RESEARCH PAPER

Contrasting One Health With Microplastics

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Abstract: -
A rapidly growing global environmental and public health hazard is microplastic contamination. Uncontrolled usage of plastics and lack of appropriate disposal and recycling technology have led to increase the concentration of microplastic in environment. Microplastics, or plastic residues are considered to be omnipresent nowadays they are found in an aquatic and terrestrial environment as well as in air. These particles come from a variety of primary and secondary sources, they are basically released in environment by breaking down of bigger plastic material either due to physical withering, chemical reactions or biological activity. Microplastics act as vectors of environmental toxins by absorbing and transporting hazardous materials such as pesticides, heavy metals, polychlorinated biphenyls, and persistent complex organic compounds. All life forms and environment are continuously exposed to microplastics via., consumption of microplastics contaminated food material, inhalation of microplastic particles in the air, and use of cosmetics containing microplastics. These particles penetrate physiological and cellular barriers and interfere with life processes. Their occurrence in human lungs, blood, placenta, and faeces have raised grave worries about possible bioaccumulation and long-term health implications. This review critically narrates the pros and cons of plastics, impact of microplastics with reference to one health and environment, their detection and possible bio-remediations.
KEYWORDS: One Health; plastics; Microplastics; Environment; toxicity

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Introduction

Plastics one of the most essential synthetic elements in the modern world, they have transformed the way people transport, store, package, and consume commodities. They are extensively used in the packaging, construction, electric materials, automotive, and healthcare sectors due to their affordability, flexibility, durability, and low cost [1]. Nevertheless, there exist substantial environmental cost associated with these benefits. Production of plastic has increased alarmingly in past 50 years. Global plastic output topped 360 million tons in 2019 and is still increasing yearly [2]. Recycling rates are still low despite increased awareness of the plastic pollution; only over 9% of it is recycled, while the remaining is dumped in the environment, including dumping in water bodies, landfills and burned [3]. Microplastics are considered omnipresent, found in freshwater systems, drinking water, urban air, agricultural fields, marine sediments, and even polar ice caps [4,5]. Environmental factors like wind, UV light, and mechanical abrasion cause larger plastic waste to break down into increasingly smaller pieces, which eventually form microplastics and nanoplastics (particles smaller than 100 nm) [6]. Plastics sustain their original chemical characteristics even after breaking down into smaller particles instead they become more reactive in leu of increased surface area [7]. The environmental buildup of microplastics, and nanoplastic particles is one of the biggest challenges in to-days scenario. These particles, formerly assumed to be harmless, are increasingly recognized as potential risks to ecological systems and human health [8].

Microplastics

Release of microplastics

Microplastics are purposefully produced for usage in industrial abrasives, air-blasting technologies, and cosmetic items (including toothpaste, exfoliants, and face scrubs) [9]. The breakdown of bigger plastic debris comprising of polyethylene (PE), polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), Polyethylene terephthalate (PET) and Polyamide (nylon)., generally found in rivers, oceans, agricultural soils, and municipal waste systems, resulting in small sized microplastics particle [6]. Human activities including inappropriate dumping, industrial effluents, wastewater treatment output, and road traffic (via., tire wear particles), natural vectors like wind, rain, and river outflows also contribute to this extensive distribution [10].

PE are widely used in bags, bottles, and containers [11]. Depending on density they are classified as high-density (HDPE) and low-density (LDPE) types. PP are used in preparing bottle caps, straws, food containers, and synthetic fibers [12]. PS are used in disposable cutlery, packaging foam, and insulation materials [13]. PVC one of the most resistant types of plastic find applications as construction materials, piping, and as consumer goods [14]. Single use plastics materials are generally made from PET. They are used in beverage bottles and

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synthetic textiles while Polyamide (nylon) are employed for preparing fishing nets, textiles, and ropes [15].

Characterization of Microplastics

To effectively assess microplastics present in environment, their behaviour, and associated health issues, these must be identified and characterized accurately. Based on origin they are broadly classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured small plastic particles, typically spherical or fibrous in shape, with uniform surface characteristics. These are commonly used in cosmetic and personal care products such as sunscreen, hair dye, makeup, shower gels, nail polish, scrubs, eye shadow, facial cleansers, air-blasting agents, and toothpaste [16–19]. Synthetic fibres released during clothing production and laundering are also considered as primary microplastics [20].

Generally when larger plastic objects break down through weathering, photodegradation, and other degradation processes, secondary microplastics are formed. These particles vary in shape, size, and color due to their degradation process [6,21]. The shape influences transport behavior and biological uptake [22]. In environmental samples microplastic particles may be found as pellets, fragments, and fibres, but other forms such as ropes, films, sponges, foam rubber, and microbeads are also prevalent [23]. Particles larger than 500 µm can be separated using standard sieves and can be visualised using dissecting microscope. In contrast, particles smaller than 500 µm are typically separated using density-based methods and filtration techniques but their accurate detection is difficult since they may be confused with other particles possessing same size range [22]. Although no global standard exists for the classification of microplastics, several classification manuals have been proposed [24,25]. Based on size microplastics are defined as large microplastics (1–5 mm), small microplastics (100 µm–1 mm) and nanoplastics (<100 nm). The size significantly affects ingestion likelihood, bioavailability, and ability to cross biological membranes [7,26]. In addition to size, color plays a crucial role in the characterization. Microplastic may vary in colours include black, blue, white, transparent, red, green, purple, yellow, and pink [24,27]. These techniques help classify the plastic type and determine the degree of environmental degradation [28,29].

Density separation and filtration: These are commonly applied to isolate microplastics from complex environmental matrices like soil, sediment, or water, using salt solutions and membrane filters [32].

***Surface morphology and functional groups*:** Environmental aging change the texture of microplastics, they become more porous and chemically reactive. Thereby making microplastics adsorb pollutants and interfere with biological systems [30]. Visual inspection under a dissecting microscope is used for identifying particles >300 µm but prone to human error and misidentification, especially for smaller or transparent particles [22]. While scanning electron microscopy(SEM) and transmission electron microscopy(TEM) are useful in identifying changes associated with microplastics degradation [31].

Analytical techniques for detection: In addition to microscopic techniques the molecular and chemical identification can be studied more accurately using Fourier-transform infrared spectroscopy (FTIR), while Raman spectroscopy are widely used to identify polymer types based on their characteristic molecular vibration patterns [28]. Toxics effect of leached microplastics from mask made up polypropylene (PP), was studied on using *Chlorella* Sp. and *Scenedesmus* Sp.. The analysis of morphological changes in surface as well as cell aggregation were performed using Optical microscope and FTIR. [32] . The identification of microplastics is also possible using spectrophotometric techniques. The lambda max of plastic polymers is mentioned in Table 1.

Table 1. Lambda Max of Microplastic Polymers

Polymer Type	**Average wavelengths (nm)**	**Reference**
Polyethylene (PE)	200–800	[33]
Polypropylene (PP)	300–360	[34]
Polystyrene (PS)	200–300	[35]
Polyvinyl chloride (PVC)	290–340	[36]
Polyethylene terephthalate (PET)	300–750	[37]

***Thermal methods*:** Pyrolysis–Gas Chromatography/Mass Spectrometry (Py-GC/MS), Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) allow decomposition of polymers into thermal fragments, which can be analyzed to determine plastic type [38].

However, there is still a lack of globally standardized protocols, which complicates inter-study comparisons and the formulation of consistent policies [3,39].

Microplastics vs Environment Health

These size ranges reflect common particle dimensions found in environmental and experimental studies and underscore their potential for cellular interaction and internalization. The toxicity and environmental fate of each polymer are influenced by its unique density, chemical characteristics, and degrading behaviours [22,40,41]. Microplastic creates negative impact on flora and fauna depends on their absorptivity and interaction with surroundings. It has been noticed that microplastic interaction with soil alters its water holding capacity and its permeability which in turn reduce the agricultural productivity [42], raising the risk of desertification and ultimately jeopardising human and animal provisioning.

Environmental entry points of microplastics

Microplastics are no longer confined to surface waters like rivers, lakes, and ponds—they have also been identified in deep-sea sediments, polar regions, and other remote environments [5,43, 44,45]. Plastics make up roughly 10% by weight of the debris found in municipal drainage systems and sewage effluents [2]. Additionally, sewage sludge spills can introduce microplastics into the soil, contributing to terrestrial pollution [46]. Over 150 million metric tons of plastic waste has been dumped in oceans [43], representing approximately 2.6% of all primary plastic production [3].

Significant plastic pollution also arises from tourism activities such as visits to beaches, waterfalls, and dams, where plastics are improperly discarded [13,40,47]. Furthermore, plastic debris from damaged fishing and agricultural equipment—including nets, lines, and films—is frequently dumped into both aquatic and terrestrial environments [47,48]. Plastic waste from households, daily activities, and industrial processes also significantly contributes to plastic pollution.

In the atmosphere, sources of microplastics include synthetic textiles, construction materials, abrasive powders, 3D printing processes, waste incineration, and tire wear particles [49]. In agriculture, microplastic contamination arises from materials used for making greenhouse, irrigation pipes, soil conditioners, fertilizers, irrigation water, atmospheric deposition, and abrasion of plastic materials used on farms [50].

Industrial processes such as cutting, grinding, and manufacturing of polymers release large amount of microplastc in air. Also release microplastics into the air. Although some plastic polymers are considered biochemically inert because of greater molecular size, hence they are not considered directly harmful to their nearby surrounding [51]. Residual monomers remaining after polymerization can leach out posing environmental risks. Although the associate risk depends on physicochemical properties of the polymer [52]. Leithner et al. [53] introduced a method for assessing hazardous effects of a polymer, based on the toxicological classification of its monomeric constituents. According to Lebreton et al. [54], an estimated 300 million tons of microplastics have already been accumulated on the Earth's thereby posing alarming threat to ecosystems [55].

Infiltration of microplastics in the environment

Plastic waste is carried into water bodies via stormwater drainage and urban runoff [13]. The discharge of microplastics is largely caused by wastewater treatment plants (WWTPs). A significant amount of microplastics escape into effluents, despite the fact that many facilities maintain a high percentage of microplastics in sludge [56,57]**.** Agricultural runoff contributes microplastics into soil ecosystems, especially when sewage sludge or plastic mulch is employed [58]. Synthetic fibres, construction dust, vehicle emissions, and tire wear release microplastics in atmosphere resulting in air pollution [4,59]. Recreational activities, plastic packaging, abandoned fishing gear, and riverine transportation are all sources of inputs to freshwater and marine systems [11,54].

Similarly, microplastics disruption of light penetration and other sea ice processes [60] may have detrimental impacts on the local ecosystem and the climate globally, hurting the environment as well as the health of people and animals. Plastic litter may have an impact on dune systems in coastal environments. This includes release microplastic which may interfere with germination of seed by mimicking phytohormones production of plastic leachates that may change seed germination by imitating phytohormones, which could have an effect on the dynamic dune formation [61]. Because dunes are crucial for preventing flooding and coastal erosion [62], microplastic impacts may have broader effects on the geomorphology, economy, and health of these areas. These numerous channels of entry draw attention to how complicated microplastic pollution is and how challenging it is to identify and reduce its sources.

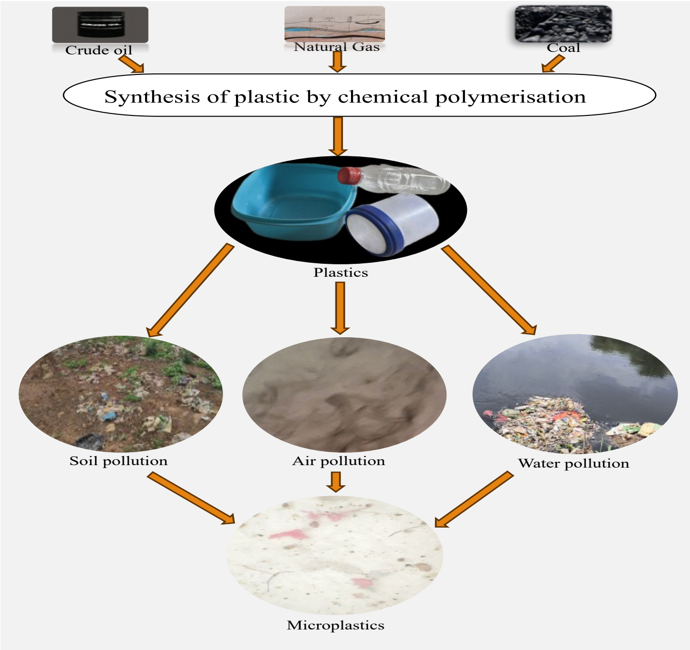

Figure 1. Source of plastics and microplastics entering the environment.

Microplastics vs human health

Microplastics being omnipresent may enter human body by various routes and interfere with human's metabolism. With microplastics present in seafood, sea salt, honey, drinking water, and a variety of other foods, ingestion is arguably the most well-established route [63,64]. Another important pathway is inhalation, especially indoors where it is easy to breathe in fibers from household dust and textiles [9]. Though skin penetration of microplastics is still poorly understood, recent research have also increased the risk of cutaneous exposure, especially through cosmetic goods and occupational use of materials containing plastic [65]. Personal care products containing microbeads may lead to accumulation of microplastics on skin thereafter penetrating inside body [17].

The biological fate of microplastics in the human body whether they build up, are eliminated, or eventually have subclinical or clinical health effects is still not established. Internal environment of organism such as pH, temperature, enzymes, organic molecules etc plays a major role in deciding its impact. The size, shape, type of polymer, and surface charge of the particles all affect some of these effects, which are dose dependent. The chronic and cumulative effects, especially from persistent low-level exposure, are still mostly unknown, even if acute toxicity may not necessarily be seen at environmentally relevant concentrations [66]. Occurrence of microplastics in human blood raised the possibility that they may circulate throughout the body and reach different organs [67]. They have also been detected in blood, stool, lung tissue, and placental tissue [67–69]. *In vitro* studies on impact of microplastics on human cell lines such as HT29, MTX-E12, CaCo 2, T98G, and HeLa have shown to cause oxidative stress, DNA damage, pro-inflammatory reactions, and even apoptosis [70–72]. An average adult could ingest over 50,000 microplastic particles per year, and even more when including inhalation sources [73]. These ingested particles may interact with the gastrointestinal lining, causing inflammation and potentially entering systemic circulation [10].

Microplastics vs animal health

Aquatic animals

Although the effect of microplastics on metabolic functions of aquatic animals is not clearly implicit, scientific reports confirmed adverse effects in growth, survival, and reproduction [74]. Filter feeders like mussels, clams, and oysters ingest microplastics from aquatic environments, which then accumulate in their tissues [63]. In a marine aquaculture system's microplastics had 100–5000 times more antibiotic-resistant bacteria than the surrounding water, endangering both human and fish health [75]. As fish make up 20% of the world's total animal protein intake, both direct and indirect effects of microplastics on fish populations may result in nutritional inadequacies in humans [76]. The adversative impacts of microplastics on biota may affect fisheries as well as aquaculture, which provides half of the fish consumed [77]. This may arise from the disruption of digestive functions brought on by exposure to microplastics, which can alter enzymes like trypsin and amylase [78]. A large amount of wild fish accumulate microplastics [79] through food and fish meal which pollute with these particles [80], adverse consequences may have an impact on aquaculture gains. Similar to this, aquatic habitats may experience a decline in these creatures' gains or survival. Furthermore, worries about microplastics in seafood may cause people to eat less of it, which could have a unfavourable effect on nutrition [81]. Marine animals have been found to consume microplastic particles in oceanic places around the world [82–85]. Research on

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marine species consuming microplastics has been conducted; the majority of these studies are based on stomach contents examination [86–88]. When consumed by marine life, microplastics injure them chemically and physically.

Microplastics may stick to external surface of marine organism and impede their movement, on other hand when consumed may clog the digestive tract and cause hepatic stress, they may induce inflammation and retard growth [83]. It has been reported that microplastics effect organisms living in various trophic levels in marine ecosystem. They have been largely detected in invertebrates such as lugworms [85,89], mussels [90,91], barnacles, sea cucumbers, amphipods, and zooplankton [88,92], fish-eating birds, fish, turtles, and mammals [86,93–95].

The entry of microplastics in marine organisms usually takes place through process of ventilation wherein water moves from the base of organisms limbs , absorbs tiny particle debris into the gill chamber and finally inside gills [96]. Microplastic is frequently found in marine cetaceans, such as dolphins and whales. Hernandez-Gonzalez et al. [97], reported presence of microplastics in stomach of dolphins'. Synthetic polymers of various sizes and shapes, including nylon, polyvinyl chloride, and polystyrene have been detected in gut of *Megaptera* Sp. [98]. Both acute and chronic toxicity might result from the consumption of these microplastics by cetacean species. According to Besseling et al. [98] eating microplastic can impede digestion by obstructing the intestinal track. Additionally, research revealed that microplastic may obstruct or clog marine organisms' (Balaenoptera Physalus L.) filtering systems. There have also been reports of marine turtles ingesting microplastic [99]. Some frequent harmful effects linked to a turtle ingesting microplastic include severe digestive tract damage and obstruction, decreased stomach capacity, and death. Additional detrimental consequences linked to marine turtles consuming microplastic include changes in swimming habits, immunological response, growth rate, and ability to evade prey. The number of marine turtles is declining as a result of all these reasons. Additionally, Camedda et al. [100] and Wilcox et al. [101] noted that turtles can become entangled in plastic waste, which can lead to several turtle deaths. Plastic waste can have an adverse effect on environmental elements like temperature in the turtle's habitat, and this change in habitat quality has an adverse effect on the sea turtle's ability to reproduce.

Terrestrial animals

Sacred cows in India died of malnutrition after consuming plastics because it obstructed their digestive tracts [102]. Livestock or wild animals may experience the same fate if there are significant levels of plastics or microplastics in the environment. Humans would lose out on nutrient-dense and valuable animal food products or ecosystem services that these animals provide (such as grazing to manage vegetation). Although it is not anticipated that microplastics will have such negative impacts on large cattle, they might have comparable negative effects on smaller organisms that also provide ecosystem services, including detritivores [103,104].

Toxicological effects on human cells

Can microplastics affect human cells and tissues? Clearly, there's an absence of toxicity data for humans in vivo at this point. However, several studies have investigated the impact of microplastics on human cells. Not surprisingly, in a number of these studies, despite documenting some degree of cellular uptake, signs of cellular toxicity were found to be either absent or insignificant, except in cases involving very high concentrations of microplastics [105].

In their investigation involving polyethylene terephthalate (PET) produced via laser ablation and assessed on the human gut adenocarcinoma epithelial line Caco-2, researchers [106] observed a marked tendency for nanoparticle uptake and penetration through a Caco-2 cell-derived intestinal barrier model.

Several other studies have demonstrated some degree of cellular toxicity or pathological effects on a range of human cell lines. Shirinzi et al. [72] carefully documented a clear but modest level of reactive oxygen species (ROS) in the cytotoxic effects caused by microplastics (MPs) in both T98G and HeLa cell lines. In their study involving Caco-2 cells, Wu et al. [107] shed light on the cellular impact that PS nanoparticles (0.1 and 5 μm) had on mitochondrial depolarization and ATP-binding cassette (ABC) transporter function. Consequently, arsenic toxicity was increased.

In their comprehensive investigation spanning various human and mouse cell types, Hwang et al. [108] documented the manifestation of cytotoxicity linked to high concentrations of 20 μm polypropylene (PP) microplastics, accompanied by notable reactive oxygen species (ROS) induction. Moreover, the MPs elicited the production of pro-inflammatory cytokines IL-6 and TNF-α from human peripheral blood mononuclear cells (PBMCs) and heightened histamine release from mast cell lines. In their investigation, Poma et al. [109] found that 100 nm polystyrene (PS) nanoparticles elicited heightened reactive oxygen species (ROS) production, leading to the induction of genotoxic stress and DNA damage.

Due to the presence of large amounts of plastic particles in the air, terrestrial animals are also exposed to microplastics and nanoplastics via inhalation. In this context, Dong et al. [110] and associates found that PS microplastics produced cytotoxic effects, oxidative stress, and inflammatory responses in human lung epithelial cells and were disruptive to the epithelial cell layer in vitro. Xu et al. [111] and colleagues found that PS nanoplastics (25 and 70 nm) impaired viability, induced cell cycle arrest, and upregulated nuclear factor (NF)-kB as well as some pro-inflammatory cytokines in the human alveolar epithelial line A549. Additionally, it was revealed that polystyrene (PS) nanoparticles exhibited cytotoxic effects only at elevated concentrations. Nanoplastics also instigated metabolic alterations and triggered endoplasmic reticulum (ER) stress within a human bronchial epithelial cell line [112].

Overall, the trials with pristine microplastic on human cells reported so far did not indicate severe cytotoxic or cytostatic effects. However, their effects cannot be ignored. Therefore, more in-depth study is needed in this area.

Table 2. Summary of toxicological findings associated with MPs/NPs in human cells

Human cell models	**MPs/NPs (Type and size)**	**Effect**	**References**
HeLa (human cervical adenocarcinoma cell line) T98G (human glioblastoma cell line)	Polyethylene (PE) and Polystyrene (PS), from 10 ng/mL to 10 µg/mL	• Induced cytotoxic effects in both cell lines. • Elevated reactive oxygen species (ROS) generation.	[72]
Human colon adenocarcinoma Caco-2 cells	Polystyrene microplastics (PS-MPs) from 0.1 mm and 5 mm	• Minimal effects on cell viability, oxidative stress, and membrane integrity. • Disruption of mitochondrial membrane potential. • Inhibition of ATP-binding cassette (ABC) transporter activity.	[107]
HMC-1 (The human mast cell line −1) Peripheral blood mononuclear cells (PBMCs) Human dermal fibroblasts	Polypropylene microplastics of approximately ~20 µm and 25–200 µm	• Increased secretion of cytokines and histamines in PBMCs and HMC-1. • Mild cytotoxicity at high concentrations of 20 µm particles.	[108]
Human lung epithelial BEAS-2B cells	PS-MPs were 1.72 ± 0.26 μm (1.67–2.17 μm)	• Elevated risk of respiratory impairment and chronic lung disease. • Potential contributor to chronic obstructive pulmonary disease (COPD).	[110]
Human alveolar epithelial A549 cell line	PS-NP 25 nm and 70 nm	• Decreased cell viability and induced cell cycle arrest. • Altered expression of pro-apoptotic and cell cycle-related proteins.	[111]
Human bronchial epithelial (BEAS-2B) cells	PS nanoparticles	• Cytotoxic only at high concentrations. • Induced metabolic disruption at lower exposures.	[112]
Hs27 cell line	Polystyrene nanoparticles 100nm	• Increased ROS production. • Genotoxic effects and DNA damage confirmed via cytokinesis-block micronucleus assay.	[109]

Microplastics vs Plants and Algal Health

The alteration of microalgae populations, either through decreased nutrient absorption or altered populations of predator species, may have an additional ecosystem-wide impact of microplastics. This could affect the survival of these organisms, which account for half of the primary net production, for preserving water quality, several biogeochemical processes, and significant O_2 production [113].

The number of algae that serve as a source of energy for several other aquatic species that eat them may also be impacted by the presence of microplastics in aquatic bodies. There have been numerous reports of algae, including *Chlorella* Sp., *Scenedesmus*, and *Dunaliella* Sp., absorbing and accumulating microplastics [114]. Microplastics have harmful consequences on algae, including oxidative stress and a decrease in photosynthetic activity. The microplastic's positive charge and the algae's negative charge facilitate its absorption and buildup through the algae. When microplastics are present, a decrease in photosynthetic activity has a direct detrimental impact on algae biomass, which lowers the total amount of food available to other marine animals that depend on algae [115]. The detrimental impact of microplastics on the marine biota was thoroughly demonstrated by the investigations.

Mao et al. [116] conducted experiment using 0.1 mm and 1.0 mm size microplastics, in three concentration (10mg/l, 50mg/l, and 100mg/l) gradient, and found dose dependent toxic effect on growth of *Chlorella pyrenoidosa*. The other associated effect included physical damage to thylakoids and membranes. polymethyl methacrylate (PMMA) microplastics adversely affected growth and photosynthetic activity of *Phaeodactylum tricornutum*. They found of microplastics and salinity both together can significantly affect chlorophyll fluorescence parameters. Accumulation of soluble protein, alteration in antioxidant activity and malondialdehyde (MDA) content were observed inside algal cells when exposed to microplastics [117].

Studies were conducted using PVC microplastics where *Phaeodactylum tricornutum* (B255), *Chaetoceros* *gracilis* (B13), and *Thalassiosira* Sp. were exposed for 24, 48, 72, and 92 hours with microplastics. Studies reported high PVC concentration (200 mg/L) reduced chlorophyll content, inhibited Fv/Fm, and affected photosynthesis of all three marine diatoms. Physical damage to the structure of algae cells [118]. While Zhang, et. al. [119] used SEM to observe interactions between microplastics and algae. Microplastics (PVC, average diameter 1 mm) inhibited the growth of microalgae, and the maximum growth inhibition ratio reached 39.7% after 96 hours of exposure. Photosynthesis was negatively impacted as both chlorophyll content and photosynthetic efficiency (ɸPSII) decreased under PVC treatment. Have been studied by Ziajahromi, et al. [120] they identified microplastics using FTIR, they found an average of 0.9 ± 0.3 and 4.0 ± 2.4 microplastic particles/L in the water phase in the inlet and outlet samples, respectively. The sediment contained 595 ± 120 and 320 ± 42 microplastic particles/kg of dry sediment in the inlet and outlet sediments, respectively.

Microplastics as Vectors

Once released into the environment, microplastics interact with a range of contaminants, including organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides like dichloro diphenyl trichloroethane (DDT), heavy metals like cadmium, lead, and mercury can be adsorbed on microplastic surface [121] and serve as carriers for a wide range of dangerous compounds [26]. Large surface area and hydrophobicity, enable microplastics to adsorb and transport organic pollutants across environmental compartments, thereby amplifying their ecological impact [122]. These may interact with a variety of biological systems such as human, animal, plants, microbes etc along with their microhabitat and macrohabitats and their surroundings. A study by Bakir et al. [123] investigated the adsorption and desorption behaviours of PVC and PE in relation to several organic pollutants, including DDT, phenanthrene, perfluorooctanoic Acid (PFOA), and Di(2-ethylhexyl) phthalate (DEHP). The research assessed the environmental hazard of combinations of plastics and pollutants and categorizing them according to the level of environmental impact. Seidensticker et al. [124] examined 19 different pollutants across three pH levels, using two types of plastic materials and discovered hydrophobic organic compounds exhibited significantly stronger adsorption of microplastics as compared to neutral or polar substances, highlighting the role of chemical characteristics in pollutant-plastic interactions. In addition to organic compounds, microplastics may adsorb heavy metals on their surfaces. When microplastics enter the soil, they geochemically interact with heavy metals. Hodson et al. [125] demonstrated microplastics enhance the mobility and bioavailability of heavy metals in terrestrial ecosystems. The adsorption rates of heavy metals vary greatly depending on chemical and physical properties of microplastics [121,126]. Exposure to ultraviolet (UV) radiation further modifies the surface properties of microplastics, enhancing their adsorption capacity. Bandow et al. [127] reported that after 2000 hours of UV irradiation, the adsorption of copper (Cu) and zinc (Zn) on microplastics increased significantly. Similarly, Brennecke et al. [126] found that aged PVC debris accumulated higher concentrations of Cu and Zn. A study by Massos and Turner [128] quantified the adsorption rates of cadmium (Cd) and lead (Pb) on plastic surfaces, reporting values of 6.9% for Cd and 7.5% for Pb, indicating the adsorption heterogeneity of different microplastics. These variations are influenced by polymer type, surface aging, and environmental conditions.

Upon ingestion or inhalation, these bound pollutants may desorb in human tissues, increasing systemic toxicity and bioaccumulation [121,121]. The sorption process depends on microplastic properties like polymer type, aging, surface charge, as well as environmental factors such as pH and temperature [129]. These interactions raise concern that microplastics act not only as physical particulates but also as chemical vectors, potentially enhancing exposure to persistent organic pollutants and heavy metals in humans.

Degradation and Bioremediation

Degradation mechanisms of plastics and microplastics are generally slow and incomplete under natural environmental conditions, particularly in low-light, low-temperature, or anoxic settings [130] as a result, microplastics can persist for decades, contributing to long-term environmental contamination. Photodegradation, triggered by sunlight, is often the initial step, which prepares plastic polymers for subsequent oxidative and hydrolytic breakdown [131]. Several other natural processes can aid in the degradation of plastics, including thermo-oxidative degradation, hydrolysis, and biodegradation by microorganisms [40]. Moreover, the biodegradation potential of plastic-consuming insects, such as mealworms (*Tenebrio molitor*) and waxworms (*Galleria mellonella*), is a growing field of interest. These organisms have demonstrated the ability to ingest and degrade synthetic polymers like polystyrene and polyethylene through gut microbiota-assisted mechanisms. Further research into such insect-plastic interactions could uncover novel enzymes or metabolic pathways for biotechnological applications [132].

Microbial Biodegradation

Microbial biodegradation of plastics has emerged as promising approach, as many microbes possess enzymes capable of breaking down plastic polymers through chain cleavage and depolymerization. Microorganisms involved in plastic biodegradation harbour genes encoding enzymes such as monooxygenases, peroxidases, dehydrogenases, lipases, hydrolases, esterases, and depolymerases, all of which contribute to the breakdown of complex polymer chains [133,134]. As a result, the polymers become brittle and fragment into monomers, oligomers, and dimers, which can then be metabolized by microbial pathways [40,133,135,136] Numerous bacteria capable of degrading plastic polymers have been identified. For example, Singh et al.

[137] reported that *Staphylococcus* Sp., *Pseudomonas* Sp., and *Bacillus* Sp. Isolated from soil were able to degrade plastic [115]. Similarly, Caruso et al. [138] reported the degradation of PVC by *Pseudomonas putida*. In another study by Asmita et al. [139], microorganisms such as *Aspergillus niger, Pseudomonas aeruginosa,* and *Bacillus subtilis,* demonstrated the ability to degrade PET and PS. These findings highlight the potential of microbial approaches for the biodegradation of microplastics and warrant further investigation into the metabolic pathways and enzyme systems involved.

Table 2. Some of the microorganisms capable of degrading plastic are listed in the table

Species	**Polymer Targeted**	**Pivotal takeaways/inferences**	**Enzymes Involved**	**References**
Pseudomonas aeruginosa	PE, PS	The PS composites were decomposed in vitro. For hydrocarbon degradation	Trypsin, monooxygenases	[140–142]
Bacillus subtilis	PET	Not specified: more research needed PET-hydrolase activity in the formation of terephthalic acid upon incubation with PET.	Unknown	[143]
Staphylococcus Sp.	PE	Decomposition of 40µ polythene.	Unknown	[137]
Pseudomonas Sp.	PE	Degradation of Polyethylene.	Esterase	[144]
Bacillus Sp.	PS	Degradation of High Impact polystyrene film.	Lipase, esterase	[137,144]
Rhodococcusruber	PE	Polymerization and subsequent processing, such as unsaturated carbon–carbon double bonds, carbonyl groups, and hydroperoxide groups.	Esterase	[145,146]

Enzymes such as monooxygenases, peroxidases, dehydrogenase lipases, hydrolases, esterase, and depolymerases play a role in the cleavage of polymer chains into monomers [133,134]. Biodegradation is influenced by environmental factors like temperature, Ph, and polymer crystallinity.

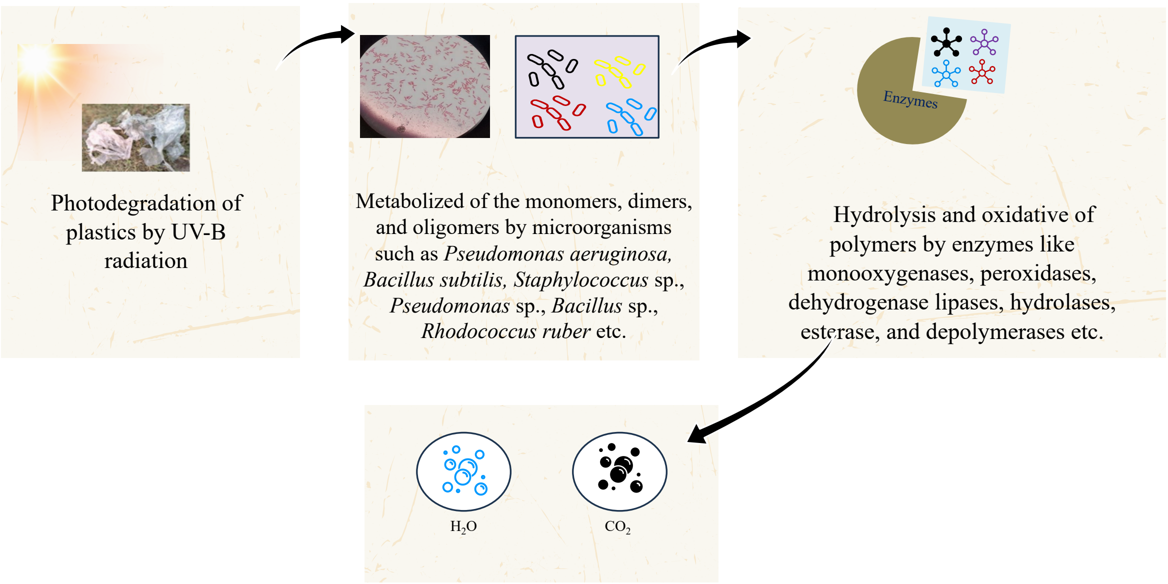

Figure 2. Degradation of plastic pollution by microorganisms.

Regulatory Measures and Global Responses

In addition to scientific solutions, public awareness is essential. Governments and regulatory bodies must take strong legislative actions to curb plastic pollution. In 2015, the United States government banned the manufacture, packaging, and distribution of rinse-off cosmetic products containing microbeads [147]. Under the *REACH regulation*, the European Chemicals Agency (ECHA) proposed restrictions on the intentional use of microplastics in cosmetics, detergents, paints, and agricultural products. The regulation is expected to prevent the release of 500,000 tonnes of microplastics over 20 years [148]. In India, states have implemented bans on single-use plastics while at national-level the Plastic Waste Management Rules (2022) have emphasized Extended Producer Responsibility (EPR) for treating plastic waste, including microplastic generation [149]. Cooperation among biologists, aquaculture managers, and environmental scientists could help determine the exposure and impact of microplastics. Meanwhile, medical experts can communicate potential health risks to humans and promote a sustainable, healthy lifestyle. Involvement of all stakeholders including engineers, consumers, producers and designers involved in development of plastic packaging and process may help in facing alarming situations arising because of microplastic pollution. However, effective implementation of policies remains challenging in developing economies due to a lack of infrastructure and regulatory capacity [150].

Future Directions

Environmental pollution caused by microplastics and nanoplastics derived from conventional plastic materials has emerged as a global concern due to their persistence, ecological impact, and potential toxicity. Addressing this issue requires a multi-pronged approach involving materials science, microbiology, and environmental policy. A systematic review of microbial plastic degradation is essential to identify sustainable and scalable solutions [151]. In particular, the isolation and genetic characterization of plastic-degrading microorganisms offer great promise. Identification of key biodegradation genes serves as baseline for engineering more efficient microbial strains or enzyme systems for useful in degrades microplastics residues.

Recent studies have advocated the use of free-living algae for plastic degradation due to their enzymatic capabilities and potential to integrate into recycling processes [152]. Algae not only colonize plastic surfaces but also facilitate photo-oxidation and enzymatic hydrolysis, making them viable candidates for bio-recycling systems.

Supporting interdisciplinary research in this domain and providing platforms for scientific innovation are critical to accelerating the transition toward a circular plastic economy.

Conclusion

Microplastics are a silent but pervasive threat, with implications for ecosystem stability and human health. Their interaction with biological systems, particularly at the cellular level, underscores the urgency of addressing this crisis. They are reported to cause oxidative stress, mitochondrial malfunction, DNA damage, inflammatory reactions, and altered immunological activities in living cells. While acute toxicity is often minimal, chronic exposure and bioaccumulation may lead to profound effects. As plastic production continues to rise, so does our responsibility to manage its life cycle sustainably. A unified global response integrating science, policy, and community action is critical to mitigate the long-term impact of microplastics on human health and the environment. Additionally, emphasis should be placed on the development and use of eco-friendly and biodegradable plastics that are less harmful to the environment and easier to degrade.

Highlight the pressing need to confront this new hazard through combined scientific, regulatory, and societal methods. Microplastics are a growing environmental contaminant of major concern because of their pervasiveness and the current knowledge gaps about their long-term health impacts. With suggestions to restrict purposeful plastic additives and prohibitions on microbeads in cosmetics in a number of nations, regulatory frameworks are starting to change. However, there is an urgent need for a comprehensive worldwide strategy that combines environmental policy, scientific research, and public health surveillance. The exposure pathways, cellular biological reactions, the function of microplastics as pollutant vectors, and current advancements in biodegradation techniques are also highlighted. In order to safeguard the environment and public health, this study aims to guide research directions, public policy, and risk mitigation methods by examining the wider ramifications of microplastic pollution.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

1. Thompson, R.C., Moore, C.J., Vom Saal, F.S. and Swan, S.H., (2009) Plastics, the Environment and Human Health: Current Consensus and Future Trends. *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**, 2153–2166. doi: 10.1098/rstb.2009.0053.
2. Plastics Europe, "Plastics—the Facts 2020. Available online at: https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020.
3. Geyer, R., Jambeck, J.R. and Law, K.L., (2017) Production, Use, and Fate of All Plastics Ever Made. *Science Advances* **3**, e1700782. doi: 10.1126/sciadv.1700782.
4. Dris, R., Gasperi, J., Saad, M., Mirande, C. and Tassin, B., (2016) Synthetic Fibers in Atmospheric Fallout: A Source of Microplastics in the Environment? *Marine Pollution Bulletin* **104**, 290–293. doi: 10.1016/j.marpolbul.2016.01.006.
5. Lusher, A.L., Tirelli, V., O'Connor, I. and Officer, R., (2015) Microplastics in Arctic Polar Waters: The First Reported Values of Particles in Surface

and Sub-Surface Samples. *Scientific Reports* **5**, 14947. doi: 10.1038/srep14947.

6. Cole, M., Lindeque, P., Halsband, C. and Galloway, T.S., (2011) Microplastics as Contaminants in the Marine Environment: A Review. *Marine Pollution Bulletin* **62**, 2588–2597. doi: 10.1016/j.marpolbul.2011.09.025.
7. Gigault, J., Halle, A.T., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., El Hadri, H., Grassl, B. and Reynaud, S., (2018) Current Opinion: What Is a Nanoplastic? *Environmental Pollution*, **235**, 1030–1034. doi: 10.1016/j.envpol.2018.01.024.
8. GESAMP. (2015) Sources, Fate and Effects of Microplastics in the Marine Environment. Journal Series GESAMP Reports and Studies. Available online at: http://www.gesamp.org/publications/reports-and-studies-no-90.
9. Prata, J.C., (2018) Airborne Microplastics: Consequences to Human Health? *Environmental Pollution* **234**, 115–126. doi: 10.1016/j.envpol.2017.11.043.
10. Wright, S.L. and Kelly, F.J., (2017) Plastic and Human Health: A Micro Issue? *Environmental Science & Technology* **51**, 6634–6647. doi: 10.1021/acs.est.7b00423.
11. Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. and Law, K.L., (2015) Plastic Waste Inputs from Land into the Ocean. *Science* **347**, 768–771. doi: 10.1126/science.1260352.
12. Andrady, A.L., (2017) The Plastic in Microplastics: A Review. *Marine Pollution Bulletin* **119**, 12–22. doi: 10.1016/j.marpolbul.2017.01.082.
13. Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T. and Thompson, R., (2011) Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks. *Environmental Science & Technology* **45**, 9175–9179. doi: 10.1021/es201811s.
14. Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D. and Russell, A.E., (2004) Lost at Sea: Where Is All the Plastic? *Science* **304**, 838–838. doi: 10.1126/science.1094559.
15. Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A. and Romano, D., (2018) Marine Litter Plastics and Microplastics and Their Toxic Chemicals Components: The Need for Urgent Preventive Measures. *Environmental Sciences Europe* **30**, 13. doi: 10.1186/s12302-018-0139-z.
16. Napper, I.E., Bakir, A., Rowland, S.J. and Thompson, R.C., (2015) Characterisation, Quantity and Sorptive Properties of Microplastics Extracted from Cosmetics. *Marine Pollution Bulletin* **99**, 178–185. doi: 10.1016/j.marpolbul.2015.07.029.
17. Fendall, L.S. and Sewell, M.A., (2009) Contributing to Marine Pollution by Washing Your Face: Microplastics in Facial Cleansers. *Marine Pollution Bulletin* **58**, 1225–1228. doi: 10.1016/j.marpolbul.2009.04.025.
18. Lei, K., Qiao, F., Liu, Q., Wei, Z., Qi, H., Cui, S., Yue, X., Deng, Y. and An, L., (2017) Microplastics Releasing from Personal Care and Cosmetic Products in China. *Marine Pollution Bulletin* **123**, 122–126. doi: 10.1016/j.marpolbul.2017.09.016.
19. Chang, M., (2015) Reducing Microplastics from Facial Exfoliating Cleansers in Wastewater through Treatment versus Consumer Product Decisions. *Marine Pollution Bulletin* **101**, 330–333. doi: 10.1016/j.marpolbul.2015.10.074.
20. Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O. and Hughes, K.A., (2017) Microplastics in the Antarctic Marine System: An Emerging Area of Research. *Science of The Total Environment* **598**, 220–227. doi: 10.1016/j.scitotenv.2017.03.283.
21. Crawford, C.B. and Quinn, B., (2017) Microplastics, Standardisation and Spatial Distribution. Microplastic Pollutants, Elsevier, 101–130. doi: 10.1016/B978-0-12-809406-8.00005-0.
22. Hidalgo-Ruz, V., Gutow, L., Thompson, R.C. and Thiel, M. (2012) Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environmental Science & Technology* **46**, 3060–3075. doi: 10.1021/es2031505.
23. Frias, J.P.G.L. and Nash, R., (2019) Microplastics: Finding a Consensus on the Definition. *Marine Pollution Bulletin* **138**, 145–147. doi: 10.1016/j.marpolbul.2018.11.022.
24. Frias, J., Pagter, E., Nash, R., O'Connor, I., Carretero, O., Filgueiras, A., Viñas, L., Gago, J., Antunes, J., Bessa, F., Sobral, P., Goruppi, A., Tirelli, V., Pedrotti, M.L., Suaria, G., Aliani, S., Lopes, C., Raimundo, J., Caetano, M. and Gerdts, G., (2018) Standardised Protocol for Monitoring Microplastics in Sediments. Deliverable 4.2. JPI-Oceans BASEMAN Project. https://doi.org/10.25607/OBP-723.
25. Rocha-Santos, T. and Duarte, A.C., Eds., (2017) Characterization and Analysis of Microplastics. Elsevier, Amsterdam, Netherlands; Oxford, United Kingdom; Cambridge, MA, United States.
26. Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., Meibom, A. and Baun, A., (2017) Microplastics as Vectors for Environmental Contaminants: Exploring Sorption, Desorption, and Transfer to Biota. *Integrated Environmental Assessment and Management* **13**, 488–493. doi: 10.1002/ieam.1904.
27. Ory, N.C., Gallardo, C., Lenz, M. and Thiel, M., (2018) Capture, Swallowing, and Egestion of Microplastics by a Planktivorous Juvenile Fish. *Environmental Pollution* **240**, 566–573. doi: 10.1016/j.envpol.2018.04.093.
28. Shim, W.J., Hong, S.H. and Eo, S.E., (2017) Identification Methods in Microplastic Analysis: A Review. *Analytical Methods* **9**, 1384–1391. doi: 10.1039/C6AY02558G.

29. Araujo, C.F., Nolasco, M.M., Ribeiro, A.M.P. and Ribeiro-Claro, P.J.A., (2018) Identification of Microplastics Using Raman Spectroscopy: Latest Developments and Future Prospects. *Water Research* **142**, 426–440. doi: 10.1016/j.watres.2018.05.060.
30. Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J. and Thompson, R.C., (2013) Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity. *Current Biology* **23**, 2388–2392. doi: 10.1016/j.cub.2013.10.012.
31. Kalaronis, D., Ainali, N.M., Evgenidou, E., Kyzas, G.Z., Yang, X., Bikiaris, D.N. and Lambropoulou, D.A., (2022) Microscopic Techniques as Means for the Determination of Microplastics and Nanoplastics in the Aquatic Environment: A Concise Review. *Green Analytical Chemistry* **3**, 100036. doi: 10.1016/j.greeac.2022.100036.
32. Das, S., Chandrasekaran, N. and Mukherjee, A., (2023) Unmasking Effects of Masks: Microplastics Released from Disposable Surgical Face Masks Induce Toxic Effects in Microalgae Scenedesmus Obliquus and Chlorella Sp. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology* **267**, 109587. doi: 10.1016/j.cbpc.2023.109587.
33. Kaczmarek, H., Oldak, D. and Podgórski, A., (2003) Photochemical Properties of Polyethylene Modified by Low-Molecular Organic Compounds. *Polymer Journal* **35**, 634–639. doi: 10.1295/polymj.35.634.
34. Zhenfeng, Z., Xingzhou, H. and Zubo, L., (1996) Wavelength Sensitivity of Photooxidation of Polypropylene. *Polymer Degradation and Stability* **51**, 93–97. doi: 10.1016/0141-3910(95)00210-3.
35. Goyal, T., Das Gupta, G. and Verma, S.K., (2023) Development and Validation of Simple UV-Spectrophotometric Method for the Estimation of Polystyrene Plastic/Microplastic. *Pharmaspire* **15**, 44–47. doi: 10.56933/Pharmaspire.2023.15107.
36. Amar, A. and Parisi, A.V., (2013) Spectral Response of Solvent-Cast Polyvinyl Chloride (PVC) Thin Film Used as a Long-Term UV Dosimeter. *Journal of Photochemistry and Photobiology B: Biology* **125**, 115–120. doi: 10.1016/j.jphotobiol.2013.05.012.
37. Ouchi, I., Miyamura, R., Sakaguchi, M., Hosaka, S. and Kitagawa, M., (1999) Excitation and Emission Spectra of Polyethylene Terephthalate and Polyethylene 2,6-Naphthalate Films. *Polymers for Advanced Technologies* **10**, 195–198. doi: 10.1002/(SICI)1099-1581(199903)10:3<195::AID-PAT875>3.0.CO;2-0.
38. Dümichen, E., Barthel, A.-K., Braun, U., Bannick, C.G., Brand, K., Jekel, M. and Senz, R., (2015) Analysis of Polyethylene Microplastics in Environmental Samples, Using a Thermal Decomposition Method. *Water Research* **85**, 451–457. doi: 10.1016/j.watres.2015.09.002.
39. Cowger, W., Booth, A.M., Hamilton, B.M., Thaysen, C., Primpke, S., Munno, K., Lusher, A.L., Dehaut, A., Vaz, V.P., Liboiron, M., Devriese, L.I., Hermabessiere, L., Rochman, C., Athey, S.N., Lynch, J.M., De Frond, H., Gray, A., Jones, O.A.H., Brander, S., Steele, C., Moore, S., Sanchez, A. and Nel, H., (2020) Reporting Guidelines to Increase the Reproducibility and Comparability of Research on Microplastics. *Applied Spectroscopy* **74**, 1066–1077. doi: 10.1177/0003702820930292.
40. Andrady, A.L., (2011) Microplastics in the Marine Environment. *Marine Pollution Bulletin*, **62**, 1596–1605. doi: 10.1016/j.marpolbul.2011.05.030.
41. Lambert, S., Scherer, C. and Wagner, M., (2017) Ecotoxicity Testing of Microplastics: Considering the Heterogeneity of Physicochemical Properties. *Integrated Environmental Assessment and Management*, Oxford University Press (OUP) **13**, 470–475. doi: 10.1002/ieam.1901.
42. De Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R. and Rillig, M.C., (2018) Impacts of Microplastics on the Soil Biophysical Environment. *Environmental Science & Technology* **52**, 9656–9665. doi: 10.1021/acs.est.8b02212.
43. The New Plastics Economy: Rethinking the Future of Plastics (2016). The Ellen MacArthur Foundation and McKinsey & Company. Available online at: https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics.
44. Mathalon, A. and Hill, P., (2014) Microplastic Fibers in the Intertidal Ecosystem Surrounding Halifax Harbor, Nova Scotia. *Marine Pollution Bulletin* **81**, 69–79. doi: 10.1016/j.marpolbul.2014.02.018.
45. Gola, D., Kumar Tyagi, P., Arya, A., Chauhan, N., Agarwal, M., Singh, S.K. and Gola, S., (2021) The Impact of Microplastics on Marine Environment: A Review. *Environmental Nanotechnology, Monitoring & Management* **16**, 100552. doi: 10.1016/j.enmm.2021.100552.
46. Zubris, K.A.V. and Richards, B.K., (2005) Synthetic Fibers as an Indicator of Land Application of Sludge. *Environmental Pollution* **138**, 201–211. doi: 10.1016/j.envpol.2005.04.013.
47. Yang, H., Xiong, H., Mi, K., Xue, W., Wei, W. and Zhang, Y., (2020) Toxicity Comparison of Nano-Sized and Micron-Sized Microplastics to Goldfish Carassius Auratus Larvae. *Journal of Hazardous Materials* **388**, 122058. doi: 10.1016/j.jhazmat.2020.122058.
48. Al-Oufi, H., McLean, E., Kumar, A.S., Claereboudt, M. and Al-Habsi, M., (2004) The Effects of Solar Radiation upon Breaking Strength and Elongation of Fishing Nets. *Fisheries Research* **66**, 115–119. doi: 10.1016/S0165-7836(03)00103-6.
49. Catarino, A.I., Frutos, A. and Henry, T.B., (2019) Use of Fluorescent-Labelled Nanoplastics (NPs) to

Demonstrate NP Absorption Is Inconclusive without Adequate Controls. *Science of The Total Environment* **670**, 915–920. doi: 10.1016/j.scitotenv.2019.03.194.

50. Song, Y., Cao, C., Qiu, R., Hu, J., Liu, M., Lu, S., Shi, H., Raley-Susman, K.M. and He, D., (2019) Uptake and Adverse Effects of Polyethylene Terephthalate Microplastics Fibers on Terrestrial Snails (Achatina Fulica) after Soil Exposure. *Environmental Pollution* **250**, 447–455. doi: 10.1016/j.envpol.2019.04.066.
51. Matlack, A.S., (2010) Introduction to Green Chemistry. *CRE Press*. doi: 10.1201/9781439882115.
52. Brown, D.M., Wilson, M.R., MacNee, W., Stone, V. and Donaldson, K., (2001) Size-Dependent Proinflammatory Effects of Ultrafine Polystyrene Particles: A Role for Surface Area and Oxidative Stress in the Enhanced Activity of Ultrafines. *Toxicology and Applied Pharmacology* **175**, 191–199. doi: 10.1006/taap.2001.9240.
53. Lithner, D., Larsson, Å. and Dave, G., (2011) Environmental and Health Hazard Ranking and Assessment of Plastic Polymers Based on Chemical Composition. *Science of The Total Environment* **409**, 3309–3324. doi: 10.1016/j.scitotenv.2011.04.038.
54. Lebreton, L.C.M., Van Der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A. and Reisser, J., (2017) River Plastic Emissions to the World's Oceans. *Nature Communications* **8**, 15611. doi: 10.1038/ncomms15611.
55. Wang, Z., Qin, Y., Li, W., Yang, W., Meng, Q. and Yang, J., (2019) Microplastic Contamination in Freshwater: First Observation in Lake Ulansuhai, Yellow River Basin, China. *Environmental Chemistry Letters* **17**, 1821–1830. doi: 10.1007/s10311-019-00888-8.
56. Murphy, L., Germaine, K., Dowling, D.N., Kakouli-Duarte, T. and Cleary, J., (2020) Association of Potential Human Pathogens with Microplastics in Freshwater Systems. In: Cocca, M., Di Pace, E., Errico, M.E., Gentile, G., Montarsolo, A., Mossotti, R. and Avella, M., Eds., Proceedings of the 2nd International Conference on Microplastic Pollution in the Mediterranean Sea, Springer International Publishing, Cham, 112–120. doi: 10.1007/978-3-030-45909-3_19.
57. Carr, S.A., Liu, J. and Tesoro, A.G., (2016) Transport and Fate of Microplastic Particles in Wastewater Treatment Plants. *Water Research* **91**, 174–182. doi: 10.1016/j.watres.2016.01.002.
58. Nizzetto, L., Futter, M. and Langaas, S., (2016) Are Agricultural Soils Dumps for Microplastics of Urban Origin? *Environmental Science & Technology* **50**, 10777–10779. doi: 10.1021/acs.est.6b04140.
59. Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M. and Sukumaran, S., (2020) Plastic Rain in Protected Areas of the United States. *Science* **368**, 1257–1260. doi: 10.1126/science.aaz5819.
60. Geilfus, N.-X., Munson, K.M., Sousa, J., Germanov, Y., Bhugaloo, S., Babb, D. and Wang, F., (2019) Distribution and Impacts of Microplastic Incorporation within Sea Ice. *Marine Pollution Bulletin* **145**, 463–473. doi: 10.1016/j.marpolbul.2019.06.029.
61. Menicagli, V., Balestri, E. and Lardicci, C., (2019) Exposure of Coastal Dune Vegetation to Plastic Bag Leachates: A Neglected Impact of Plastic Litter. *Science of The Total Environment* **683**, 737–748. doi: 10.1016/j.scitotenv.2019.05.245.
62. Hanley, M.E., Hoggart, S.P.G., Simmonds, D.J., Bichot, A., Colangelo, M.A., Bozzeda, F., Heurtefeux, H., Ondiviela, B., Ostrowski, R., Recio, M., Trude, R., Zawadzka-Kahlau, E. and Thompson, R.C., (2014) Shifting Sands? Coastal Protection by Sand Banks, Beaches and Dunes. *Coastal Engineering* **87**, 136–146. doi: 10.1016/j.coastaleng.2013.10.020.
63. Van Cauwenberghe, L. and Janssen, C.R., (2014) Microplastics in Bivalves Cultured for Human Consumption. *Environmental Pollution* **193**, 65–70. doi: 10.1016/j.envpol.2014.06.010.
64. Karami, A., Golieskardi, A., Keong Choo, C., Larat, V., Galloway, T.S. and Salamatinia, B., (2017) The Presence of Microplastics in Commercial Salts from Different Countries. *Scientific Reports* **7**, 46173. doi: 10.1038/srep46173.
65. Vianello, A., Jensen, R.L., Liu, L. and Vollertsen, J., (2019) Simulating Human Exposure to Indoor Airborne Microplastics Using a Breathing Thermal Manikin. *Scientific Reports* **9**, 8670. doi: 10.1038/s41598-019-45054-w.
66. Campanale, C., Massarelli, C., Savino, I., Locaputo, V. and Uricchio, V.F., (2020) A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *International Journal of Environmental Research and Public Health* **17**, 1212. doi: 10.3390/ijerph17041212.
67. Leslie, H.A., Van Velzen, M.J.M., Brandsma, S.H., Vethaak, A.D., Garcia-Vallejo, J.J. and Lamoree, M.H., (2022) Discovery and Quantification of Plastic Particle Pollution in Human Blood. *Environment International* **163**, 107199. doi: 10.1016/j.envint.2022.107199.
68. Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M. and Giorgini, E., (2021) Plasticenta: First Evidence of Microplastics in Human Placenta. *Environment International* **146**, 106274. doi: 10.1016/j.envint.2020.106274.
69. Jenner, L.C., Rotchell, J.M., Bennett, R.T., Cowen, M., Tentzeris, V. and Sadofsky, L.R., (2022) Detection of Microplastics in Human Lung Tissue Using μFTIR Spectroscopy. *Science of The Total Environment* **831**, 154907. doi: 10.1016/j.scitotenv.2022.154907.

70. Hesler, M., Aengenheister, L., Ellinger, B., Drexel, R., Straskraba, S., Jost, C., Wagner, S., Meier, F., Von Briesen, H., Büchel, C., Wick, P., Buerki-Thurnherr, T. and Kohl, Y., (2019) Multi-Endpoint Toxicological Assessment of Polystyrene Nano- and Microparticles in Different Biological Models in Vitro. *Toxicology in Vitro* **61**, 104610. doi: 10.1016/j.tiv.2019.104610.
71. Wu, B., Wu, X., Liu, S., Wang, Z. and Chen, L., (2019) Size-Dependent Effects of Polystyrene Microplastics on Cytotoxicity and Efflux Pump Inhibition in Human Caco-2 Cells. *Chemosphere* **221**, 333–341. doi: 10.1016/j.chemosphere.2019.01.056.
72. Schirinzi, G.F., Pérez-Pomeda, I., Sanchís, J., Rossini, C., Farré, M. and Barceló, D., (2017) Cytotoxic Effects of Commonly Used Nanomaterials and Microplastics on Cerebral and Epithelial Human Cells. *Environmental Research* **159**, 579–587. doi: 10.1016/j.envres.2017.08.043.
73. Senathirajah, K., Attwood, S., Bhagwat, G., Carbery, M., Wilson, S. and Palanisami, T., (2021) Estimation of the Mass of Microplastics Ingested – A Pivotal First Step towards Human Health Risk Assessment. *Journal of Hazardous Materials* **404**, 124004. doi: 10.1016/j.jhazmat.2020.124004.
74. Foley, C.J., Feiner, Z.S., Malinich, T.D. and Höök, T.O., (2018) A Meta-Analysis of the Effects of Exposure to Microplastics on Fish and Aquatic Invertebrates. *Science of The Total Environment* **631–632**, 550–559. doi: 10.1016/j.scitotenv.2018.03.046.
75. Zhang, Y., Lu, J., Wu, J., Wang, J. and Luo, Y., (2020) Potential Risks of Microplastics Combined with Superbugs: Enrichment of Antibiotic Resistant Bacteria on the Surface of Microplastics in Mariculture System. *Ecotoxicology and Environmental Safety* **187**, 109852. doi: 10.1016/j.ecoenv.2019.109852.
76. The State of the World Fisheries and Aquaculture. States, F., A.O. of the U. (2018, 2019) Available online at: http://www.fao.org/state-of-fisheries-aquaculture.
77. European Commission. Directorate General for Research and Innovation. and European Commission's Group of Chief Scientific Advisors. (2018) Microplastic Pollution: The Policy Context: Background Paper. Publications Office, LU. Available online at: https://data.europa.eu/doi/10.2777/998601.
78. Wen, B., Zhang, N., Jin, S.-R., Chen, Z.-Z., Gao, J.-Z., Liu, Y., Liu, H.-P. and Xu, Z., (2018) Microplastics Have a More Profound Impact than Elevated Temperatures on the Predatory Performance, Digestion and Energy Metabolism of an Amazonian Cichlid. *Aquatic Toxicology* **195**, 67–76. doi: 10.1016/j.aquatox.2017.12.010.
79. Sequeira, I.F., Prata, J.C., Da Costa, J.P., Duarte, A.C. and Rocha-Santos, T., (2020) Worldwide Contamination of Fish with Microplastics: A Brief Global Overview. *Marine Pollution Bulletin* **160**, 111681. doi: 10.1016/j.marpolbul.2020.111681.
80. Hanachi, P., Karbalaei, S., Walker, T.R., Cole, M. and Hosseini, S.V., (2019) Abundance and Properties of Microplastics Found in Commercial Fish Meal and Cultured Common Carp (Cyprinus Carpio). *Environmental Science and Pollution Research* **26**, 23777–23787. doi: 10.1007/s11356-019-05637-6.
81. Smith, M., Love, D.C., Rochman, C.M. and Neff, R.A., (2018) Microplastics in Seafood and the Implications for Human Health. *Current Environmental Health Reports* **5**, 375–386. doi: 10.1007/s40572-018-0206-z.
82. Neves, D., Sobral, P., Ferreira, J.L. and Pereira, T., (2015) Ingestion of Microplastics by Commercial Fish off the Portuguese Coast. *Marine Pollution Bulletin* **101**, 119–126. doi: 10.1016/j.marpolbul.2015.11.008.
83. Setälä, O., Fleming-Lehtinen, V. and Lehtiniemi, M., (2014) Ingestion and Transfer of Microplastics in the Planktonic Food Web. *Environmental Pollution* **185**, 77–83. doi: 10.1016/j.envpol.2013.10.013.
84. Devriese, L.I., Van Der Meulen, M.D., Maes, T., Bekaert, K., Paul-Pont, I., Frère, L., Robbens, J. and Vethaak, A.D., (2015) Microplastic Contamination in Brown Shrimp (Crangon Crangon, Linnaeus 1758) from Coastal Waters of the Southern North Sea and Channel Area. *Marine Pollution Bulletin* **98**, 179–187. doi: 10.1016/j.marpolbul.2015.06.051.
85. Green, D.S., Boots, B., Sigwart, J., Jiang, S. and Rocha, C., (2016) Effects of Conventional and Biodegradable Microplastics on a Marine Ecosystem Engineer (Arenicola Marina) and Sediment Nutrient Cycling. *Environmental Pollution* **208**, 426–434. doi: 10.1016/j.envpol.2015.10.010.
86. Rehse, S., Kloas, W. and Zarfl, C., (2016) Short-Term Exposure with High Concentrations of Pristine Microplastic Particles Leads to Immobilisation of Daphnia Magna. *Chemosphere* **153**, 91–99. doi: 10.1016/j.chemosphere.2016.02.133.
87. Rochman, C.M., Browne, M.A., Underwood, A.J., Van Franeker, J.A., Thompson, R.C. and Amaral-Zettler, L.A., (2016) The Ecological Impacts of Marine Debris: Unraveling the Demonstrated Evidence from What Is Perceived. *Ecology* **97**, 302–312. doi: 10.1890/14-2070.1.
88. Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J. and Galloway, T.S., (2013) Microplastic Ingestion by Zooplankton. *Environmental Science & Technology* **47**, 6646–6655. doi: 10.1021/es400663f.
89. Besseling, E., Wegner, A., Foekema, E.M., Van Den Heuvel-Greve, M.J. and Koelmans, A.A., (2013) Effects of Microplastic on Fitness and PCB Bioaccumulation by the Lugworm *Arenicola Marina* (L.). *Environmental Science & Technology* **47**, 593–600. doi: 10.1021/es302763x.
90. Von Moos, N., Burkhardt-Holm, P. and Köhler, A., (2012) Uptake and Effects of Microplastics on

Cells and Tissue of the Blue Mussel *Mytilus Edulis* L. after an Experimental Exposure. *Environmental Science & Technology* **46**, 11327–11335. doi: 10.1021/es302332w.

91. Avio, C.G., Gorbi, S. and Regoli, F., (2015) Experimental Development of a New Protocol for Extraction and Characterization of Microplastics in Fish Tissues: First Observations in Commercial Species from Adriatic Sea. *Marine Environmental Research* **111**, 18–26. doi: 10.1016/j.marenvres.2015.06.014.
92. Goldstein, M.C., Rosenberg, M. and Cheng, L., (2012) Increased Oceanic Microplastic Debris Enhances Oviposition in an Endemic Pelagic Insect. *Biology Letters*, The Royal Society **8**, 817–820. doi: 10.1098/rsbl.2012.0298.
93. Fossi, M.C., Marsili, L., Baini, M., Giannetti, M., Coppola, D., Guerranti, C., Caliani, I., Minutoli, R., Lauriano, G., Finoia, M.G., Rubegni, F., Panigada, S., Bérubé, M., Urbán Ramírez, J. and Panti, C., (2016) Fin Whales and Microplastics: The Mediterranean Sea and the Sea of Cortez Scenarios. *Environmental Pollution* **209**, 68–78. doi: 10.1016/j.envpol.2015.11.022.
94. Neves, D., Sobral, P., Ferreira, J.L. and Pereira, T., (2015) Ingestion of Microplastics by Commercial Fish off the Portuguese Coast. *Marine Pollution Bulletin* **101**, 119–126. doi: 10.1016/j.marpolbul.2015.11.008.
95. Caron, A.G.M., Thomas, C.R., Berry, K.L.E., Motti, C.A., Ariel, E. and Brodie, J.E., (2018) Ingestion of Microplastic Debris by Green Sea Turtles (Chelonia Mydas) in the Great Barrier Reef: Validation of a Sequential Extraction Protocol. *Marine Pollution Bulletin* **127**, 743–751. doi: 10.1016/j.marpolbul.2017.12.062.
96. Watts, A.J.R., Urbina, M.A., Corr, S., Lewis, C. and Galloway, T.S., (2015) Ingestion of Plastic Microfibers by the Crab *Carcinus Maenas* and Its Effect on Food Consumption and Energy Balance. *Environmental Science & Technology* **49**, 14597–14604. doi: 10.1021/acs.est.5b04026.
97. Hernandez-Gonzalez, A., Saavedra, C., Gago, J., Covelo, P., Santos, M.B. and Pierce, G.J., (2018) Microplastics in the Stomach Contents of Common Dolphin (Delphinus Delphis) Stranded on the Galician Coasts (NW Spain, 2005–2010). *Marine Pollution Bulletin* **137**, 526–532. doi: 10.1016/j.marpolbul.2018.10.026.
98. Besseling, E., Foekema, E.M., Van Franeker, J.A., Leopold, M.F., Kühn, S., Bravo Rebolledo, E.L., Heße, E., Mielke, L., IJzer, J., Kamminga, P. and Koelmans, A.A., (2015) Microplastic in a Macro Filter Feeder: Humpback Whale Megaptera Novaeangliae. *Marine Pollution Bulletin* **95**, 248–252. doi: 10.1016/j.marpolbul.2015.04.007.
99. Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H., Hamann, M., Lindeque, P.K. and Godley, B.J., (2016) Plastic and Marine Turtles: A Review and Call for Research. *ICES Journal of Marine Science: Journal du Conseil* **73**, 165–181. doi: 10.1093/icesjms/fsv165.
100. Camedda, A., Marra, S., Matiddi, M., Massaro, G., Coppa, S., Perilli, A., Ruiu, A., Briguglio, P. and De Lucia, G.A., (2014) Interaction between Loggerhead Sea Turtles (Caretta Caretta) and Marine Litter in Sardinia (Western Mediterranean Sea). *Marine Environmental Research* **100**, 25–32. doi: 10.1016/j.marenvres.2013.12.004.
101. Wilcox, C., Van Sebille, E. and Hardesty, B.D., (2015) Threat of Plastic Pollution to Seabirds Is Global, Pervasive, and Increasing. *Proceedings of the National Academy of Sciences* **112**, 11899–11904. doi:10.1073/pnas.1502108112.
102. Krulwich, R. Why Are Cows in India Dying With Stomachs Full of Plastic? National Geographic. Available online at: https://www.nationalgeographic.com/science/article/why-are-cows-in-india-dying-with-stomachs-full-of-plastic.
103. Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.-C., Werorilangi, S. and Teh, S.J., (2015) Anthropogenic Debris in Seafood: Plastic Debris and Fibers from Textiles in Fish and Bivalves Sold for Human Consumption. *Scientific Reports* **5**, 14340. doi: 10.1038/srep14340.
104. Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M. and Bengtson Nash, S.M., (2018) Turning Microplastics into Nanoplastics through Digestive Fragmentation by Antarctic Krill. *Nature Communications* **9**, 1001. doi: 10.1038/s41467-018-03465-9.
105. Yong, C., Valiyaveettil, S. and Tang, B., (2020) Toxicity of Microplastics and Nanoplastics in Mammalian Systems. *International Journal of Environmental Research and Public Health* **17**, 1509. doi: 10.3390/ijerph17051509.
106. Magrì, D., Sánchez-Moreno, P., Caputo, G., Gatto, F., Veronesi, M., Bardi, G., Catelani, T., Guarnieri, D., Athanassiou, A., Pompa, P.P. and Fragouli, D., (2018) Laser Ablation as a Versatile Tool To Mimic Polyethylene Terephthalate Nanoplastic Pollutants: Characterization and Toxicology Assessment. *ACS Nano* **12**, 7690–7700. doi: 10.1021/acsnano.8b01331.
107. Wu, B., Wu, X., Liu, S., Wang, Z. and Chen, L., (2019) Size-Dependent Effects of Polystyrene Microplastics on Cytotoxicity and Efflux Pump Inhibition in Human Caco-2 Cells. *Chemosphere* **221**, 333–341. doi: 10.1016/j.chemosphere.2019.01.056.
108. Hwang, J., Choi, D., Han, S., Choi, J. and Hong, J., (2019) An Assessment of the Toxicity of Polypropylene Microplastics in Human Derived Cells. *Science of The Total Environment* **684**, 657–669. doi: 10.1016/j.scitotenv.2019.05.071.
109. Poma, A., Vecchiotti, G., Colafarina, S., Zarivi, O., Aloisi, M., Arrizza, L., Chichiriccò, G. and Di Carlo, P., (2019) In Vitro Genotoxicity of Polystyrene Nanoparticles on the Human Fibroblast Hs27 Cell Line. *Nanomaterials* **9**, 1299. doi: 10.3390/nano9091299.

110. Dong, C.-D., Chen, C.-W., Chen, Y.-C., Chen, H.-H., Lee, J.-S. and Lin, C.-H., (2020) Polystyrene Microplastic Particles: In Vitro Pulmonary Toxicity Assessment. *Journal of Hazardous Materials* **385**, 121575. doi: 10.1016/j.jhazmat.2019.121575.
111. Xu, M., Halimu, G., Zhang, Q., Song, Y., Fu, X., Li, Y., Li, Y. and Zhang, H., (2019) Internalization and Toxicity: A Preliminary Study of Effects of Nanoplastic Particles on Human Lung Epithelial Cell. *Science of The Total Environment* **694**, 133794. doi: 10.1016/j.scitotenv.2019.133794.
112. Lim, S.L., Ng, C.T., Zou, L., Lu, Y., Chen, J., Bay, B.H., Shen, H.-M. and Ong, C.N., (2019) Targeted Metabolomics Reveals Differential Biological Effects of Nanoplastics and nanoZnO in Human Lung Cells. *Nanotoxicology* **13**, 1117–1132. doi: 10.1080/17435390.2019.1640913.
113. Barbosa, A.B., (2009) Dynamics of Living Phytoplankton: Implications for Paleoenvironmental Reconstructions. *IOP Conference Series: Earth and Environmental Science* **5**, 012001. doi: 10.1088/1755-1307/5/1/012001.
114. Sjollema, S.B., Redondo-Hasselerharm, P., Leslie, H.A., Kraak, M.H.S. and Vethaak, A.D., (2016) Do Plastic Particles Affect Microalgal Photosynthesis and Growth? *Aquatic Toxicology* **170**, 259–261. doi: 10.1016/j.aquatox.2015.12.002.
115. Auta, H.S., Emenike, C.U. and Fauziah, S.H., (2017) Distribution and Importance of Microplastics in the Marine Environment: A Review of the Sources, Fate, Effects, and Potential Solutions. *Environment International* **102**, 165–176. doi: 10.1016/j.envint.2017.02.013.
116. Mao, Y., Ai, H., Chen, Y., Zhang, Z., Zeng, P., Kang, L., Li, W., Gu, W., He, Q. and Li, H., (2018) Phytoplankton Response to Polystyrene Microplastics: Perspective from an Entire Growth Period. *Chemosphere* **208**, 59–68. Doi: 10.1016/j.chemosphere.2018.05.170.
117. Dong, J., Li, L., Liu, Q., Yang, M., Gao, Z., Qian, P., Gao, K. and Deng, X., (2022) Interactive Effects of Polymethyl Methacrylate (PMMA) Microplastics and Salinity Variation on a Marine Diatom Phaeodactylum Tricornutum. *Chemosphere* **289**, 133240. Doi: 10.1016/j.chemosphere.2021.133240.
118. Wang, S., Wang, Y., Liang, Y., Cao, W., Sun, C., Ju, P. and Zheng, L., (2020) The Interactions between Microplastic Polyvinyl Chloride and Marine Diatoms: Physiological, Morphological, and Growth Effects. *Ecotoxicology and Environmental Safety* **203**, 111000. Doi: 10.1016/j.ecoenv.2020.111000.
119. Zhang, C., Chen, X., Wang, J. and Tan, L., (2017) Toxic Effects of Microplastic on Marine Microalgae Skeletonema Costatum: Interactions between Microplastic and Algae. *Environmental Pollution* **220**, 1282–1288. Doi: 10.1016/j.envpol.2016.11.005.
120. Ziajahromi, S., Drapper, D., Hornbuckle, A., Rintoul, L. and Leusch, F.D.L., (2020) Microplastic Pollution in a Stormwater Floating Treatment Wetland: Detection of Tyre Particles in Sediment. *Science of The Total Environment* **713**, 136356. Doi: 10.1016/j.scitotenv.2019.136356.
121. Teuten, E.L., Rowland, S.J., Galloway, T.S. and Thompson, R.C., (2007) Potential for Plastics to Transport Hydrophobic Contaminants. *Environmental Science & Technology* **41**, 7759–7764. doi: 10.1021/es071737s.
122. Frias, J.P.G.L., Sobral, P. and Ferreira, A.M., (2010) Organic Pollutants in Microplastics from Two Beaches of the Portuguese Coast. *Marine Pollution Bulletin* **60**, 1988–1992. doi: 10.1016/j.marpolbul.2010.07.030.
123. Bakir, A., O'Connor, I.A., Rowland, S.J., Hendriks, A.J. and Thompson, R.C., (2016) Relative Importance of Microplastics as a Pathway for the Transfer of Hydrophobic Organic Chemicals to Marine Life. *Environmental Pollution* **219**, 56–65. doi: 10.1016/j.envpol.2016.09.046.
124. Seidensticker, S., Grathwohl, P., Lamprecht, J. and Zarfl, C., (2018) A Combined Experimental and Modeling Study to Evaluate pH-Dependent Sorption of Polar and Non-Polar Compounds to Polyethylene and Polystyrene Microplastics. *Environmental Sciences Europe* **30**, 30. doi: 10.1186/s12302-018-0155-z.
125. Hodson, M.E., Duffus-Hodson, C.A., Clark, A., Prendergast-Miller, M.T. and Thorpe, K.L., (2017) Plastic Bag Derived-Microplastics as a Vector for Metal Exposure in Terrestrial Invertebrates. *Environmental Science & Technology* **51**, 4714–4721. doi: 10.1021/acs.est.7b00635.
126. Brennecke, D., Duarte, B., Paiva, F., Caçador, I. and Canning-Clode, J., (2016) Microplastics as Vector for Heavy Metal Contamination from the Marine Environment. *Estuarine, Coastal and Shelf Science* **178**, 189–195. doi: 10.1016/j.ecss.2015.12.003.
127. Bandow, N., Will, V., Wachtendorf, V. and Simon, F.-G., (2017) Contaminant Release from Aged Microplastic. *Environmental Chemistry* **14**, 394. doi: 10.1071/EN17064.
128. Massos, A. and Turner, A., (2017) Cadmium, Lead and Bromine in Beached Microplastics. *Environmental Pollution* **227**, 139–145. doi: 10.1016/j.envpol.2017.04.034.
129. Holmes, L.A., Turner, A. and Thompson, R.C., (2012) Adsorption of Trace Metals to Plastic Resin Pellets in the Marine Environment. *Environmental Pollution* **160**, 42–48. doi: 10.1016/j.envpol.2011.08.052.
130. Shah, A.A., Hasan, F., Hameed, A. and Ahmed, S., (2008) Biological Degradation of Plastics: A Comprehensive Review. *Biotechnology Advances* **26**, 246–265. doi: 10.1016/j.biotechadv.2007.12.005.
131. Gewert, B., Plassmann, M.M. and MacLeod, M., (2015) Pathways for Degradation of Plastic Polymers Floating in the Marine Environment. *Environmental Science: Processes & Impacts* **17**, 1513–1521. doi: 10.1039/C5EM00207A.

132. Yang, H., Chen, G. and Wang, J., (2021) Microplastics in the Marine Environment: Sources, Fates, Impacts and Microbial Degradation. *Toxics* **9**, 41. doi: 10.3390/toxics9020041.
133. Miri, S., Saini, R., Davoodi, S.M., Pulicharla, R., Brar, S.K. and Magdouli, S., (2022) Biodegradation of Microplastics: Better Late than Never. *Chemosphere* **286**, 131670. doi: 10.1016/j.chemosphere.2021.131670.
134. Vaksmaa, A., Hernando-Morales, V., Zeghal, E. and Niemann, H., (2021) Microbial Degradation of Marine Plastics: Current State and Future Prospects. In: Joshi, S.J., Deshmukh, A. and Sarma, H., Eds., *Biotechnology for Sustainable Environment, Springer Singapore, Singapore,* pp. 111–154. doi: 10.1007/978-981-16-1955-7_5.
135. Raquez, J., Bourgeois, A., Jacobs, H., Degée, P., Alexandre, M. and Dubois, P., (2011) Oxidative Degradations of Oxodegradable LDPE Enhanced with Thermoplastic Pea Starch: Thermo-mechanical Properties, Morphology, and UV-ageing Studies. *Journal of Applied Polymer Science* **122**, 489–496. doi: 10.1002/app.34190.
136. Zheng, Y., Yanful, E.K. and Bassi, A.S., (2005) A Review of Plastic Waste Biodegradation. *Critical Reviews in Biotechnology*, **25**, 243–250. doi: 10.1080/07388550500346359.
137. Singh, G., singh, ashok and Bhatt, K., (2016) Biodegradation of Polythenes by Bacteria Isolated from Soil. *International Journal of Research and Development in Pharmacy and Life Sciences* **Vol. 5,** No.2, pp 2056–2062. Available online at: http//www.ijrdpl.com.
138. Caruso, G., (2015) Plastic Degrading Microorganisms as a Tool for Bioremediation of Plastic Contamination in Aquatic Environments. *Journal of Pollution Effects & Control* **03**. doi: 10.4172/2375-4397.1000e112.
139. Asmita, K., Shubhamsingh, T. and Tejashree, S., (2015) Isolation of Plastic Degrading Micro-Organisms from Soil Samples Collected at Various Locations in Mumbai, India.". *nternational Research Journal of Environment Sciences* **Vol. 4(3),** 77-85, March (2015). Available online at: www.isca.in, www.isca.me.
140. Shimpi, N., Borane, M., Mishra, S. and Kadam, M., (2012) Biodegradation of Polystyrene (PS)-Poly (Lactic Acid) (PLA) Nanocomposites Using Pseudomonas Aeruginosa. *Macromolecular Research* **20**, 181–187. doi: 10.1007/s13233-012-0026-1.
141. Cacciari, I., Quatrini, P., Zirletta, G., Mincione, E., Vinciguerra, V., Lupattelli, P. and Giovannozzi Sermanni, G., (1993) Isotactic Polypropylene Biodegradation by a Microbial Community: Physicochemical Characterization of Metabolites Produced. *Applied and Environmental Microbiology* **59**, 3695–3700. doi: 10.1128/aem.59.11.3695-3700.1993.
142. Verce, M.F., Ulrich, R.L. and Freedman, D.L., (2000) Characterization of an Isolate That Uses Vinyl Chloride as a Growth Substrate under Aerobic Conditions. *Applied and Environmental Microbiology*, **66**, 3535–3542. doi: 10.1128/AEM.66.8.3535-3542.2000.
143. Ribitsch, D., Heumann, S., Trotscha, E., Herrero Acero, E., Greimel, K., Leber, R., Birner-Gruenberger, R., Deller, S., Eiteljoerg, I., Remler, P., Weber, T., Siegert, P., Maurer, K., Donelli, I., Freddi, G., Schwab, H. and Guebitz, G.M., (2011) Hydrolysis of Polyethyleneterephthalate by *p* -nitrobenzylesterase from *Bacillus Subtilis*. *Biotechnology Progress* **27**, 951–960. doi: 10.1002/btpr.610.
144. Mohan, A.J., Sekhar, V.C., Bhaskar, T. and Nampoothiri, K.M., (2016) Microbial Assisted High Impact Polystyrene (HIPS) Degradation. *Bioresource Technology* **213**, 204–207. doi: 10.1016/j.biortech.2016.03.021.
145. Mor, R. and Sivan, A., (2008) Biofilm Formation and Partial Biodegradation of Polystyrene by the Actinomycete Rhodococcus Ruber: Biodegradation of Polystyrene. *Biodegradation* **19**, 851–858. doi: 10.1007/s10532-008-9188-0.
146. (Orr), I.G., Hadar, Y. and Sivan, A., (2004) Colonization, Biofilm Formation and Biodegradation of Polyethylene by a Strain of Rhodococcus Ruber. *Applied Microbiology and Biotechnology* **65**. doi: 10.1007/s00253-004-1584-8.
147. U.S. Congress, Microbead-Free Waters Act of 2015, H.R. 1321, 114th Congress, 2015. Available online at: https://www.congress.gov/bill/114th-congress/house-bill/1321.
148. European Chemicals Agency (ECHA), Restriction Proposal on Intentionally Added Microplastics. Helsinki, Finland, 2023. Available online at: https://echa.europa.eu/documents/10162/05bd96e3-b969-0a7c-c6d6-44d1a5a4a6d1.
149. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, Plastic Waste Management Amendment. Available online at: http://moef.gov.in/wp-content/uploads/2022/02/Plastic-Waste-Management-Amendment-Rules-2022.pdf.
150. United Nations Environment Programme (UNEP), From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution,. Nairobi, Kenya, 2021. Available online at: https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.
151. Sangale, M.K., (2012) A Review on Biodegradation of Polythene: The Microbial Approach. *Journal of Bioremediation and Biodegradation* **03**. doi: 10.4172/2155-6199.1000164.
152. Ali, S.S., Elsamahy, T., Al-Tohamy, R., Zhu, D., Mahmoud, Y.A.-G., Koutra, E., Metwally, M.A., Kornaros, M. and Sun, J., (2021) Plastic Wastes Biodegradation: Mechanisms, Challenges and Future Prospects. *Science of The Total Environment* **780**, 146590. doi: 10.1016/j.scitotenv.2021.146590.