Cambridge Prisms: Plastics

www.cambridge.org/plc

Overview Review

Cite this article: Talukdar A, Banerjee A, Dey S and Bhattacharya S (2024). The good, the bad and the ugly: Critical insights on the applications of microbes in microplastic degradation. *Cambridge Prisms: Plastics*, **2**, e27, 1–20
https://doi.org/10.1017/plc.2024.26

Received: 13 October 2023
Revised: 28 June 2024
Accepted: 26 July 2024

Keywords:
Microorganisms; Plastic degradation; Microplastics; Plastisphere; Biofilms; Absorption

Corresponding author:
Sayan Bhattacharya;
Emails: sayan.evs@gmail.com;
sbhattacharya@nalandauniv.edu.in

The good, the bad and the ugly: Critical insights on the applications of microbes in microplastic degradation

Avishek Talukdar[1], Ayantika Banerjee[2], Satarupa Dey[3] and Sayan Bhattacharya[4]

[1]Department of Zoology, University of Calcutta, Kolkata, India; [2]Decontamination and Decommissioning Division, Quantum Energy Chemical Engineering, Korea Atomic Energy Research Institute (KAERI), Daejeon, Korea; [3]Department of Botany, Shyampur Siddheswari Mahavidyalaya, Howrah, India and [4]School of Ecology and Environment Studies, Nalanda University, Rajgir, India

Abstract

Microplastic pollution has become a global environmental challenge, with significant impacts on ecosystems and human health. Microbes have emerged as a promising tool in the combating against microplastic contamination. However, the complex relationship between microbes and microplastics presents both opportunities and challenges, leading to a nuanced understanding of their applications in degradation. This paper provides critical insights into the multifaceted roles of different microorganisms in microplastic degradation. It begins by highlighting the 'good' aspects, where several strains of microorganisms show the potential to break down microplastics through enzymatic activities and the formation of biofilms. Conversely, the 'bad' aspects of microbial involvement in microplastic degradation are examined. Microorganisms can facilitate the transport and bioaccumulation of microplastics in various ecosystems, potentially exacerbating their harmful effects. The 'ugly' side of microplastic degradation includes the production of harmful byproducts during microbial breakdown, raising concerns about secondary pollution and toxicity. The concept of plastisphere is discussed in this context, focusing on the phototrophs, photoheterotrophs and heterotrophs. Novel technologies involving microbial degradation of microplastics are also explained. The work emphasises the need for a comprehensive and balanced approach regarding the application of microorganisms in microplastic degradation and remediation.

Impact statement

This review summarises current available knowledge on microplastic degradation by microbes and explores the novel and emerging techniques for microplastic remediation using microbes. The paper incorporates in depth discussion on microbial (bacteria, fungi and enzymatic degradation) action on microplastics and discusses why the 'plastisphere' is considered to be the new delicacy for the microbial communities. The paper further explores how microplastics can develop antibiotic resistance in bacteria. The effect of environmental factors and biofilms on microbial degradation of microplastics is discussed. The key knowledge gaps and future research directions were identified regarding the use of microbes for microplastic bioremediation.

Introduction

Plastics are durable, lightweight, cost-effective, and have become the most widely and frequently used synthetic materials. Plastics are almost indispensable in many aspects of human life in modern society (Chae and An, 2018). Various items like shopping bags, plastic bottles, food containers, disposable cups, plumbing pipes, microwavable containers, plastic films, automotive parts, hookup wire, coaxial cables, and so on are made using plastic additives like polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), nylon, polycarbonate, polytetrafluoroethylene (PTFE) (Amobonye et al., 2021). Between 1950 and 2019, the annual global production of plastics had increased dramatically from 2 million tons to 368 million tons, of this around 40% were for single-use plastics (Plastic Europe, 2020) which resulted in the rapid accumulation of plastics in the environment (Nielsen et al., 2019). Around 2050, the global volume of plastic wastes will reach 26 billion tonnes, of which around 50% will eventually enter various compartments of terrestrial as well as aquatic ecosystems, causing serious environmental impacts (Jambeck et al., 2015).

Microplastics (MPs) are defined as plastic particles having size less than 5 mm and can be categorised based on primary and secondary types, sizes, shapes and polymer compositions. They are widespread in the biosphere and are potential contaminants of grave concern (Klein et al., 2018a; Blair Espinoza, 2019) and are ubiquitously found in sediments (Zamprogno et al., 2021), water, sea salt (Kosuth et al., 2018), food (Barboza et al., 2018), the atmosphere (Brahney et al., 2021) and sewage sludge. The total amount of microplastics in the aquatic ecosystems is expected to reach 12,000 metric tons (Mt) by 2050 (Geyer et al., 2017). MPs are persistent (Lambert and Wagner, 2018) and can bioaccumulate in the food chain and subsequently can affect plants and animals, including humans. MPs accumulation in the environment has adverse effects on the organisms including molecular stress, reduced growth rate and reproductive complications (Batel et al., 2016). MPs also affect plant growth and fish reproduction (Guo and Wang, 2019). Due to the wide range of adverse effects of MPs reducing the levels of MPs pollution is the need of the hour (Vince and Hardesty, 2017). MPs contain various toxic substances added during manufacturing or collected from the environment (Andrady, 2011). Plastic pollution has long been regarded to be an irreversible problem (because of poor degradation and the inability to collect all plastic particles) that will affect Earth system processes. As a result, certain techniques to limit micro (plastics) loss to the environment during manufacture, use, and disposal have been proposed (Lambert and Wagner, 2018). However, isolating MPs in environmental matrices might be difficult (Lambert and Wagner, 2018). In recent times, bio-plastics have been developed but their biodegradation also produces MPs (Wei et al., 2022). Physical treatment methods like sedimentation, filtration, and so on do separate MPs but retain them in the sludge. Current practices for handling plastic wastes (e.g., recycling, landfilling, incineration) have drawbacks that potentially exacerbate existing environmental problems. For example, incinerating synthetic plastics releases volatile and hazardous waste products, such as dioxins, heavy metals, sulphides, nitrogen oxides, and furans, all of which are thought to have the potential to cause cancer (Verma et al., 2016). Furthermore, downcycling (Rahimi and Garcia, 2017) and cost-ineffectiveness (Gradus et al., 2017) are also associated with synthetic plastic recycling. Additionally, landfilling is also not a good option since it takes a lot of space and has chances for leakage into the environment. Due to these drawbacks efforts are directed towards finding more environmental friendly approaches for managing plastic wastes. In this context, microorganisms have emerged as a likely alternative with numerous researches highlighting the capability of various microbial species for degrading MPs including PET (Taniguchi et al., 2019), PE (Restrepo-Flórez et al., 2014), PU (Magnin et al., 2020), PS (Ho et al., 2018) and PP (Arutchelvi et al., 2008). In this context, bioremediation of MPs has emerged as an attractive and alternate method to remove MPs from the environment. The use of microbes for MPs degradation can help in the remediation of MPs without any environmental damage (Restrepo-Flórez et al., 2014; Kumar Sen and Raut, 2015; Qi et al., 2017), thus making it a promising and safe avenue for cleaning our natural ecosystems (Shah et al., 2008). Various efforts have also been made to screen potential plastic-degrading microbes (Hidalgo-Ruz et al., 2012) and develop biodegradable polymers. However, presently only a few microorganisms are known to be able to degrade MPs and there is a dearth of knowledge in the context of microbial degradation of MPs (Gu, 2003).

MP are mainly considered as persistent compounds offering a large ecological niche for the colonisation of microbial communities (Kooi et al., 2017; Rummel et al., 2017). Numerous investigations have been carried out to examine the interaction between MPs and the MP colonising microorganisms, which could likely impact the behaviour of MP in the environment by altering their chemical or physical properties (Rummel et al., 2017; Roager and Sonnenschein, 2019; Oberbeckmann and Labrenz, 2020). However, there was no consensus on whether these microorganisms specifically chose plastics to colonise. According to some research, the microbial communities on plastics do not seem to be substrate-specific (Oberbeckmann et al., 2016). For instance, the lifetime and relative mobility of microplastics in the water column were shown to account for the differences in the microbial community compositions between floating microplastics and other substrates, such as stones and sediments (Zettler et al., 2013; Fazey and Ryan, 2016). However, multiple investigations showed differences in microbial community between MP surface and the surrounding, possibly due to the limitation of nutrients or the type of MPs (Kirstein et al., 2019). Research in other areas revealed that the types of carbon sources largely drive the turnovers of microbial community compositions (Goldford et al., 2018). While microplastics are not commonly used by microbes, some specific bacteria that break down plastic may be able to obtain carbon from them (Aravinthan et al., 2016; Green et al., 2016). This suggests that some microorganisms have a selection advantage when it comes to breaking down microplastics. Furthermore, certain microbes also favour adhering to the hydrophobic surface of microplastics and interacting with them (Krasowska and Sigler, 2014).

Therefore, a deeper understanding of the properties of the microbial communities colonising microplastics – such as their structure, stability, and mechanism of community assembly – based on stochastic and deterministic models was required in order to gain insight into the relationship between microplastics and the attached microorganism (Stegen et al., 2012; De Vries et al., 2018). Nevertheless, there is still a dearth of pertinent data regarding microbial communities that colonise microplastics in different environments. MP degradation in nature mainly occurs via physical, chemical and biological means (Shah et al., 2008; Ter Halle et al., 2017; Ariza-Tarazona et al., 2018). Light and oxygen can cause the degradation of MPs through abiotically and enhance the microbial availability through photodegradation, thermooxidative degradation and hydrolysis (Andrady, 2011). In deep sediments, light and oxygen are limited and redox conditions are the vital environmental factor for MP degradation, which requires further study (Rogers et al., 2020). Under anaerobic conditions, microorganisms found on MPs utilise either plastics or other organic matters surrounding MPs as electron donors (Rogers et al., 2020). To date, various anaerobic and facultative anaerobic plastic-degrading bacterial strains have been successfully isolated from plastics (Kathiresan, 2003; Auta et al., 2017), suggesting possible biodegradation of microplastics in anoxic sediments.

Multi-disciplinary approaches are required in order to address complex issues regarding MP bioremediation such as screening of efficient microbes and their characterisation, evaluation of in situ toxicity, and so on. MP assessment is necessary for the preparation of appropriate feedstock for the biotransformation of MPs which are recalcitrant.

Microplastics in the environment: Distribution, accumulation, toxicity and health effects

MPs are known to occur ubiquitously in marine environment, in surface water and sediments. The presence of MP has been extensively reported in deep sea water, sea surface, on shorelines, and in aquatic organisms in several countries around the world (Gray et al., 2018; Khalik et al., 2018). The existence of MPs has been reported in diverse types of ecosystems, including permafrost, both in Arctic (Zhang et al., 2023), Antarctica (Aves et al., 2022); Tibetan plateau (Wang et al., 2023) and European alpine regions (Materić et al., 2020, 2021). The occurrence and accumulation of MPs were also evident in several mangrove ecosystems and coral reefs (John et al., 2022). Occurrence of MP is also reported in different fresh water systems, including Ottawa River (Vermaire et al., 2017), Antuã River (Rodrigues et al., 2018), Yangtze River (Hu et al., 2018), Vembanand Lake (Sruthy and Ramasamy, 2017) in North America, Portugal, China and India. These MP particles have negative effects on diverse marine organisms (Wright et al., 2013) and mainly act as potential vectors for Persistent organic pollutants (POP) and other toxic pollutants (Hermabessiere et al., 2017). The presence of MP was also reported in air using different types of sampling methods such as atmospheric sampling (Abbasi et al., 2019), dust collection (Zhang et al., 2019) and wet and dry deposition (Klein and Fischer, 2019). The size of the MP fibres ranges from 100 to 5000 μm (Cai et al., 2017). In most cases, population density and proximity to urban areas are the main factors which influence the abundance of MP. The presence of MP was mostly reported in various touristic centres of China (Jiang et al., 2019), Rhine and Main Rivers, China's Qinghai Lake (Xiong et al., 2018), the Lagoon of Venice (Klein et al., 2015), Jakarta Bay (Manalu et al., 2017) and the Ottawa river (Vermaire et al., 2017). Both domestic and industrial sewage spillage are significant sources of MPs. According to study made by Carr et al. (2016), no MP was found in effluents of a tertiary waste water treatment plant, whereas, one plastic particle per 1.14 litre of effluent was reported from secondary waste water treatment plant. The density of the MP particles effects the vertical distribution and buoyancy of the particles. Usually, low-density MP occur more in surface zone whereas, while high-density MPs accumulate in deep seas and benthic organisms (Eerkes-Medranoet al., 2015).

Most MP are toxic and known to disrupts endocrine activity. On exposure to MPs, the catalytic activity of the acetylcholinesterase (AChE) (which is essential for neurotransmission in neuromuscular junctions and brain synapses) in zebrafish larva can led to death (Chen et al., 2017). Similar AChE activity inhibition was also reported in *Dicentrarchus labrax, Artemia franciscana* and *Oreochromis niloticus.* Moreover, body size, age influences the impact of MP on AChE activity. The presence of MP can also increase antioxidant defence response, cellular oxidative stress and lead to peroxidation of lipid which can induce disruption of membranes of presynaptic vesicles and damages the gill, muscles and liver in several fish species (Wen et al., 2018). According to Lei et al. (2018a, 2018b) MP caused neurodegeneration on *Caenorhabditis elegans.* The MP can accumulate in the gastrointestinal tract of fishes which effect the health and growth of fishes (Yin et al., 2018). However, there is a lack of adequate data related to the impact of MP in the GI tract of marine organisms. It was also reported that both chemical composition and shape may influence the ecotoxicology of MP particles. MP present in sediments are mostly fibres followed by fragments, beads, films and foam (Kooi and Koelmans, 2019); fibres are found to induce more toxic effects compared to fragments and beads. Polysterene (PS) MP was reported to upregulate nfa, il1b and ifng1–2 gene expressions, resulting in inflammatory responses on livers, guts and gills of zebrafish, induce ROS production and decrease GSH and SOD levels (Lu et al., 2018). MPs are considered to be potentially toxic to human health as it may enter the gastrointestinal (GI) tract by endocytosis of M cells and translocate to different parts of the body (Cox et al., 2019). According to study made by Forte et al. (2016), it was reported that PS nanoplastics can up-regulate IL-6 and IL-8 gene expression, resulting in inflammatory responses and morphological alterations. Moreover, high concentration of PS nanoparticles can lead to cell death through apoptosis by activating Caspase 3, 7 and 9 (Bexiga et al., 2011). The cytotoxicity of MP particles can also lead to DNA double-strand breaks and/or the high depletion of GSH (Paget et al., 2015). The study made by Xu et al. (2019) reported PS can affect the human lung cells and inhibit cell viability. The presence of excess MP particles can cause abnormal behaviour, produce ROS and impacts the immune system of fish. Further research is needed to understand the underlying mechanisms of MP toxicity.

Plastisphere: A new delicacy for the microbes?

Plastisphere describes a novel microbial community attached to plastics and distinct from the surroundings. Marine plastic debris provides a selective hydrophobic environment that stimulates the growth of early colonisers accelerating biofilm formation and further microbial succession (ZoBell and Anderson, 1936). Stimulation of microbial growth and respiration by inert surfaces is a well-documented phenomenon, which creates a favourable environment for microbial colonisation through micronutrient concentration (ZoBell, 1943). This could play an important role for increasing microbial activity in the upper layer of ocean gyres owing to the abundant plastic debris in oligotropic areas of the oceans (Zettler et al., 2013).

Early scanning electron micrographs of plastic surface biofilms (Sieburth, 1975) provided clues about microbial diversity within the plastisphere. The bacterial community found on the MP surface is found to be significantly different from that in surrounding middle and upper waters or other particle types (Oberbeckmann et al., 2018). Various factors like season, temperature, humidity, surrounding environment, polymer type, surface morphology and size of MPs influence the abundance and diversity of colonising microbial groups (Reisser et al., 2014; De Tender et al., 2015; Dussud et al., 2018a, 2018b). For example, studies have shown different microbial communities attached to MPs from two different oceans, and the diversity of bacteria living in water columns and bacteria attached to microplastic debris (Amaral-Zettler et al., 2015). Heterotrophic bacteria are capable of rapidly colonising plastic surfaces, which can survive longer than in the surrounding aquatic environments (Webb et al., 2009). The biodegradability of plastic is influenced not only by the capacity of microorganisms but also by surface texture, hydrophobicity, electrostatic interactions and free energy of the material (Falahudin et al., 2020). MPs provide a novel ecological niche for microbial growth and colonisation and serves as a carbon source. Recent studies on the basis of molecular data (Zettler et al., 2013; Bryant et al., 2016; Dussud et al., 2018a, 2018b; Kirstein et al., 2018) also confirmed that plastispheres are comprised of various organisms including primary producers (e.g., phototrophs), heterotrophs, predators, symbionts and decomposers. Members of genus *Vibrio* are reported to be enriched on microplastic surface (Frere et al., 2018; Zettler et al., 2013), however, other researchers have contradicted the claim (Schmidt et al., 2014; Bryant et al., 2016; Oberbeckmann et al., 2018). SEM photomicrographs confirmed the presence of varied eukaryotic and bacterial microbiota on both Polypropelene (PP) and Polyethelene (PE) samples. DNA analyses validated that the communities on plastics and the surrounding water differed consistently. For example, photosynthetic filamentous cyanobacteria including *Phormidium* and *Rivularia* OTUs

https://doi.org/10.1017/plc.2024.26 Published online by Cambridge University Press

occurred on plastics but were absent from seawater samples where unicellular *Prochlorococcus* dominated the bacterial phototroph community (Zettler et al., 2013). Marine suctorian ciliates of the genus *Ephelota* was also present known to harbour ectosymbiotic rod-shaped bacteria (Chen et al., 2008). Also, sulphide-oxidising Gammaproteobacteria of the genus *Thiobios* was present in the samples and on the surface of stalked ciliates (Zettler et al., 2013). Moreover, polycystine colonial radiolaria were found on MP surface. The identification of the *Vibrio* sequence recovered in high abundance and showed similarity (100%) with various *Vibrio* species from the gene bank. From the Mediterranean Sea, harmful dinoflagellate species under genus *Alexandrium* were reported to be present on plastic marine debris (Maso et al., 2007) and also a few from Atlantic Ocean.

Phototrophs

Diatoms are common and omnipresent residents of plastisphere and are one of the early and dominant colonisers (Oberbeckmann et al., 2014; Eich et al., 2015; Masó et al., 2016; Michels et al., 2018; Kettner et al., 2019). Diatoms belonging to number of bacillariophyte genera including *Navicula*, *Nitzschia*, *Sellaphora*, *Stauroneis* and *Chaetoceros* (Zettler et al., 2013). Studies from Sargasso Sea reported diatoms including *Mastogloia angulata*, Mastogloia *pusilla, Mastogloia hulburti, Cyclotella meneghiniana* and *Pleurosigma* sp. (Carpenter and Smith, 1972), and amplicon reads belonging to *genera Sellaphora, Amphora and Nitzschia* (Zettler et al., 2013). Furthermore, the taxa *Mastogloia, Nitzschia*, and *Amphora* have been reported from the Arabian Gulf only on the basis of morphological traits (Muthukrishnan et al., 2019). Metagenomic surveys (Bryant et al., 2016) have placed diatom clades at less than 1% of the eukaryotic community suggesting their replacement as the community matures. Cyanobacteria are also present along with diatoms (Bryant et al., 2016). Various filamentous bacteria like *Phormidium, Rivularia* and *Leptolyngbya* are also continuously reported on microplastics (Amaral-Zettler et al., 2020). Additionally, other known photosynthetic representatives included *prasinophytes*, *rhodophytes*, *cryptophytes*, *haptophytes*, *dinoflagellates*, *chlorarachniophytes*, *chrysophytes*, *pelagophytes* and *phaeophytes.*

Fungi are able to form chemical bonds like carbonyl, carboxyl and ester bonds which decreased the hydrophobicity of the MP. Fungi also uses MPs as a carbon source and as a result are able to degrade them. Yamada-Onodera et al. (2001) demonstrated *Penicillium simplicissimum* YK to successfully grow on solid medium supplemented with 0.5% PE after UV irradiation for 500 h. *Aspergillus niger* and *Penicillium pinophilum* was able to degrade thermo-oxidised (80°C, 15 days) low-density polyethylene (TO-LDPE) by 0.57 and 0.37% after 31 months. Additionally, the TO-LDPE weight decreased by three crystallinity and crystalline lamellar thickness units (0.4–1.8 Å), and increased small-crystal content (up to 3.2%) and mean crystallite size (8.4–14 Å) were observed. Dantzler et al. showed that serine hydrolase secreted from *Pestalotiopsis microspora* isolates were responsible for biodegrading polyurethane (PUR) MP. *Aspergillus tubingensis* VRKPT1 and *Aspergillus flavus* VRKPT2 are able to degrade high-density polyethylene (HDPE) efficiently (Sangeetha Devi et al., 2015) having weight loss of HDPE around 6.02 ± 0.2 and 8.51 ± 0.1%, respectively. White-rot fungi IZU154, *Trametes versicolor* and *Phanerochaete chrysosporium* have also shown excellent capability to degrade MPs (Deguchiet al.).

Photoheterotrophs and heterotrophs

In addition to phototrophs, potential photoheterotrophic bacteria of the genera *Erythrobacter, Roseobacter* and *'Candidatus Pelagibacter'* (REF) are also common residents of plastisphere. Heterotrophic bacteria in seawater samples were dominated by *Pelagibacter* along with other free-living picoplanktonic bacterial groups with different levels of abundance in PP and PE (Giovannoni et al., 1990). Experiments to culture bacteria with plastic as only carbon source have given various assortments, including members of Gammaproteobacteria (Nakamiya et al., 1997; Yoon et al., 2012) and Firmicutes (Harshvardhan and Jha, 2013), as well as Actinobacteria (Gilan and Sivan, 2013). Fungal sequences from plastic debris have also been reported by various studies (Zettler et al., 2013; Debroas et al., 2017; Kettner et al., 2017, 2019). Fungal diversity in the plastisphere is somewhat less known, however, recent studies highlighted that in brackish and freshwaters fungal assemblages are dominated by members of *Chytridiomycota, Cryptomycota* and *Ascomycota* (Kettner et al., 2019). From visual analysis of microbial population, members of fungal genus *Malassezia* were also reported (Amend et al., 2019).

Studies have shown that bacterial groups belonging to phyla *Bacteroidetes*, *Proteobacteria*, *Cyanobacteria* and *Firmicutes* are frequent colonisers of MPs (Zettler et al., 2013; Dussud et al., 2018a, 2018b).

Bacteria belonging to genus *Corynebacterium*, *Arthrobacter*, *Pseudomonas*, *Micrococcus*, *Streptomyces* and *Rhodococcus* are capable of biodegrading plastics and have demonstrated that they can use plastics as their carbon source under laboratory conditions (Shah et al., 2008). Interestingly, it was discovered that significant differences exist in the diversity, abundance and activity of bacterial and physiochemical characters of plastics between biodegradable and non-biodegradable plastics, indicating the presence of plastic-degrading microbes (Negoro, 2000).

Auta et al. (2018) described two pure bacterial cultures, *Rhodococcus* sp. strain 36 and *Bacillus* sp. strain 27 from mangrove sediments having capability for PP MP degradation. *Bacillus cereus* and *Bacillus gottheilii* were found to degrade PE (weight loss: 1.6%), polyethylene terephthalate (PET; 6.6%), and PS (7.4%) while, for *B. gottheilii* MP weight loss was 6.2%, 3.0%, 3.6% and 5.8% for PE, PET, PP and PS, respectively (Auta et al., 2018). *Stenotrophomonas maltophilia* LB 2-3 was found to decrease molecular weight and tensile properties of polylactic acid (PLA) (Jeon and Kim, 2013a). *E. coli* was able to degrade polyurethanes (1–2% after 72 hours) (Uscategui et al., 2016). Polypropylene films (PP) and Bioriented Polypropylene (BOPP) polymers were reported to be degraded by microorganisms to some extent (Longo et al., 2011). *Pseudomonas aeruginosa* was found to degrade PS-PLA nanocomposites (Shimpi et al., 2012). Mohan et al. (2016) found that newly isolated Bacillus strains were able to degrade brominated high-impact polystyrene (HIPS). Bacterial strains (*Enterobacter asburiae* YT1 and *Bacillus* sp. YP1) residing in gut of waxworms were able to degrade PE (Yang et al., 2014).

Park and Kim (2019) reported a bacterial consortium consisting mainly of *Bacillus* sp. and *Paenibacillus* sp. was able to reduce the dry weight of MP particles by 14.7% and the mean diameter of MP particles by 22.8% after 60 days. Tsiota et al. (2018) reported Agios and Souda bacterial community to decrease the weight of HDPE MPs by 8 and 18% after 2 months, respectively. The gut microbes of earthworm (*Lumbricus terrestris*) containing members of *Actinobacteria* and *Firmicutes* genera were able to degrade LDPE MPs upon ingestion by the earthworm (Huerta Lwanga et al., 2018).

Syranidou et al., (2017) demonstrated that bacterial consortium was capable of developing dense biofilm on the weathered surface of PE and induced alterations in the surface topography and rheological properties. *Exiguobacterium* sp. strain YT2 isolated from gut of mealworm showed potential signs of degrading and mineralising PS MP over a time of 28 days (Yang et al., 2015a; Brandon et al., 2018).

Predators

Predatory ciliate *Ephelota* and sulphide-oxidising ectosymbiotic bacteria were reported to exist in a symbiotic relationship on the plastisphere (Zettler et al., 2013; Kettner et al., 2019). Positive associations between *Amoebophrya* and *Suessiaceae* on polyethylene were reported as well (Kettner et al., 2019). SEM and molecular data have also confirmed that choanoflagellates, radiolaria and small flagellates such as *Micromonas* also constitute the predatory guild in the plastisphere that devours bacteria and other organisms (Amaral-Zettler et al., 2020).

Pathogens

Various potentially pathogenic microorganisms are reported to be attached with plastic debris (Zettler et al., 2013) including the members of the *Campylobacteraceae, Aeromonas salmonicida* or *Arcobacter* spp. from all over the world (McCormick et al., 2014; Kirstein et al., 2016; Oberbeckmann et al., 2016; Jiang et al., 2018; Curren and Leong, 2019). Various phototrophic species able to cause harmful algal blooms are also reported from plastic debris (Masó et al., 2016; Casabianca et al., 2019). Plastisphere communities can be dominated by genus *Vibrio* during the summer months. Moreover, they can transport potential protistan coral pathogens (Goldstein et al., 2014) and a known fish pathogen (Virsek et al., 2017). A recent study has reported the presence of *Campylobacteraceae* in microplastic particles which can cause gastrointestinal infections in humans (McCormick et al., 2014).

The knowledge regarding the microbial composition of MP-associated biofilm has revolutionised in the last half of the decade with the advent of metagenomics (Ivar do Sul et al., 2018). The biofilm communities differ significantly from their surrounding environment (Zettler et al. 2013; Oberbeckmann et al. 2014; Amaral-Zettler et al. 2015; Bryant et al. 2016; Debroas et al. 2017; Frere et al. 2018), which is obvious since microbial community compositions on natural particles usually differ from free-living microorganisms (Crespo et al. 2013; Rieck et al., 2015).

The outline of plastisphere is shown in Figure 1. Different strains of bacteria and fungi capable of degrading plastics, along with the types of microplastics degraded are summarised in Table 1.

Action of microorganisms on microplastics

Microbial degradation of MPs occurs through various steps: (1) Initial degradation of polymers to small-size particles from large polymeric structures, (2) Degradation of polymers to their oligomer, dimer and monomers and, (3) Mineralisation of MPs by microbial biomass (Blair Espinoza, 2019). Upon complete mineralisation, microplastics breakdown forming carbon dioxide by various enzymes, and the transformation of produced intermediates to use as a source of energy and biomass production.

The majority of synthetic polymers such as polyethylene (PE), polypropylene (PP) and polystyrene (PS) are degraded very slowly (Weinstein et al., 2016). Even the novel consortia like *Enterobacter*

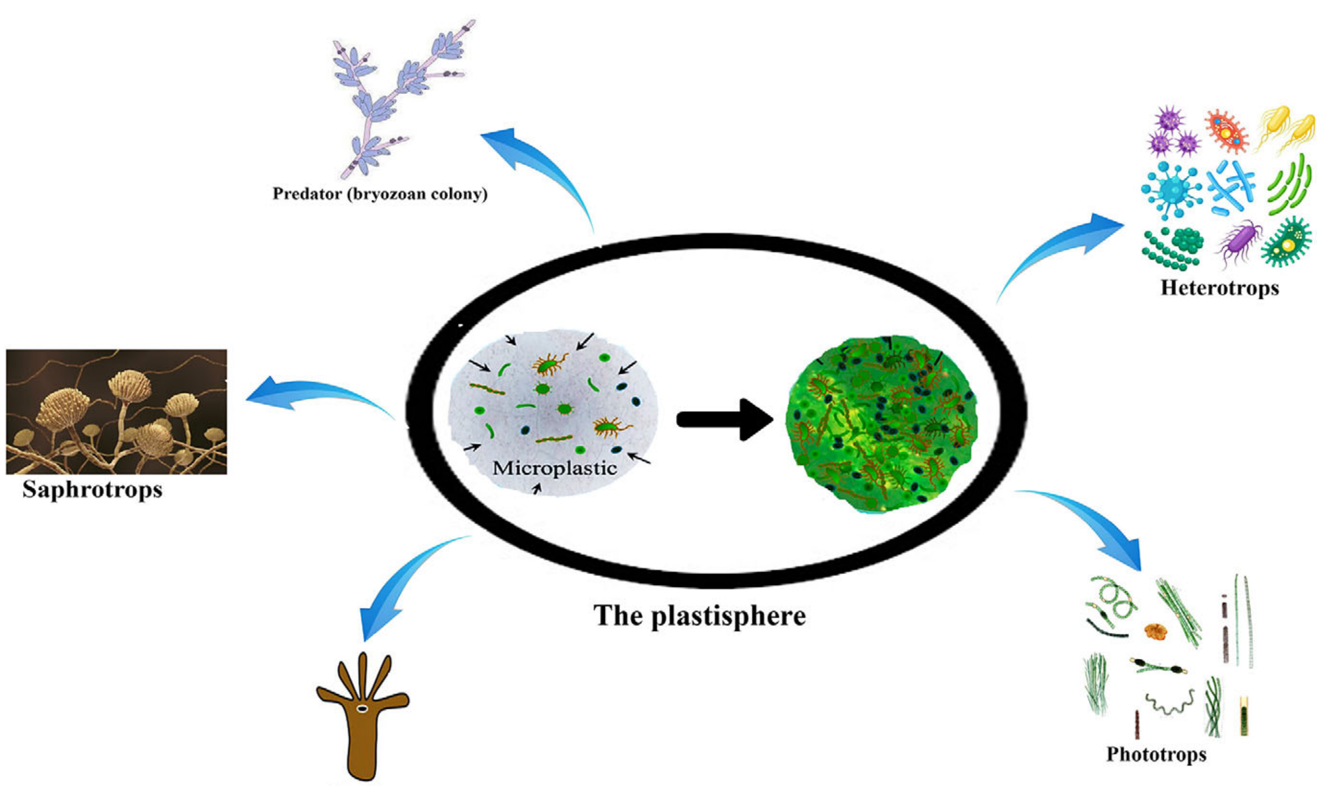

Figure 1. Plastisphere, the novel microbial community colonising and thriving on the plastic debris.

Table 1. Different strains of bacteria and fungi capable of degrading plastics, along with the types of microplastics degraded

Source of microbes	Isolate	Type of MP degraded	Incubation period	% of degradation	References
Bacterial isolates					
Polluted soil samples	*Lysinibacillus* sp.	Polypropylene and polyethylene	26 days	4 and 9%,	Jeon et al., 2021
Compost	*Bacillus cereus*, *Bacillus thuringenesis*, *Bacillus licheniformis*	Polypropylene (PP) and poly–L–lactide (PLLA)	6 months		Jain et al., 2021
Cow dung sample	*Enterobacter* sp nov. bt DSCE01, *Enterobacter cloacae* nov. bt DSCE02, *Pseudomonas aeruginosa* nov. bt DSCE–CD03	Low–density polyethylene (LDPE) and polypropylene (PP)	160 days	64.25 ± 2% and 63.00 ± 2%	Skariyachan et al., 2021
Antarctic soil	*Pseudomonas* sp. ADL15, *Rhodococcus* sp. ADL36	Polypropylene (PP) microplastics	40 days	17.3% and 7.3%	Habib et al., 2020
Municipal landfill sediment	*Bacillus* sp., *Paenibacillus* sp.	PP	60 days	14.7%	Park and Kim, 2019
Mediterranean Sea	Alcanivorax borkumensis	HDPE	80 days	3.5%	Delacuvellerie et al., 2019
Landfill site	*Cupriavidus necator*	LDPE	21 days	33.7%	Montazer et al., 2019
Landfill site	*Micrococcus luteus*	LDPE	21 days	18.9%	Montazer et al., 2019
Landfill sites and waste treatment facilities	*Aneurinibacillus* sp., *Brevibacillus* spp.	LDPE and HDPE strips and pellets	140 days	LDPE and HDPE strips: 58.21 and 46.6% weight loss LDPE and HDPE pellets: 45.7 and 37.2% weight loss	Skariyachan et al., 2018
Dumpsite (Africa)	*Bacillus cereus*	LDPE film	16 weeks	35.72%	Muhonja et al., 2018
Mangrove sediments	*Bacillus gottheilii Rhodococcus*	PE, PET, PP, PS	40 days	6.2, 3.0, 3.6, 5.8 and 6.4	Auta et al., 2018
Compost	*Bacillus thuringiensis, Bacillus licheniformis*	PP and poly–L–lactide (PLLA)	15 days	12%, 10%	Jain et al., 2018
Laboratory isolate	*Klebsiella pneumoniae*	LDPE film pretreated with hot dry air (70° C, 10 days)	60 days	18.4%	Awasthi et al., 2017
Plastic waste in soil	*Delftia* sp., *Stenotrophomonas* sp.	Untreated LDPE	90 days	Change of chemical properties	Peixoto et al., 2017
Mangrove sediments in Peninsular Malaysia	*Bacillus cereus*, *Sporosarcina Globispora*	Polypropylene	40 days	12 and 11 %	Helen et al., 2017
Marine	*Lysinibacillus* sp. *Salinibacterium* sp.	PE	6 months	19%	Syranidou et al., 2017
Municipal solid waste	*Stenotrophomonas panacihumi* PA3–2	polypropylene (PP)	90 days	20.3 ± 1.39%	Jeon and Kim, 2016
	Nitrosomonas sp., *Nitrobacter* sp., *Burkholderia* sp., *Pseudomonas* sp.	HDPE, LDPE and PP	90 days	20%, 5% and 9%	Muenmee et al., 2016
Source of microbes	**Isolate**	**Type of MP degraded**	**Incubation period**	**% of degradation**	**Reference**
Fungal isolates					
	Aspergillus sp., *Penicillium* sp.	PP/PBAT	30 days		Oliveira et al., 2020
Guts of wax moth *Galleria mellonella*	*Aspergillus flavus*	HDPE	28 days		Zhang et al., 2020
Marine sediments	*Zalerion maritimum*	PE pellets	28 days		Paco et al., 2017
	Bjerkandera adusta	Gamma irradiated polypropylene and biomass			Butnaru et al., 2016

https://doi.org/10.1017/plc.2024.26 Published online by Cambridge University Press

and *Pseudomonas* developed from cow dung showed faster biodegradation of PE and PP, demonstrated up to 15% weight loss after 120 days (Skariyachan et al., 2021). No information is available till date about the actions of depolymerases enzymes and the microbial degradation mechanisms of these microplastics and plastic debris (Ru et al., 2020). Bacteria, fungi and enzymes are identified based on their bioremediation capacity for PP, PE and PVC has been demonstrated based on their capacity of biofilm formation on plastic films, surface deterioration, thermal and mechanical properties alteration of plastics (Yang et al., 2015b; Auta et al., 2018; Giacomucci et al., 2019; Ru et al., 2020). Though most of the studies are based on macro-plastic films, however the same can be applied to MPs as well.

Bacterial metabolism and degradation of microplastics

Biodegradation of plastics requires the action of microbial enzymes (both bacterial and fungal) for converting them into easily metabolizable fractions (dimers, oligomers and monomers) for example lipase hydroxylase, depolymerase and protease (Haider et al., 2019). After disintegration, microorganisms feed on those products as carbon source for their growth and reproduction (Haider et al., 2019; Zuo et al., 2019a). Apart from that, the potential microbial degrading organisms must possess appropriate enzymatic and metabolic pathways. Physical characteristics of microplastics should facilitate attachment of microorganisms to the surface and biological reactions should not be affected by the branching pattern.

The complex interaction between the available surfaces for the colonisation of microorganisms forming biofilm was studied by Fleming et al. (2017). The attachment processes that act on MP biofilm include (1) biofouling, (2) plasticiser breakdown, (3) assault on the polymer backbone, (4) hydration and (5) organism penetration into the polymer structure.

Various bacterial taxa are renowned as plastic colonisers, for example, *Arcobacter* spp., *Vibrio* spp., *Colwellia* spp., *Escherichia* spp. and *Pseudomonas* spp. (Oberbeckmann and Labrenz, 2020). In research conducted by Oberbeckmann et al. (2016), it was reported that assemblages of microbes on the surface of polymers are not substrate-specific. Curren and Leong (2019) found colonisation of diverse epiplastic bacteria including *Erthrobacter*, *Vibrio* and *Pseudomonas* species. While another research reported rapid colonisation of low-density polyethylene (LDPE) microplastic by costal marine sediments bacteria including *Arcobacter* and *Colwellia* spp. (Harrison et al., 2014). Members of bacterial families like *Rhodobacteraceae* and *Flavobacteriaceae* and the genera *Albirhodobacter*, *Methylotenera*, and *Hydrogenophaga* have been found to be widespread on the surface of MPs (Oberbeckmann and Labrenz, 2020). Rosato et al. (2020) used a PCB-dechlorinating microbial culture to study microbial colonisation of various MPs (polyethylene, polyethylene terephthalate, polystyrene, polypropylene and polyvinyl chloride) and found all the MP to be colonised by microbes and also the microbes performed dechlorination proving their potential to remediate toxicity related to PCB polluted MPs (Rosato et al., 2020).

Research indicates that using bacterial consortia in MP biodegradation is more efficient rather than using single bacterial culture. Recent research conducted on MP degradation by using microbial consortia demonstrated maximum mineralisation in around 15 days (MeyerCifuentes et al., 2020).

Bacterial and fungal strains, including *Phaeosphaeria spartinicola*, *P. halima*, *Mycosphaerella* sp. assemblages can decompose complex polymers and may potentially form biofilms on the surface and ingest MP particles (Kawai et al., 2019). Various marine hydrocarbonoclastic bacteria (e.g., *Alcanivorax borkumensis*) demonstrated capacity to degrade alkanes, branched aliphatic, as well as isoprenoid hydrocarbons, and alkyl cycloalkanes (Davoodi et al., 2020). Researchers have also found possible potential of various marine bacteria for MP biodegradation due to their ability to form biofilms (Salvador et al., 2019). Evidence of LDPE degradation by *A. borkumensis* was observed while investigating biofilm formation on LDPE surface (Delacuveellerie et al., 2019). *Alcanivorax* sp. also interacts with plastic surface by adjusting its hydrophilicity of the cell membrane (Delacuvellerie et al., 2019). Recently, putative laccase isolated from actinomycete *Rhodococcus ruber* was found to be involved in PE biodegradation. Some bacterial strains obtained from sewage treatment plants, mulch films and landfills waste demonstrated the ability to utilise unpretreated PE, and PP strips as a carbon source (Jeyakumar et al., 2013). In the presence of starch, microorganisms showed accelerated hydrolytic biodegradation of PP and PE (Cacciari et al., 1993) also the enzymatic reactions make the polymers more vulnerable to biodegradation (Ru et al., 2020).

Fungal metabolism and degradation of microplastics

Fungi are excellent candidates for potential plastic degradation owing to their variety of metabolic potential and ability to degrade complex chemical structures (Lacerda et al., 2020). Marine fungus *Zalerion maritimumis* was reported to be successfully biodegrade PE (Paço et al., 2017). A wide diversity of epiplastic fungal species was reported from various geographic locations indicating their abundance in aquatic environments (Lacerda et al., 2020). Different fungal genera such as *Aspergillus, Cladosporium, and Wallemia* as well as a wide variety of taxa such as, *Chytridiomycota* and *Aphelidomycota* were reported from various locations (Lacerda et al., 2020). The fungal diversity thriving in the biofilm of microplastics found dominance of members from *Chytridiomycota, Cryptomycota* and *Ascomycota* (Kettner et al., 2017). Brunner et al. (2018) reported around 100 fungal species able to degrade MP debris highlighting the potential of marine epiplastic fungal communities. The isolated fungal strains were found successful to degrade Polyurethane (PU) but not PE polymers (Brunner et al., 2018). Lignin-biodegrading fungi catalyses the oxidation of aromatic and non-aromatic substrates like chorophenolic or nonphenolic compounds (polymethylmethacrylate [PMMA] and polyhydroxybutyrate [PHB]) by producing laccase (Straub et al., 2017).

Enzymatic degradation of microplastic: Microbial gene action and metabolism

Enzymes play a vital role in cellular functions regulation; microbes tend to modify their enzyme activity in response to changing environmental conditions. Inside the biofilm, the microbial enzymes build up a microenvironment interacting with the MP causing its degradation. Extracellular enzymes of microbes (esterase, lipase, lignin peroxides, laccase and manganese peroxides) are indispensable for increasing the hydrophilicity of plastic polymers by converting to functional carbonyl or alcohol groups, which can enhance microbial attachment and promotes biodegradation (Shahnawaz et al., 2019; Taniguchi et al., 2019). Extracellular enzymes such as hydrolases (such as lipases, esterase, poly (3-hydroxybutyrate) depolymerases and cutinases) operate on the plastic surface to break it down into smaller molecules (Sol et al., 2020). Integration of monomers transported into the cytoplasm of microbes and finally their metabolism results in their assimilation (Zettler et al., 2013). There are two types of MP degrading enzymes according to their mechanisms namely, surface modification mechanisms and degradation mechanisms (Vertommen et al., 2005). The first category of enzymes consists of a group of hydrolases (lipases, carboxylesterases, cutinases and proteases), while the polymer degrading enzymes includes oxidases, amidases, laccases, hydrolases and peroxidases (Álvarez-Barragán et al., 2016; Gómez-Méndez et al., 2018). Large polymers are broken down into smaller fragments with the help of enzymes, the fragment then gets ingested by the microbes and finally gets incorporated into the metabolic cell cycle. The extracellular polymeric substance (EPS) regulates the microenvironment and maintains the microbial community (Lucas et al., 2008) also governing the characteristics of the biofilm determining microbial penetration rate (Lucas et al., 2008) and ultimately control the fate of the plastic particles.

Despite ample evidence that EPS and enzymes have a significant influence on the biodeterioration of MPs, there is currently a dearth of technical options for the total destruction of these MPs (Kumar et al., 2020). Thus, it can be said that although a variety of microplastic (PE, PP and PVC) degrading microbes has been identified but microbial enzymes known to successfully degrade PE (laccase, soybean peroxidase, manganese peroxidase) and PS (hydroquinone peroxidase) are very few (Zhang et al., 2004; Santos et al., 2013) and none for PP degradation (Arutchelvi et al., 2008).

Microorganisms are able to produce enzymes that can breakdown complex polymer of plastics using them as carbon source for their growth and metabolism. Their ubiquity in different environments makes them the most promising natural and sustainable approach of MPs degradation. MPs degradation by microbes is influenced by various factors, including the type and structure of the plastic, environmental conditions (e.g., temperature, pH, oxygen availability) and microbial diversity and biochemical activities (Syranidou et al., 2017a). Among the reported potential MP degraders, bacteria play a significant role through various mechanisms. Bacterial strains in the genera *Pseudomonas*, *Bacillus* and *Rhodococcus* have the ability to breakdown and utilise different types of MPs (Yakimov et al., 2007; Syranidou et al., 2017a). Various types of extracellular enzymes like lipases and esterases are produced by the bacteria which help in MPs degradation (Auta et al., 2018). MPs degradation potential have also been shown by fungi, especially by the species of *Aspergillus*, *Penicillium* and *Fusarium* (Tournier et al., 2020; Solanki et al., 2022). Enzymes like cellulases and ligninases are secreted by fungi which are able to degrade MPs polymers (Yang et al., 2022). Algae, especially diatoms, can also potentially degrade MPs with the help of their extracellular enzymes like lipases and proteases, which are able to degrade and modify MPs surface properties (Sun et al., 2020a; Zhu et al., 2021). Algae such as *Scenedesmus dimorphus* (a green alga), *Anabaena spiroides* (a blue-green alga), *Navicula pupula* (a diatom), and various species of *Oscillatoria*, have been observed to thrive on polythene surfaces in sewage water (Chia et al., 2020). The adhesion of these colonising algae on to the MPs surface marks the start of biodegradation, and various ligninolytic and exopolysaccharide enzymes produced by them facilitates plastic degradation (Priya et al., 2022). Additionally, with biofilm formation on the plastic surface, enhanced degradation of MPs takes place due to the secretion of a range of microbial enzymes, which also facilitates the establishment of a diverse microbial community, promoting efficient microplastics degradation (Oberbeckmann et al., 2018; Ogonowski et al., 2018). Within the biofilm, synergistic interactions among various microorganisms creates a microenvironment favourable for enzymatic activity which further enhances the degradation potential (Wei and Zimmermann, 2017; Tournier et al., 2020).

Addressing the burning issue of plastic pollution requires detailed knowledge of the MPs degradation mechanism for implementation of effective remediation (Lopez-Pedrouso et al., 2020; Othman et al., 2021). A wide range of enzymatic processes including hydrolysis, oxidation, reduction and esterification, can breakdown polymer bonds or modify polymer functional groups (Lopez-Pedrouso et al., 2020; Othman et al., 2021). These enzymatic processes are crucial for breakdown of plastic polymer chains into smaller molecules that can serve as microorganisms' source of carbon and energy. One of the most common plastics in our daily life polyethylene terephthalate (PET) can be degraded by PET hydrolases (Carniel et al., 2017), which can be obtained from microorganisms like *Ideonella sakaiensis* and *Rhodococcus* sp. (Yoshida et al., 2016; Wei and Zimmermann, 2017) and offers a promising avenue for PET plastic waste management. Also, cutinases have shown excellent ability in PET degradation (O'Neill et al., 2007; Furukawa et al., 2019) especially, microorganisms *Thermobifida alba* and *Thermobifida fusca* can achieve this. Additionally, Microbes like *Trametes versicolor* and *Pycnoporus cinnabarinus* with the help of laccases oxidise phenolic compounds, influencing the fate of PS and PU (Bilal et al., 2019; Ghatge et al., 2020; Yao et al., 2022). Notably, in plastic degradation lignin peroxidases and manganese peroxidases, obtained from microorganisms such as *Phanerochaete chrysosporium* and *Pleurotus ostreatus*, have shown promise (Mukherjee and Kundu, 2014; Ojha et al., 2017; Rovaletti et al., 2023). Excellent plastic degrading potential is also shown by Cellulases, particularly against PS (Koeck et al., 2014; Pathak, 2017; Yan et al., 2021c). The likes of *Clostridium thermocellum* and *Cellulomonas fimi* contribute to our understanding of this multifaceted enzymatic approach to plastic waste management.

Can microplastic develop antibiotic resistance in bacteria?

In the context of antibiotic resistance, two freshwater studies demonstrated microplastic-associated assemblages having an increased transfer frequency of a plasmid coding for trimethoprim resistance (Arias-Andres et al., 2018) and higher abundance of the gene int1, a proxy for anthropogenic pollution (Eckert et al., 2018).

MPs can selectively enrich both antibiotics and antibiotic-resistant bacteria on their surfaces in various environments (Wu et al., 2019; Su et al., 2020; Sun et al., 2020b; Wang et al., 2020). Zhang et al. (2020) isolated and characterised antibiotic-resistant marine bacteria from MP particles which showed the presence of several multidrug-resistant marine bacteria including pathogenic *Vibrio* species (Zhang et al., 2020). Other studies showed the presence of multidrug-resistant pathogens from *Vibrio* sp. (Laverty et al., 2020) and *E. coli* (Song et al., 2020) on marine microplastics. A study published recently described whole genome sequencing (WGS) of antibiotic-resistant microorganisms isolated from marine plastics (Radisic et al., 2020).

Enrichment of various Antibiotic Resistant Genes (ARGs) like sul1, tetA, tetC, tetX and ermE was reported from plastic particles in both sea and freshwater (Wang et al., 2020) and selective enrichment of strB, blaTEM, ermB, tetM and tetQ was seen on MP particles from landfill leachates (Shi et al., 2020). Lu et al. (2020) reported the presence of upto 43 different ARGs on MP surface from vegetable soil using advanced high-throughput qPCR screening.

Using Shotgun metagenomics 64 different ARG subtypes providing resistance against 13 different antibiotics on macroplastics and microplastics were collected from North Pacific Gyre (Yang et al., 2019). This research and numerous others have discovered clinically relevant ARGs on MP particles, such as sul1, tetA, tetC, tetX, ermE, aac(3), macB and blaTEM, which are typically present in human infections (Alcock et al., 2020), suggesting that MPs serves as reservoirs of clinically important antibiotic resistance genes. The numerous antibiotics and active metabolites present in various chemicals and heavy metals (Godoy et al., 2019; Chen et al., 2020; Mammo et al., 2020; Wang et al., 2020) adsorbed to MPs leads to multidrug resistance among different bacteria within microbial biofilm resulting in active selection of antibiotic resistance on MP surfaces.

Imran et al. (2019) have advocated that the development and spread of multiple drug-resistant human pathogens occur by co-contamination of MPs and heavy metals through co-selection mechanisms.

Role of environmental factors in microbial degradation of microplastics

Various environmental factors like pH, moisture, salinity and temperature play vital roles in bioplastic degradation (Gong et al., 2012). While, factors like temperature and ionic strength facilitate the colonisation of microbes and biofilm formation (Rummel et al., 2017), the presence of nutrients and other pollutants, as well as the availability of light and pressure are known to affect the nature and extent of microbial attachment (Harrison et al., 2018). The surrounding environment is a major player for biofilm structuring and low nutrient and high salinity forms substrate-specific assemblages (Oberbeckmann et al., 2018). An optimum temperature is required which favours enzymatic activity and microbial growth (Shruti and Kutralam-Muniasamy, 2019). Moisture content and salinity are other important factors for biodegradation (Gong et al., 2012). Bioplastic degradation is kick-started by water uptake followed by the breakage of ester bonds. pH of the medium also affects the rate of reaction, alkaline condition favours hydrolysis of PLA (Elsawy et al., 2017). Comparative analysis revealed that the plastic material is a minor factor determining MP-associated biofilms while the most important factor was geographical region (Amaral-Zettler et al., 2015).

Keeping the above facts in mind, it can be inferred that finding a natural environment for complete bioplastic degradation is a difficult task. A potential solution to this situation is the use of engineered microorganisms which can degrade bioplastics with highest efficiency while withstanding extreme environmental conditions (Danso et al., 2018b).

Role of microbial biofilms in microplastic degradation

Biofilms are diverse microbial communities consisting of bacteria, fungi, algae, and so on thriving on any surface submerged and in spatial proximity (Donal, 2002). The microorganisms are collectively benefited by having a stable consortia, availability of nutrients, and protection from desiccation (Zettler et al., 2013). Biofilm can affect microplastic structure and function in various ways, with the help of various enzymes. These enzymes can transform surface properties, additive degradation and metabolic by-product release, thus can determine the fate of MPs in marine environments (Miao et al., 2019).

MP biodegradation starts off after the attachment of first microbes and development of biofilm on the plastic surface (plastisphere). The plastisphere comprises of various microbial communities developing into a biofilm (Urbanek et al., 2018). The plastic surface encourages microbial colonisation and biofilm formation leading to a reduction in polymer buoyancy and hydrophobicity (Lobelle and Cunliffe, 2011). Various polymer additives being easily metabolised, encourages microorganisms' initial attachments and biofilm formation (Ru et al., 2020). Microbes ensure surface attachment by various mechanisms like, cell surface charge changes and hydrophobicity and modifications in EPS production, pioneer microbes then modify surface morphology for additional microbial colonisation. Various substratum property like crystallinity, melting temperature, roughness, and so on might influence microbial community assemblages during colonisation stages (Rummel et al., 2017). Various factors affecting biofilm degradation of MPs are summarised in Figure 2; biofilm formation process and microplastic degradation are shown in Figure 3.

Biofilm maturation into complex structures is apparently achieved through quorum sensing (QS) processes among cells. QS Signalling gene gets accumulated in the external environment and regulates neighbouring cells specific gene expression. A few bacterial species use QS to coordinate and regulate the disassembly of the biofilm (Sharma et al., 2019). Various researches have suggested active QS involvement in the organisation and development of multispecies biofilms in the marine environment (Hmelo, 2017).

After colonisation, biodeterioration of the polymer follows leading to loss in physical integrity and loss of polymer's mechanical properties (Kumar et al., 2020). The process is primarily achieved by exoenzymes secreted by microbes. At this point, the microbe's EPS offers strong adherence to the polymer surface, and the enzymes' catalytic activity commences the dissolution of the polymeric structure. EPS and enzymes are thought to have significant influences on the biodeterioration of MPs (Kumar et al., 2020). The deteriorated polymers are then converted to oligomers, dimers and monomers through biofragmentation and finally get assimilated (Amobonye et al., 2020). The catalytic axctivities of microbial enzymes control the biodegradation of MPs mediated by biofilm promoting fragmentation of the polymer. The fragments formed through enzymatic depolymerisation can be assimilated by microbes resulting in increase in their biomass (Degli-Innocenti, 2014). These enzymes hydrolyze polymers by a nucleophilic attack on the carbonyl carbon, resulting in either readily assimilable oligomeric or monomeric elements or compounds that require more processing before they can be digested by the microorganisms (Kumar et al., 2020).

During assimilation, the fragmented polymers gets integrated in the microbial cells (Lucas et al., 2008). Enzymes and carrier proteins are involved in assimilation of monomers with catabolic cycles for energy production (Hosaka et al., 2013; Durairaj et al., 2016). The assimilation step is mostly followed by mineralisation, in which the polymers get completely degraded and final products like CO_2, N_2, H_2O and CH_4 are released. Complete mineralisation of PET has been reported to produce acetic acid which gets used in the Krebs cycle or integrated into lipid synthesis (Wilkes and Aristilde, 2017). Polymer physiochemical properties such as hydrophobicity, surface energies and functional groups influence the formation of biofilm (Bhagwat et al., 2021). For biological sedimentation, the

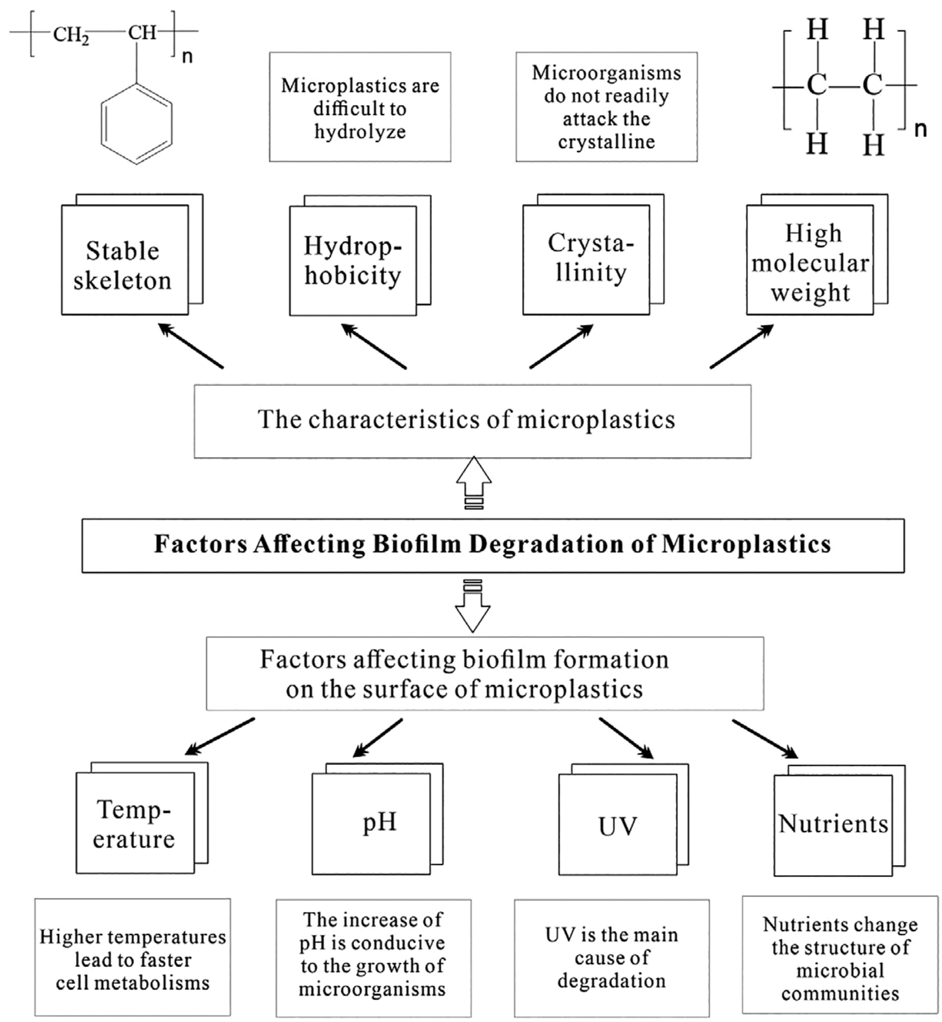

Figure 2. Various factors affecting biofilm degradation of microplastics. Reprinted after Sun et al. (2023), under a creative commons licence, open access.

conditioning layer is very important, which actually depends on the roughness, hydrophobicity and chemical nature of the initial matrix surface (Tu et al., 2020).

Different biochemical processes in microbe-mediated microplastic degradation and related biotechnological interventions are shown in Figure 4.

Microbial remediation of microplastic: Novel and emerging techniques

Absorption of microplastics by green algae

Algal cells can be effectively used for the breakdown of complex polymeric materials (Manzi et al., 2022). These algal cells may interact with MP particles and alter their properties which may determine the adsorption rate and fate of these MP particles (Kershaw et al., 2015). Algal consortium can be used in degradation of MP polymers as they do not require carbon source in the growth media and can easily adapt to different environmental conditions. Microalgae are known to produce biofilms on the surface of MP particles and help in the degradation process by producing ligninolytic and exopolysaccharide enzymes, this polymers on the other hand act as a source of carbon which promotes the growth of algal cells. The crucial processes that promote the degradation of MP particles includes corrosion, hydrolysis penetration and fouling (Chia et al., 2020). Green algae such as *Oscillatoria subbrevis* and *Phormidium lucidum* have been reported to colonise the surface of LDPE and degrade it without any pretreatment (Sarmah and Rout, 2018). Recent advancement in biotechnology have led to the production of genetically modified microalgal cell factories capable of producing hydrolytic enzymes having the ability to degrade plastics. Green microalgae *Chlamydomonas reinhardtii* was genetically modified to produce polyethylene terephthalate hydrolase, able to degrade polyethylene terephthalate films and terephthalic acid (Kim et al., 2020). These microalgae affect the vertical flux of the polymers by varying the density of the polymers which can be incorporated into hetero-aggregates promoting adsorption. However, this process is poorly understood (Tadsuwan et al., 2021).

Application of whole cell biocatalysis and microplastic immobilisation

Biocatalysis uses whole cells of bacteria, fungi, microalgae and plants to catalyse organic reaction. This provides high enantioselectivity and is considered as low or non-toxic, ecofriendly and green alternative to treat pollutant. Recent publications on

https://doi.org/10.1017/plc.2024.26 Published online by Cambridge University Press

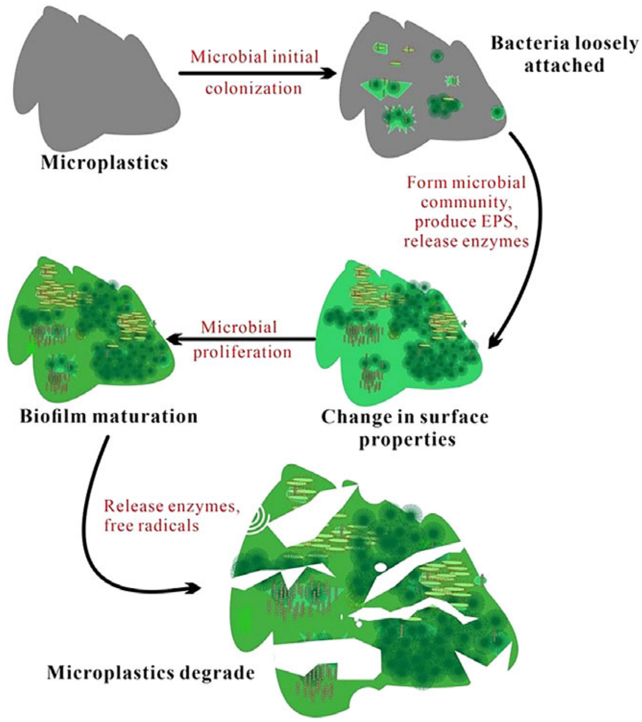

Figure 3. Bacterial colonisation, biofilm formation and degradation of microplastics. Reprinted after Sun et al. (2023), under a creative commons licence, open access.

biocatalysis concentrates on the use of enzymes and overexpression of enzymes in genetically engineered microbes but they are considered to be expensive as it requires resources to renew cofactors required for enzyme activities (Monti et al., 2011; Sheldon and Pereira, 2017). Biocatalysis may result in chemical transformation which may help in preparation of chiral compounds and organic compounds. They can effectively reduce carbon–carbon double bonds using highly selective processes and mild reactions. Thus, whole cell biocatalysis can be a sustainable technique in organic synthesis (Iqbal et al., 2012). Biocatalytic hydrogenation of alkanes can also serve as a crucial strategy for metal-assisted hydrogenation reactions. MP contains complex structures which can be effectively degraded and immobilised using whole cell biocatalysis.

Microplastic biodegradation by hyperthermophilic composting technology

Hyperthermophilic composting (*h*TC) is done at high temperature above 90°C using hyperthermophilic bacteria (Yu et al., 2018). As this process is performed at a very high temperature it leads to more efficient bioconversion within short period. Moreover, *h*TC is also effective for the reduction of antibiotic resistance genes and mobile genetic elements in sewage sludge due to the involvement of high temperature (Liao et al., 2019). Sewage sludge is one of the major sources of MP particles and removal of these MP particles by conventional treatment procedures can be ineffective. *h*TC can be effectively used for *in situ* biodegradation of sludge-based MPs. In a study made by Chen et al. (2019) *h*TC reported removal of 43.7% of MP from sewage sludge. *h*TC was also capable of degradation of 7.3 % of the PS-MPs at 70°C in 56 days through bio-oxidation. High-throughput sequencing showed the presence of Bacillus, Geobacillus and Thermus was directly linked with *h*TC which accelerate MP degradation and associated −C−C− bonds cleavage at high temperature (Manzur et al., 2004). In addition, *h*TC leads to the killing of pathogens associated with MP and lacks nitrification and denitrification processes, preventing the excess loss of nitrogen (Kanazawa et al., 2008).

Future research directions in microplastic bioremediation

Studies regarding accumulation, characterisation, identification of microplastics are numerous, however, studies regarding their mitigation are still lagging. Biodegradation process of microplastics can be understood following four common approaches namely, (1) the depletion of substrates, (2) accumulation of biomass, (3) reaction products and (4) changes in substrate properties. Additionally, standard processes for plastic biodegradation involves producing microbial films on the polymeric surfaces followed by thier breakdown into smaller pieces (<20 μm). However, the methods are not economical and also not widely applicable. The micro-Fourier transform infrared (FTIR) can facilitate the mapping of samples, multiple polymer characterisation and identification of irregular shaped MPs and is widely accepted (Gong et al., 2018), however, the method is quite expensive and time-consuming. Other analytical methods employed for MP identification includes scanning electron microscope-energy dispersive spectroscopy (SEM-EDS), pyrolysis-gas chromatography-mass spectrometry and ESEM-EDS (Horton et al., 2017). MPs are classified as an emerging pollutants due to a paucity of MPs data from soil and water, which limits knowledge of their environmental impact. It is difficult to show the ecotoxicological risks of microplastics on the surrounding ecosystems due to a lack of quantitative data (Harrison et al., 2012; Goel, 2017; Gong et al., 2018). In a nutshell, microplastic research is still in its infancy and more research is needed to address links between plastics and microplastics generation.

MPs have become a potential substrate for colonisation in the oceans, with members of the family *Sphingomonadaceae* in particular selectively colonising microplastic polymers. Based on our reanalysis of available literature and critical review, available information and evidences of MPs degradation by microbes are not adequate. According to Tagg and Labrenz (2018) for ensuring environmental compatibility and sustainability, collective actions are needed in order to better understand microbial degradation of plastics focused research on understanding the microbial pathways that can potentially degrade plastic are needed.

Future studies should consider genomics and proteomics approach in order to amplify the rate of microbe-mediated degradation of MP. The use of fungi for degrading MP effectively is now receiving increased attention. Fungi that are able to withstand oxidation and corrosion will be identified and screened for investigating their degradation properties on MPs that are difficult to degrade paving the way towards new and innovative strategies focused at mitigating the environmental impacts of MPs (Paco et al., 2017). Since MP biodegradation is a complex issue testing the efficacy of the process under real-world conditions is of prime importance.

Although advanced and innovative methods have been developed for isolating strains capable of degrading MPs, still the number of bacteria selected for screening is mostly limited to taxa like *Bacillus*, *Pseudomonas*, *Chelatococcus* and *Lysinibacillus fusiformis*. However, the bacterial degradation efficiency of MPs is quite low (0–15%) and takes a long time (usually 0–3 months) showing that microbial degradation of MP is a slow and time consuming process. Thus, future studies should look into improving the bacteria-mediated degradation potential of MPs with the help of modern

https://doi.org/10.1017/plc.2024.26 Published online by Cambridge University Press

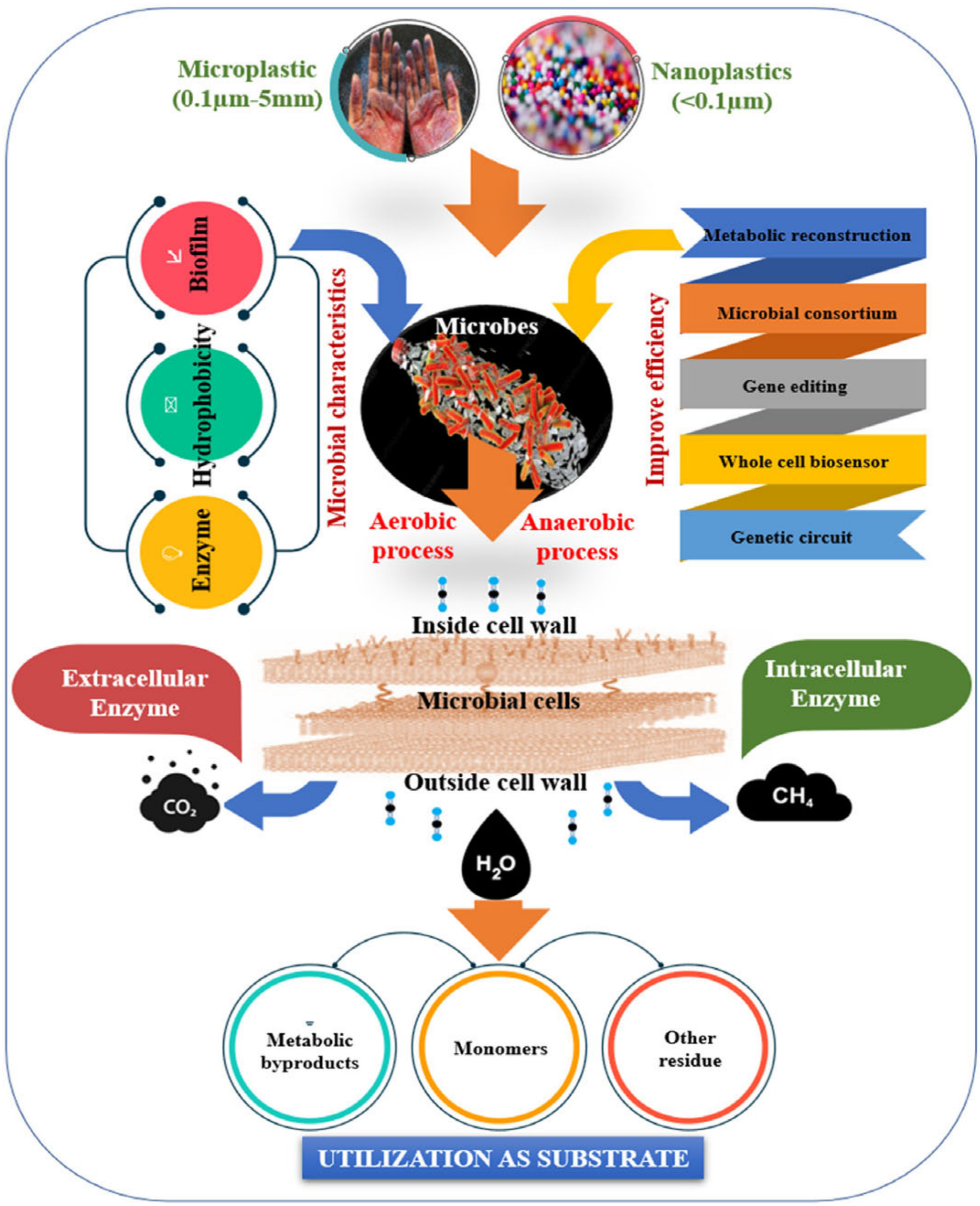

Figure 4. Different biochemical processes in microbe-mediated microplastic degradation and related biotechnological interventions. Reprinted after Zhou et al. (2022) (Elsevier), licence number 5647011139377.

molecular techniques like in vitro transcription, in situ hybridization, high-throughput sequencing and PCR. Also, multiple bacterial consortia have been identified from various environments (Sangwan and Wu, 2008) which have potential for MP degradation. However, these are complex processes due to the involvement of various microorganisms and multiple enzymes. Therefore, in depth studies are needed to get a clear idea about the factors influencing and mechanisms involved in the degradation process.

Also, the progression of the whole process of biofilm formation needs to be studied in detail, especially the microorganisms initiating the colonisation of a novel MP particle in different environments and the successional process leading to further colonisation by other microorganisms. This will help us in getting an idea about the whole process of MP biodegradation.

Future research should be oriented towards microbial remediation of plastic, especially understanding the microbial degradation mechanism and factors affecting it under real-world conditions so that it can be applied in real-world situations and can perform optimally and especially in developing innovative approaches towards microbial remediation through novel methods which are environmentally sound and sustainable.

Conclusions

Human activities have long continued to modify planet earth, but now it is time to access our impacts on the planet. Plastics have provided many benefits and have made our life easier. Perhaps it is time to reconsider the importance we place on contemporary conveniences. Planet Earth, with its many ecosystems and over 1030 microbial inhabitants (Flemming and Wuertz, 2019), has discovered a mechanism to biotransform and even to some extent degrade plastic materials. MPs are an emerging class of contaminants having ubiquitous presence in every environment and affecting them negatively. Currently, MPs are a serious issue not only in the aquatic ecosystem but also in terrestrial ecosystems. In this scenario, there is an urgent need to develop strategies for mitigating this problem. Very little knowledge is available on key depolymerase and the mechanisms of biodegradation of Low biodegradable MPs (e.g., PP, PE, PS, PVC) and the most common depolymerising method is pyrolysis. Thus, more research efforts are needed to identify depolymerases from the plastic-degrading strains. Surface-modifying enzymes and esterase's (e.g., cutinases, lipase, PETase) have been tested for MPs and their catalytic efficiency towards initial PET hydrolysis varies depending on crystallinity and environment conditions. Thus, to protect enzymes within an engineered cellular environment application of whole-cell biodegradation has been recommended. Nevertheless, degradation of biodegradable MPs takes place under assisted conditions. Regarding the highly crystalline MPs sustained thermal hydrolysis has been recommended to make the polymer bioavailable to microbes. For composting biodegradation, uncertainty remains in the requirement for specific collection and composting facilities and various contaminated and toxic MPs residues. Thus, the primary focus should be to reduce MP footprint through the use of natural alternatives (e.g., jojoba beads, pumice, ground nutshells) and MPs isolation in environmental matrices in order to reduce MPs release into the environment. Future studies should aim at multi-omics approaches to decipher biochemical transformation mediated by microbes. Furthermore, biotransformation of plastic debris by microbes may potentially have an important role in the generation of micron- and sub-micron-scale polymer particles, which could impact human health and food security.

In marine environments, biofilms induce transformation of surface properties, the degradation of additives, and the release of metabolic by-products with the help of modifying/hydrolysing microbial enzymes. Thus, biofilms can be potential candidates for mitigation of microplastics. However, we have limited knowledge about microbial communities on MPs coated by biofilm, factors affecting their colonisation and their interaction with plastic substrate. There is an urgent need for studies regarding epispastic marine microbial communities and their ability to remediate MPs from aquatic environment. Bioengineered microbes and modified enzyme systems can provide exciting avenues of research in this regard.

Open peer review. To view the open peer review materials for this article, please visit http://doi.org/10.1017/plc.2024.26.

Author contribution. Conceptualization: S.B.; Submission: S.B.; Supervision: S.B.; Writing – original draft: A.T., A.B., S.D., S.B.; Writing – review and editing: S.D., S.B.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interest. The authors declare none.

References

Abbasi S, Keshavarzi B, Moore F, Turner A, Kelly FJ, Dominguez AO and Jaafarzadeh N (2019) Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. *Environmental Pollution* **244**, 153–164.

Alcock BP, Raphenya AR, Lau TT, Tsang KK, Bouchard M, Edalatmand A, Huynh W, Nguyen A-LV, Cheng AA and Liu S (2020) CARD 2020: Antibiotic resistome surveillance with the comprehensive antibiotic resistance database. *Nucleic Acids Research* **48**(D1), D517–D525.

Álvarez-Barragán J, Domínguez-Malfavón L, Vargas-Suárez M, González-Hernández R, Aguilar-Osorio G and Loza-Tavera H (2016) Biodegradative activities of selected environmental fungi on a polyester polyurethane varnish and polyether polyurethane foams. *Applied and Environmental Microbiology* **82**, 5225–5235.

Amaral-Zettler LA, Zettler ER and Mincer TJ (2020) Ecology of the plastisphere. *Nature Reviews Microbiology* **18**(3), 139–151.

Amaral-Zettler LA, Zettler ER, Slikas B, Boyd GD, Melvin DW, Morrall CE, Proskurowski G and Mincer TJ (2015) The biogeography of the Plastisphere: Implications for policy. *Frontiers in Ecology and the Environment* **13**, 541–546.

Amend A, Burgaud G, Cunliffe M, Edgcomb VP, Ettinger CL, Gutiérrez MH, Heitman J, Hom EF, Ianiri G, Jones AC and Kagami M (2019) Fungi in the marine environment: Open questions and unsolved problems. *MBio* **10**(2), 10–128.

Amobonye A, Bhagwat P, Singh S and Pillai S (2020) Plastic biodegradation: Frontline microbes and their enzymes. *Science of the Total Environment* **759**, 143536.

Amobonye A, Bhagwat P, Singh S and Pillai S (2021) Plastic biodegradation: Frontline microbes and their enzymes. *Science of the Total Environment* **759**, 1–16. https://doi.org/10.1016/j.scitotenv2020.143536.

Andrady AL (2011) Microplastics in the marine environment. *Marine Pollution Bulletin* **62**, 1596–1605.

Aravinthan A, Arkatkar A, Juwarkar AA and Doble M (2016) Synergistic growth of bacillus and pseudomonas and its degradation potential on pretreated polypropylene. *Preparative Biochemistry and Biotechnology* **46**(2), 109–115.

Arias-Andres M, Klumper U, Rojas-Jimenez K and Grossart HP (2018) Microplastic pollution increases gene exchange in aquatic ecosystems. *Environmental Pollution* **237**, 253–261.

Ariza-Tarazona MC, Villarreal-Chiu JF, Barbieri V, Siligardi C and Cedillo-González EI (2018) New strategy for microplastic degradation: Green photocatalysis using a protein-based porous N-TiO_2 semiconductor. *Ceramics International* **45**(7), Part B, 9618–9624.

Arutchelvi J, Muniyasamy S, Arkatkar A, Doble M, Bhaduri S and Uppara P (2008) Biodegradation of polyethylene and polypropylene. *Indian Journal of Biotechnology* **7**, 9–22.

Auta HS, Emenike CU and Fauziah SH (2017) Screening of bacillus strains isolated from mangrove ecosystems in peninsular Malaysia for microplastic degradation. *Environmental pollution* **231**(Part 2), 1552–1559.

Auta HS, Emenike CU, Jayanthi B and Fauziah SH (2018) Growth kinetics and biodeterioration of polypropylene microplastics by *Bacillus* sp. and *Rhodococcus* sp. isolated from mangrove sediment. *Marine Pollution Bulletin* **127**, 15–21. https://doi.org/10.1016/j.marpolbul.2017.11.036.

Aves AR, Revell LE, Gaw S, Ruffell H, Schuddeboom A, Wotherspoon NE, LaRue M and McDonald AJ (2022) First evidence of microplastics in Antarctic snow. *The Cryosphere* **16**(6), 2127–2145.

Awasthi S, Srivastava P, Singh P, Tiwary D and Mishra PK (2017) Biodegradation of thermally treated high-density polyethylene (HDPE) by *Klebsiella pneumoniae* CH001. *3 Biotech* **7**(5), 332.

Barboza LGA, Vethaak AD, Lavorante BR, Lundebye AK and Guilhermino L (2018) Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin* **133**, 336–348.

Batel A, Linti F, Scherer M, Erdinger L and Braunbeck T (2016) Transfer of benzo[a]pyrene from microplastics to Artemia nauplii and further to zebrafish via a trophic food web experiment: CYP1A induction and visual tracking of persistent organic pollutants. *Environmental Toxicology and Chemistry* **35**, 1656–1666.

Bexiga MG, Varela JA, Wang F, Fenaroli F, Salvati A, Lynch I, Simpson JC and Dawson KA (2011) Cationic nanoparticles induce caspase 3-, 7- and 9-mediated cytotoxicity in a human astrocytoma cell line. *Nanotoxicology* **5**(4), 557–567.

Bhagwat G, O'Connor W, Grainge I and Palanisami T (2021) Understanding the fundamental basis for biofilm formation on plastic surfaces: Role of conditioning films. *Frontiers in Microbiology* **12**, 1615.

Bilal M, Iqbal HMN and Barcelo D (2019) Mitigation of bisphenol A using an array of laccase-based robust bio-catalytic cues – A review. *Science of the Total Environment* **689**, 160–177. https://doi.org/10.1016/j.scitotenv.2019.06.403.

Blair Espinoza RM (2019) *Microplastics in Wastewater Treatment Systems and Receiving Waters*. Glasgow: University of Glasgow.

Brahney J, Mahowald N, Prank M, Cornwell G, Klimont Z, Matsui H and Prather KA (2021) Constraining the atmospheric limb of the plastic cycle. *Proceedings of the National Academy of Sciences* **118**(16), e2020719118.

Brandon AM, Gao SH, Tian R, Ning D, Yang SS, Zhou J, Wu WM and Criddle CS (2018) Biodegradation of polyethylene and plastic mixtures in mealworms (larvae of Tenebrio molitor) and effects on the gut microbiome. *Environmental Science & Technology* **52**, 6526–6533.

Brunner I, Fischer M, Rüthi J, Stierli B and Frey B (2018) Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. *PLoS One* **13**, e0202047.

Bryant JA, Clemente TM, Viviani DA, Fong AA, Thomas KA, Kemp P, Karl DM, White AE and DeLong EF (2016) Diversity and activity of communities inhabiting plastic debris in the North Pacific Gyre. *MSystems* **1**(3), e00024–e00016.

Butnaru E, Darie-Niţă RN, Zaharescu T, Balaeş T, Tănase C, Hitruc G, Doroftei F and Vasile, C (2016) Gamma irradiation assisted fungal degradation of the polypropylene/biomass composites. *Radiation Physics and Chemistry* **125**, 134–144.

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**(11), 3695–3700.

Cai LQ, Wang JD, Peng JP, Tan Z, Zhan ZW, Tan XL and Chen QQ (2017) Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: Preliminary research and first evidence. *Environmental Science Pollution Research* **24**, 24928–24935.

Carniel A, Valoni E, Nicomedes J, Gomes A da Cand Castro A M de(2017) Lipase from Candida antarctica (CALB) and cutinase from Humicola insolens act synergistically for PET hydrolysis to terephthalic acid. *Process Biochemistry* **59**, 84–90. https://doi.org/10.1016/j.procbio.2016.07.023.

Carpenter EJ and Smith KL (1972) Plastics on the Sargasso Sea surface. *Science* **175**, 1240–1241.

Carr SA, Liu J and Tesoro AG (2016) Transport and fate of microplastic particles in waste-water treatment plants. *Water Research* **91**, 174–182.

Casabianca S, Capellacci S, Giacobbe MG, Dell'Aversano C, Tartaglione L, Varriale F, Narizzano R, Risso F, Moretto P, Dagnino A and Bertolotto R (2019) Plastic-associated harmful microalgal assemblages in marine environment. *Environmental Pollution* **244**, 617–626.

Chae Y and An YJ (2018) Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environmental Pollution* **240**, 387–395. https://doi.org/10.1016/j.envpol2018.05.008.

Chen X, Gu X, Bao L, Ma S and Mu Y (2020) Comparison of adsorption and desorption of triclosan between microplastics and soil particles. *Chemosphere* **263**, 127947.

Chen Q, Gundlach M, Yang S, Jiang J, Velki M, Yin D and Hollert H (2017) Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. *Science of the Total Environment* **584**, 1022–1031.

Chen X, Miao M, Song W, Warren A, Al-Rasheid KAS, Al-Farraj SA and Al-Quraishy SA (2008) Redescriptions of two poorly known marine Suctorian ciliates, Ephelota truncata Fraipont, 1878 and Ephelota mammillata Dons, 1918 (Protozoa, Ciliophora, Suctoria), from Qingdao, China. *Acta Protozology* **47**, 247−256.

Chen Z, Zhao W, Xing R, Xie S, Yang X, Cui P, L u J, Liao H, Yu Z, Wang S and Zhou S (2019) Enhanced *in situ* biodegradation of microplastics in sewage sludge using hyperthermophilic composting technology. *Journal of Hazardous Materials* **384**, 121271. https://doi.org/10.1016/j.jhazmat.2019.121271.

Chia WY, Ying Tang DY, Khoo KS, Kay Lup AN and Chew KW (2020) Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. *Environmental Science and Ecotechnology* **4**, 100065. https://doi.org/10.1016/j.ese.2020.100065.

Cox KD, Covernton GA, Davies HL, Dower JF, Juanes F and Dudas SE (2019) Human consumption of microplastics. *Environmental Science & Technology* **53**(12), 7068–7074.

Crespo BG, Pommier T, Fernandez-Gomez B, Pedros-Alio C (2013) Taxonomic composition of the particle attached and free-living bacterial assemblages in the Northwest Mediterranean Sea analyzed by pyrose quencing of the 16S rRNA. *Microbiology Open* **2**, 541–552.

Curren E and Leong SC (2019) Profiles of bacterial assemblages from microplastics of tropical coastal environments. *Science of the Total Environment* **655**, 313–320.

Danso D, Schmeisser C, Chow J, Zimmermann W, Wei R, Leggewie C, Li X, Hazen T and Streit WR (2018b) New insights into the function and global distribution of polyethylene terephthalate (PET)-degrading bacteria and enzymes in marine and terrestrial metagenomes. *Applied Environmental Microbiology* **84**, e02773–e02717.

Davoodi SM, Miri S, Taheran M, Brar SK, Galvez-Cloutier R and Martel R (2020) Bioremediation of unconventional oil contaminated ecosystems under natural and assisted conditions: a review. *Environmental Science & Technology* **54**(4), 2054–2067.

De Tender CA, Devriese LI, Haegeman A, Maes S, Ruttink T and Dawyndt P (2015) Bacterial community profiling of plastic litter in the Belgian part of the North Sea. *Environmental Science & Technology* **49**, 9629–9638.

De Vries FT, Griffiths RI, Bailey M, Craig H, Girlanda M, Gweon HS, Hallin S, Kaisermann A, Keith AM, Kretzschmar M, Lemanceau P, Lumini E, Mason KE, Oliver A, Ostle N, Prosser JI, Thion C, Thomson B and Bardgett RD (2018) Soil bacterial networks are less stable under drought than fungal networks. *Nature Communnication* **9**(1), 3033.

Debroas D, Mone A and Ter Halle A (2017) Plastics in the North Atlantic garbage patch: A boat-microbe for hitchhikers and plastic degraders. *Science of the Total Environment* **599–600**, 1222–1232.

Degli-Innocenti F (2014) Biodegradation of plastics and ecotoxicity testing: When should it be done. *Frontiers in Microbiology* **5**, 475.

Delacuvellerie A, Cyriaque V, Gobert S, Benali S and Wattiez R (2019) The plastisphere in marine ecosystem hosts potential specific microbial degraders including Alcanivorax borkumensis as a key player for the low-density polyethylene degradation. *Journal of Hazardous Materials* **380**, e120899. https://doi.org/10.1016/j.jhazmat.

Donlan RM (2002) Biofilms: Microbial life on surfaces. *Emerging Infectious Diseases* **8**, 881–890.

Durairaj P, Hur JS and Yun H (2016) Versatile biocatalysis of fungal cytochrome P450 monooxygenases. *Microbial Cell Factories* **15**, 1–6.

Dussud C, Hudec C, George M, Fabre P, Higgs P, Bruzaud S, Delort AM, Eyheraguibel B, Meistertzheim AL, Jacquin J, Cheng J, Callac N, Odobel C, Rabouille S and Ghiglione JF (2018a) Colonization of non-biodegradable and biodegradable plastics by marine microorganisms. *Frontiers in Microbiology* **1571**, 9.

Dussud C, Meistertzheim AL, Conan P, Pujo-Pay M, George M, Fabre P, Coudane J, Higgs P, Elineau A, Pedrotti ML and Gorsky G (2018b) Evidence of niche partitioning among bacteria living on plastics, organic particles and surrounding seawaters. *Environmental Pollution* **236**, 807–816.

Eckert EM, Di Cesare A, Kettner MT, Arias-Andres M, Fontaneto D, Grossart HP and Corno G (2018) Microplastics increase impact of treated wastewater on freshwater microbial community. *Environmental Pollution* **234**, 495–502.

Eerkes-Medrano D, Thompson RC and Aldridge DC (2015) Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research* **75**, 63–82.

Eich A, Mildenberger T, Laforsch C and Weber M (2015) Biofilm and diatom succession on polyethylene (PE) and biodegradable plastic bags in two marine habitats: Early signs of degradation in the pelagic and benthic zone? *PLoS One* **10**, e0137201.

Elsawy MA, Kim KH, Park JW and Deep A (2017) Hydrolytic degradation of polylactic acid (PLA) and its composites. *Renewable and Sustainable Energy Reviews* **79**, 1346–1352.

Falahudin D, Cordova MR, Sun X, Yogaswara D, Wulandari I, Hindarti D and Arifin Z (2020) The first occurrence, spatial distribution and characteristics of microplastic particles in sediments from Banten Bay, Indonesia. *Science of the Total Environment* **705**, 135304.

Fazey FMC and Ryan PG (2016) Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. *Environmental Pollution* **210**, 354–360.

Fleming D, Chahin L and Rumbaugh K (2017) Glycoside hydrolases degrade polymicrobial bacterial biofilms in wounds. *Antimicrobial Agents and Chemotherapy* **61**, e01998–e01916.

Flemming HC and Wuertz S (2019) Bacteria and archaea on earth and their abundance in biofilms. *Nature Reviews Microbiology* **17**, 247–260.

Forte M, Iachetta G, Tussellino M, Carotenuto R, Prisco M, De Falco M, Laforgia V and Valiante S (2016) Polystyrene nanoparticles internalization in human gastric adenocarcinoma cells. *Toxicology In Vitro* **31**, 126–136.

Frère L, Maignien L, Chalopin M, Huvet A, Rinnert E, Morrison H, Kerninon S, Cassone AL, Lambert C, Reveillaud J and Paul-Pont I (2018) Microplastic bacterial communities in the bay of Brest: Influence of polymer type and size. *Environmental Pollution* **242**, 614–625.

Furukawa M, Kawakami N, Tomizawa A and Miyamoto K (2019) Efficient degradation of poly (ethylene terephthalate) with Thermobifida fusca Cutinase exhibiting improved catalytic activity generated using mutagenesis and additive-based approaches. *Scientific Reports* **9**(1), 16038. https://doi.org/10.1038/s41598-019-52379-z.

Ghatge S, Yang Y, Ahn JH and Hur HG (2020) Biodegradation of polyethylene: A brief review. *Applied Biological Chemistry* **63** (1), 27. https://doi.org/10.1186/s13765-020-00511-3.

Geyer R, Jambeck JR and Law KL (2017) Production, use, and fate of all plastics ever made. *Science Advances* **3**(7), e1700782.

Giacomucci L, Raddadi N, Soccio M, Lotti N and Fava F (2019) Polyvinyl chloride biodegradation by pseudomonas citronellolis and Bacillus flexus. *New Biotechnology* **52**, 35–41.

Gilan I and Sivan A (2013) Effect of proteases on biofilm formation of the plastic-degrading actinomycete Rhodococcus ruber C208. *FEMS Microbiology Letters* **342**, 18–23.

Giovannoni SJ, Britschgi TB, Moyer CL and Field KG (1990) Genetic diversity in Sargasso Sea bacterioplankton. *Nature* **345**, 60–63.

Godoy V, Blázquez G, Calero M, Quesada L and Martín-Lara M (2019) The potential of microplastics as carriers of metals. *Environmental Pollution* **255**, 113363.

Goel S (2017) *Advances in Solid and Hazardous Waste Management*. Cham: Springer.

Goldford JE, Lu N, Bajić D, Estrela S, Tikhonov M, Sanchez-Gorostiaga A, Segrè D, Mehta P and Sanchez A (2018) Emergent simplicity in microbial community assembly. *Science* **361**(6401), 469–474.

Goldstein MC, Carson HS and Eriksen M (2014) Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. *Marine Biology* **161**, 1441–1453.

Gómez-Méndez LD, Moreno-Bayona DA, Poutou-Pinales RA, Salcedo-Reyes JC, Pedroza-Rodríguez AM, Vargas A and Bogoya JM (2018) Biodeterioration of plasma pretreated LDPE sheets by Pleurotus ostreatus. *PLoS One* **13** (9), e0203786. https://doi.org/10.1371/journal.pone.0203786.

Gong J, Duan N and Zhao X (2012) Evolutionary engineering of Phaffia rhodozyma for astaxanthin-overproducing strain. *Frontiers in Chemical Science Engineering* **6**, 174–178.

Gong J, Kong T, Li Y, Li Q, Li Z and Zhang J (2018) Biodegradation of microplastic derived from poly (ethylene terephthalate) with bacterial whole-cell biocatalysts. *Polymers* **10**, 1326.

Gradus R, Nillesen P, Dijkgraaf E and Koppen R (2017) A cost-effectiveness analysis for incineration or recycling of Dutch household plastic waste. *Ecological Economics* **135**, 22–28. https://doi.org/10.1016/j.ecolecon.2016.12.021.

Gray AD, Wertz H, Leads RR and Weinstein JE (2018) Microplastic in two South Carolina Estuaries: Occurrence, distribution, and composition. *Marine Pollution Bulletin* **128**, 223–233.

Green DS, 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**(Part B), 426–434.

Gu J-D (2003) Microbiological deterioration and degradation of synthetic polymeric materials: Recent research advances. *International Biodeterioration & Biodegradation* **52**, 69–91.

Guo X and Wang J (2019) The chemical behaviors of microplastics in marine environment: A review. *Marine Pollution Bulletin* **142**, 1–14.

Habib S, Iruthayam A, Abd Shukor MY, Alias SA, Smykla J and Yasid NA (2020) Biodeterioration of untreated polypropylene microplastic particles by Antarctic bacteria. *Polymers* **12**(11), 2616. https://doi.org/10.3390/polym12112616.

Haider TP, Volker C, Kramm J, Landfester K and Wurm FR (2019) Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angewandte Chemie, International Edition* **58**, 50–62.

Harrison JP, Hoellein TJ, Sapp M, Tagg AS, Ju-Nam Y and Ojeda JJ (2018) Microplastic-associated biofilms: A comparison of freshwater and marine environments. In *Freshwater Microplastics*. Cham: Springer, pp. 181–201.

Harrison JP, Ojeda JJ and Romero-Gonzalez ME (2012) The applicability of reflectance micro-Fourier-transform infrared spectroscopy for the detection of synthetic microplastics in marine sediments. *Science of the Total Environment* **416**, 455–463.

Harrison JP, Schratzberger M, Sapp M and Osborn AM (2014) Rapid bacterial colonization of low-density polyethylene microplastics in coastal sediment microcosms. *BMC Microbiology* **14**, 1–5.

Harshvardhan K and Jha B (2013) Biodegradation of low density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India. *Marine Pollution Bulletin* **77**, 100–106.

Helen AS, Uche EC and Hamid FS (2017) Screening for polypropylene degradation potential of bacteria isolated from mangrove ecosystems in peninsular Malaysia. *International Journal of Bioscience, Biochemistry and Bioinformatics* **7**(4), 245–251.

Hermabessiere L, Dehaut A, Paul-Pont I, Lacroix C, Jezequel R, Soudant P and Duflos G (2017) Occurrence and effects of plastic additives on marine environments and organisms: A review. *Chemosphere* **182**, 781–793.

Hidalgo-Ruz V, Gutow L, Thompson RC 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.

Hmelo LR (2017) Quorum sensing in marine microbial environments. *Annual Reviews in Marine Science* **9**, 257–281.

Ho BT, Roberts TK and Lucas S (2018) An overview on biodegradation of polystyrene and modified polystyrene: The microbial approach. *Critical Reviews in Biotechnology* **38**, 308–320. https://doi.org/10.1080/07388551.2017.1355293.

Horton AA, Walton A, Spurgeon DJ, Lahive E and Svendsen C (2017) Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment* **586**, 127–141.

Hosaka M, Kamimura N, Toribami S, Mori K, Kasai D, Fukuda M and Masai E (2013) Novel tripartite aromatic acid transporter essential for terephthalate uptake in Comamonas sp. strain E6. *Applied and Environmental Microbiology* **79**, 6148–6155.

Hu L, Chernick M, Hinton DE and Shi H (2018) Microplastics in small waterbodies and tadpoles from Yangtze River Delta, China. *Environmental Science & Technology* **52**(15), 8885–8893.

Huerta Lwanga E, Thapa B, Yang X, Gertsen H, Salanki T, Geissen V and Garbeva P (2018) Decay of low-density polyethylene by bacteria extracted from earthworm's guts: A potential for soil restoration. *Science of the Total Environment* **624**, 753–757.

Imran M, Das KR and Naik MM (2019) Co-selection of multi-antibiotic resistance in bacterial pathogens in metal and microplastic contaminated environments: An emerging health threat. *Chemosphere* **215**, 846–857.

Iqbal N, Rudroff F, Brigé A, Van Beeumen J and Mihovilovic MD (2012) Asymmetric bioreduction of activated carbon–carbon double bonds using Shewanella yellow enzyme (SYE-4) as novel enoate reductase. *Tetrahedron* **68**(37), 7619–7623.

Ivar do Sul JA, Tagg AS and Labrenz M (2018) Exploring the common denominator between microplastics and microbiology: a scientometric approach. *Scientometrics* **117**, 2145–57.

Jain K, Bhunia H and Reddy MS (2018) Degradation of polypropylene-poly-L-lactide blend by bacteria isolated from compost. *Bioremediation Journal* **22**(3–4), 73–90.

Jain K, Bhunia H and Reddy MS (2021) Degradation of polypropylene-poly-L-lactide blends by Bacillus isolates: A microcosm and field evaluation. *Bioremediation Journal* **26**, 64–75. https://doi.org/10.1080/10889868.2021.1886037.

Jambeck JR, **Geyer R**, **Wilcox C**, **Siegler TR**, **Perryman M**, **Andrady A**, **Narayan R and Law KL** (2015) Marine pollution: Plastic waste inputs from land into the ocean. *Science* **347**, 768–771. https://doi.org/10.1126/science.1260352.

Jeon HJ and Kim MN (2013a) Biodegradation of poly(l-lactide) (PLA) exposed to UV irradiation by a mesophilic bacterium. *International Biodeterioration & Biodegradation* **85**, 289–293.

Jeon HJ and Kim MN (2016) Isolation of mesophilic bacterium for biodegradation of polypropylene. *International Biodeterioration and Biodegradation* **115**, 244–249.

Jeon JM, **Park SJ**, **Choi TR**, **Park JH**, **Yang YH and Yoon JJ** (2021) Biodegradation of polyethylene and polypropylene by Lysinibacillus species JJY0216 isolated from soil grove. *Polymer Degradation and Stability* **191**, 109662.

Jeyakumar D, **Chirsteen J and Doble M** (2013) Synergistic effects of pretreatment and blending on fungi mediated biodegradation of polypropylenes. *Bioresource Technology* **148**, 78–85.

Jiang C, **Yin L**, **Li Z**, **Wen X**, **Luo X**, **Hu S**, **Yang H**, **Long Y**, **Deng B**, **Huang L and Liu Y** (2019) Microplastic pollution in the rivers of the Tibet Plateau. *Environmental Pollution* **249**, 91–98.

Jiang P, **Zhao S**, **Zhu L and Li D** (2018) Microplastic associated bacterial assemblages in the intertidal zone of the Yangtze estuary. *Science of the Total Environment* **624**, 48–54.

John J, **Nandhini AR**, **Velayudhaperumal Chellam P and Sillanpää M** (2022) Microplastics in mangroves and coral reef ecosystems: A review. *Environmental Chemistry Letters* **20**, 397–416.

Kanazawa S, **Ishikawa Y**, **Tomita-Yokotani K**, **Hashimoto H**, **Kitaya Y**, **Yamashita M**, **Nagatomo M**, **Oshima T**, **Wada H and Force SAT** (2008) Space agriculture for habitation on Mars with hyper-thermophilic aerobic composting bacteria. *Advances in Space Research* **41**(5), 696–700.

Kathiresan K (2003) Polythene and plastics-degrading microbes from the mangrove soil. *Revista De Biologia Tropical* **51**(3), 629–634.

Kawai F, **Kawabata T and Oda M** (2019) Current knowledge on enzymatic PET degradation and its possible application to waste stream management and other fields. *Applied Microbiology and Biotechnology* **103**, 4253–4268.

Kershaw PJ and Rochman CM (2015) Sources, fate and effects of microplastics in the marine environment: Part 2 of a global assessment. *Reports and Studies-IMO/FAO/Unesco-IOC/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Eng No. 93.*

Kettner MT, **Oberbeckmann S**, **Labrenz M and Grossart HP** (2019) The eukaryotic life on microplastics in brackish ecosystems. *Frontiers in Microbiology* **10**, 538.

Kettner MT, **Rojas-Jimenez K**, **Oberbeckmann S**, **Labrenz M and Grossart HP** (2017) Microplastics alter composition of fungal communities in aquatic ecosystems. *Environmental Microbiology* **19**, 4447–4459.

Khalik WMAWM, **Ibrahim YS**, **Anuar ST**, **Govindasamy S and Baharuddin NF** (2018) Microplastics analysis in Malaysian marine waters: A field study of Kuala Nerus and Kuantan. *Marine Pollution Bulletin* **135**, 451–457.

Kim JW, **Park SB**, **Tran QG**, **Cho DH**, **Choi DY**, **Lee YJ and Kim HS** (2020) Functional expression of polyethylene terephthalate degrading enzyme (PETase) in green microalgae. *Microbial Cell Factories* **19**(1), 1–9. https://doi.org/10.1186/s12934-020-01355-8.

Kirstein IV, **Kirmizi S**, **Wichels A**, **Garin-Fernandez A**, **Erler R**, **Löder M and Gerdts G** (2016) Dangerous hitchhikers? Evidence for potentially pathogenic Vibrio spp. on microplastic particles. *Marine Environmental Research* **120**, 1–8.

Kirstein IV, **Wichels A**, **Gullans E**, **Krohne G and Gerdts G** (2019) The Plastisphere-uncovering tightly attached plastic "specific" microorganisms. *PLoS One* **14**(4), e0215859.

Kirstein IV, **Wichels A**, **Krohne G and Gerdts G** (2018) Mature biofilm communities on synthetic polymers in seawater – Specific or general? *Marine Environment Research* **142**, 147–154.

Klein S, **Dimzon IK**, **Eubeler J and Knepper TP** (2018a) *Analysis, Occurrence, and Degradation of Microplastics in the Aqueous Environment. Freshwater Microplastics*. Cham: Springer, pp. 51–67.

Klein M and Fischer EK (2019) Microplastic abundance in atmospheric deposition within the metropolitan area of Hamburg, Germany. *Science of the Total Environment* **685**, 96–103.

Koeck DE, **Pechtl A**, **Zverlov VV and Schwarz WH** (2014) Genomics of cellulolytic bacteria. *Current Opinion in Biotechnology* **29**, 171–183. https://doi.org/10.1016/j.copbio.2014.07.002.

Kooi M, **Koelmans AA** (2019) Simplifying microplastic via continuous probability distributions for size, shape, and density. *Environmental Science & Technology Letters* **6**(9), 551–557. https://doi.org/10.1021/acs.estlett.9b00379.

Kooi M, **Van Nes EH**, **Scheffer M and Koelmans AA** (2017) Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. *Environmental Science & Technology* **51**(14), 7963–7971.

Kosuth M, **Mason SA and Wattenberg EV** (2018) Anthropogenic contamination of tap water, beer, and sea salt. *PLoS One* **13**(4), e0194970.

Krasowska A and Sigler K (2014) How microorganisms use hydrophobicity and what does this mean for human needs? *Frontiers in Cellular and Infection Microbiology* **4**, 1–7.

Kumar GA, **Anjana K**, **Hinduja M**, **Sujitha K and Dharani G** (2020) Review on plastic wastes in marine environment–biodegradation and biotechnological solutions. *Marine Pollution Bulletin* **150**, 110733.

Kumar Sen S and Raut S (2015) Microbial degradation of low density polyethylene (LDPE): A review. *Journal of Environmental Chemical Engineering* **3**, 462–473.

Lacerda AL, **Proietti MC**, **Secchi ER and Taylor JD** (2020) Diverse groups of fungi are associated with plastics in the surface waters of the Western South Atlantic and the Antarctic peninsula. *Molecular Ecology* **29**, 1903–1918.

Lambert S and Wagner M (2018) *Microplastics Are Contaminants of Emerging Concern in Freshwater Environments: An Overview. Freshwater Microplastics*. Cham: Springer, pp. 1–23.

Laverty AL, **Primpke S**, **Lorenz C**, **Gerdts G and Dobbs FC** (2020) Bacterial bioflms colonizing plastics in estuarine waters, with an emphasis on Vibrio spp. and their antibacterial resistance. *PLoS One* **15**(8), e0237704.

Lei L, **Liu M**, **Song Y**, **Lu S**, **Hu J**, **Cao C**, **Xie B**, **Shi H and He D** (2018a) Polystyrene (nano) microplastics cause size-dependent neurotoxicity, oxidative damage and other adverse effects in Caenorhabditis elegans. *Environmental Science: Nano* **5**(8), 2009–2020.

Lei L, **Wu S**, **Lu S**, **Liu M**, **Song Y**, **Fu Z**, **Shi H**, **Raley-Susman KM and He D** (2018b) Microplastic particles cause intestinal damage and other adverse effects in zebrafish Danio rerio and nematode Caenorhabditis elegans. *Science of the Total Environment* **619**, 1–8.

Liao H, **Zhao Q**, **Cui P**, **Chen Z**, **Yu Z**, **Geisen S**, **Friman VP and Zhou S** (2019) Efficient reduction of antibiotic residues and associated resistance genes in tylosin antibiotic fermentation waste using hyperthermophilic composting. *Environment International* **133**, 105203.

Lobelle D and Cunliffe M (2011) Early microbial biofilm formation on marine plastic debris. *Marine Pollution Bulletin* **62**, 197–200.

Longo C, **Savaris M**, **Zeni M**, **Brandalise RN and Grisa AMC** (2011) Degradation study of polypropylene (PP) and bioriented polypropylene (BOPP) in the environment. *Materials Research* **14**, 442–448.

Lopez-Pedrouso M, **Varela Z**, **Franco D**, **Fernandez JA and Aboal JR** (2020) Can proteomics contribute to biomonitoring of aquatic pollution? A critical review. *Environmental Pollution* **267**, 115473. https://doi.org/10.1016/j.envpol.2020.115473.

Lu X-M, **Lu P-Z and Liu X-P** (2020) Fate and abundance of antibiotic resistance genes on microplastics in facility vegetable soil. *Science of the Total Environment* **709**, 136276.

Lu K, **Qiao R**, **An H and Zhang Y** (2018) Influence of microplastics on the accumulation and chronic toxic effects of cadmium in zebrafish (Danio rerio). *Chemosphere* **202**, 514–520.

Lucas N, **Bienaime C**, **Belloy C**, **Queneudec M**, **Silvestre F and NavaSaucedo JE** (2008) Polymer biodegradation: Mechanisms and estimation techniques – A review. *Chemosphere* **73**, 429–442.

Magnin A, **Pollet E**, **Phalip V and Avérous L** (2020) Evaluation of biological degradation of polyurethanes. *Biotechnology Advances* **39**, 1–24. https://doi.org/10.1016/j.biotechadv.2019.107457.

Mammo F, **Amoah I**, **Gani K**, **Pillay L**, **Ratha S**, **Bux F and Kumari S** (2020) Microplastics in the environment: Interactions with microbes and chemical contaminants. *Science of the Total Environment* **743**, 140518.

Manalu AA, **Hariyadi S and Wardiatno Y** (2017) Microplastics abundance in coastal sediments of Jakarta Bay, Indonesia. *Aquaculture, Aquarium, Conservation & Legislation* **10**(5), 1164–1173.

Manzi HP, **Abou-Shanab RA**, **Jeon BH**, **Wang J and Salama ES** (2022) Algae: A frontline photosynthetic organism in the microplastic catastrophe. *Trends in Plant Science* **S1360–1385**(22), 00157–00161. https://doi. org/10.1016/j.tplants.2022.06.005.

Manzur A, **Limon-Gonzalez M and Favela-Torres E** (2004) Biodegradation of physicochemically treated LDPE by a consortium of filamentous fungi. *Journal of Applied Polymer Science* **92**(1), 265–271.

Masó M, **Fortuño JM**, **De Juan S and Demestre M** (2016) Microfouling communities from pelagic and benthic marine plastic debris sampled across Mediterranean coastal waters. *Scientia Marina* **80**, 117–127.

Maso M, **Garce ́s E**, **Page ́s F and Camp J** (2007) Drifting plastic debris` as a potential vector for dispersing harmful algal bloom (HAB) species. *Scientia Marina* **67**(1), 107–111.

Materić D, **Kasper-Giebl A**, **Kau D**, **Anten M**, **Greilinger M**, **Ludewig E**, **van Sebille E**, **Röckmann T and Holzinger R** (2020) Micro- and nanoplastics in alpine snow: A new method for chemical identification and (semi)quantification in the Nanogram range. *Environmental Science and Technology* **54**, 2353–2359. https://doi.org/10.1021/acs.est.9b07540.

Materić D, **Ludewig E**, **Brunner D**, **Röckmann T and Holzinger R** (2021) Nanoplastics transport to the remote, high-altitude Alps. *Environmental Pollution* **288**, 117697. https://doi.org/10.1016/j.envpol.2021.117697.

McCormick A, **Hoellein TJ**, **Mason SA**, **Schluep J and Kelly JJ** (2014) Microplastic is an abundant and distinct microbial habitat in an urban river. *Environmental Science and Technology* **48**, 11863–11871.

Meyer-Cifuentes IE, **Werner J**, **Jehmlich N**, **Will SE**, **Neumann-Schaal M and Öztürk B** (2020) Synergistic biodegradation of aromatic-aliphatic copolyester plastic by a marine microbial consortium. *Nature Communictions* **11**, 1–3.

Miao L, **Wang P**, **Hou J**, **Yao Y**, **Liu Z**, **Liu S and Li T** (2019) Distinct community structure and microbial functions of biofilms colonizing microplastics. *Science of the Total Environment* **650**, 2395–2402.

Michels J, **Stippkugel A**, **Lenz M**, **Wirtz K and Engel A** (2018) Rapid aggregation of biofilm-covered microplastics with marine biogenic particles. *Proceedings of the Biological Sciences* **285**, 20181203.

Mohan AJ, **Sekhar VC**, **Bhaskar T and Nampoothiri KM** (2016) Microbial assisted high impact polystyrene (HIPS) degradation. *Bioresource Technology* **213**, 204–207.

Montazer Z, **Habibi Najafi MB and Levin DB** (2019) Microbial degradation of low-density polyethylene and synthesis of polyhydroxyalkanoate polymers, can. *Journal of Microbiology* **65**, 1–11. https://doi.org/10.1139/cjm-2018-0335.

Monti D, **Ottolina G**, **Carrea G and Riva S** (2011) Redox reactions catalyzed by isolated enzymes. *Chemical Reviews* **111**(7), 4111–4140.

Muenmee S, **Chiemchaisri W and Chiemchaisri C** (2016) Enhancement of biodegradation of plastic wastes via methane oxidation in semi-aerobic landfill. *International Biodeterioration and Biodegradation* **113**, 244–255.

Muhonja CN, **Makonde H**, **Magoma G and Imbuga M** (2018) Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya, *PLoS One* **13**, e0198446.

Mukherjee S and Kundu PP (2014) Alkaline fungal degradation of oxidized polyethylene in black liquor: Studies on the effect of lignin peroxidases and manganese peroxidases. *Journal of Applied Polymer Science* **131** (17). https://doi.org/10.1002/app.40738.

Muthukrishnan T, **Al Khaburi M and Abed RMM** (2019) Fouling microbial communities on plastics compared with wood and steel: Are they substrate- or location specific? Microb. *Ecology* **78**, 361–374.

Nakamiya K, **Sakasita G**, **Ooi T and Kinoshita S** (1997) Enzymatic degradation of polystyrene by hydroquinone peroxidase of Azotobacter beijerinckii HM121. *Journal of Fermentation and Bioengineering* **84**, 480–482.

Negoro S (2000) Biodegradation of nylon oligomers. *Applied Microbiology and Biotechnology* **54**, 461–466.

Nielsen T, **Hasselbalch J**, **Holmberg K and Stripple J** (2019) Politics and the plastic crisis: A review throughout the plastic life cycle. *WIREs Energy and Environment* **9**, 1–18. https://doi.org/10.1002/wene.360.

O'Neill A, **Araújo R**, **Casal M**, **Guebitz G and Cavaco-Paulo A** (2007) Effect of the agitation on the adsorption and hydrolytic efficiency of cutinases on polyethylene terephthalate fibres. *Enzyme and Microbial Technology* **40**(7), 1801–1805. https://doi.org/10.1016/j.enzmictec.2007.02.012.

Oberbeckmann S, **Kreikemeyer B and Labrenz M** (2018) Environmental factors support the formation of specific bacterial assemblages on microplastics. *Frontiers in Microbiology* **8**, 2709. https://doi.org/10.3389/fmicb.2017.02709.

Oberbeckmann S and Labrenz M (2020) Marine microbial assemblages on microplastics: Diversity, adaptation, and role in degradation. *Annual Reviews in Marine Science* **12**, 209–232.

Oberbeckmann S, **Loeder MG**, **Gerdts G and Osborn AM** (2014) Spatial and seasonal variation in diversity and structure of microbial biofilms on marine plastics in northern European waters. *FEMS Microbiology Ecology* **90**, 478–492.

Oberbeckmann S, **Osborn AM and Duhaime MB** (2016) Microbes on a bottle: Substrate, season and geography influence community composition of microbes colonizing marine plastic debris. *PLoS One* **11**, e0159289.

Ogonowski M, **Motiei A**, **Ininbergs K**, **Hell E**, **Gerdes Z**, **Udekwu KI**, **Bacsik Z and Gorokhova E** (2018) Evidence for selective bacterial community structuring on microplastics. *Environmental Microbiology* **20**(8), 2796–2808. https://doi.org/10.1111/1462-2920.14120.

Ojha N, **Pradhan N**, **Singh S**, **Barla A**, **Shrivastava A**, **Khatua P**, **Rai V and Bose S** (2017) Evaluation of HDPE and LDPE degradation by fungus, implemented by statistical optimization. *Scientific Reports* **7**(1), 39515. https://doi.org/10.1038/srep39515.

Oliveira J, **Belchior A**, **da Silva VD**, **Rotter A**, **Petrovski Ž**, **Almeida PL.**, **Lourenco ND and Gaudencio SP** (2020) Marine environmental plastic pollution: mitigation by microorganism degradation and recycling valorization. *Frontiers in Marine Science* **7**, 567126.

Othman AR, **Hasan HA**, **Muhamad MH**, **Ismail NI and Abdullah SRS** (2021) Microbial degradation of microplastics by enzymatic processes: A review. *Environmental Chemistry Letters* **19**(4), 3057–3073. https://doi.org/10.1007/s10311-021-01197-9.

Paço A, **Duarte K**, **da Costa JP**, **Santos PS**, **Pereira R**, **Pereira ME**, **Freitas AC**, **Duarte AC and Rocha-Santos TA** (2017) Biodegradation of polyethylene microplastics by the marine fungus Zalerion maritimum. *Science of the Total Environment* **586**, 10–15.

Paget V, **Dekali S**, **Kortulewski T**, **Grall R**, **Gamez C**, **Blazy K**, **Aguerre-Chariol O**, **Chevillard S**, **Braun A**, **Rat P and Lacroix G** (2015) Specific uptake and genotoxicity induced by polystyrene nanobeads with distinct surface chemistry on human lung epithelial cells and macrophages. *PLoS One* **10**(4), e0123297.

Park SY and Kim CG (2019) Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. *Chemosphere* **222**, 527–533.

Pathak VM (2017) Review on the current status of polymer degradation: A microbial approach. *Bioresources and Bioprocessing* **4**(1), 15. https://doi.org/10.1186/s40643-017-0145-9.

Peixoto J, **Silva LP and Kruger RH** (2017) Brazilian Cerrado soil reveals an untapped microbial potential for unpretreated polyethylene biodegradation. *Journal of Hazardous Material* **324**, 634–644. https://doi.org/10.1016/j.jhazmat.2016.11.037.

Plastic Europe (2020) Plastics – The Facts 2020 [Internet]. Brussels: Plastics Europe; c2022 [cited 31 October 2022]. Available at: https://plasticseurope.org/knowledge-hub/plastics-thefacts-2020/.

Priya AK, **Jalil AA**, **Dutta K**, **Rajendran S**, **Vasseghian Y**, **Karimi-Maleh H and SotoMoscoso M** (2022) Algal degradation of microplastic from the environment: Mechanism, challenges, and future prospects. *Algal Research* **67**, 102848. https://doi. org/10.1016/j.algal.2022.102848.

Qi X, **Ren Y and Wang X** (2017) New advances in the biodegradation of poly(lactic) acid. *International Biodeterioration & Biodegradation* **117**, 215–223.

Radisic V, **Nimje PS**, **Bienfait AM and Marathe NP** (2020) Marine plastics from Norwegian west coast carry potentially virulent fsh pathogens and opportunistic human pathogens harboring new variants of antibiotic resistance genes. *Microorganisms* **8**(8), 1200.

Rahimi A and Garcia J (2017) Chemical recycling of waste plastics for new materials production. *Nature Reviews Chemistry* **1**, 1–11. https://doi.org/10.1038/s41570-017-0046.

Reisser J, Shaw J, Hallegraeff G, Proietti M, Barnes DKA, Thums M, Wilcox C, Hardesty BD and Pattiaratchi C (2014) Millimeter sized marine plastics: A new pelagic habitat for microorganisms and invertebrates. *PLoS ONE* **9**, e100289.

Restrepo-Flórez J-M, Bassi A and Thompson M (2014) Microbial degradation and deterioration of polyethylene – A review. *International Biodeterioration & Biodegradation* **88**, 83–90. https://doi.org/10.1016/j.ibiod.2013.12.014.

Rieck A, Herlemann DP, Jurgens K and Grossart HP (2015) Particle-associated differ from free-living bacteria in surface waters of the Baltic Sea. *Frontiers Microbiology* **6**, 1297.

Roager L and Sonnenschein EC (2019) Bacterial candidates for colonization and degradation of marine plastic debris. *Environmental Science & Technology* **53**(20), 11636–11643.

Rodrigues MO, Abrantes N, Gonçalves FJM, Nogueira H, Marques JC and Gonçalves AMM (2018) Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antuã River, Portugal). *Science of the Total Environment* **633**, 1549–1559.

Rogers KL, Carreres-Calabuig JA, Gorokhova E and Posth NR (2020) Micro-by-micro interactions: How microorganisms influence the fate of marine microplastics. *Limnology and Oceanography Letters* **5**(2), 18–36.

Rosato A, Barone M, Negroni A, Brigidi P, Fava F, Xu P, Candela M and Zanaroli G (2020) Microbial colonization of different microplastic types and biotransformation of sorbed PCBs by a marine anaerobic bacterial community. *Science of the Total Environment* **705**, 135790.

Rovaletti A, De Gioia L, Fantucci P, Greco C, Vertemara J, Zampella G, Arrigoni F and Bertini L (2023) Recent theoretical insights into the oxidative degradation of biopolymers and plastics by Metalloenzymes. *International Journal of Molecular Sciences* **24**(7), 6368. https://doi.org/10.3390/ijms24076368.

Ru J, Huo Y and Yang Y (2020) Microbial degradation and valorization of plastic wastes. *Frontiers in Microbiology* **11**, 442–452. https://doi.org/10.3389/fmicb.2020.00442.

Rummel CD, Jahnke A, Gorokhova E, Kühnel D and Schmitt-Jansen M (2017) Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environmental Science & Technology Letters* **4**, 258–267.

Salvador M, Abdulmutalib U, Gonzalez J, Kim J, Smith AA, Faulon JL, Wei R, Zimmermann W and Jimenez JI (2019) Microbial genes for a circular and sustainable bio-PET economy. *Genes* **10**, 373.

Sangeetha Devi R, Rajesh Kannan V, Nivas D, Kannan K, Chandru S and Robert Antony A (2015) Biodegradation of HDPE by Aspergillus spp. from marine ecosystem of Gulf of Mannar, India. *Marine Pollution Bulletin* **96**, 32–40.

Sangwan P and Wu DY (2008) New insights into polylactide biodegradation from molecular ecological techniques. *Macromol. Biosci.* **8**, 304–315.

Santos M, Gangoiti J, Keul H, Moller M, Serra JL and Llama MJ (2013) Polyester hydrolytic and synthetic activity catalyzed by the medium-chain-length poly(3- hydroxyalkanoate) depolymerase from Streptomyces venezuelae SO1. *Applied Microbiology and Biotechnology* **97**, 211–222.

Sarmah P and Rout J (2018) Efficient biodegradation of low-density polyethylene by cyanobacteria isolated from submerged polyethylene surface in domestic sewage water. *Environmental Science Pollution Research* **25**(33), 33508–33520. https://doi.org/10.1007/s11356-018-3079-7.

Schmidt VT, Reveillaud J, Zettler E, Mincer TJ, Murphy L and Amaral-Zettler LA (2014) Oligotyping reveals community level habitat selection within the genus vibrio. *Frontiers in Microbiology* **5**, 563.

Shah AA, Hasan F, Hameed A and Ahmed S (2008) Biological degradation of plastics: A comprehensive review. *Biotechnology Advances* **26**, 246–265.

Shahnawaz M, Sangale MK and Ade AB (2019) Bioremediation Technology for Plastic Waste.

Sharma D, Misba L and Khan AU (2019) Antibiotics versus biofilm: An emerging battleground in microbial communities. *Antimicrobial Resistance and Infection Control* **8**, 76.

Sheldon RA and Pereira PC (2017) Biocatalysis engineering: The big picture. *Chemical Society Reviews* **46**(10), 2678–2691.

Shi J, Wu D, Su Y and Xie B (2020) Selective enrichment of antibiotic resistance genes and pathogens on polystyrene microplastics in landfill leachate. *Science of the Total Environment* **765**, 142775.

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.

Shruti V and Kutralam-Muniasamy G (2019) Bioplastics: Missing link in the era of microplastics. *Science of the Total Environment* **697**, 134139.

Sieburth JM (1975) *Microbial Seascapes: A Pictorial Essay on Marine Microorganisms and their Environments*. Baltimore, MD: University Park Press.

Skariyachan S, Patil AA, Shankar A, Manjunath M, Bachappanavar N and Kiran S (2018) Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of Brevibacillus sps. And Aneurinibacillus sp. screened from waste management landfills and sewage treatment plants. *Polymer Degradation and Stability* **149**, 52–68.

Skariyachan S, Taskeen N, Kishore AP, Krishna BV and Naidu G (2021) Novel consortia of enterobacter and pseudomonas formulated from cow dung exhibited enhanced biodegradation of polyethylene and polypropylene. *Journal of Environment Management* **284**, 112030. https://doi.org/10.1016/j.jenvman.2021.112030.

Sol D, Laca A, Laca A and Díaz M (2020) Approaching the environmental problem of microplastics: Importance of WWTP treatments. *Science of the Total Environment* **740**, 140016.

Solanki S, Sinha S and Singh R (2022) Myco-degradation of microplastics: An account of identified pathways and analytical methods for their determination. *Biodegradation* **33**(6), 529–556. https://doi.org/10.1007/s10532-022-10001-6.

Song J, Jongmans-Hochschulz E, Mauder N, Imirzalioglu C, Wichels A and Gerdts G (2020) The travelling particles: Investigating microplastics as possible transport vectors for multidrug resistant E. cOLI in the Weser estuary (Germany). *Science of the Total Environment* **720**, 137603.

Sruthy S and Ramasamy EV (2017) Microplastic pollution in Vembanad Lake, Kerala, India: The first report of microplastics in lake and estuarine sediments in India. *Environmental Pollution* **222**, 315–322.

Stegen JC, Lin X, Konopka AE and Fredrickson JK (2012) Stochastic and deterministic assembly processes in subsurface microbial communities. *The International Society for Microbial Ecology Journal* **6**, 1653e1664.

Straub S, Hirsch PE and Burkhardt-Holm P (2017) Biodegradable and petroleum-based microplastics do not differ in their ingestion and excretion but in their biological effects in a freshwater invertebrate Gammarus fossarum. *International Journal of Environmental Research and Public Health* **14**, 774.

Su Y, Zhang Z, Zhu J, Shi J, Wei H, Xie B and Shi H (2020) Microplastics act as vectors for antibiotic resistance genes in landfill leachate: The enhanced roles of the long-term aging process. *Environmental Pollution* **270**, 116278.

Sun Y, Cao N, Duan C, Wang Q, Ding C and Wang J (2020b) Selection of antibiotic resistance genes on biodegradable and non-biodegradable microplastics. *Journal of Hazardous Materials* **409**, 124979.

Sun Q, Ren SY and Ni HG (2020a) Incidence of microplastics in personal care products: An appreciable part of plastic pollution. *Science of the Total Environment* **742**, 140218. https://doi.org/10.1016/j.scitotenv.2020.140218.

Sun XL, Xiang H, Xiong HQ, Fang YC and Wang Y (2023) Bioremediation of microplastics in freshwater environments: A systematic review of biofilm culture, degradation mechanisms, and analytical methods. *Science of the Total Environment* **863**, 160953.

Syranidou E, Karkanorachaki K, Amorotti F, Franchini M, Repouskou E, Kaliva M, Vamvakaki M, Kolvenbach B, Fava F, Corvini PFX and Kalogerakis N (2017a) Biodegradation of weathered polystyrene films in seawater microcosms. *Scientific Reports* **7**(1), 17991. https://doi.org/10.1038/s41598-017-18366-y.

Syranidou E, Karkanorachaki K, Amorotti F, Repouskou E, Kroll K, Kolvenbach B, Corvini PF, Fava F and Kalogerakis N (2017) Development of tailored indigenous marine consortia for the degradation of naturally weathered polyethylene films. *PLoS One* **12**, e0183984.

Tadsuwan K and Babel S (2021) Microplastic contamination in a conventional wastewater treatment plant in Thailand. *Waste Management & Research* **39**(5), 754–761.

Tagg AS and Labrenz M (2018) Closing microplastic pathways before they open: A model approach. *Environmental Science & Technology* **52**, 3340–3341.

Taniguchi I, Yoshida S, Hiraga K, Miyamoto K, Kimura Y and Oda K (2019) Biodegradation of PET: Current status and application aspects. *ACS Catalysis* **9**, 4089–4105.

Ter Halle A, Ladirat L, Martignac M, Mingotaud AF, Boyron O and Perez E (2017) To what extent are microplastics from the open ocean weathered? *Environmental Pollution* **227**, 167–174.

Tournier V, Topham CM, Gilles A, David B, Folgoas C, Moya-Leclair E, Kamionka E, Desrousseaux ML, Texier H, Gavalda S, Cot M, Gu´emard E, Dalibey M, Nomme J, Cioci G, Barbe S, Chateau M, Andr´e I, Duquesne S and Marty A (2020) An engineered PET depolymerase to break down and recycle plastic bottles. *Nature* **580**(7802), 216–219. https://doi.org/10.1038/s41586-020-2149-4.

Tsiota P, Karkanorachaki K, Syranidou E, Franchini M and Kalogerakis N (2018) Microbial degradation of HDPE secondary microplastics: Preliminary results. In *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea*. Cham: Springer, pp. 181–188.

Tu C, Zhou Q, Zhang C, Liu Y and Luo Y (2020) Biofilms of microplastics. In He D and Luo Y (eds.), *Microplastics in Terrestrial Environments. The Handbook of Environmental Chemistry*, Vol. **95**. Cham: Springer. https://doi.org/10.1007/698_2020_461.

Urbanek AK, Rymowicz W and Mirończuk AM (2018) Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology* **102**, 7669–7678.

Uscategui YL, Arevalo FR, Diaz LE, Cobo MI and Valero MF (2016) Microbial degradation, cytotoxicity and antibacterial activity of polyurethanes based on modified castor oil and polycaprolactone. *Journal of Biomaterials Science. Polymer Edition* **27**, 1860–1879.

Verma R, Shankarappa V, Papireddy M and Gowda ANS (2016) Toxic pollutants from plastic waste - A review. *Procedia Environmental Sciences* **35**, 701–708. https://doi.org/10.1016/j.proenv.2016.07.069.

Vermaire JC, Pomeroy C, Herczegh SM, Haggart O and Murphy M (2017) Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. *Facets* **2**(1), 301–314.

Vertommen M, Nierstrasz V, van Der VM and Warmoeskerken MMCG (2005) Enzymatic surface modification of poly(ethylene terephthalate). *Journal of Biotechnology* **120**, 376–386.

Vianello A, Boldrin A, Guerriero P, Moschino V, Rella R, Sturaro A and Da Ros L (2013) Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. *Estuarine, Coastal and Shelf Science* **130**, 54–61.

Vince J and Hardesty BD (2017) Plastic pollution challenges in marine and coastal environments: From local to global governance. *Restoration Ecology* **25**, 123–128.

Virsek MK, Lovsin MN, Koren S, Krzan A and Peterlin M (2017) Microplastics as a vector for the transport of the bacterial fish pathogen species Aeromonas salmonicida. *Marine Pollution Bulletin* **125**, 301–309.

Wang T, Qu L, Luo D, Ji X, Ma Z, Wang Z, Dahlgren RA, Zhang M and Shang X (2023) Microplastic pollution characteristics and its future perspectives in the Tibetan Plateau. *Journal of Hazardous Materials* **25**, 131711.

Wang S, Xue N, Li W, Zhang D, Pan X and Luo Y (2020) Selectively enrichment of antibiotics and ARGs by microplastics in river, estuary and marine waters. *Science of the Total Environment* **708**, 134594.

Webb HK, Crawford RJ, Sawabe T and Ivanova EP (2009) Poly(ethylene terephthalate) polymer surfaces as a substrate for bacterial attachment and biofilm formation. *Microbes and Environments* **24**, 39–42.

Wei R and Zimmermann W (2017) Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: How far are we? Microb. *Biotechnology* **10**(6), 1308–1322. https://doi.org/10.1111/1751-7915.12710.

Wei XF, Hedenqvist MS, Zhao L, Barth A and Yin H (2022) Risk for the release of an enormous amount of nanoplastics and microplastics from partially biodegradable polymer blends. *Green Chemistry* **24**(22), 8742–8750.

Weinstein JE, Crocker BK and Gray AD (2016) From macroplastic to microplastic: Degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. *Environmental Toxicology and Chemistry* **35**, 1632–1640.

Wen B, Jin SR, Chen ZZ, Gao JZ, Liu YN, Liu JH and Feng XS (2018) Single and combined effects of microplastics and cadmium on the cadmium accumulation, antioxidant defence and innate immunity of the discus fish (Symphysodon aequifasciatus). *Environmental Pollution* **243**, 462–471.

Wilkes RA and Aristilde L (2017) Degradation and metabolism of synthetic plastics and associated products by *Pseudomonas* sp.: Capabilities and challenges. *Journal of Applied Microbiology* **123**, 582–593.

Wright SL, Thompson RC and Galloway TS (2013) The physical impacts of microplastics on marine organisms: A review. *Environmental Pollution* **178**, 483–492.

Wu X, Pan J, Li M, Li Y, Bartlam M and Wang Y (2019) Selective enrichment of bacterial pathogens by microplastic bioflm. *Water Research* **165**, 114979.

Xiong X, Zhang K, Chen X, Shi H, Luo Z and Wu C (2018) Sources and distribution of microplastics in China's largest inland Lake–Qinghai Lake. *Environmental Pollution* **235**, 899–906.

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.

Yakimov MM, Timmis KN and Golyshin PN (2007) Obligate oil-degrading marine bacteria. *Current Opinion in Biotechnology* **18**(3), 257–266. https://doi.org/10.1016/j.copbio.2007.04.006.

Yamada-Onodera K, Mukumoto H, Katsuyaya Y, Saiganji A and Tani Y (2001) Degradation of polyethylene by a fungus, Penicillium simplicissimum YK. *Polymer Degradation and Stability* **72**, 323–327.

Yan F, Wei R, Cui Q, Bornscheuer UT and Liu Y (2021c) Thermophilic whole-cell degradation of polyethylene terephthalate using engineered clostridium thermocellum. *Microbial Biotechnology* **14**(2), 374–385. https://doi.org/10.1111/1751-7915.13580.

Yang Y, Liu G, Song W, Ye C, Lin H, Li Z and Liu W (2019) Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. *Environment International* **123**, 79–86.

Yang S, Xu W, Zhang K, Hu J, Gao Y, Cui G, Grossart HP and Luo Z (2022) Fungal communities differ with microplastic types in deep sea sediment enrichments of the eastern Pacific. *International Biodeterioration & Biodegradation* **173**, 105461. https://doi.org/10.1016/j.ibiod.2022.105461.

Yang J, Yang Y, Wu WM, Zhao J and Jiang L (2014) Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. *Environmental Science & Technology* **48**, 13776–13784.

Yang Y, Yang J, Wu WM, Zhao J, Song Y, Gao L, Yang R and Jiang L (2015b) Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 2. Role of gut microorganisms. *Environmental Science and Technology* **49**, 12087–12093.

Yang Y, Yang J, Wu WM, Zhao J, Song Y, Gao L, Yang R and Jiang L (2015a) Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 1. Chemical and physical characterization and isotopic tests. *Environmental Science & Technology* **49**, 12080–12086.

Yao C, Xia W, Dou M, Du Y and Wu J (2022) Oxidative degradation of UV-irradiated polyethylene by laccase-mediator system. *Journal of Hazardous Material* **440**, 129709. https://doi.org/10.1016/j.jhazmat.2022.129709.

Yin L, Chen B, Xia B, Shi X and Qu K (2018) Polystyrene microplastics alter the behavior, energy reserve and nutritional composition of marine jacopever (Sebastes schlegelii). *Journal of Hazardous Material* **360**, 97–105.

Yoon MG, Jeon HJ and Kim MN (2012) Biodegradation of polyethylene by a soil bacterium and alkB cloned recombinant cell. *Journal of Bioremediation & Biodegradation* **3**, 1000145.

Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K, Miyamoto K, Kimura Y and Oda K (2016) A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* **351**(6278), 1196–1199. https://doi.org/10.1126/science.aad6359.

Yu Z, Tang J, Liao H, Liu X, Zhou P, Chen Z, Rensing C and Zhou S (2018) The distinctive microbial community improves composting efficiency in a full-scale hyperthermophilic composting plant. *Bioresource Technology* **265**, 146–154.

Zamprogno GC, **Caniçali FB**, **dos Reis Cozer C**, **Otegui MBP**, **Graceli JB and da Costa MB** (2021) Spatial distribution of microplastics in the superficial sediment of a mangrove in Southeast Brazil: A comparison between fringe and basin. *Science of the Total Environment* **784**, 146963.

Zettler ER, **Mincer TJ and Amaral-Zettler LA** (2013) Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science & Technology* **47**, 7137–7146.

Zhang Y, **Gao T**, **Kang S**, **Allen D**, **Wang Z**, **Luo X**, **Yang L**, **Chen J**, **Hu Z**, **Chen P and Du W** (2023) Cryosphere as a temporal sink and source of microplastics in the Arctic region. *Geoscience Frontiers* **14**(4), 101566.

Zhang Y, **Lu J**, **Wu J**, **Wang J**, **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.

Zhang J, **Wang X**, **Gong J and Gu Z** (2004) A study on the biodegradability of polyethylene terephthalate fiber and diethylene glycol terephthalate. *Journal of Applied Polymer Science* **93**, 1089–1096.

Zhang J, **Wang L and Kannan K** (2019) Microplastics in house dust from 12 countries an associated human exposure. *Environment International* **134**, 105314.

Zhou Y, **Kumar M**, **Sarsaiya S**, **Sirohi R**, **Awasthi SK**, **Sindhu R**, **Binod P**, **Pandey A**, **Bolan NS**, **Zhang Z**, **Singh L**, **Kumar S and Awasthi MK** (2022) Challenges and opportunities in bioremediation of micro-nano plastics: A review. *Science of the Total Environment* **802**, 149823.

Zhu D, **Li G**, **Wang HT and Duan GL** (2021) Effects of nano- or microplastic exposure combined with arsenic on soil bacterial, fungal, and protistan communities. *Chemosphere* **281**, 130998. https://doi.org/10.1016/j.chemosphere.2021.130998.

ZoBell CE (1943) The effect of solid surfaces upon bacterial activity. *Journal of Bacteriology* **46**, 39–56.

ZoBell CE and Anderson DQ (1936) Observations on the multiplication of bacteria in different volumes of stored water and the influence of oxygen tension and solid surfaces. *The Biological Bulletin* **71**, 324–342.

Zuo LZ, **Li HX**, **Lin L**, **Sun YX**, **Diao ZH**, **Liu S**, **Zhang ZY and Xu XR** (2019a) Sorption and desorption of phenanthrene on biodegradable poly (butylene adipate co-terephtalate) microplastics. *Chemosphere* **215**, 25–32.