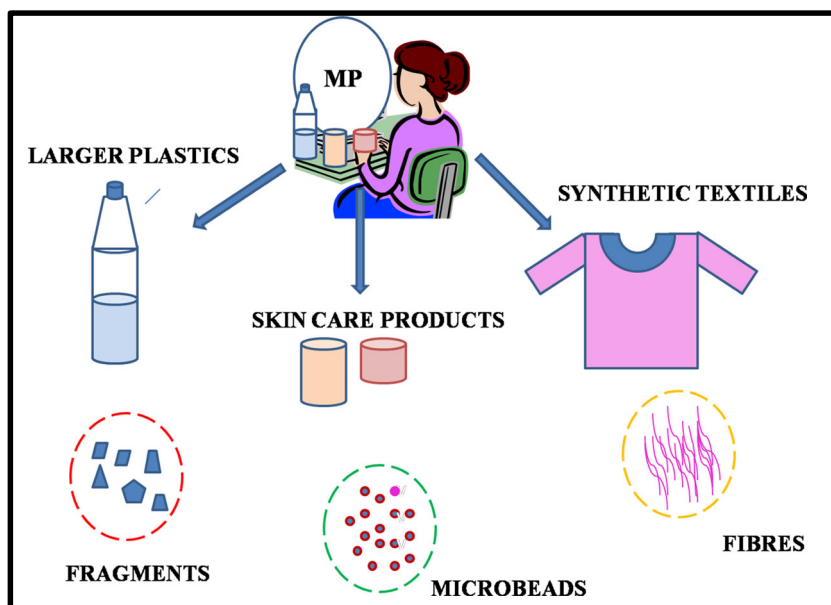
During wastewater treatments, the reduced size of microplastics results in their infiltration and direct release into the water resources. Microplastics, in general, are considered resilient to biotic degradation. Certain materials are subject to biotic degradation through fungi and bacteria and are imbibed or passively adsorbed by consumers at successive trophic levels after degradation, resulting in blockage of the gastrointestinal system (A. Glaser 2019). Microplastic is identified in species at all phases of marine food chain (Setälä et al. 2018). The sum of MPs consumed differs around organisms and location, and also can vary substantially even in the same region. Aquatic organisms are well known to swallow microplastics along with their food, showing clear signs of several animals that consume microplastics due to the size similarity with their food (Desforges et al. 2015; Walkinshaw et al. 2020). Study results imply that nearly all aquatic organisms ingest microplastics, showing a considerable variation in the volume of ingestion among various species. Foreseeably, there are three forms of deleterious effects connected to absorption of microplastics: (1) physiological effects attributed to ingestion (Davidson and Dudas 2016; Pedersen et al. 2020). The greater the number of MPs intake, the more likely it is to have a risk on the consumed species, such as reduced development and variance in feed habits (Horton et al. 2018). (2) Deadly reactions from the discharge of hazardous substances—additives such as plasticizer, antioxidant, flame retardant, pigments, etc. incorporated during the manufacture of plastic may be leached into body tissues, resulting in induced changes or bioaccumulation. The toxicity can also differ according to the ratio of additives needed for each plastic (Botterell et al. 2019). (3) Noxious reaction to pollutants absorbed involuntarily by microplastics—large surface area due to weathering, longer exposure periods and hydrophobic nature promote the sorption of pollutants to microplastic surface at a higher concentration thus making it as a carrier for contaminants to enter into the aquatic species. Polycyclic aromatic hydrocarbons, PCB, DDT, organo halogenated pesticides, hexachlorocyclohexanes, and chlorinated benzenes are some of the common contaminants present on microplastics (O'Donovan et al. 2018). POPs like PBDE, PCB, and some other chemicals have found to imitate natural hormones, causing disorder in reproduction. The dynamics of the absorption of persistent organic pollutants into plastic material depend, of course, on the properties of both the particular polymer and the specific contaminant (da Costa et al. 2017). Humans get subjected to microplastics through

cosmetics, eating habits, dust particles, and usage of plastic products. The proportion of microplastic in the marine ecosystem keeps increasing with the steady boosts in plastic production and thereby showing detrimental effects (Willis et al. 2017).

Sundry types of microplastics

Microplastic particulates vary with dimension, color, composition, density, and are categorized into different types (shown in Fig. 3). Plastic particulates with size range greater than 25 mm, between 5 to 25 mm, 1 to 5 mm, and 1 nm to 1 µm were defined as macro, meso, micro, and nano, respectively (Lee et al. 2015; Gigault et al. 2018). Concerning their source and usage, microplastics are categorized as primary and secondary. Primary microplastics are generated microscopically and are present in products for personal care like toothpaste, scrubbers, and other cosmetics (Duis and Coors 2016; Auta et al. 2017). This kind of microplastic skincare product (Napper et al. 2015) supersedes many naturally used cosmetics containing oatmeal, walnuts, or almonds. Tiny plastic particles, usually about 0.25 mm size, are extensively used in beauty products and industrial abrasive shot-blasting agents. Particles of microplastic dimensions such as granules and powders are explicitly used in a wide range of applications (Sharma and Chatterjee 2017; Ng et al. 2018). The MPs show varying sizes, i.e., different sized granules in the same product. Gregory studied the size variations of microplastics, and in 1996, he reported that in a similar cosmetic, PE and PP granules of size less than 5 mm and PS spheres of size less than 2 mm were present (Gregory 1996). Discharge of primary microplastics from households factories and sewerage occurs directly into the environment. Microplastics beads from skincare products would be transported via the sewage system with wastewater (Kalčíková et al. 2017) and are not effectively eliminated through sewerages and thus accumulate in the ecosystem. Synthetic clothes containing microplastics as fibers release an average of about 700,000 fibers from 6 kg of clothes in a single wash (Napper and Thompson 2016). Pellets used in industrial applications as a feedstock for plastic products are also a source of microplastic entering into the environment (LI et al. 2016). In medical fields, microplastics used in dental and pharmaceutical carriers get into the environment through wastewaters. The reduced size and lower perceptibility of primary microplastics make it challenging to be removed from the aqueous systems (Auta et al. 2017). Apart from the unswerving discharge of primary microplastics, the debris of larger plastics under the influence of UV and heat can slowly become fragile and then fragmented to smaller particles with the help of mechanical forces like winds and ocean currents (Thompson 2015).

Fig 3 Microplastic forms



The majority of microplastics formed in the aquatic environments are due to the breaking up of larger plastics that results in secondary microplastics (Waller et al. 2017). Fragmentation of larger plastics depends on the temperature and amount of UV radiations (LI et al. 2016). Besides the fragmentation occurring in the atmosphere, several materials get splintered while in use leading to the formation of microsized particles into the atmosphere as in the case of fibers released from cloths during wash (De Falco et al. 2019). Secondary microplastics are created because of incremental deterioration or disintegration by ultraviolet light, wave abrasion, or microbial degradation of large plastics that are already in the atmosphere. Environmental microplastics deteriorate to generate nanoplastics 100 nm, which have virtually unknown plights and toxic properties in comparison with other plastic debris (Koelmans 2015).

Intense weathering and other mechanical actions results in splintering of plastics, thereby escalating secondary microplastics in the aquatic systems than the primary microplastics. Based on shape, microplastics subdivided into filaments, microbeads, nurdles, foams, and fragments. Biopolymers (Haider et al. 2019) present in addition to the synthetic microplastics are of less concern due to their less hydrophobicity, and biodegradability forming carbon dioxide and water.

Microplastics: provenance and distribution

Ingress of microplastics into the aquatic systems occurs through disparate sources and pursue multiple pathways (Browne 2015; Browne et al. 2008). The sources relate to the manufacturing of plastic products (Fadare et al. 2020),

water (Sighicelli et al. 2018; Luo et al. 2019) and sewage treatment plants (Ziajahromi et al. 2016), industrial or agricultural wastes (Deng et al. 2020; Wang et al. 2020a), weathering of plastics (Eo et al. 2018), fisheries, or aquaculture (Zhang et al. 2017; Xue et al. 2020; Zhang et al. 2020b) that may enter into the marine system affecting the aquatics (Harmon 2018; de Sá et al. 2018; Xu et al. 2020). Table 1 shows the microplastic abundance, types, and source of various locations

Plastic wastes from households, industries, etc. act as a source that may enter into the marine system directly or by other water bodies, thereby raising its amount and affecting the life of aquatics (Nizzetto et al. 2016) (shown in Fig. 4).

In agriculture, microcapsule fertilizers primarily favored to avoid nitrate leaching to groundwater are a primary source of MP contamination in the marine ecosystem that flows out to oceans through paddy field channels, denoting a high volume of MP flow during irrigation than the non-irrigation season. Scratches and discoloration displaced on the top surface of microcapsules during the paddy runoff process imply the emission of secondary microplastics (Katsumi et al. 2020).

A study conducted by the government of UK in 2020 concluded that microplastics shed from vehicle tyres are now among the other major contributors of microplastic pollutions in the sea. Tyre is a blend of elastomer, carbon black, fiber, as well as other organic and inorganic materials that enhance its stability (Evangelidou et al. 2020). The major portion of tyre particles directly reach the sea through air or other waterways (Chen et al. 2020).

Fishing, fish hatcheries, and offshore drilling (Barboza et al. 2018) are all plastic sources that enter the aquatic systems directly and pose a threat to biota as secondary microplastics following a long-term deterioration. Inadequacy in the management of waste imparted the

Table 1 Study on abundance, types, and source of microplastics from various locations

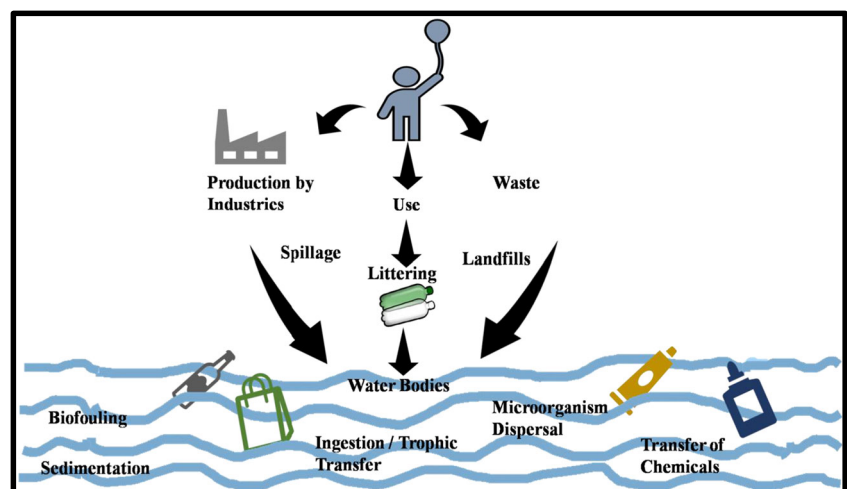
Location	Samples collected	MP abundance	MP type	Source	Reference
Dongting Lake (China)	15 each (surface water and sediment)	Surface water: 0.62–4.31 items/m ² Sediment : 21–52 items/100 g dw	50–91% fibres, 5.67–33.33% beads, 2.63–20.00% fragments	Man-made and surrounding rivers	Hu et al. 2020
Kuwait coastal areas	44 (beach sediments)	37 (number)	PP PE PS	Storm sewer and Seaport	Saeed et al. 2020
Northern Tyrrhenian sea (Italy)	58 sediments	1.70 ± 0.93 particles kg ⁻¹	73.8% filaments, 17.2% fragments, 9.0% films	Marine and domestic based	Mistri et al. 2020
Salina Island (Italy)	60 sediments and 5 species	Sediments: 49.0 ± 1.4 items/kg (landslides), 153.5 ± 41.7 items/kg (cliff), 106.0 ± 104.7 items/kg (banks) Holothurian species: 1.3 ± 0.9 items/animal (landslides), 3.8 ± 0.7 items/animal (cliff), 2.47 ± 0.3 items/animal (banks)	Sediments : PVC, PET, PE, PS, PA, PP Holothurian species: PET, PA	Landslides, cliffs and banks	Renzi et al. 2020
Ganges river (India)	120 water samples	71.6% (pre-monsoon), 61.6% (post-monsoon)	91% fiber, 9% fragments	Domestic	Napper et al. 2021

microplastic pollution in freshwater ecosystems (Free et al. 2014). The limited size and low densities of microplastics make them dispersed by winds and waves and are thus ubiquitous (Shahul Hamid et al. 2018). Plastic debris drifted along with wastewaters are not successfully eliminated by treatment plants, and so gets cumulated in the atmosphere (Li et al. 2018; Akarsu et al. 2020; Naji et al. 2021). Source of microplastic ingestion can also occur in an indirect manner in which the organisms that accidentally feed on microplastics are fed directly by the higher organisms in the food web.

Apart from physiochemical processes, the nature and entry point of the source also persuade the microplastic allocation in the water resources. Source recognition is a salient feature to

achieve an accurate appraisal of quantity of microplastics that enter into the marine surface and also to introduce viable handling measures. The probable impacts of microplastics can be accessed from its allocation all through the aquatic system. The impact of pollutants is less in place of fewer microplastics and high in a place where the microplastics get cumulated. So to lessen the impending risks, it is indispensable to understand the allocation of microplastics.

The distribution and transportation of microplastics guided intricately by a multitude of factors, such as weathering and fragmenting, biofouling, tides, and strong currents. Microplastics allocate between the floor of the ocean, column of water, seabed, coastline, and in ecology with different

Fig 4 Microplastic distribution


biological, physical, and chemical mechanisms occurring on microplastics at each compartment (Katija et al. 2017; Choy et al. 2019). Due to a lack of information of compartments, the implications and possibilities for diminution are unclear.

Role of plastics in the fate of microplastics

Microplastics consist of a complex array of polymers with repeated monomers that constitute the polymer's backbone. The fundamental distinction between polymer is this backbone structure that specifies the physicochemical properties of a plastic (Rochman et al. 2019). Plastics are classified into two thermoplastic and thermosetting plastic. Thermoplastic can melt on heating and solidifies on cooling. PE, PP, PS, PET, ABS, PC, PA, etc. all belongs to thermoplastics. Thermosets are those which remain in permanent solid state after being cured once and they include polyurethane, urea formaldehyde, vinyl ester, etc. MP, thus, not only consists of a single polymer, but originates from a diverse group of substances that are chemically specific (Rochman et al. 2019).

Bioavailability is the percentage of overall amount of particles available for absorption by an organism found in the environment (Vallero 2016). The bioavailability of microplastics can be influenced by a variety of factors of which the abundance and properties of plastic is an important one. With further decay and fragmentation of plastic particles, the availability of microplastic that becomes biologically available to species will rise with time (Botterell et al. 2019). However, microplastics are prone to alter density and buoyancy regularly due to biofouling and ingestion, thereby being bioavailable to species at various levels throughout the water column. Higher density plastics are biologically available to benthic species whereas lower density plastics are mainly bioavailable to pelagic species. The microplastic composition is therefore an essential characteristic (de Sá et al. 2018).

Plastic composition refers to type of polymer, which in turn defines the density of debris. Plastics with low density, such as PP and PE, create debris that are less denser than water and is thus likely to stay floating, whereas PET, PS, and cellulose acetate contain plastics which are denser than water and hence appear to settle (Driedger et al. 2015) with respect to their rise and sink velocity.

The velocity of rise and sink (w_r) (Mountford and Morales Maqueda 2019) is calculated (Eq. 1) by

$$w_r = \frac{|\rho_w - \rho_p|}{\rho_w - \rho_p} \sqrt{\frac{|\rho_w - \rho_p| g L}{\rho_p}} \quad (1)$$

ρ_p is the plastic density, ρ_w is the density of oceanwater, g is the acceleration due to gravity, and L is the frictional length (10–6 m).

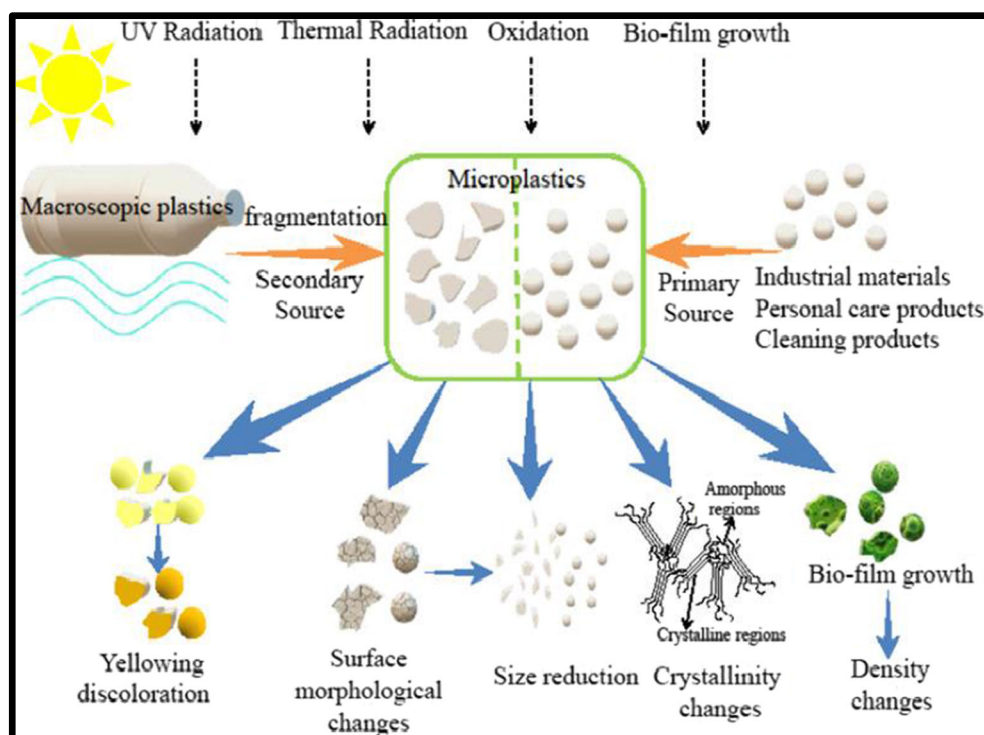
For positively buoyant plastics, often hovering on the water surface will only be temporary until they are continuously fouled and end up in the benthic zone. Diminution in surface fouling on sinking plastics due to grazing can temporarily refloat them, resulting in cyclic floating and sinking until they eventually settle in the depth of oceans (Alimi et al. 2021). Plastics with positive buoyancy are distributed within the top 100 to 150 m of the ocean surface, whereas neutral buoyant plastics are found above 3500 m from the depths (Mountford and Morales Maqueda 2019). High-density polymers, bio fouled materials, polymers with fillers, composites, all have a tendency to settle. Biofouling occurring due to the aggregation of microorganisms or algae will raise microplastic density and contribute to settling into pelagic or benthic regions. Plastics are protected from UV light when accumulated at the bottom of ocean, thus greatly delaying the deterioration process (Corcoran 2015). Different polyethylene grades range in density, strength, crystallinity, and weatherability, with particular uses for each grade, such as LLDPE and LDPE for plastic bags and HDPE for jugs. The properties of the polymers that constitute them, however, decide their existence, fate, degradation, and their tendency to sorb/release persistent organic pollutants (Andrady 2017).

Semi crystalline polymers (Guo and Wang 2019) are distinguished by their higher strength and resistance to fatigue, whereas amorphous polymer exhibits low strength and poor resistance to fatigue (Sysel 2016). Plastics such as PE, PP, and PET have a semi-crystalline structure that typically makes the material tough, but at high degrees of crystallinity it can be made brittle thus contributing to the ease of cracking and fracturing during weathering. Higher crystallinity ratios contribute to higher density of microplastics resulting in negative buoyancy, therefore crystallinity is an important factor that determines position in column of water and type of aquatic species it deals with (Andrady 2017). Characteristic properties, including crystallinity and density of MP, are not intrinsic features, and can be readily modified by the weathering or aging processes (Guo and Wang 2019).

As a result of oxidation, discoloration occurs in PE, PP, PS, PET, PC, and PVC turning it from yellow to yellow orange which is usually attributed to the accumulation of degradation products or the stabilizers used during production (Gautam et al. 2020; Sharma et al. 2021). In PVC, photodegradation entails loss of HCl forming yellow-colored conjugate unsaturation. MP photodegradation is significantly delayed in oceans, due to low concentration of oxygen and temperature. In fact, MP in the ocean surface is more efficient in surface fouling than that present on land, which can keep them safe from ultraviolet rays thereby resulting in slower discoloration (Guo and Wang 2019). Figure 5 shows changes in characteristic properties of microplastic as a result of degradation.

The negative impacts on microplastic-exposed species can be grouped into 2 types—physical and chemical effects.

Fig. 5 Degradation of microplastic. Reprinted with permission from ref. (Guo and Wang 2019). Copyright 2019, ELSEVIER



Physical refers to microplastic shape, size, and concentration, whereas chemical relates to its associated harmful chemicals (Campanale et al. 2020). The sorption rates for hydrophobic contaminants by microplastics varies with its shape and type of polymer (Tourinho et al. 2019). Microplastics are often present as part of a combination or a complex collection of chemicals thereby showing that it can accumulate organic chemicals and trace metals from its surroundings. Additives or raw materials obtained from plastics and chemicals from the surrounding medium are the main chemicals contained in MP (Campanale et al. 2020). Owing to their elevated surface area to charge ratio, MPs adsorb persistent organic pollutant and other inorganic contaminants. Intake of MPs by marine animals results in higher toxicity due to the aggregation of organic hydrophobic compounds (Sunday 2020). Polymer's physical and chemical property such as diffusivity, surface area, crystalline, and hydrophobic nature determines the quantity and type of chemicals to be accumulated by the plastic (Rochman et al. 2019). Polyethylene and polypropylene rubbery polymers are supposed to diffuse more chemicals than the PET, PVC glass polymers. PE often displays a higher affinity for toxins than other plastics (Robeson et al. 2015). In exception, PS glass polymer (Hüffer and Hofmann 2016) shows a higher sorption rate due to the existence of benzene ring that enables the addition of chemicals onto the polymer thus showing the relation between sorption and chemistry of plastic (Alimi et al. 2018).

MP when consumed by aquatic species, gets bioaccumulated, thereby displaying particle or chemical

toxicity and mixture effects contributing to disturbance in their metabolism, feed patterns, development, and reproduction with differing degrees of toxicological risks for each species (Sunday 2020). For example, polystyrene concentration resulted in diminished chlorophyll concentration in algae (Hazeem et al. 2020), whereas *Daphnia magna* displayed impairment in reproductive cycles (Aljaibachi and Callaghan 2018).

Effects of microplastics in various organisms

Cumulating concentration of pollutants at trophic levels results in the effectual transmission of noxious substances in the food chain. The retention of plastic debris might occur inside the organisms resulting in chemical leakages if any additives (shown in Table 2) present, thus creating cumulation leading to detrimental effects (Setälä et al. 2014). Microplastics found in marine systems worldwide influence the feeding, growth, spawning, and existence of organisms in the aquatics. However, the extent to which the microplastics affect by transferring of chemicals present in and on the surface of MP to the higher complex food chains is not known (Granek et al. 2020). Only limited information (Furtado et al. 2016) is available on trophic transfer so whether the pollutants are ejected or get bioaccumulated in higher trophic levels are still need to be studied. Diminution in the feeding of aquatic organisms is the collective effect found during microplastic injections; other challenges include effects on growth and

Table 2 Additives present in microplastics

Additives	Properties	Effects	Reference
UV Stabilizers/absorbers	Prevents photodegradation	Mutagenic, toxic, bioaccumulated and show estrogenic activity	Hammer et al. 2012
Antioxidants	Delay oxidation, prevents aging	Estrogenic effects	Hermabessiere et al. 2017
Plasticizers	Renders the material pliable	Renal, reproductive, cardio, and neuro-toxicity	Rowdhwai and Chen 2018
Flame retardants	Diminish flammability	Endocrine disruptors	Fred-Ahmadu et al. 2020
Pigments	Colour	Duplication of food resulting gut blockage	Hammer et al. 2012
Surfactants	Modification of surface properties	Destroy mucus layer, damage gills	Rani et al. 2015

proliferation. The chronic effects of MPs can be pass on to successive level throughout the food chain, negatively affecting the organisms. The effects of microplastics vary with the organism species and microplastic type and concentrations.

Sussarellu et al. (2016), in their studies, showed the adverse impact of polystyrene microplastics on reproduction and feeding of oysters due to amendation in their food intake and energy distribution. On exposure to micro-sized polystyrene, oyster showed a reduction in number of eggs produced, ovocyte quality, and sperm motility. Fertilization in oysters occurs externally in the sea where the eggs and sperms are released, but due to the intake of micro polystyrene, fertilization is affected by reduced sperm speed and its fewer amount (Sussarellu et al. 2016). In its feces, a 6- μ m micro polystyrene ingested by oyster was found, with no cumulation in the gut suggesting a large polystyrene ejection. The yield and growth of offsprings of microplastic exposed oysters dropped by 41% and 18%, respectively. The study stipulated information on the hostile effects of micro-sized PS on development and reproduction of oysters with considerable impacts on progeny. Apportioning of energy from reproduction to growth with the abatement in fertilization success is the result of exposure studies of polystyrene (Galloway and Lewis 2016).

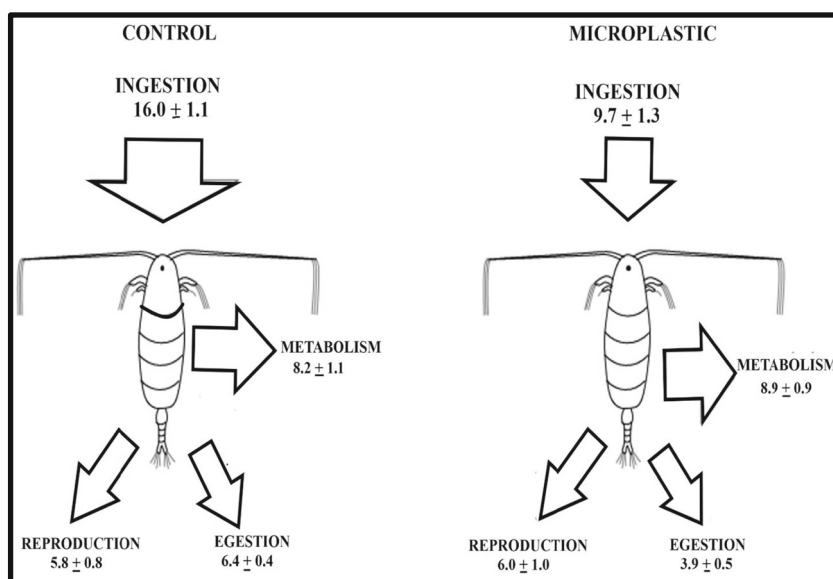
In 2019, Bessa et al. studied the contagion in the aquatic ecosystem of Antarctic by assessing the presence of microplastics in gentoo penguins. In Antarctic regions, water contained microplastics, but the idea about its ingestion and entry through the food chain has not been studied in depth. Seabirds identified as biological markers of changes occurring in the environment also contemplated as indicators of environmental plastic pollution. The limited motion of gentoo penguins outside their vicinity makes them a standard indicator for the tracking of plastic particles in Antarctic marine systems. The occurrence, identification, and characterization of microplastics analyzed from the scats of gentoo penguins. Penguin scats from two different islands were collected, which

contained 58% of microfibers, 26% fragments, and 16% of films. The entry of microplastics into the gastrointestinal tract of penguins are either directly due to misconception of plastics as food or feeding on contaminated prey or through polluted waters. The plastics debris gets cumulated in the guts of penguins preventing it from the consumption of food and also results in the absorption of toxic substances from water, thus affecting their growth and development (Bessa et al. 2019).

Cole et al. (2015) showed how ingestion of MPs affected the feed habit, fertility, and functioning of zooplanktons like copepods (shown in Fig. 6). The studies conducted on *Calanus helgolandicus* copepod mostly found in the Atlantic, a vital species acting as prey for larvae of many fishes due to their supersize, substantial amount of lipids and opulence. Ingestion of microplastics by copepod shows significant impacts on feeding, hatching, and their health. Copepod exposed to polystyrene microbeads of 20 μ m resulted in a 40% reduction in the carbon biomass with a deficiency in their energy, showing the rapid consumption of lipids, thereby affecting their growth. The energy deficiencies also result in the death of copepods. Microplastic long-term exposure leads to small-sized eggs with reduced hatchings (Cole et al. 2015).

Zocchi and Sommaruga (2019) studied how the toxicity of glyphosate, a herbicide, varies with the incorporation of microplastics. The tests were conducted on *Daphnia Magna* as it is both microplastic and glyphosate sensitive. *Daphnia Magna* crustaceans are food for many aquatic organisms and feed themselves with small particles present in the water. Three glyphosate formulations like glyphosate-monoisopropylamine salt, glyphosate acid, roundup gran, and two different microplastics consisting of beads and fibers were used. Without the incorporation of microplastics, the fatality rate was high for glyphosate-monoisopropylamine salt 23.3%, but when microplastics were incorporated, a modification in the toxicity observed with the highest mortality rate

Fig. 6 Effects of copepod in the controlled and microplastic medium. Reprinted with permission from Ref (Cole et al. 2015). Copyright; 2015. ACS



for glyphosate acid. With polyethylene beads, glyphosate acid showed the toxicity of 53.3%, and with polyamide fibers, it showed 30%. So modification on noxious effects of contaminants is observed on combining with microplastics besides the pessimistic effects of microplastics alone. *Daphnia Magna* shows high fatality when ingested with microplastics (Zocchi and Sommaruga 2019).

Mussels, when subjected to microplastics, results in their grip loss due to a reduction in thread production that helps them to stick. Mussels adhere together, forming reefs for their shelter and breeding, thereby playing an imperative role in aquatic systems (Green et al. 2019). Berglund et al. studied the microplastic effects on mussels in 2019. An elevation in the number of microplastics observed with an increase in the mussel size. Large-sized mussel absorbs large amounts of water while storing higher quantities of fibers. The size-related filter function is less evident for plastic debris. The sum of fibers was higher than the number of plastics, and that may be due to the lower concentration or size of plastics. Elevation in the concentration of microplastics leads to fecal impaction or malnutrition in mussels. Furthermore, the ability to attract pollutants is high for plastics that would result in the emission of noxious substances into the mussels (Berglund et al. 2019).

The presence of microplastics and fibres were found in the demersal shark species of United Kingdom for the first time (Parton et al. 2020). The major intake route of MP by sharks can be through its foods, which are mostly crustaceans and molluscs, or through direct feeding (Germanov et al. 2019). Owing to the small particle size detected by the researchers, there is a chance of immediate excretion but however the presence of chemicals bound to the fibres can have repercussions on their reproductive cycle and immune systems (Parton et al. 2020).

A work by Besseling et al. in 2017 reported on how the microplastic consumption increases susceptibility of marine worms to chemicals (PCB). *Arenicola marina* when exposed to polyethylene for 28 days showed reduced feeding and growth, high mortality rate, and bioaccumulation (Besseling et al. 2017). Table 3 shows microplastic effects on different species along with the polymer type, microplastic size, number of specimens used, and its experimental conditions.

The presence of microplastics detected at all stages in the food web affecting the gastrointestinal tracts and tissues, which varies with the genus and emplacement. Organisms present in the marine ecosystem mistook microplastics as their food due to their similar size. Studies imply that all marine organisms intake microplastics, but the amount of their ingestion may vary with the type of species. It is important to monitor the excessive use of plastic additives and to enact laws and standards to control plastic litter sources due to the resulting danger of MPs to marine biota. Figure 7 depicts adequate primary methods adapted to reduce pollution.

Current studies on microplastic pollution

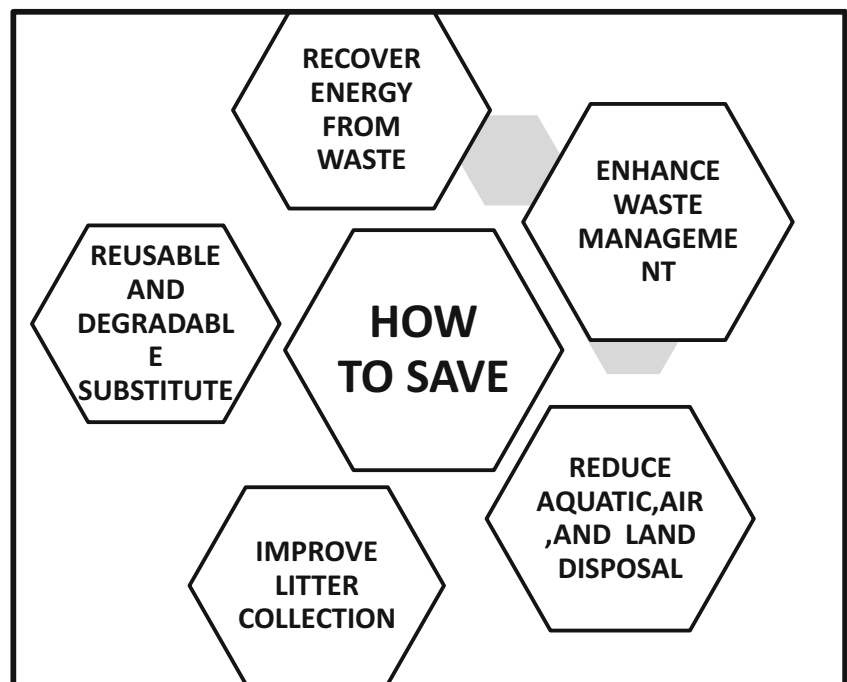
Microplastics have been found in the air we breathe (Enyoh et al. 2019), in the food we consume (Eerkes-Medrano et al. 2019; Zhang et al. 2020c, b), or in the soil where our crops grow (Corradini et al. 2019). They were discovered on peak of Everest (Napper et al. 2020) and at the depths of the deep ocean (Zhang et al. 2020a; Courtene-Jones et al. 2020). In humans, existence of microplastics in human stool (Schwabl et al. 2019) and for the first time MP fragments in human placenta (Ragusa et al. 2021) were confirmed.

Table 3 Study of microplastic impacts on various aquatic species

Name	Polymer	Microplastic size	Number of test species	Experiment conditions	Impact	Reference
Nematode (Caenorhabditis elegans)	PS	1 μm	40	72 h, 0.45 NaOH, 2% HClO	Intestinal injury, oxidative stress	Yu et al. 2020
Zebra fish (Dania rerio)	PA PE PP PVC	70 μm	48	23 \pm 1 $^{\circ}\text{C}$ 12 h photoperiod	Intestinal damage	Lei et al. 2018
Ascidian ciona intestinalis	PS	1 μm	30	18 \pm 1 $^{\circ}\text{C}$ 8 days	Growth, food uptake	Messinetti et al. 2019
Sardinella gibbose (Fish)	PET PA	1 μm	25	Oscillation incubator at 65 $^{\circ}\text{C}$ at 80 rpm, 24 h, 1.2 g/mL NaCl	Feed habit, body weight	Hossain et al. 2019
Emys orbicularis (pond turtle)	PE	500–1000 mg kg^{-1}	36	1 month, 22 \pm 2 $^{\circ}\text{C}$, photoperiod-14 light and 10 dark	Liver and kidney	Banaee et al. 2020
Crepidula onyx (Mollusca)	PS	2 μm	1000 larvae	22 \pm 0.5 $^{\circ}\text{C}$, 12:12 light/dark cycle	Growth	Lo and Chan 2018

Even the most isolated and pristine areas of the earth have been invaded by plastic particles. A recent study (Ross et al. 2021) found that the Arctic is rampantly contaminated by MP fibers that would possibly come from the laundering of clothes. Because of the increase in textile manufacturing and the lack of microfiber deterioration, aggregation of microfibers will become more extreme (Liu et al. 2021). In 96 out of 97 samples collected from around the arctic ocean, the most detailed analysis to date has detected microplastics. Fibers accounted for more than 92% of the MP and 73% of that were found

to be polyester having the same size and color as those found in garments (Ross et al. 2021). The reduced microfiber density (Brahney et al. 2020) can make them more transportable over a long range by water and wind (Liu et al. 2021) and their high surface to volume ratio can bind more noxious contaminants, potentially making them more dangerous to the aquatic species than other forms of microplastics (Liu et al. 2019). A large proportion of microfiber can slip out of treatment plants owing to their limited size and get discharged into marine habitats (Napper and Thompson 2016).

Fig 7 Strategies to reduce plastic pollution

Glass reinforced plastics primarily used in boat manufacturing due to their non-corrosive properties are a new emerging pollutant whose breakdown results in the release of microplastic and fiberglass. Powdered GRP, when exposed to blue mussel, revealed the presence of MP in the mantle cavity and inflammation in the gills, while in daphnia magna it culminated in the formation of clumps of smaller polymer materials in their appendages, resulting in an increase in its average weight, allowing it to sink, impacting its swimming pattern (Ciocan et al. 2020).

Countless numbers of marine organisms are at risk of swallowing or getting entangled in an enormous amount of plastic waste dumped in the water, and what attracts species to interact with plastic in the oceans is still a confounding aspect. One of the speculating factor might be the way plastic resembles food such as plastic bags are mistaken for jelly fish. A study on sea turtles reveals that aquatic species are not only drawn to plastic waste by how it appears, but also by how it smells. Plastic debris get covered with algae and other micro-organism after several days in the oceans that they start to scent like food. Sea turtles react to airborne olfactory receptors originating from bio-fouled plastics in the similar manner they react to food odors (Pfaller et al. 2020), so the places where plastic wastes are concentrated can act as olfactory traps (Savoca 2018) that can drive the attention of other species and can be harmful.

Eurythenes plasticus, a new amphipod crustaceans occurring in marine habitats, was named after the plastic waste found in its hindgut by researchers. The particle found was about 649.648 μm long and was 83.74% similar to PET, a common polymer used in bottles, food packaging, and textile fabrics was found in the guts of the species. The shrimp-like creature, about two inches long, was found 20,000 ft underwater in the Pacific Ocean (WESTON et al. 2020) reveals that even creatures from undiscovered habitat are already polluted with plastics as they are feeding on MPs throughout their lifespan, which may have acute and permanent health consequences. Although the ecotoxicological effects of microplastic toxicity on deep-sea amphipods have yet to be studied, it is quite possible that the other undiscovered species living in the depths of pacific ocean are equally vulnerable to the ingestion of microplastic fibres (Peng et al. 2020). The settling of MP on its own to the bottom of the oceans may take several years, as in the case of spherical MP, it may take around 15 years and for fibers it may take about 6 and 8 months (Chubarenko et al. 2016). The development of ecocorona by macromolecule or other microorganism on the MP surface can change its size, hydrophobic nature, and chemical behavior and can act as a potential method for MPs to enter seabed (Galloway et al. 2017). The biofouled particles seem to be absorbed faster but slowly excreted when reaching the seabed, resulting in their accumulation on the tissue of species that cause malnutrition or impaired growth (Michels et al. 2018).

The Norway Nephrops norvegicus lobsters are deep sea scavengers (Andrades et al. 2019) that inhabits in European climatic conditions and are a strong bioindicator (Cau et al. 2019) of MP pollution. Analysis performed by Italian scientists in 2020 (Cau et al. 2020) found that crustaceans can modulate the deterioration of microplastics into tiny particles in which their stomach can essentially serve as a grinding mill that grinds the plastic particles into even smaller ones thus affecting the lower trophic levels of food chain. In the study, 85% of the examined specimens showed higher amount of microplastics in the intestine than in the stomach with length of 0.23 ± 0.16 and 1 ± 0.16 mm, respectively, indicating that a considerable proportion of absorbed microplastics leaving the stomach are broken by gastric mills, preceded by filtering systems that discourage larger particles from accessing the intestine. These results demonstrate the presence of a new form of “secondary” microplastic releasing into the marine environment by the lobsters (Cau et al. 2020). However, earlier studies (Welden and Cowie 2016) have already shown that continuous fed on plastics by lobsters results in higher mortality rate or affects their growth and reproduction.

Clustered mussels serve as barriers to microplastic waste poured into the ocean by delaying the ocean water that flows over it, leading to the tripling of the amount of plastic taken up by the filter feeders (Lim et al. 2020). The greater surface area of the mussel bed is thus more likely to settle higher concentrations of waste particles floating over them, thereby acting as a natural sink (Nel and Froneman 2018).

COVID-19 and microplastics

In 2019, the world witnessed the onset of the global COVID-19 pandemic, first reported in Wuhan China (Khan et al. 2020), impacting millions of people. The use of plastic-based personal protection equipments as a measure to mitigate infection has risen dramatically since the COVID-19 epidemic was declared as a global epidemic on 11 March 2020 by the World Health Organization (Shah and Farrow 2020). Not only are we experiencing the new pandemic but also the recurrence of single-use plastics. Countries like the USA have stopped recycling projects as a result of the pandemic, as officials have been cautious about the possibility of the transmission of COVID-19 in recycling plants. Italy prevented infected people from sorting out their waste (Zambrano-Monserrate et al. 2020). Trading firms that once allowed customers to take their bags have reconsidered the ban on plastic bags and have gradually moved to single-use plastics promoting more online food services (Soares et al. 2020).

In the COVID-19 epidemic, pollution from PPE is becoming a rising concern as the wearing of masks to contain the spread of corona virus from person to person was instructed globally (Wu et al. 2020) and has become a frequent sight in

countries around the world. Nanofiber electrospinning, often used in the manufacture of personal protection equipments, indicates that this PPEs can become a source for microfibers. PPEs are mainly composites consisting of multiple non-degrading polymers so their fate and sinks can vary according to the characteristics of polymeric materials used (De-la-Torre and Aragaw 2021). Surgical masks are made from various polymer materials like polyethylene, PAN, polypropylene, polyester, etc. Three layers of disposable mask consist of an inner fibrous layer, a middle filtering layer, and an outer water resisting layer (Aragaw 2020). About 11 and 4.5 g of PP and other plastic derivatives can occur in one N95 and surgical mask. Until properly disposed of, this extremely infectious litter from the COVID-19 pandemic will persist in the atmosphere for decades and eventually begin to split into microplastics owing to a combination of factors such as temperature, ultraviolet, hydrophobicity, and pH change, probably influencing biota (Akber Abbasi et al. 2020).

PPE overuse during pandemic exacerbates plastic waste in the seas as the final conclusion of all sources of degradation is geared toward the ocean. The problem will escalate as the outbreak drifts on, leading to a potential spike in the already existing plastic pollution in the marine environments (De-la-Torre and Aragaw 2021).

Conclusion and future scope

Microsized particles, commonly referred to as microplastics, are infesting the aquatic habit globally where a vast array of organisms absorb these minute particles in which a significant portion of the population comprises plastic remnants, causing chronic effects. The eminence of plastics as a carrier for the transportation of toxic substances or as an abrasive that physically harm the species in the habitat is far less evident. Microplastic concentrations persist to an upsurge in the ecosystem as a consequence of the emergence of primary microplastic and the disintegration of larger plastics. Microplastic impacts epitomize a severe issue in almost every marine system on the earth, regardless of how isolated from potentially polluting sources. However, the study on freshwater micropollutants are limited compared to that of marine systems; recently, it has become a matter of great concern. Due to the nearness to sources and reachability to more pollutants, MP present in freshwater is more critical to accumulation of contaminants. Therefore, species in freshwater environments can undergo greater exposure, particularly in the vicinity of industrial and densely populated areas where both hydrophobic toxins and microplastics may have higher concentrations. A reduction in growth of *Gammarus pulex*, freshwater crustacean, was observed with increasing polystyrene concentration (Redondo-Hasselerharm et al. 2018).

In order to tackle the destructive impacts of microplastics, low cost, high-quality, and environmentally sustainable plastic waste management is required. Although the main problem of plastic waste in water originates mainly from soil-based activities, it is recommended that this issue be addressed. Waste management measures include the minimization of sources, innovation in products, reuse of water, recycling and mulching, the transformation of waste into power, and hindering of debris at entrance points into the ocean. Microplastics may be used as an alternative to metals such as aluminium and its combination as it causes adverse toxic impacts on human body under administration, the application of microplastics in medicines as an active and alternate ingredient can treat the disease like duodenal ulcer and gastritis in the future. The removal and biodegradation of microplastics from water and aquatic systems are still limited in the laboratory which can be commercialized under large scale using microorganisms such as fungi, protozoans, and bacterial spores in the future. Methods can be implemented before the microplastics get converted into nanoplastics by segregating the high-density plastics that accumulate at the bottom and the low-density plastics that float at the surface of the water, to prevent further aquatic contaminations. This can be accomplished by the incorporation of coagulants; however, the harmful effects of these materials in our human body is still not figured out. The sewage outlets from industries fitted with ceramic filters can hinder the microplastics from entering into the water bodies preventing its contamination. In addition, considering the role of COVID-19 pandemic in microplastic pollutions, there is high need for environmentally responsible solutions so more and more study on biodegradable PPEs need to be done in order to prevent a potential pandemic of microplastics.

Acknowledgement The authors are thankful to Dr. C. P. Ramanarayanan, Vice-Chancellor of DIAT (DU), Pune for the motivation, and support. The first author acknowledges Dr. B. Srinivasulu, Principal Director & Head of CIPET: Institute of Plastic Technology (IPT), Kochi, for the support. The authors are thankful to Mr. RaviPrakashMagisetty, Mr. Prakash M. Gore, and Mr. Swaroop Gharde, for their persistent technical support throughout the review writing. The authors are thankful to all anonymous Reviewers and the Editor for improving the quality of the revised manuscript by their valuable suggestions, and comments.

Author contribution MI performed literature study, data analysis, and technical writing. BK supervised the the results and data analysis and performed the technical revisions of the manuscript. All authors read and approved the final manuscript.

Funding The authors did not receive any funding for this work.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

- Akarsu C, Kumbur H, Gökdağ K et al (2020) Microplastics composition and load from three wastewater treatment plants discharging into Mersin Bay, north eastern Mediterranean Sea. *Mar Pollut Bull* 150:110776. <https://doi.org/10.1016/j.marpolbul.2019.110776>
- Akber Abbasi S, Khalil AB, Arslan M (2020) Extensive use of face masks during COVID-19 pandemic: (micro-)plastic pollution and potential health concerns in the Arabian Peninsula. *Saudi J Biol Sci* 27:3181–3186. <https://doi.org/10.1016/j.sjbs.2020.09.054>
- Alimi OS, Farner Budarz J, Hernandez LM, Tufenkji N (2018) Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. *Environ Sci Technol* 52:1704–1724. <https://doi.org/10.1021/acs.est.7b05559>
- Alimi OS, Fadare OO, Okoffo ED (2021) Microplastics in African ecosystems: current knowledge, abundance, associated contaminants, techniques, and research needs. *Sci Total Environ* 755:142422. <https://doi.org/10.1016/j.scitotenv.2020.142422>
- Aljaibachi R, Callaghan A (2018) Impact of polystyrene microplastics on *Daphnia magna* mortality and reproduction in relation to food availability. *PeerJ* 6:e4601. <https://doi.org/10.7717/peerj.4601>
- Anbumani S, Kakkar P (2018) Ecotoxicological effects of microplastics on biota: a review. *Environ Sci Pollut Res* 25:14373–14396. <https://doi.org/10.1007/s11356-018-1999-x>
- Andrades R, dos Santos RA, Martins AS et al (2019) Scavenging as a pathway for plastic ingestion by marine animals. *Environ Pollut* 248:159–165. <https://doi.org/10.1016/j.envpol.2019.02.010>
- Andrady AL (2017) The plastic in microplastics: a review. *Mar Pollut Bull* 119:12–22. <https://doi.org/10.1016/j.marpolbul.2017.01.082>
- 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>
- 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>
- Avio CG, Gorbi S, Regoli F (2017) Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. *Mar Environ Res* 128:2–11. <https://doi.org/10.1016/j.marenvres.2016.05.012>
- Ayalew A, Gonte RR, Balasubramanian K (2012) Development of polymer composite beads for dye adsorption. *Int J Green Nanotechnol* 4: 440–454. <https://doi.org/10.1080/19430892.2012.739480>
- Banaee M, Gholamhosseini A, Sureda A et al (2020) Effects of microplastic exposure on the blood biochemical parameters in the pond turtle (*Emys orbicularis*). *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-020-11419-2>
- Barboza LGA, Dick Vethaak A, Lavorante BRBO et al (2018) Marine microplastic debris: An emerging issue for food security, food safety and human health. *Mar Pollut Bull* 133:336–348. <https://doi.org/10.1016/j.marpolbul.2018.05.047>
- Berglund E, Fogelberg V, Nilsson PA, Hollander J (2019) Microplastics in a freshwater mussel (*Anodonta anatina*) in Northern Europe. *Sci Total Environ* 697:134192. <https://doi.org/10.1016/j.scitotenv.2019.134192>
- Bessa F, Ratcliffe N, Otero V et al (2019) Microplastics in gentoo penguins from the Antarctic region. *Sci Rep* 9:14191. <https://doi.org/10.1038/s41598-019-50621-2>
- Besseling E, Foekema EM, van den Heuvel-Greve MJ, Koelmans AA (2017) The effect of microplastic on the uptake of chemicals by the lugworm *Arenicola marina* (L.) under environmentally relevant exposure conditions. *Environ Sci Technol* 51:8795–8804. <https://doi.org/10.1021/acs.est.7b02286>
- Botterell ZLR, Beaumont N, Dorrington T et al (2019) Bioavailability and effects of microplastics on marine zooplankton: A review. *Environ Pollut* 245:98–110. <https://doi.org/10.1016/j.envpol.2018.10.065>
- Brahney J, Hallerud M, Heim E et al (2020) Plastic rain in protected areas of the United States. *Science* (80-) 368:1257–1260. <https://doi.org/10.1126/science.aaz5819>
- Browne MA (2015) Sources and pathways of microplastics to habitats. In: *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp 229–244
- Browne MA, Dissanayake A, Galloway TS et al (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environ Sci Technol* 42:5026–5031. <https://doi.org/10.1021/es800249a>
- Campanale, Massarelli, Savino et al (2020) A detailed review study on potential effects of microplastics and additives of concern on human health. *Int J Environ Res Public Health* 17:1212. <https://doi.org/10.3390/ijerph17041212>
- Cau A, Avio CG, Dessi C et al (2019) Microplastics in the crustaceans *Nephrops norvegicus* and *Aristeus antennatus*: flagship species for deep-sea environments? *Environ Pollut* 255:113107. <https://doi.org/10.1016/j.envpol.2019.113107>
- Cau A, Avio CG, Dessi C et al (2020) Benthic crustacean digestion can modulate the environmental fate of microplastics in the deep sea. *Environ Sci Technol* 54:4886–4892. <https://doi.org/10.1021/acs.est.9b07705>
- 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>
- Cherukattu Gopinathanicker J, Inamdar A, Anand A et al (2020) Radar transparent, impact-resistant, and high-temperature capable radome composites using polyetherimide-toughened cyanate ester resins for high-speed aircrafts through resin film infusion. *Ind Eng Chem Res* aacs.19b06439. <https://doi.org/10.1021/acs.iecr.9b06439>
- Choi JS, Hong SH, Park J-W (2020) Evaluation of microplastic toxicity in accordance with different sizes and exposure times in the marine copepod *Tigriopus japonicus*. *Mar Environ Res* 153:104838. <https://doi.org/10.1016/j.marenvres.2019.104838>
- Choy CA, Robison BH, Gagne TO et al (2019) The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Sci Rep* 9:7843. <https://doi.org/10.1038/s41598-019-44117-2>
- Chubarenko I, Bagaev A, Zobkov M, Esiukova E (2016) On some physical and dynamical properties of microplastic particles in marine environment. *Mar Pollut Bull* 108:105–112. <https://doi.org/10.1016/j.marpolbul.2016.04.048>
- Ciocan C, Kristova P, Annels C, et al (2020) Glass reinforced plastic (GRP) a new emerging contaminant—first evidence of GRP impact on aquatic organisms. *Mar Pollut Bull* 160:111559. doi: <https://doi.org/10.1016/j.marpolbul.2020.111559>
- Cole M, Lindeque P, Fileman E et al (2015) The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. *Environ Sci Technol* 49:1130–1137. <https://doi.org/10.1021/es504525u>
- Corcoran PL (2015) Benthic plastic debris in marine and fresh water environments. *Environ Sci Process Impacts* 17:1363–1369. <https://doi.org/10.1039/C5EM00188A>
- Corradini F, Meza P, Eguiluz R et al (2019) Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Sci Total Environ* 671:411–420. <https://doi.org/10.1016/j.scitotenv.2019.03.368>
- da Costa JP, Duarte AC, Rocha-Santos TAP (2017) Microplastics—occurrence, fate and behaviour in the environment. pp 1–24

- Courtene-Jones W, Quinn B, Ewins C et al (2020) Microplastic accumulation in deep-sea sediments from the Rockall Trough. *Mar Pollut Bull* 154:111092. <https://doi.org/10.1016/j.marpolbul.2020.111092>
- Cowger W, Gray A, Christiansen SH et al (2020) Critical review of processing and classification techniques for images and spectra in microplastic research. *Appl Spectrosc* 74:989–1010. <https://doi.org/10.1177/0003702820929064>
- Cozar A, Echevarria F, Gonzalez-Gordillo JI et al (2014) Plastic debris in the open ocean. *Proc Natl Acad Sci* 111:10239–10244. <https://doi.org/10.1073/pnas.1314705111>
- Davidson K, Dudas SE (2016) Microplastic ingestion by wild and cultured manila clams (*Venerupis philippinarum*) from Baynes Sound, British Columbia. *Arch Environ Contam Toxicol* 71:147–156. <https://doi.org/10.1007/s00244-016-0286-4>
- De Falco F, Di Pace E, Cocca M, Avella M (2019) The contribution of washing processes of synthetic clothes to microplastic pollution. *Sci Rep* 9:6633. <https://doi.org/10.1038/s41598-019-43023-x>
- De-la-Torre GE, Aragaw TA (2021) What we need to know about PPE associated with the COVID-19 pandemic in the marine environment. *Mar Pollut Bull* 163:111879. <https://doi.org/10.1016/j.marpolbul.2020.111879>
- Deng H, Wei R, Luo W et al (2020) Microplastic pollution in water and sediment in a textile industrial area. *Environ Pollut* 258:113658. <https://doi.org/10.1016/j.envpol.2019.113658>
- Desforges J-PW, Galbraith M, Ross PS (2015) Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Arch Environ Contam Toxicol* 69:320–330. <https://doi.org/10.1007/s00244-015-0172-5>
- Driedger AGJ, Dürr HH, Mitchell K, Van Cappellen P (2015) Plastic debris in the Laurentian Great Lakes: a review. *J Great Lakes Res* 41:9–19. <https://doi.org/10.1016/j.jglr.2014.12.020>
- Duis K, Coors A (2016) Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environ Sci Eur* 28:2. <https://doi.org/10.1186/s12302-015-0069-y>
- Eerkes-Medrano D, Leslie HA, Quinn B (2019) Microplastics in drinking water: a review and assessment. *Curr Opin Environ Sci Heal* 7:69–75. <https://doi.org/10.1016/j.coesh.2018.12.001>
- Enyoh CE, Verla AW, Verla EN et al (2019) Airborne microplastics: a review study on method for analysis, occurrence, movement and risks. *Environ Monit Assess* 191:668. <https://doi.org/10.1007/s10661-019-7842-0>
- Eo S, Hong SH, Song YK et al (2018) Abundance, composition, and distribution of microplastics larger than 20 µm in sand beaches of South Korea. *Environ Pollut* 238:894–902. <https://doi.org/10.1016/j.envpol.2018.03.096>
- Espinosa C, Esteban MÁ, Cuesta A (2016) Microplastics in aquatic environments and their toxicological implications for fish. *Toxicology - New Aspects to This Scientific Conundrum*. InTech, In
- Evangelou N, Grythe H, Klimont Z et al (2020) Atmospheric transport is a major pathway of microplastics to remote regions. *Nat Commun* 11:3381. <https://doi.org/10.1038/s41467-020-17201-9>
- Fadare OO, Wan B, Guo LH, Zhao L (2020) Microplastics from consumer plastic food containers: Are we consuming it? *Chemosphere* 253:126787. <https://doi.org/10.1016/j.chemosphere.2020.126787>
- Fred-Ahmadu OH, Bhagwat G, Oluyoye I et al (2020) Interaction of chemical contaminants with microplastics: Principles and perspectives. *Sci Total Environ* 706:135978. <https://doi.org/10.1016/j.scitotenv.2019.135978>
- Free CM, Jensen OP, Mason SA et al (2014) High-levels of microplastic pollution in a large, remote, mountain lake. *Mar Pollut Bull* 85:156–163. <https://doi.org/10.1016/j.marpolbul.2014.06.001>
- Frias JGPL, Nash R (2019) Microplastics: Finding a consensus on the definition. *Mar Pollut Bull* 138:145–147. <https://doi.org/10.1016/j.marpolbul.2018.11.022>
- Furtado R, Menezes D, Santos CJ, Catry P (2016) White-faced storm-petrels *Pelagodroma marina* predated by gulls as biological monitors of plastic pollution in the pelagic subtropical Northeast Atlantic. *Mar Pollut Bull* 112:117–122. <https://doi.org/10.1016/j.marpolbul.2016.08.031>
- Galloway TS, Lewis CN (2016) Marine microplastics spell big problems for future generations. *Proc Natl Acad Sci* 113:2331–2333. <https://doi.org/10.1073/pnas.1600715113>
- Galloway TS, Cole M, Lewis C (2017) Interactions of microplastic debris throughout the marine ecosystem. *Nat Ecol Evol* 1:0116. <https://doi.org/10.1038/s41559-017-0116>
- Gandara e Silva PP, Nobre CR, Resaffe P et al (2016) Leachate from microplastics impairs larval development in brown mussels. *Water Res* 106:364–370. <https://doi.org/10.1016/j.watres.2016.10.016>
- Gardon T, Reisser C, Soyez C et al (2018) Microplastics affect energy balance and gametogenesis in the pearl oyster *Pinctada margaritifera*. *Environ Sci Technol* 52:5277–5286. <https://doi.org/10.1021/acs.est.8b00168>
- Gautam A, Gore PM, Kandasubramanian B (2020) Nanocluster materials in photosynthetic machines. *Chem Eng J* 385:123951. <https://doi.org/10.1016/j.cej.2019.123951>
- Germanov ES, Marshall AD, Hendrawan IG et al (2019) Microplastics on the menu: plastics pollute Indonesian Manta Ray and Whale Shark Feeding Grounds. *Front Mar Sci* 6. <https://doi.org/10.3389/fmars.2019.00679>
- Gharde S, Kandasubramanian B (2019) Mechanochemical and chemical recycling methodologies for the Fibre Reinforced Plastic (FRP). *Environ Technol Innov* 14:100311. <https://doi.org/10.1016/j.eti.2019.01.005>
- Gigault J, ter Halle A, Baudrimont M et al (2018) Current opinion: what is a nanoplastic? *Environ Pollut* 235:1030–1034. <https://doi.org/10.1016/j.envpol.2018.01.024>
- Glaser AJ (2019) Biological degradation of polymers in the environment. *Plastics in the Environment*. IntechOpen, In
- Gonte RR, Balasubramanian K (2012) Chemically modified polymer beads for sorption of gold from waste gold solution. *J Hazard Mater* 217–218:447–451. <https://doi.org/10.1016/j.jhazmat.2012.03.020>
- Gonte RR, Shelar G, Balasubramanian K (2014) Polymer–agro-waste composites for removal of Congo red dye from wastewater: adsorption isotherms and kinetics. *Desalin Water Treat* 52:7797–7811. <https://doi.org/10.1080/19443994.2013.833876>
- Gore PM, Kandasubramanian B (2018a) Functionalized aramid fibers and composites for protective applications: a review. *Ind Eng Chem Res* 57:16537–16563. <https://doi.org/10.1021/acs.iecr.8b04903>
- Gore PM, Kandasubramanian B (2018b) Heterogeneous wettable cotton based superhydrophobic Janus biofabric engineered with PLA/functionalized-organoclay microfibrils for efficient oil–water separation. *J Mater Chem A* 6:7457–7479. <https://doi.org/10.1039/C7TA11260B>
- Gore PM, Dhanshetty M, K. B (2016) Bionic creation of nano-engineered Janus fabric for selective oil/organic solvent absorption. *RSC Adv* 6:111250–111260. <https://doi.org/10.1039/C6RA24106A>
- Gore PM, Khurana L, Dixit R, Balasubramanian K (2017) Keratin-Nylon 6 engineered microbeads for adsorption of Th (IV) ions from liquid effluents. *J Environ Chem Eng* 5:5655–5667. <https://doi.org/10.1016/j.jece.2017.10.048>
- Gore P, Khraisheh M, Kandasubramanian B (2018a) Nanofibers of resorcinol–formaldehyde for effective adsorption of As (III) ions from mimicked effluents. *Environ Sci Pollut Res* 25:11729–11745. <https://doi.org/10.1007/s11356-018-1304-z>
- Gore PM, Khurana L, Siddique S et al (2018b) Ion-imprinted electrospun nanofibers of chitosan/1-butyl-3-methylimidazolium tetrafluoroborate for the dynamic expulsion of thorium (IV) ions from mimicked

- effluents. *Environ Sci Pollut Res* 25:3320–3334. <https://doi.org/10.1007/s11356-017-0618-6>
- Gore PM, Naebe M, Wang X, Kandasubramanian B (2019a) Progress in silk materials for integrated water treatments: fabrication, modification and applications. *Chem Eng J* 374:437–470. <https://doi.org/10.1016/j.cej.2019.05.163>
- Gore PM, Naebe M, Wang X, Kandasubramanian B (2019b) Silk fibres exhibiting biodegradability & superhydrophobicity for recovery of petroleum oils from oily wastewater. *J Hazard Mater* 121823. <https://doi.org/10.1016/j.jhazmat.2019.121823>
- Gore PM, Purushothaman A, Naebe M et al (2019c) Nanotechnology for oil-water separation. In: Prasad R, Karchiyappan T (eds) *Advanced Research in Nanosciences for Water Technology*, 1st edn. Springer Nature Switzerland AG, Cham, pp 299–339
- Gore PM, Gawali P, Naebe M et al (2020) Polycarbonate and activated charcoal-engineered electrospun nanofibers for selective recovery of oil/solvent from oily wastewater. *SN Appl Sci* 2:1786. <https://doi.org/10.1007/s42452-020-03609-x>
- Granek EF, Brander SM, Holland EB (2020) Microplastics in aquatic organisms: Improving understanding and identifying research directions for the next decade. *Limnol Oceanogr Lett* 5:1–4. <https://doi.org/10.1002/lo2.10145>
- Green DS (2016) Effects of microplastics on European flat oysters, *Ostrea edulis* and their associated benthic communities. *Environ Pollut* 216: 95–103. <https://doi.org/10.1016/j.envpol.2016.05.043>
- Green DS, Colgan TJ, Thompson RC, Carolan JC (2019) Exposure to microplastics reduces attachment strength and alters the haemolymph proteome of blue mussels (*Mytilus edulis*). *Environ Pollut* 246:423–434. <https://doi.org/10.1016/j.envpol.2018.12.017>
- Gregory MR (1996) Plastic ‘scrubbers’ in hand cleansers: a further (and minor) source for marine pollution identified. *Mar Pollut Bull* 32: 867–871. [https://doi.org/10.1016/S0025-326X\(96\)00047-1](https://doi.org/10.1016/S0025-326X(96)00047-1)
- Guo X, Wang J (2019) The chemical behaviors of microplastics in marine environment: a review. *Mar Pollut Bull* 142:1–14. <https://doi.org/10.1016/j.marpolbul.2019.03.019>
- Gupta P, Kandasubramanian B (2017) Directional fluid gating by janus membranes with heterogeneous wetting properties for selective oil-water separation. *ACS Appl Mater Interfaces* 9:19102–19113. <https://doi.org/10.1021/acsami.7b03313>
- Gupta P, Lapalika V, Kundu R, Balasubramanian K (2016) Recent advances in membrane based waste water treatment technology: a review. *Energy Environ Focus* 5:241–267. <https://doi.org/10.1166/eef.2016.1227>
- Haider TP, Völker C, Kramm J et al (2019) Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angew Chem Int Ed* 58:50–62. <https://doi.org/10.1002/anie.201805766>
- Hammer J, Kraak MHS, Parsons JR (2012) Plastics in the marine environment: the dark Side of a modern gift. pp 1–44
- Harmon SM (2018) The effects of microplastic pollution on aquatic organisms. In: *microplastic contamination in aquatic environments*. Elsevier, pp 249–270
- Hazeem LJ, Yesilay G, Bououdina M et al (2020) Investigation of the toxic effects of different polystyrene micro-and nanoplastics on microalgae *Chlorella vulgaris* by analysis of cell viability, pigment content, oxidative stress and ultrastructural changes. *Mar Pollut Bull* 156:111278. <https://doi.org/10.1016/j.marpolbul.2020.111278>
- Hermabessiere L, Dehaut A, Paul-Pont I et al (2017) Occurrence and effects of plastic additives on marine environments and organisms: a review. *Chemosphere* 182:781–793. <https://doi.org/10.1016/j.chemosphere.2017.05.096>
- Horton AA, Jürgens MD, Lahive E et al (2018) The influence of exposure and physiology on microplastic ingestion by the freshwater fish *Rutilus rutilus* (roach) in the River Thames, UK. *Environ Pollut* 236:188–194. <https://doi.org/10.1016/j.envpol.2018.01.044>
- Hossain MS, Sobhan F, Uddin MN et al (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>
- Hu D, Zhang Y, Shen M (2020) Investigation on microplastic pollution of Dongting Lake and its affiliated rivers. *Mar Pollut Bull* 160:111555. <https://doi.org/10.1016/j.marpolbul.2020.111555>
- Hüffer T, Hofmann T (2016) Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. *Environ Pollut* 214:194–201. <https://doi.org/10.1016/j.envpol.2016.04.018>
- Inamdar A, Cherukattu J, Anand A, Kandasubramanian B (2018) Thermoplastic-toughened high-temperature cyanate esters and their application in advanced composites. *Ind Eng Chem Res* 57:4479–4504. <https://doi.org/10.1021/acs.iecr.7b05202>
- Issac MN, Kandasubramanian B (2020) Review of manufacturing three-dimensional-printed membranes for water treatment. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-020-09452-2>
- Jayalakshmi CG, Inamdar A, Anand A, Kandasubramanian B (2018) Polymer matrix composites as broadband radar absorbing structures for stealth aircrafts. *J Appl Polym Sci* 47241. <https://doi.org/10.1002/app.47241>
- Jayalakshmi CG, Anand A, Kandasubramanian B, Joshi M (2020) High temperature composite materials for electromagnetic applications through a cost effective manufacturing process; resin film infusion. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2020.03.804>
- Jeong C-B, Kang H-M, Lee M-C et al (2017) Adverse effects of microplastics and oxidative stress-induced MAPK/Nrf2 pathway-mediated defense mechanisms in the marine copepod *Paracyclops nana*. *Sci Rep* 7:41323. <https://doi.org/10.1038/srep41323>
- Kalčíková G, Alič B, Skalar T et al (2017) Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. *Chemosphere* 188:25–31. <https://doi.org/10.1016/j.chemosphere.2017.08.131>
- Katija K, Choy CA, Sherlock RE et al (2017) From the surface to the seafloor: how giant larvaceans transport microplastics into the deep sea. *Sci Adv* 3:e1700715. <https://doi.org/10.1126/sciadv.1700715>
- Katsumi N, Kusube T, Nagao S, Okochi H (2020) The role of coated fertilizer used in paddy fields as a source of microplastics in the marine environment. *Mar Pollut Bull* 161:111727. <https://doi.org/10.1016/j.marpolbul.2020.111727>
- Kavitha VU, Kandasubramanian B (2020) Tannins for wastewater treatment. *SN Appl Sci* 2:1081. <https://doi.org/10.1007/s42452-020-2879-9>
- Khan S, Ali A, Shi H et al (2020) COVID-19: Clinical aspects and therapeutics responses. *Saudi Pharm J* 28:1004–1008. <https://doi.org/10.1016/j.jsps.2020.06.022>
- Koelmans AA (2015) Modeling the role of microplastics in bioaccumulation of organic chemicals to marine aquatic organisms. A critical review. In: *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp 309–324
- Kumar P, Gore PM, Magisetty R et al (2020) Poly(1,6-heptadiyne)/ABS functionalized microfibers for hydrophobic applications. *J Polym Res* 27:14. <https://doi.org/10.1007/s10965-019-1981-4>
- Law KL, Thompson RC (2014) Microplastics in the seas. *Science* (80-) 345:144–145. <https://doi.org/10.1126/science.1254065>
- Lee J, Lee JS, Jang YC et al (2015) Distribution and size relationships of plastic marine debris on beaches in South Korea. *Arch Environ Contam Toxicol* 69:288–298. <https://doi.org/10.1007/s00244-015-0208-x>
- Lei L, Wu S, Lu S et al (2018) Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*. *Sci Total Environ* 619–620:1–8. <https://doi.org/10.1016/j.scitotenv.2017.11.103>
- Leng Z, Padhan RK, Sreeram A (2018) Production of a sustainable paving material through chemical recycling of waste PET into crumb

- rubber modified asphalt. *J Clean Prod* 180:682–688. <https://doi.org/10.1016/j.jclepro.2018.01.171>
- LI WC, TSE HF, FOK L (2016) Plastic waste in the marine environment: a review of sources, occurrence and effects. *Sci Total Environ* 566–567:333–349. <https://doi.org/10.1016/j.scitotenv.2016.05.084>
- Li X, Chen L, Mei Q et al (2018) Microplastics in sewage sludge from the wastewater treatment plants in China. *Water Res* 142:75–85. <https://doi.org/10.1016/j.watres.2018.05.034>
- Lim HS, Fraser A, Knights AM (2020) Spatial arrangement of biogenic reefs alters boundary layer characteristics to increase risk of microplastic bioaccumulation. *Environ Res Lett* 15:064024. <https://doi.org/10.1088/1748-9326/ab83ae>
- Liu J, Yang Y, Ding J et al (2019) Microfibers: a preliminary discussion on their definition and sources. *Environ Sci Pollut Res* 26:29497–29501. <https://doi.org/10.1007/s11356-019-06265-w>
- Liu J, Liang J, Ding J et al (2021) Microfiber pollution: an ongoing major environmental issue related to the sustainable development of textile and clothing industry. *Environ Dev Sustain*. <https://doi.org/10.1007/s10668-020-01173-3>
- Lo HKA, Chan KYK (2018) Negative effects of microplastic exposure on growth and development of *Crepidula onyx*. *Environ Pollut* 233: 588–595. <https://doi.org/10.1016/j.envpol.2017.10.095>
- Luo W, Su L, Craig NJ et al (2019) Comparison of microplastic pollution in different water bodies from urban creeks to coastal waters. *Environ Pollut* 246:174–182. <https://doi.org/10.1016/j.envpol.2018.11.081>
- Lusher A (2015) Microplastics in the marine environment: distribution, interactions and effects. In: *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp 245–307
- Mam N, Jusup M, Kooijman SALM, Klanjscek T (2020) Quantifying impacts of plastic debris on marine wildlife identifies ecological breakpoints. *Ecol Lett* 23:1479–1487. <https://doi.org/10.1111/ele.13574>
- Mason SA, Welch VG, Neratko J (2018) Synthetic polymer contamination in bottled water. *Front Chem*:6. <https://doi.org/10.3389/fchem.2018.00407>
- Messinetti S, Mercurio S, Scari G et al (2019) Ingested microscopic plastics translocate from the gut cavity of juveniles of the ascidian *Ciona intestinalis*. *Eur Zool J* 86:189–195. <https://doi.org/10.1080/24750263.2019.1616837>
- Michels J, Stippkugel A, Lenz M et al (2018) Rapid aggregation of biofilm-covered microplastics with marine biogenic particles. *Proc R Soc B Biol Sci* 285:20181203. <https://doi.org/10.1098/rspb.2018.1203>
- Mistri M, Scoptoni M, Granata T et al (2020) Types, occurrence and distribution of microplastics in sediments from the northern Tyrrhenian Sea. *Mar Pollut Bull* 153:111016. <https://doi.org/10.1016/j.marpolbul.2020.111016>
- Mountford AS, Morales Maqueda MA (2019) Eulerian modeling of the three-dimensional distribution of seven popular microplastic types in the global ocean. *J Geophys Res Ocean* 124:8558–8573. <https://doi.org/10.1029/2019JC015050>
- Naji A, Azadkhan S, Farahani H et al (2021) Microplastics in wastewater outlets of Bandar Abbas city (Iran): A potential point source of microplastics into the Persian Gulf. *Chemosphere* 262:128039. <https://doi.org/10.1016/j.chemosphere.2020.128039>
- 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* 112:39–45. <https://doi.org/10.1016/j.marpolbul.2016.09.025>
- Napper IE, Bakir A, Rowland SJ, Thompson RC (2015) Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. *Mar Pollut Bull* 99:178–185. <https://doi.org/10.1016/j.marpolbul.2015.07.029>
- Napper IE, Davies BFR, Clifford H et al (2020) Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. *One Earth* 3:621–630. <https://doi.org/10.1016/j.oneear.2020.10.020>
- Napper IE, Baroth A, Barrett AC et al (2021) The abundance and characteristics of microplastics in surface water in the transboundary Ganges River. *Environ Pollut* 116348. <https://doi.org/10.1016/j.envpol.2020.116348>
- Nel H, Froneman P (2018) Presence of microplastics in the tube structure of the reef-building polychaete *Gunnarea gaimardi* (Quatrefages 1848). *Afr J Mar Sci* 40:87–89. <https://doi.org/10.2989/1814232X.2018.1443835>
- Ng E-L, Huerta Lwanga E, Eldridge SM et al (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>
- Nitesh Singh NS, Balasubramanian K (2014) An effective technique for removal and recovery of uranium(<sc>vi</sc>) from aqueous solution using cellulose–camphor soot nanofibers. *RSC Adv* 4: 27691–27701. <https://doi.org/10.1039/C4RA01751J>
- Nizzetto L, Bussi G, Futter MN et al (2016) A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. *Environ Sci Process Impacts* 18:1050–1059. <https://doi.org/10.1039/C6EM00206D>
- O'Donovan S, Mestre NC, Abel S et al (2018) Ecotoxicological effects of chemical contaminants adsorbed to microplastics in the clam *Scrobicularia plana*. *Front Mar Sci*:5. <https://doi.org/10.3389/fmars.2018.00143>
- Pabortsava K, Lampitt RS (2020) High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. *Nat Commun* 11:4073. <https://doi.org/10.1038/s41467-020-17932-9>
- Parton KJ, Godley BJ, Santillo D et al (2020) Investigating the presence of microplastics in demersal sharks of the North-East Atlantic. *Sci Rep* 10:12204. <https://doi.org/10.1038/s41598-020-68680-1>
- Paul-Pont I, Lacroix C, González Fernández C et al (2016) Exposure of marine mussels *Mytilus* spp. to polystyrene microplastics: toxicity and influence on fluoranthene bioaccumulation. *Environ Pollut* 216: 724–737. <https://doi.org/10.1016/j.envpol.2016.06.039>
- Pedersen AF, Gopalakrishnan K, Boegehold AG et al (2020) Microplastic ingestion by quagga mussels, *Dreissena bugensis*, and its effects on physiological processes. *Environ Pollut* 260: 113964. <https://doi.org/10.1016/j.envpol.2020.113964>
- Peng G, Bellerby R, Zhang F et al (2020) The ocean's ultimate trashcan: hadal trenches as major depositories for plastic pollution. *Water Res* 168:115121. <https://doi.org/10.1016/j.watres.2019.115121>
- Pfäler JB, Goforth KM, Gil MA et al (2020) Odors from marine plastic debris elicit foraging behavior in sea turtles. *Curr Biol* 30:R213–R214. <https://doi.org/10.1016/j.cub.2020.01.071>
- Piccardo M, Provenza F, Grazioli E et al (2020) PET microplastics toxicity on marine key species is influenced by pH, particle size and food variations. *Sci Total Environ* 715:136947. <https://doi.org/10.1016/j.scitotenv.2020.136947>
- Ragusa A, Svelato A, Santacroce C et al (2021) Plasticenta: first evidence of microplastics in human placenta. *Environ Int* 146:106274. <https://doi.org/10.1016/j.envint.2020.106274>
- Rajhans A, Gore PM, Siddique SK, Kandasubramanian B (2019) Ion-imprinted nanofibers of PVDF/1-butyl-3-methylimidazolium tetrafluoroborate for dynamic recovery of europium (III) ions from mimicked effluent. *J Environ Chem Eng* 7:103068. <https://doi.org/10.1016/j.jece.2019.103068>
- Rani M, Shim WJ, Han GM et al (2015) Qualitative analysis of additives in plastic marine debris and its new products. *Arch Environ Contam Toxicol* 69:352–366. <https://doi.org/10.1007/s00244-015-0224-x>
- Rastogi S, Kandasubramanian B (2020a) Application of electrospun materials in water treatment. In: Inamuddin, Boddula R, Ahamed MI, Asiri AM (eds) *Electrospun Materials and Their Allied Applications*, 1st edn. Wiley, Hoboken, USA, pp 151–183

- Rastogi S, Kandasubramanian B (2020b) Processing trends of silk fibers: silk degumming, regeneration and physical functionalization. *J Text Inst*:1–17. <https://doi.org/10.1080/00405000.2020.1727269>
- Rastogi S, Sharma G, Kandasubramanian B (2020) Nanomaterials and the environment. *The ELSI Handbook of Nanotechnology*. Wiley, In, pp 1–23
- Redondo-Hasselerharm PE, Falahudin D, Peeters ETHM, Koelmans AA (2018) Microplastic effect thresholds for freshwater benthic macro-invertebrates. *Environ Sci Technol* 52:2278–2286. <https://doi.org/10.1021/acs.est.7b05367>
- Renzi M, Blašković A, Broccoli A et al (2020) Chemical composition of microplastic in sediments and protected detritivores from different marine habitats (Salina Island). *Mar Pollut Bull* 152:110918. <https://doi.org/10.1016/j.marpolbul.2020.110918>
- Robeson LM, Liu Q, Freeman BD, Paul DR (2015) Comparison of transport properties of rubbery and glassy polymers and the relevance to the upper bound relationship. *J Membr Sci* 476:421–431. <https://doi.org/10.1016/j.memsci.2014.11.058>
- Rochman CM, Brookson C, Bikker J et al (2019) Rethinking microplastics as a diverse contaminant suite. *Environ Toxicol Chem* 38:703–711. <https://doi.org/10.1002/etc.4371>
- Rodrigues JP, Duarte AC, Santos-Echeandía J, Rocha-Santos T (2019) Significance of interactions between microplastics and POPs in the marine environment: a critical overview. *TrAC Trends Anal Chem* 111:252–260. <https://doi.org/10.1016/j.trac.2018.11.038>
- Ross PS, Chastain S, Vassilenko E et al (2021) Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. *Nat Commun* 12:106. <https://doi.org/10.1038/s41467-020-20347-1>
- Rowdhwil SSS, Chen J (2018) Toxic effects of Di-2-ethylhexyl phthalate: an overview. *Biomed Res Int* 2018:1–10. <https://doi.org/10.1155/2018/1750368>
- de Sá LC, Oliveira M, Ribeiro F et al (2018) Studies of the effects of microplastics on aquatic organisms: What do we know and where should we focus our efforts in the future? *Sci Total Environ* 645: 1029–1039. <https://doi.org/10.1016/j.scitotenv.2018.07.207>
- Saeed T, Al-Jandal N, Al-Mutairi A, Taqi H (2020) Microplastics in Kuwait marine environment: results of first survey. *Mar Pollut Bull* 152:110880. <https://doi.org/10.1016/j.marpolbul.2019.110880>
- Saha M, Naik A, Desai A et al (2021) Microplastics in seafood as an emerging threat to marine environment: a case study in Goa, west coast of India. *Chemosphere* 270:129359. <https://doi.org/10.1016/j.chemosphere.2020.129359>
- Sahetya TJ, Dixit F, Balasubramanian K (2015) Waste citrus fruit peels for removal of Hg(II) ions. *Desalin Water Treat* 53:1404–1416. <https://doi.org/10.1080/19443994.2013.852483>
- Savoca M (2018) The ecology of an olfactory trap. *Science* (80-) 362: 904.1-904. <https://doi.org/10.1126/science.aav6873>
- Schwabl P, Köppel S, Königshofer P et al (2019) Detection of various microplastics in human stool. *Ann Intern Med* 171:453. <https://doi.org/10.7326/M19-0618>
- Seltenrich N (2015) New Link in the Food Chain? Marine plastic pollution and seafood safety. *Environ Health Perspect* 123. <https://doi.org/10.1289/ehp.123-A34>
- Selvam S, Manisha A, Venkatramanan S et al (2020) Microplastic presence in commercial marine sea salts: a baseline study along Tuticorin Coastal salt pan stations, Gulf of Mannar, South India. *Mar Pollut Bull* 150:110675. <https://doi.org/10.1016/j.marpolbul.2019.110675>
- 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>
- Setälä O, Lehtiniemi M, Coppock R, Cole M (2018) Microplastics in marine food webs. *Microplastic Contamination in Aquatic Environments*. Elsevier, In, pp 339–363
- Shah SGS, Farrow A (2020) A commentary on “World Health Organization declares global emergency: a review of the 2019 novel Coronavirus (COVID-19).” *Int J Surg* 76:128–129. doi: <https://doi.org/10.1016/j.ijsu.2020.03.001>
- Shahul Hamid F, Bhatti MS, Anuar N et al (2018) Worldwide distribution and abundance of microplastic: how dire is the situation? *Waste Manag Res J a Sustain Circ Econ* 36:873–897. <https://doi.org/10.1177/0734242X18785730>
- Sharma S, Balasubramanian K (2015) Molecularly imprinted and nanoengineered camphor soot functionalized PAN-nanofibers for effluent treatment. *RSC Adv* 5:31732–31741. <https://doi.org/10.1039/c5ra02861b>
- Sharma S, Chatterjee S (2017) Microplastic pollution, a threat to marine ecosystem and human health: a short review. *Environ Sci Pollut Res* 24:21530–21547. <https://doi.org/10.1007/s11356-017-9910-8>
- Sharma S, Balasubramanian K, Arora R (2016) Adsorption of arsenic (V) ions onto cellulosic-ferric oxide system: kinetics and isotherm studies. *Desalin Water Treat* 57:9420–9436. <https://doi.org/10.1080/19443994.2015.1042066>
- Sharma A, Gore PM, Kandasubramanian B (2021) Reduction of carbon dioxide (CO₂) using ‘p’ & ‘d’ block electro-catalysts: a review. *J Environ Chem Eng* 9:104798. <https://doi.org/10.1016/j.jece.2020.104798>
- Sighicelli M, Pietrelli L, Lecce F et al (2018) Microplastic pollution in the surface waters of Italian Subalpine Lakes. *Environ Pollut* 236:645–651. <https://doi.org/10.1016/j.envpol.2018.02.008>
- Smith M, Love DC, Rochman CM, Neff RA (2018) Microplastics in seafood and the implications for human health. *Curr Environ Heal Reports* 5:375–386. <https://doi.org/10.1007/s40572-018-0206-z>
- Soares J, Miguel I, Venâncio C et al (2020) Perspectives on micro(Nano)plastics in the marine environment: biological and societal considerations. *Water* 12:3208. <https://doi.org/10.3390/w12113208>
- Sunday NF (2020) Microplastics: Holistic overview of source, identification, interaction, health and environmental implications and strategies of abatement. *Acta Chem Malaysia*. <https://doi.org/10.2478/acmy-2021-0004>
- Sussarellu R, Suquet M, Thomas Y et al (2016) Oyster reproduction is affected by exposure to polystyrene microplastics. *Proc Natl Acad Sci* 113:2430–2435. <https://doi.org/10.1073/pnas.1519019113>
- Sysel P (2016) Amorphous polymers and the amorphous region. In: *Encyclopedia of Membranes*. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp 66–68
- Thakur K, Kandasubramanian B (2019) Graphene and graphene oxide-based composites for removal of organic pollutants: a review. *J Chem Eng Data* 64:833–867. <https://doi.org/10.1021/acs.jced.8b01057>
- Thompson RC (2015) Microplastics in the marine environment: sources, consequences and solutions. In: *Marine Anthropogenic Litter*. Springer International Publishing, Cham, pp 185–200
- Thushari GGN, Senevirathna JDM (2020) Plastic pollution in the marine environment. *Heliyon* 6:e04709. <https://doi.org/10.1016/j.heliyon.2020.e04709>
- Tong H, Jiang Q, Hu X, Zhong X (2020) Occurrence and identification of microplastics in tap water from China. *Chemosphere* 252:126493. <https://doi.org/10.1016/j.chemosphere.2020.126493>
- Tourinho PS, Koči V, Loureiro S, van Gestel CAM (2019) Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. *Environ Pollut* 252:1246–1256. <https://doi.org/10.1016/j.envpol.2019.06.030>
- Udayakumar KV, Gore PM, Kandasubramanian B (2021) Foamed materials for oil-water separation. *Chem Eng J Adv* 5:100076. <https://doi.org/10.1016/j.cej.2020.100076>
- Vallero DA (2016) *Environmental Biochemodynamic Processes*. Environmental Biotechnology. Elsevier, In, pp 89–150
- Walkinshaw C, Lindeque PK, Thompson R et al (2020) Microplastics and seafood: lower trophic organisms at highest risk of

- contamination. *Ecotoxicol Environ Saf* 190:110066. <https://doi.org/10.1016/j.ecoenv.2019.110066>
- Waller CL, Griffiths HJ, Waluda CM et al (2017) Microplastics in the Antarctic marine system: an emerging area of research. *Sci Total Environ* 598:220–227. <https://doi.org/10.1016/j.scitotenv.2017.03.283>
- Wang F, Wang B, Duan L et al (2020a) Occurrence and distribution of microplastics in domestic, industrial, agricultural and aquacultural wastewater sources: a case study in Changzhou, China. *Water Res* 182:115956. <https://doi.org/10.1016/j.watres.2020.115956>
- Wang X, Huang W, Wei S et al (2020b) Microplastics impair digestive performance but show little effects on antioxidant activity in mussels under low pH conditions. *Environ Pollut* 258:113691. <https://doi.org/10.1016/j.envpol.2019.113691>
- Weber A, Scherer C, Brennholt N et al (2018) PET microplastics do not negatively affect the survival, development, metabolism and feeding activity of the freshwater invertebrate *Gammarus pulex*. *Environ Pollut* 234:181–189. <https://doi.org/10.1016/j.envpol.2017.11.014>
- Weis JS (2020) Aquatic microplastic research—a critique and suggestions for the future. *Water* 12:1475. <https://doi.org/10.3390/w12051475>
- Welden NAC, Cowie PR (2016) Long-term microplastic retention causes reduced body condition in the langoustine, *Nephrops norvegicus*. *Environ Pollut* 218:895–900. <https://doi.org/10.1016/j.envpol.2016.08.020>
- WESTON JNJ, CARRILLO-BARRAGAN P, LINLEY TD et al (2020) New species of Eurythenes from hadal depths of the Mariana Trench, Pacific Ocean (Crustacea: Amphipoda). *Zootaxa* 4748: 163–181. <https://doi.org/10.11646/zootaxa.4748.1.9>
- Willis KA, Eriksen R, Wilcox C, Hardesty BD (2017) Microplastic distribution at different sediment depths in an urban estuary. *Front Mar Sci* 4. <https://doi.org/10.3389/fmars.2017.00419>
- Wu H, Huang J, Zhang CJP et al (2020) Facemask shortage and the novel coronavirus disease (COVID-19) outbreak: Reflections on public health measures. *EClinicalMedicine* 21:100329. <https://doi.org/10.1016/j.eclinm.2020.100329>
- Xu S, Ma J, Ji R et al (2020) Microplastics in aquatic environments: occurrence, accumulation, and biological effects. *Sci Total Environ* 703:134699. <https://doi.org/10.1016/j.scitotenv.2019.134699>
- Xue B, Zhang L, Li R et al (2020) Underestimated microplastic pollution derived from fishery activities and “hidden” in deep sediment. *Environ Sci Technol* 54:2210–2217. <https://doi.org/10.1021/acs.est.9b04850>
- Yang Y, Liu W, Zhang Z et al (2020) Microplastics provide new microbial niches in aquatic environments. *Appl Microbiol Biotechnol* 104:6501–6511. <https://doi.org/10.1007/s00253-020-10704-x>
- Yu Y, Chen H, Hua X et al (2020) Polystyrene microplastics (PS-MPs) toxicity induced oxidative stress and intestinal injury in nematode *Caenorhabditis elegans*. *Sci Total Environ* 726:138679. <https://doi.org/10.1016/j.scitotenv.2020.138679>
- Zambrano-Monserrate MA, Ruano MA, Sanchez-Alcalde L (2020) Indirect effects of COVID-19 on the environment. *Sci Total Environ* 728:138813. <https://doi.org/10.1016/j.scitotenv.2020.138813>
- Zhang W, Zhang S, Wang J et al (2017) Microplastic pollution in the surface waters of the Bohai Sea, China. *Environ Pollut* 231:541–548. <https://doi.org/10.1016/j.envpol.2017.08.058>
- Zhang D, Liu X, Huang W et al (2020a) Microplastic pollution in deep-sea sediments and organisms of the Western Pacific Ocean. *Environ Pollut* 259:113948. <https://doi.org/10.1016/j.envpol.2020.113948>
- Zhang Q, Xu EG, Li J et al (2020b) A review of microplastics in table salt, drinking water, and air: direct human exposure. *Environ Sci Technol* 54:3740–3751. <https://doi.org/10.1021/acs.est.9b04535>
- Zhang Q, Zhao Y, Li J, Shi H (2020c) Microplastics in food: health risks. pp 343–356
- Zhang N, Bin LY, He HR et al (2021) You are what you eat: microplastics in the feces of young men living in Beijing. *Sci Total Environ* 767:144345. <https://doi.org/10.1016/j.scitotenv.2020.144345>
- Ziajahromi S, Neale PA, Leusch FDL (2016) Wastewater treatment plant effluent as a source of microplastics: review of the fate, chemical interactions and potential risks to aquatic organisms. *Water Sci Technol* 74:2253–2269. <https://doi.org/10.2166/wst.2016.414>
- Zocchi M, Sommaruga R (2019) Microplastics modify the toxicity of glyphosate on *Daphnia magna*. *Sci Total Environ* 697:134194. <https://doi.org/10.1016/j.scitotenv.2019.134194>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.