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Review

# Linking effects of microplastics to ecological impacts in marine environments

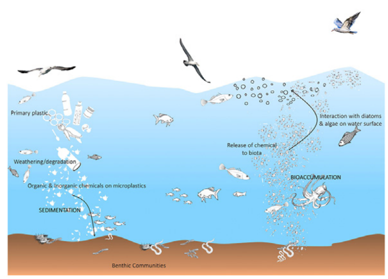
Noreen Khalid [a, *], Muhammad Aqeel [b], Ali Noman [c], Mohamed Hashem [d, e], Yasser S. Mostafa [d], Haifa Abdulaziz S. Alhaithloul [f], Suliman M. Alghanem [g]

[a] Department of Botany, Government College Women University, Sialkot, Pakistan
[b] State Key Laboratory of Grassland Agroecosystems, School of Life Science, Lanzhou University, Lanzhou, Gansu, PR China
[c] Department of Botany, Government College University, Faisalabad, Pakistan
[d] King Khalid University, College of Science, Department of Biology, Abha 61413, Saudi Arabia
[e] Assiut University, Faculty of Science, Botany and Microbiology Department, Assiut, 71516, Egypt
[f] Biology Department, College of Science, Jouf University, Sakaka, Saudi Arabia
[g] Biology Department, Faculty of Science, Tabuk University, Tabuk, Saudi Arabia

## HIGHLIGHTS

- Inorganic and organic chemicals sorbed to microplastics could be extremely harmful to marine biota.
- Disease-causing microbes have been found on microplastics.
- Exotic invasive species could hitch-hike on microplastics to reach new habitats.
- Plastic contamination of sediments could adversely affect benthic communities.
- Heating properties of plastics could have localized effects on populations of marine organisms.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Recently, efforts to determine the ecological impacts of microplastic pollutants have increased because of plastic's accelerated contamination of the environment. The tiny size, variable surface topography, thermal properties, bioavailability and biological toxicity of microplastics all offer opportunities for these pollutants to negatively impact the environment. Additionally, various inorganic and organic chemicals sorbed on these particles may pose a greater threat to organisms than the microplastics themselves. However, there is still a big knowledge gap in the assessment of various toxicological effects of microplastics in the environment. Ecological risk assessment of microplastics has become more challenging with the current data gaps. Thus, a current literature review and identification of the areas where research on ecology of microplastics can be extended is necessary. We have provided an overview of various aspects of microplastics by which they interact negatively or positively with marine organisms. We hypothesize that biogeochemical interactions are critical to fully understand the ecological impacts, movement, and fate of microplastics in oceans. As microplastics are now ubiquitous in marine environments and impossible to remove, we recommend that it's not too late to converge research on plastic

* Corresponding author. Department of Botany, Govt. College Women University, Sialkot, Pakistan.
*E-mail addresses:* noreenbasra@gmail.com, Noreen.khalid@gcwus.edu.pk (N. Khalid).

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alternatives. In addition, strict actions should be taken promptly to prevent plastics from entering the environment.



**Contents**



## 1. Introduction

Microplastics are ubiquitous emerging marine environmental pollutants and have been identified as a global environmental concern by the scientific community (Law and Thompson, 2014; Gago et al., 2018; Yang et al., 2018). The production of plastics has increased rapidly in recent years. It is estimated that 8.3 billion metric tonnes of plastic have been produced since the beginning of plastic production. Of this, about 55% (4.6 billion metric tons) has been produced since 2000 (Geyer et al., 2017). According to some recent reports, 94% of the 320 million tons of plastics produced per year end up in the environment globally (Shen et al., 2020). Global oceans receive a certain portion of this plastic (Barnes et al., 2009; Law, 2017). It is largely unknown how much plastic enters and is retained in the ocean because the behavior and fate of plastics in the marine environment is still unclear.

A large portion of marine plastic remains come from land-based sources (Andrady, 2011; Khalid et al., 2020). Approximately 80% of it is human-produced litter, which make their way into oceans from land (Sheavly and Register, 2007; Law, 2017). The most common sources could be sewage effluents, municipal drainage systems, tire wears, rivers, improperly managed plastic litter farther inland, or by being directly discarded on the beach (Barnes et al., 2009; Andrady, 2011; Browne et al., 2011; Auta et al., 2017; Hüffer et al., 2019). A substantial quantity of plastic litter is also dumped into the oceans illegally from offshore platforms or vessels (Sheavly and Register, 2007). Additionally, marine aquaculture (Hinojosa and Thiel, 2009), fishing fleets (Andrady, 2011), and lost cargo shipping containers contribute to plastic debris in the oceans (Derraik, 2002).

A coherent definition of microplastics still remains under debate, although they are generally described as tiny plastic particles of various sizes (Hartmann et al., 2019). Plastics >25 mm in size are defined as macroplastics, 5–25 mm particles are mesoplastics, 100 nm-5 mm particles are microplastics and <100 nm particles are known as nanoplastics (Alimi et al., 2018). Microplastics are also divided into two main groups based on their origin and source. Primary microplastics are those microparticles which are produced by extrusion and grinding, for example, abrasives in consumer products such as toothpastes, facial and hand cleansers, and shower gels (Gregory, 2009; Browne, 2015) (Table 1). These particles can reach the ocean and other bodies of water through effluents (Browne et al., 2011). Primary microplastics also include virgin preproduction resin pellets lost during transport and abrasive materials from the air-blasting industry (Ogata et al., 2009). Hence, primary microplastics are already tiny millimetre sized particles when they enter fresh water and marine environments. On the other hand, physical, chemical, or biological fragmentation and degradation of larger floating plastic items in aquatic environments generate secondary microplastics (Browne et al., 2007; Cooper and Corcoran, 2010; Zhang et al., 2017; Arias-Villamizar and Vázquez-Morillas, 2018). Mechanical degradation (e.g., movement of waves), UV degradation and microbial degradation help form secondary microplastics in oceans.

Plastics are extremely robust and durable particles as once they are released into the marine environment, also, it is not feasible to practically recapture or recycle them. Unlike other organic matter, plastics do not undergo the simple process of degradation or mineralization in the oceans. In fact they fragment into smaller pieces (i.e. micro and nanoplastics) (Andrady, 2011). Plastic particles can travel enormous distances with ocean currents and winds, as evidenced by their presence in isolated mid-oceanic islands (Ivar et al., 2009), polar ice regions (Barnes et al., 2009; Peeken et al., 2018), the Arctic (Bergmann et al., 2019) and the Antarctic (Waller et al., 2017). They have also even been found in deep sea sediments (Van Cauwenberghe et al., 2013). Depending on their density compared to ocean water, plastic particles can be found contained in sediments, suspended in the water column, or freely floating at the surface. Hence, the composition of plastic polymer samples taken from oceans could depend upon the sampling depth. Studies have reported accumulation of various polymers of plastics such as polyvinyl chloride, polyamide, polyvinyl alcohol, polyurethane, solid polystyrene, polyethylene terephthalate, polyester, and acrylic polyoxymethylene in deep ocean sediments (Browne et al., 2010; Morét-Ferguson et al., 2010; Hidalgo-Ruz et al., 2012). Similarly, expanded polystyrene, polypropylene, and polyethylene microplastics have been discovered in neustonic organisms (Morét-Ferguson et al., 2010; Reisser et al., 2014).

Since microplastics are tiny particles in aquatic environments, they can be easily ingested by aquatic organisms, where an accumulation of microplastics can adversely affect tissues, organs, and intestinal tracts (Van Cauwenberghe et al., 2015). Microplastics also provide surfaces for the adsorption of various other contaminants in the environment, acting as vectors of these contaminants

**Table 1**
The most commonly found microplastics and their uses.

| Type of plastic | Abbreviation | Applications | Density (g cm$^{-3}$) |
|---|---|---|---|
| Polystyrene | PS | foodservice packaging, insulations in refrigerators and industrial cold storage facilities, medical devices, DVD cases, meat/poultry trays, egg cartons, all types of IT equipment | 0.28−1.04 |
| Polypropylene | PP | Flexible and rigid packaging, disposable hot drink cups, sports clothes, equipment, undergarments, carpets, mats, rugs, toys, car dashboards, bumpers, cladding, exterior trim, and many more | 0.89−0.92 |
| Polyvinyl chloride | PVC | building and construction, electronics, health care, automobile, in products ranging from piping and siding, to wire and cable insulation, blood bags and tubing, windshield system components | 1.10−1.47 |
| Low density polyethylene | LDPE | Plastic bags, six-pack rings, containers, food cartons, playground slides, plastic wraps | 0.91−0.92 |
| High density polyethylene | HDPE | Geothermal piping, underground water pipes, plastic furniture, automobile parts, garbage cans, bottle caps and bottles | 0.93−0.97 |
| Polyethylene terephthalate | PET/PETE | Bottle packaging for mineral water, carbonated soft drinks, cooking oil, peanut butter, shampoo, liquid hand soap, mouthwash, or into carpet, automotive parts, clothing, industrial strapping, construction materials, and scores of other products | 1.37−1.38 |
| Other resins, such as polycarbonate, nylon, and acrylic | Other | Used for making synthetic fibers because of flame resistance, low moisture absorption, chemical resistance, and insulation | 1.15−1.22 |

(Carbery et al., 2018; Lei et al., 2018; Zhang et al., 2018). The contaminants which have been found to be associated with plastic debris in marine environments include dichloro-diphenyl-trichloroethane (DDTs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and alkylphenols and bisphenol A (BPA) (Hirai et al., 2011; Velzeboer et al., 2014; Wang et al., 2018; Wang and Wang, 2018b). Accumulation of these contaminants with microplastics in marine food webs may cause toxicity, and once in the food chain, they may also impact human health (Andrady, 2011). However, the adverse effects of plastics on human health are not completely known and further research efforts must be made in this regard. Biological toxicity of microplastics, their surface level changes, and their internal components all contribute to the adverse effects microplastics have on the marine environment (Carbery et al., 2018; Lei et al., 2018; Zhang et al., 2018). Therefore, it is necessary to review the literature related to microplastics so that the gaps in this field can be identified.

Microorganisms also colonize on the surfaces of microplastics making biofilms in the marine environment (Oberbeckmann et al., 2015). The characteristics of microplastics change as a result of their interactions with microorganisms. Previous reviews have focused on biofilms in marine environments, emphasizing how they are formed, how they change the physical characteristics of microplastics and the factors involved in the attachment of microbial communities to microplastics (Rummel et al., 2017; Oberbeckmann and Labrenz, 2020). In this review, we address the adverse effects of microplastics and biofilms on the marine environment around them. Microplastics are also known to transport various eukaryotic organisms over long distances in the oceans. Some studies have documented the presence of exotic invasive prokaryotic species on microplastics in marine environments (Andrady, 2011; Kirstein et al., 2016). We will also discuss this aspect of microplastics along with thermal properties of microplastics and identify the subject areas that still need to be addressed.

## 2. Sorption of various pollutants on microplastics increases its toxicity

Microplastics sorb various contaminants from the surrounding water (Brennecke et al., 2016; Hodson et al., 2017; Li et al., 2018a) (Table 2). The term “sorption” is used when both mechanisms (i.e. adsorption and absorption) occur simultaneously and if it is unknown whether adsorption or absorption is occurring. Physical and chemical characteristics of plastics, for example, their small size, crystallinity, and surface area to volume ratio help in the accumulation of chemical ions on plastics and can have effect on the fate of these contaminants in the aquatic settings (Teuten et al., 2007; Karapanagioti and Klontza, 2008; Turner, 2016; Filella and Turner, 2018; Wang et al., 2018). Additionally, plastics have hydrophobic properties like organic pollutants do in aquatic environments that help them to attract organic pollutants (Lee et al., 2014). Studies have found a variety of contaminants on microplastic surfaces such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, antibiotics, trace metals, and organochlorine pesticides (Bakir et al., 2014; Brennecke et al., 2016; Hodson et al., 2017; Li et al., 2018a; Llorca et al., 2018; Wang and Wang, 2018b). The type of microplastics and the contaminant chemistry can determine the rate and amount of sorption. For example, the presence of benzene in the structure of polystyrenes allows substances to diffuse into the polymer more easily, making them highly sorptive plastics (Pascall et al., 2005). However, polyamides strongly adsorb trimethoprim compared to polystyrene (Li et al., 2018b). The large surface area of polyethylenes results in strong sorption of organic contaminants (Teuten et al., 2007). Generally, polystyrene and polyethylene have higher sorption capacities than other plastic types in laboratory conditions. Additionally, older plastics with rough surfaces have more sorption capacity compared to virgin plastics in the laboratory and in the natural marine environment (Turner and Holmes, 2015; Turner, 2016). Also, the size of various microplastic particles, as the same sized different types of microplastics may have different surface areas, play an important role in the process of sorption. Interestingly, the sorption capacity of microplastics increases with decreasing their particle size because smaller particles of the same type have bigger surface area (Liu et al., 2018a). Additionally, smaller sized microplastics gain sorption equilibrium with various contaminants more easily and quickly than larger sized particles (Wang et al., 2018).

Heavy metals are toxic key contaminants of inorganic nature (Khalid et al., 2018). However, only a few studies have been performed to understand the sorption of heavy metals on microplastics in laboratory conditions (Holmes et al., 2014; Brennecke et al., 2016; Guo and Wang, 2019). Guo and Wang (2019) studied the sorption behavior of Cd on microplastics in the laboratory. They found that the two main factors affecting the mechanism of sorption are surface charge and surface area of the microplastic. Also, in

**Table 2**
Various microplastics and their sorbed inorganic and organic chemicals.

| Pollutant category | Pollutant type | Microplastic type | Environment | Experimental condition | Sorption capacity (mg kg$^{-1}$) | Reference |
|---|---|---|---|---|---|---|
| Metallic pollutants | As | PE, PP, PS | Sandy beaches | Natural | <LOD | Li et al. (2020) |
| | Al | PE, PP, HDPE beached Pellets | Sea water | – | 45.27 | Vedolin et al. (2018) |
| | Cd | PP, PVC | Sea water | 9 months | 0.10 | Gao et al. (2019) |
| | Co | Virgin and beached PE pellets | River water, pH 4–10 | 48 h | 0.01–0.24 | Turner and Holmes (2015) |
| | | Virgin and beached PE resin pellets | Seawater, pH 7.8 | 7 days, 150 rpm, 20 ± 1 °C | 0.02–0.04 | Holmes et al. (2012) |
| | | Virgin and beached PE pellets | River water and Seawater, pH 4–10.5 | 48 h, 150 rpm | 0.02–0.079 | Holmes et al. (2014) |
| | Cr | Virgin and beached PE pellets | River water, pH 4–10 | 48 h | 0.07–0.08 | Turner and Holmes (2015) |
| | | Virgin and beached PE pellets | Seawater, pH 7.8 | 7 days, 150 rpm, 20 ± 1 °C | 0.29–0.44 | Holmes et al. (2012) |
| | | Virgin and beached PE pellets | River water and seawater, pH 4–10.5 | 48 h, 150 rpm | 0.09–0.44 | Holmes et al. (2014) |
| | Cu | PE, PP, PS | Sandy beaches | Natural | 0.89 | Li et al. (2020) |
| | | PP, PVC | Sea water | 9 months | 0.20 | Gao et al. (2019) |
| | | Virgin and aged PET | Aqueous solution, pH 3.0 to 7.0, Temp 288, 298, 308 and 318K, UV 313 nm | 144 h, 150 r/min | 175 | Wang et al. (2020b) |
| | Fe | PE, PP, HDPE beached Pellets | Sea water | – | 227.78 | Vedolin et al. (2018) |
| | Hg | Virgin PE and beached pellets | River water, pH 4–10 | 48 h | 0.17–2.78 | Turner and Holmes (2015) |
| | Mn | PE, PP, PS | Sandy beaches | Natural | 18.6 | Li et al. (2020) |
| | Ni | PE, PP, PS | Sandy beaches | Natural | 0.15 | Li et al. (2020) |
| | | Virgin and beached PE pellets | Filtered river water and seawater, pH 4–10.5 | 48 h, 150 rpm | 0.01–0.15 | Holmes et al. (2014) |
| | Pb | PP, PVC | Sea water | 9 months | 1.3 | Gao et al. (2019) |
| | | Aged Nylon | Aqueous solution, Temp 25 °C, pH 7-8 | 48 h | 1.05 | Tang et al. (2020) |
| | | Virgin and beached PE pellets | Filtered river water and seawater, pH 4–10.5 | 48 h, 150 rpm | 0.19–2.73 | Holmes et al. (2014) |
| | Zn | PE, PP, PS | Sandy beaches | Natural | 19.6 | Li et al. (2020) |
| | | Virgin and aged PET | Aqueous solution, pH 3.0 to 7.0, Temp 288, 298, 308 and 318K, UV 313 nm | 144 h, 150 r/min | 89 | Wang et al. (2020a) |
| | | Virgin PS beads (0.7–0 .9 μm) and aged PVC fragments( | Seawater | 14 days | 0.18–270 | Brennecke et al. (2016) |
| | | Plastic bag derived HDPE | Background electrolyte (0.1 M NaNO3) | 48 h, 220 rpm | 236–7171 | Hodson et al. (2017) |
| Organic pollutants | Benzene | PP virgin and aged PS | Tab water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |
| | | Aged PS | Aqueous solution. (0.01 M CaCl2) | 7 days, 125 rpm, 25 ± 2 °C. | Within $10^{-2}$–$10^{4}$ | Hüffer et al. (2018) |
| | | PE, PA, PS and PVC | Artificial seawater | 17 days for PS, 5 days for PE, PA, and PVC, 10 rpm, 25 °C | Within 1–$10^{4}$ | Hüffer and Hofmann (2016) |
| | Chlorobenzene | PE, PA, PS and PVC | Artificial seawater | 17 days for PS, 5 days for PE, PA, and PVC, 10 rpm, 25 °C | Within 1–104 | Hüffer and Hofmann (2016) |
| | Ethyl benzene | Virgin and aged PS and PP | Tab water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |
| | Ethyl benzoate | PE, PA, PS and PVC | Artificial seawater | 17 days for PS, 5 days for PE, PA, and PVC, 10 rpm, 25 °C | Within 10–104 | Hüffer and Hofmann (2016) |
| | Lubrication oil | PE and PS | Aqueous solution, NaCl 0.001–0.1 mol/L, pH 1–10, | 48 h, 293 K | 6,800,000 5,200,000 | Hu et al. (2017) |
| | Methyl *tert*-butyl ether | Virgin and aged PS and PP | Tap water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |
| | Musk xylene | PP | Simulated seawater, salinity 35‰ | 24 h, 220 rpm (for 30 min), room temperature | 1.8 | Zhang et al. (2018) |
| | Musk ketone | PP | Simulated seawater, salinity 35‰ | 24 h, 220 rpm (for 30 min), room temperature | 1.2 | Zhang et al. (2018) |
| | O-xylene | Virgin and aged PS and PP | Tap water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |
| | Perfluoroal-kyl substances | HDPE, PS | Fresh water and seawater | 50 days, 120 rpm, 20 °C | 34–210 | Llorca et al. (2018) |
| | Perfluorooctanesulfonamide | PE, PS, PVC | Aqueous solutions, pH 3–7 | 7 days, 150 rpm, 25 °C | 1.4–2.4 | Wang et al. (2015) |
| | Perfluorooctanesulfonate | PE, PS. PVC | Aqueous solutions, pH 3–7 | 7 days, 150 rpm, 25 °C | 0–1.4 | Wang et al. (2015) |
| | Phenanthrene | PVC, PE | Filtered seawater | 24 h, 220 rpm, 20 °C | 1.15–15.5 | Bakir et al. (2012) |
| | P-xylene | Virgin and aged PS, PP | Tap water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |

| | | | | | |
|---|---|---|---|---|---|
| Pyrene | PE, PS, PVC | Artificial freshwater | 120 h, 200 rpm, 25 °C | 78.7–333 | (Wang and Wang, 2018a, b) |
| Sulfadiazine | PE, PS, PP, PVC, PA | Ultrapure water and filtered seawater | 4 days, 180 rpm, 25 °C | 0–100 | Yang et al. (2018) |
| Sulfamethoxazole | PE | Aqueous solution, pH 2–12 | 72 h, 200 rpm, 25 °C | 25–700 | Xu et al. (2018a) |
| Tetracycline | PE, PP, PS | Aqueous solution, pH 2–12, Salinity 0.5%–35% | 24 h, 200 rpm, 25 °C | 109–167 | Xu et al. (2018b) |
| | PA | Ultrapure water and filtered seawater | 4 days, 180 rpm, 25 °C | 50–2000 | Yang et al. (2018) |
| Toluene | Virgin and aged PS and PP | Tap water | Two weeks, 10 rpm, 22 °C | – | Müller et al. (2018) |
| | Aged PS | Aqueous solution. (0.01 M CaCl2) | 7 days, 125 rpm, 25 ± 2 °C, | Within $10^{-2}$–$10^{4}$ | Hüffer et al. (2018) |
| | PE, PA, PS, PVC | Artificial seawater | 17 days for PS, 5 days for PE, PA, and PVC, 10 rpm, 25 °C | Within 0.1–$10^{3}$ | Hüffer and Hofmann (2016) |
| Tonalide | PP | Simulated seawater, salinity 35% | 24 h, 220 rpm (for 30 min),room temperature | 1.3 | Zhang et al. (2018) |
| Tris-(2,3-dibromopropyl) isocyanurate | PP | Simulated seawater, salinity 35% | 24 h, 220 rpm, 18 °C | 21.489 | (Liu et al., 2018a, 2018b) |
| Tylosin | PE, PP, PS, PVC | Aqueous solution | 48 h, 150 rpm, 25 °C | 1667–3333 | (Guo et al., 2018) |

this sorption process, different functional groups played an important role. In another study, concentration of Zn and Cu on microplastics in marine water was 270 and 3000 μg/g, respectively (Brennecke et al., 2016). Turner et al. (2020) found 0.1 μg/g of Pb adsorbed on the surfaces of marine water microplastics. Zou et al. (2020) reported that Pb has more sorptive strength than Cu and Cd on two polyethylene plastic particles, PVC, and chlorinated polyethylene (CPE). High electrostatic strength of Pb played a crucial role in this adsorption. Additionally, pH could be a significant factor in influencing the adsorption of Pb, Cu, and Cd on microplastics, but ionic strength only slightly affects the adsorption process (Zou et al., 2020). Polytetrafluoroethylene microplastics have a strong affinity for As metal in the water due to electrostatic force and non-covalent interactions (Dong et al., 2019). Toxicity of microplastics increases significantly if they are loaded with toxic metal ions (Hartmann et al., 2017). However, microplastic could also possibly retain metal ions reducing their bioavailability (Wang et al., 2019a). Speciation and migration of metals can be altered by microplastics, which then impacts their fate in the environment. However, there is not much literature on this aspect of microplastics in marine nor freshwater environments.

Organic pollutants such as DDTs (dichlorodiphenyl trichloroethanes), PAHs (polycyclic aromatic hydrocarbons), HCHs (hexachloro cyclohexanes), PCBs (polychlorinated biphenyls), PFASs (polyfluoroalkyl substances), ethers, antibiotics, flame retardants, fuel aromatics, and pyrenes have been found to be associated with microplastics in aquatic environments (Guo et al., 2012; Bakir et al., 2014; Lee et al., 2014; Hüffer and Hofmann, 2016; Wu et al., 2016; Hüffer et al., 2018; Wang and Wang, 2018a; Guo and Wang, 2019; Li et al., 2019; Qiu et al., 2019; Zuo et al., 2019). Microplastics have strong interactions with organic contaminants. Hence, bioavailability of these contaminants increases as aquatic organisms uptake and accumulate them in their bodies. Also, phase distribution of organic pollutants in aqueous phase and sediments is affected by sorption of these compounds on microplastics. According to Endo and Koelmans (2016), sorption of organic contaminants to microplastics is affected by temperature, composition of the water phase, inorganic salts, and type of the plastic. In the microplastics resulting from tire wears, hydrochemistry and aging of particulates are important factors which influence their sorption (Hüffer et al., 2019). Polystyrene microplastics have strong molecular interactions with non-ionic organic compounds in the water (Uber et al., 2019). Wang et al. (2019b), after finding strong interactions of naphthalene, nitrobenzene, and phenanthrene organic compounds with microplastics, concluded that the functional groups and specific surface area should be considered while studying the sorption of organic compounds to plastics.

Different organic compounds have different hydrophobicity, which affects their fate in marine environments (Lin et al., 2019). Organic compounds of different hydrophobicity have variable partitioning coefficients and thus have different affinities for microplastics (Hartmann et al., 2017; Liu et al., 2019). The sorption of 17β-estradiol and polybrominated diphenyl ether on microplastics has been found to be regulated by hydrophobic partitioning, while dissolved organic matter, pH, and salinity of marine water don't have much effect (Liu et al., 2019; Xu et al., 2019).

## 3. Plastisphere is a risk to the marine environment

Besides sorbing various organic and inorganic compounds in oceans, microplastic surfaces also provide substrates for the colonization of diverse microbial communities (Zettler et al., 2013; Hoellein et al., 2017; Dussud et al., 2018). These microplastic biofilms are commonly known as plastisphere, a new ecological niche introduced by the influx of plastic debris into oceans. The

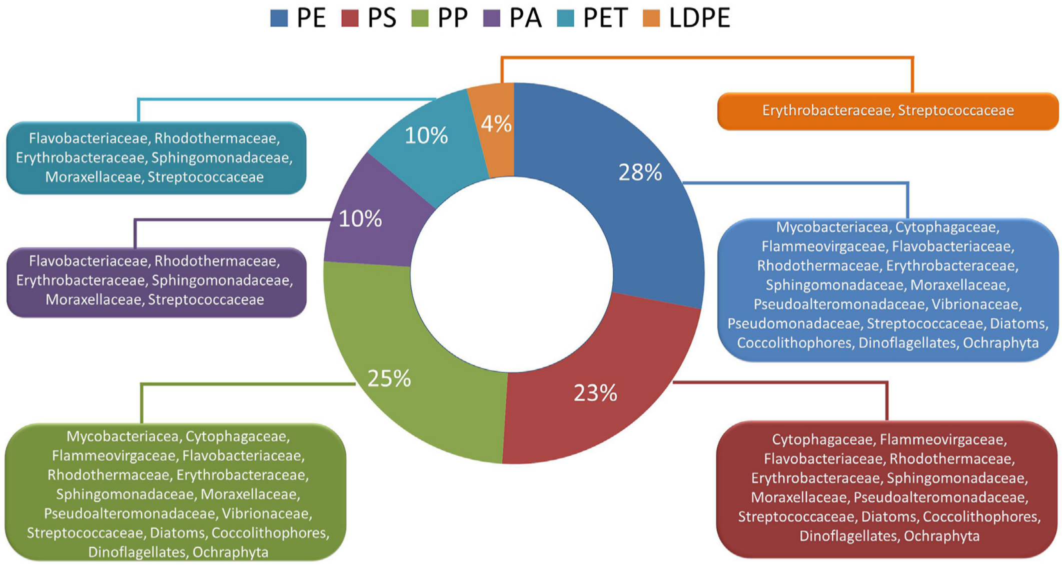


**Fig. 1.** Doughnut chart describing the percentage of various types of microplastics (PE, PS, PP, PA, PET, LDPE) in oceans holding microorganism communities on their surfaces (data has been taken from previous studies (n = 12).

composition of biofilm forming microorganisms is diverse and is different from surrounding microbial communities (De Tender et al., 2015) (Fig. 1). Various organisms such as bacteria, heterotrophic bacteria, cyanobacteria, dinoflagellates, diatoms, bryozoans, coccolithophores, and fungi have been found in the plastisphere (Reisser et al., 2014). The formation of biofilms on microplastics is influenced by variety of environmental and biogeographical factors such as particle size, substrate type, surface properties, sample location, nutrient concentration and salinity of the surrounding water (Oberbeckmann et al., 2014, 2018; Amaral-Zettler et al., 2015; Eich et al., 2015). These microbial biofilms can also alter the physical characteristics of the microplastics such as size and buoyancy. The change in size or buoyancy could be due to the hydrocarbonoclastic nature of microplastic biofilms which allows them to utilize microplastics as an energy source by degrading petroleum derivatives and complex biopolymers (Zettler et al., 2013; Ogonowski et al., 2018). The diversity in size and buoyancy of microplastics can affect their distribution vertically within the water column in oceans and can also horizontally transport microplastics to new environments with wind and ocean currents (Kooi et al., 2017).

Concerns have been raised recently about the potentially hazardous nature of plastispheres in oceans. Various genera of pathogenic bacteria, such as *Vibrio*, *Leptolyngbya*, and *Pseudomonas* spp., are frequently found to be associated with microplastics which can have severe implications for marine food webs (Jiang et al., 2018; Oberbeckmann et al., 2018). Microplastics provide ecological habitats for these pathogenic bacteria, as their relative abundance in the surrounding marine environment has been reported to be low (Zettler et al., 2013; Curren and Leong, 2019). Biofilms that are formed by these pathogenic bacteria on microplastics get protection, enhanced dispersal, and access to nutritious matter. Microplastics have also been found to promote colonization of various harmful algal blooms. Dinoflagellates known to cause harmful algal blooms, such as *Alexandrium taylori*, *Ostreopsis* spp, and *Coolia* spp, have been found on floating plastic debris in the ocean (Masó et al., 2003). *Alexandrium taylori* can also produce paralytic fish toxins (Lim et al., 2005).

As microplastics have been recently introduced into the world's oceans and are preferred substrates for microbial communities, the ratio of microplastic microbial communities to free living microbes in the oceans is likely to increase with time. Hence, these microplastics with thick biofilms can influence ecological processes in the environment. The new surfaces that plastics have introduced into oceans can be selectively enriched by the previously less active or dormant members of the marine biosphere. The increasing biomass of these metabolically inactive species could alter dissolved organic matter fluxes. Dissolved organic matter can be significantly increased by microplastic leachate, which in turn leads to increases in microbial biomass in the ocean (Romera-Castillo et al., 2018). However, knowledge on impacts of microbial communities residing on microplastics in the ocean is sparse. The potential environmental impacts of marine microplastics biofilms at varying temporal and spatial scales have also yet to be determined.

## 4. Bioaccumulation and bioavailability of microplastics impact marine food webs

To develop effective risk assessments of microplastics in marine food webs, understanding of their impacts on all levels of biological organizations is particularly important. At all levels of biological organization (i.e. from molecular to population levels), microplastics are a great hazard (Auta et al., 2017) (Fig. 2). Ecosystems are certainly affected if physiological functions and/or the fitness of a significant number of individuals of a population are disturbed (Guzzetti et al., 2018).

Due to their small size, microplastics can be ingested by a wide range of organisms in the ocean. Biomonitoring studies have confirmed the widespread consumption of microplastics by various marine organisms including estuarine crustaceans, fish, intertidal shellfish, mussels, barnacles, lugworms, sea cucumbers, amphipods, and sea birds (Van Cauwenberghe and Janssen, 2014; Digka et al., 2018; Provencher et al., 2018; Coverton et al., 2019; Iannilli et al., 2019; Mohsen et al., 2019; Xu et al., 2020) (Table 3). After mistaken or intentional ingestion, microplastics are transferred through the epithelium of the gastrointestinal tract, and are retained in the gastrointestinal tract, or may be egested through feces. Retention of microplastics in the gastrointestinal tract can severely affect the health of the organism by causing physical abrasions and/or perforations, decreasing nutrient uptake and

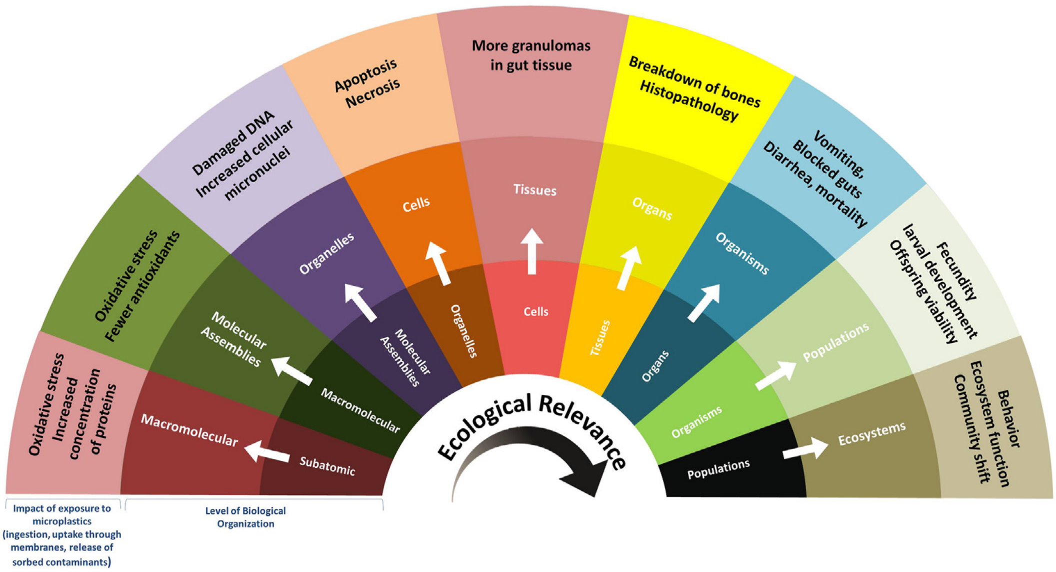


**Fig. 2.** Diagrammatical scheme demonstrating the potential toxic impacts of microplastics across all levels of biological organization and assessment of their ecological relevance.

reducing feeding activity because of the feeling of false satiety (Walkinshaw et al., 2020). The physical structure and sorbed chemicals of microplastics (flame retardants, dyes, antimicrobials, other organic compounds, and metals) can cause adverse effects on organisms after ingestion. The larger microplastics can cause internal abrasion, clogging of the digestive system, and intestinal lesions (Cole et al., 2013; Wright et al., 2013; Ahrendt et al., 2020). However, the toxic effects of the attached chemicals could be more lethal (Wang et al., 2018). Chemicals associated with microplastics have been reported to cause cellular toxicity (Rochman, 2015) and to negatively affect fish populations (Guven et al., 2018), energetic reserves in lugworms and shore crabs (Wright et al., 2013; Watts et al., 2015; Besseling et al., 2019), metabolic rate and survival in Asian green mussels (Rist et al., 2016), and growth, development and survival in *Daphnia* (Ogonowski et al., 2016) in laboratory conditions. After exposure to microplastics, marine copepods (*Centropages typicus*) show significant reduction of their algal consumption which ultimately affects their fecundity and survival (Cole et al., 2015). Ingestion of microplastics by marine filter feeders can have more severe effects on food chains because filter feeders are at the baseline of food chains. Additionally, filter feeders are more vulnerable to exposure of suspended microplastics (Scherer et al., 2017). Microplastics can disrupt the ecological balance largely by affecting the growth of these young creatures and small organisms.

Individual behavior can be altered as a response to environmental pollutants or stressors. Changes in behavior are early warning signals which can impact the whole ecosystem as they link physiological and ecological processes (Wong and Candolin, 2015). Studying behavioral changes in marine organisms is crucial for a better understanding of the impact of microplastics on ecosystems. Plastic debris can be hazardous to marine zooplankton and subsequently transferred to top consumers in the food chain, causing behavioral disorders (i.e. plastic nanoparticles can enter the brain tissue of fish) (Mattsson et al., 2017). This behavioral disorder can severely disrupt natural ecosystems. Various behavioral changes in marine organisms in response to microplastics have been observed under laboratory conditions. For example, beach hoppers (*Platorchestia smithi*) lost weight and reduced jumping heights (Tosetto et al., 2016), the daily rhythm of activities by zebrafish (*Danio rerio*) was altered (Limonta et al., 2019), reduced swimming velocity was found for European seabass (*Dicentrarchus labrax*) (Barboza et al., 2018), increased foraging time, lower sensitivity towards food, and reduced swimming speed was found for jacopever (*Sebastes schlegelii*) (Yin et al., 2018). An altered frequency of pulsation and immobility in *Aurelia* sp. jellyfish was found (Costa et al., 2020) and marine demersal fish (*Sebastes schlegelii*) reduced their swimming speed and movement (Yin et al., 2019). Similarly, decreased swimming and weakened predation competence was found for mysid shrimp (*Neomysis japonica*) (Wang et al., 2020b). On the other hand, there is not much information on behavioral responses of organisms to microplastics in natural marine habitats. Chapron et al. (2018) reported altered feeding behavior by the main engineer species (*Lophelia pertusa*) in the coral reefs of the northwestern Mediterranean Sea by microplastics. However, Doyle et al. (2020) reported that the predator-avoidance emergence behavior of an intertidal gastropod (*Littorina littorea*) didn't seem to be affected by microplastic exposure.

Humans can be exposed to microplastics by consuming the top consumers of marine food webs. Many marine species intended for human consumption such as fish, crustaceans, and invertebrates were found contaminated with microplastics (Van Cauwenberghe and Janssen, 2014; Rochman et al., 2015). However, there is insufficient information due to data gaps in microplastics research to assess the risk of exposure of microplastics to humans.

## 5. Plastic contamination of sediments pose a threat to benthos

Microplastics also pose a threat to benthic ecosystems by accumulating in the sea floor sediments. Benthic sediments accumulate significant amounts of microplastics, making them important sinks for microplastics (Fang et al., 2018). High density microplastics readily settle down the water column. On the other hand, low density microplastics freely float on the surface or in the water column until they become heavier in density than the surrounding water, after which they make their way to ocean floor sediments (Fig. 3b). The settling of microplastics to the ocean floor is enhanced by the aggregation of organic debris on their surface, adherence of phytoplankton and particles of marine snow, and

**Table 3**
The potential toxic impacts of microplastics on various marine organisms.

| Species | Plastic and/or sorbed chemical | Uptake mechanism | Concentration in the surrounding water | Effect | Reference |
|---|---|---|---|---|---|
| Yellow Seahorse (*Hippocampus kuda*) | HDPE | Ingestion | 0.10g microplastics/3 L sea water, concentrations of 0.05 mg/L copper (Cu), 0.01 mg/L cadmium (Cd), and 0.05 mg/L lead (Pb) | Reduced body weight, body length, specific growth rate, and survival rate | Jinhui et al. (2019) |
| Zebrafish (*Danio rerio*) | PCBs, BFRs, PFCs and methylmercury were sorbed | Ingestion | 2% microplastics | Liver and organs homeostasis | Rainieri et al. (2018) |
| Jacopever (*Sebastes schlegelii*) | PS | Ingestion | $1 \times 10^6$ microspheres per L | Histopathological changes in the gallbladder and liver, lower growth, lipid and protein contents | Yin et al. (2018) |
| Discus fish (*Symphysodon aequifasciatus*) | PS | Ingestion | MPs (0, 50 or 500 μg $L^{-1}$) with sorbed Cd (0 or 50 μg $L^{-1}$) | Severe oxidative stress | Wen et al. (2018) |
| Catshark (*Scyliorhinus canicular*) | PET, PA, PAC, PP, PAN, PE | unknown | In the Mediterranean Sea | Expression of immune related genes | Mancia et al. (2020) |
| Manila clam (*Ruditapes philippinarum*) | PE microbeads | Ingestion | 25 mg/L MPs and 10 mg/L Hg, co-exposure | Reduced the filtration rate, histological alterations in the gill and digestive gland tissues | Sıkdokur et al. (2020) |
| Mediterranean mussels (*Mytilus galloprovincialis*) | LDPE | Ingestion | 10 mg/L of LDPE, BaP (15 μg/g) | Slight cellular toxicity under short-term (28 days) exposure | Pittura et al. (2018) |
| Marine Medaka (*Oryzias melastigma*) | PS | Ingestion | 2, 20, and 200 μg PS | Decreased fecundity of female fish, delayed gonad maturation, decreased hatching rate, body length of the offspring, and heart rate | Wang et al. (2019b) |
| Chinese mitten crab (*Eriocheir sinensis*) | PS | Ingestion | 40000 μg $L^{-1}$ | Negatively affected growth, induces oxidative stress | Yu et al. (2018) |
| Gilthead Seabream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) | PVC, PE | Ingestion | 1, 10 and 100 mg $mL^{-1}$ | Oxidative stress in gilthead seabream leucocytes | Espinosa et al. (2018) |
| Zebrafish (*Danio rerio*) | BaP-spiked PE particles | Food chain and direct uptake | 4–6 μm and 500 μm microplastic and BaP | Did not induce any histopathological effects | Batel et al. (2020) |
| Pacific oyster (*Crassostrea gigas*) | PE, PP | Ingestion | 0.008, 10, 100 μg of particles/L | No significant effect on physiology and tissue integrity | Revel et al. (2020) |
| Goldfish (*Carassius auratus*) | Ethylene vinyl acetate (EVA) fibers, PS fragments, and polyethylene acrylate (PA) pellets | Ingestion, chewing | 0.96%, 1.36%, 1.94% and 3.81% (g (food + MPs)/g ww | Severe alterations in the liver, intestine, and circulatory system, damages to the jaws due to chewing | Jabeen et al. (2018) |
| Water flea (*Daphnia magna*) and algae (*Raphidocelis subcapitata*) | PE microbeads | Ingestion | 25, 50, and 100 mg/L fluorescent green PE microbeads at size of 63–75 μm | No significant effect on survival and reproduction of D. magna, Enhanced growth of R. subcapitata | Canniff and Hoang (2018) |
| Tropical fish (*Lates calcarifer*) | Pyrene-microplastics with sorbed polycyclic aromatic hydrocarbon | Ingestion | 100 nM | No effect on feeding, swimming speed significantly decreased | Guven et al. (2018) |
| Marine Copepod (*Pseudodiaptomus annandalei*) | PS microspheres (1:1 water emulsion, 2.5% w/v, 10 mL) | Ingestion | 0.5, 2, and 10 μm And two different microalgae concentrations ($1 \times 10^3$ and $1 \times 10^5$ cells/mL) | Induced ingestion of microalgae significantly by P. annandalei | Cheng et al. (2020) |
| Sea snail (*Crepidula onyx*) | Micro-PS | Ingestion | Ten 2-μm microplastic beads $ml^{-1}$ | Slower growth rates | Lo and Chan (2018) |
| Stony coral species Acropora, Pocillopora, and Porites | PE | Ingestion | 37–163 μm, 4000 particles $L^{-1}$ | Bleaching and tissue necrosis | Reichert et al. (2018) |
| Manila clam (*Ruditapes philippinarum*) | PET | Ingestion | 0.125 or 12.5 μg/ml | No marked histological alterations to bivalve tissues, altered oxidative status of gills | Parolini et al. (2020) |
| Marine bacterium (*Halomonas alkaliphila*) | PS | Ingestion | 80 mg/L | Induced oxidative stress | Sun et al. (2018) |
| Microalgae (*Chlorella pyrenoidosa*) | PE, PS, PA | Ingestion | PE (PE1000, 13 μm and PE, 150 μm), PA (PA1000, 13 μm and PA, 150 μm), PS (PS, 150 μm) | Caused oxidative stress, inhibited algal growth | Yang et al. (2020) |
| Marine microalga (*Tetraselmis chuii*) | Microplastics | Ingestion | 0.9 and 2.1 mg/l | Influenced toxicity of sorbed pharmaceuticals procainamide and doxycycline | Prata et al. (2018) |

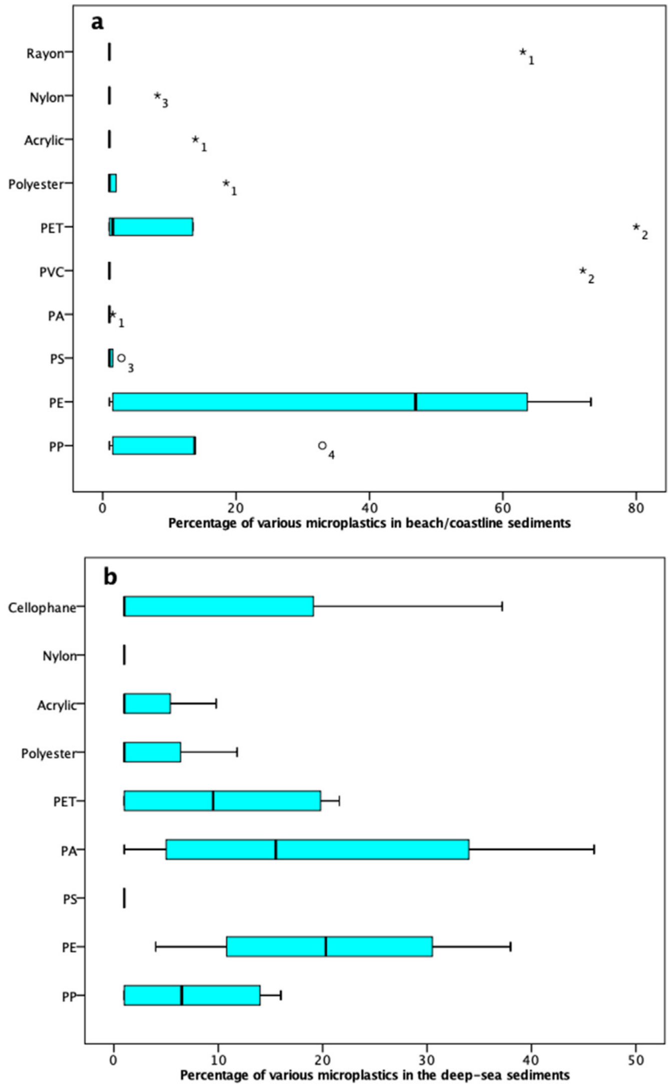


**Fig. 3.** Boxplots displaying the percentage of various microplastics (PP, PE, PS, PA, PET, Polyester, Acrylic, Nylon, Cellophane) found in beach (a)(n = 5) and deep-sea sediments (b)(n = 5). In the boxplot a, circles (o) denote mild outliers and extreme outliers are marked with asterisks (*).

colonization by microorganisms. Additionally, offshore convection, severe coastal storms, saline subduction, and dense shelf water cascading also facilitate the transfer of microplastics to benthic sediments (Sanchez-Vidal et al., 2012; Stabholz et al., 2013). The vertical and/or horizontal transfer of microplastics from shallow coastal regions to deep ocean layers is induced by all these processes. Large quantities of microplastics occur in ocean sediments as evidenced from heavily impacted coastal areas where microplastics can make up to 3% of sediment weight (Carson et al., 2011; Boucher et al., 2016).

Microplastics have been found in the deep ocean sediments at different locations including the North Atlantic Ocean, Southern Ocean, Mediterranean Sea, Gulf of Guinea (Van Cauwenberghe et al., 2013), Arctic deep-sea (Bergmann et al., 2017), Pacific Ocean (Fischer et al., 2015), Atlantic Ocean (Woodall et al., 2015), and South Yellow Sea (Wang et al., 2019c). Bergmann et al. (2017) found a large amount (42–6595 microplastics $kg^{-1}$) of microplastics in Arctic deep sea sediments, the largest proportion of which were PE, PA, and PP. However, there are only a few studies to date on microplastics in deep sea sediments. Instead there are numerous surveys on microplastics in shallow water, coastal areas, beaches, and estuarine areas. These studies have found an abundance of microplastics in the sediments of beaches, coastal lagoons, and shorelines (Bayo et al., 2019; Gomiero et al., 2019; Robin et al., 2020). The load and type of microplastics in the sediments of coastal areas strongly depend upon nearby human populations (Van Cauwenberghe et al., 2015). Generally, PE, PP, and LDPE make up the major proportion of microplastics found in sediments of beaches and coastal areas (Fig. 3a). However, denser polymer fibers of PS are also reported frequently in coastal areas with high PS inputs (Erni-Cassola et al., 2019). Similarly, high concentrations of microfibrils of textile origin were reported by Browne et al. (2011) near a discharge site of effluents of wastewater treatment.

The deposit and suspension feeders are the predominant benthic communities on the ocean floor. They obtain energy and nutrients from sediments and detritus (Griffiths, 2010). These organisms will also be affected by the settling or deposition of microplastics by ingesting them, just like pelagic suspension filter feeders (Taylor et al., 2016). Even the organisms living in intertidal zones, such as amphipods and marine worms (Wright et al., 2013), ingest microplastics and suffer health consequences such as reduced survival rates and decreased energy reserves. Several studies have highlighted the capacity of benthic organisms including polychaetes, bivalves, and starfish to ingest microplastics from the ocean floor and consequently suffer adverse health impacts (Green et al., 2016; Sussarellu et al., 2016; Fang et al., 2018). Benthic organisms can also alter the properties of microplastics through bioturbation (i.e. moving plastic particles deeper into the sediments), however, this process of microplastic burial in ocean floor sediments remains unclear.

## 6. Invasive alien species are hitchhikers on microplastics

With increasing microplastic concentrations in the world's oceans, there are more opportunities for the invasion of exotic species. Microplastics provide free rides to these species and can therefore play an important role in the dispersal of various marine organisms to new habitats (Andrady, 2011). Although the presence of various marine organisms on microplastics was documented much earlier (Barnes, 2002; Zettler et al., 2013), the phenomenon of marine alien microorganisms hitchhiking on plastic particles still remains unexplored. In a recent study, Viršek et al. (2017) discovered the presence of *Aeromonas salmonicida,* an exotic pathogenic bacterium responsible for illness in fish, on microplastics in the North Adriatic, providing evidence for the spread of pathogenic organisms by microplastics. Kirstein et al. (2016) found the pathogenic vibrio species on a number of floating microplastics, highlighting the urgent need for a biogeographical analysis of microplastics.

Some natural materials like macroalgae also provide substrate for small marine microorganisms, but they do not show the pattern of transportation that microplastic materials do. Therefore, microplastics are potentially a greater threat in the spread of invasive species compared to natural materials (Barnes and Milner, 2005). However, the mechanism by which microplastics strand alien species, and how it differs from natural materials, is still unknown and unexplored. The ecological impacts of hitchhiking of various species on microplastics cannot be established until various linkages are developed. For example, the arrival of marine algae and phytoplankton, their survival and reproduction in novel habitats in the open ocean, and their subsequent success in establishing large populations will determine their overall ecological impact.

Heating properties: could it impact the temperature of oceans?

Plastics can absorb solar radiation and consequently increase their temperature. This can have a direct effect on the temperature of its surroundings. This effect of microplastics doesn't seem to cause much change in the temperature of the water in marine environments. However, the concentration of microplastics is increasing at an accelerated rate, and even a little change in temperature can impact breeding, spawning, and rhythmic activities of marine organisms. For instance, in fresh waters, temperature affected the toxicity of microplastics in *Daphnia magna* and *Daphnia pulex*, but, it did not have any impact on *Ceriodaphnia dubia* (Jaikumar et al., 2018). Localized colonization of microplastics in the oceans may alter the temperature of any specific locality that can cause population level effects especially in the smaller marine organisms, for example, phytoplankton, algae, and zooplanktons (Wright et al., 2013).

The toxicity of microplastics may increase with a rise in temperature. For example, it can increase the bioavailability of heavy metals associated with it (Li et al., 2013; Cornu et al., 2016). Also an increased temperature can contribute to the microplastic degradation process. The tiny microplastic particles thus would be more mobile and could cause more acute toxicity. Temperature fluctuations may also impact microbial enzymes that are considered fundamental to the cycling of nutrients. However, research in this area is required to assess the extent of toxicity microplastics will have on marine organisms in an increased environmental temperature.

## 7. Conclusion and future directions

Plastics have become widely distributed in the marine environment because they have been used extensively throughout the world in the last few decades. Their concentration will be increased in the coming years because of large scale growth of plastic production. Several studies have shown the negative ecological impacts that these particles can have. However, the extent of the potential ecological effects of microplastics on marine life at different spatial and temporal scales has not yet been determined. The management and protection of oceans is clearly required as microplastics are adversely affecting marine organisms and ecological processes, which could ultimately impact human health as we are the top consumers in these ecosystems. Extensive target monitoring programs at multiscale levels should be developed to quantify the effect and frequency of the interaction of marine organisms with microplastics. The interactions between marine organisms and microplastics will be more frequent in regions where biological productivity is highest such as seas with densely populated coastal areas. Additionally, we predict that these interactions will help determine the ultimate fate of microplastic contaminants in the marine environment. Similarly, more research is required to fully understand the risk and fate of sorbed chemicals in the environment. Microplastics also serve as vectors and transporters of toxigenic and pathogenic eukaryotic organisms in the ocean which can be taken up by fish or other marine organisms, with lethal effects. Sunken particles can also harm benthic communities, and thus they have the capacity to disturb the ecosystem by adversely impacting just one trophic level in the food chain. However, further study is required in this regard to understand the impacts of microplastic-related microorganisms on marine organisms. Heating properties may also impact ecological processes in the oceans. Also, not much is known about the facilitating nature of microplastics in transporting invasive alien species to new habitats, but previous studies have raised concerns in this regard. Further research is strongly recommended in order to determine ecosystem level effects of microplastic-assisted alien communities by exploring their survival, reproduction, and establishment of large populations in new habitats in oceans.

## Credit author statement

Noreen Khalid: Conceptualization, Writing - Original Draft. Muhammad Aqeel: Visualization, Investigation. Ali Noman: Writing - Review & Editing. Mohamed Hashem: Visualization Yasser S. Mostafa: Funding Acquisition. Haifa Abdulaziz S. Alhaithloul: Writing - Review & Editing. Suliman M. Alghanem: Writing - Review & Editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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