JOURNAL OF BIOCHEMISTRY, MICROBIOLOGY AND BIOTECHNOLOGY

Website: http://journal.hibiscuspublisher.com/index.php/JOBIMB/index

JOBIMB VOL 11 NO 2 2023
BlaNDM-1 MDR gene *A. baumannii*

The Microplastics in the Marine Environment: Origin, Hazardous Effects and Possible Biological Solutions: A Review

How Swen Yap[1] and Nur Adeela Yasid[1],*

[1]Department of Biochemistry, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

*Corresponding author:
Dr. Nur Adeela Yasid
Department of Biochemistry,
Faculty of Biotechnology and Biomolecular Sciences,
Universiti Putra Malaysia,
43400 UPM Serdang,
Selangor,
Malaysia.
Email: adeela@upm.edu.my

ABSTRACT

This review explores the escalating issue of marine microplastic pollution, a consequence of the extensive use of high molecular weight polymers in various industries. It delves into the origins, types, and environmental impacts of microplastics, particularly focusing on primary and secondary forms found in marine ecosystems. The study highlights the significant role of microplastics in global plastic production and their contribution to marine pollution, exacerbated by poor waste management and environmental factors. The review also examines the ecotoxicological effects of microplastics on marine life, noting species-specific responses ranging from physical blockages to chemical toxicity, often worsened by the interaction with other pollutants. Furthermore, it discusses innovative biological approaches for microplastic remediation, including the potential roles of microorganisms and certain marine and land animals in degrading or accumulating microplastics. This comprehensive analysis emphasizes the urgent need for effective waste management strategies, recycling efforts, and sustainable alternatives to conventional plastics, aiming to balance industrial and consumer demands with environmental conservation and address the critical issue of marine microplastic pollution.

INTRODUCTION

In general, plastics are polymers with high molecular weight which can be moldable into various shapes by applying higher temperatures [1]. The mouldability property in plastics allows them to be shaped when soft and hardened to a rigid and elastic form, thus supporting the economic demand in global markets. To date, most of the commodity productions (i.e. party decorations, child entertainment, food packaging materials, textile fabrics, electronic appliances and automotive) are highly dependent on plastic polymers, notably in reducing the production costs due to their low weight, high durability and better convenience [2,3]. The huge global plastic production in 2018 (i.e. almost 360 million tons per year) was highlighted by [4], which was about 12 million tons greater than in 2017. The extensive use of plastics raises environmental threats to the surrounding organisms along with the well-being of human populations, hence the existing era was recognized as 'The Plastic Age. Few studies reported on the high robustness of plastics that makes them highly resilient to being broken down or removed, contributing to global plastic pollution in environments with persistent toxic effects [5–7]. Consequently, coastal and marine environments are the frequent vic-

tims of plastic pollution originating from human activities. In addition, [8] estimated that there are approximately 9 million tons of land-based sources polluting the marine environment every year. These plastics were accumulated on the sea floor (94%), and near the shorelines (5%), while little of them will stay on the ocean surface (1%) [9]. Several pathways for land-based plastics entering the ocean were proposed by [10], including wind transportation, stormwater runoff, marine littering and natural water movements from rivers connecting to their neighbour ocean.

Distribution of these plastic pollutants by ocean currents was observed even in some pristine environments such as the Antarctic and Arctic Oceans [11,12]. Thus, these events imply bad practices of waste management and inadequately developed infrastructure within the affected sites, leading to a worldwide environmental issue later, as it poses an ecotoxicological and ecological risk to marine organisms and humans. This review aims to discuss the origin of microplastics, highlighting its hazardous effects and the possible biological solution in marine environments.

Marine Microplastics: The Origins

Microplastic pollution in marine environments is inevitable due to the increased usage of plastics in our daily lives. In general, microplastics were defined as tiny plastic particles with a size smaller than 5 mm [13]. From the report conducted by (4), several types of plastics found in the marine environments include PE, PCL, PUR, PLA, PHB, PET, PHA, PBS, PVC, PP and PS, endangering the aquatic ecosystems and their biota. [14] further explained that these particles within marine environments were generated with various characteristics, varying in size, density, chemical composition, and shape.

The two different forms of microplastics polluting the aquatic environments are primary and secondary microplastics. They can be found in raw materials for plastic products such as resin pellets (primary microplastics), or from the degradation of larger plastic substances by environmental factors into smaller fragments (secondary microplastics) [15,16]. Although naturally occurring biopolymers were reported in marine environments, it was not discussed in this review since they are biodegradable in general and exhibit minimal effects in these regions [17,18]. The origins of plastics are illustrated in **Fig. 1** and **Fig. 2**, highlighting their contributions toward marine plastic pollution with examples of plastic commercials, respectively.

Primary microplastics

Plastic particles of microscopic size manufactured for domestic or industrial purposes were classified as primary microplastics. A study done by [19], acknowledges 18 microplastic pollution sites observed in shorelines from different places involving 6 continents. These plastics are commonly seen in daily necessities such as cosmetics and personal care products including shower gels, foundation, mascara, eye shadow, deodorant, facial cleansers, toothpaste as well and sunscreen [7,20–22]. Since these products were meant to be washed off into domestic drains and be treated by the neighbouring wastewater treatment sites, [14] described them as 'open use'.

A study conducted by [23] reported the average amount of microbead particles found in facial cleaning abrasives was 50391 particles g^{-1} and an average release of microbeads (i.e. 10000 to 100000 particles) from daily usage of these products into the residential waste treatment plants also was estimated. Apart from that, primary microplastics also can be found in artificial clothing, abrasives and essential media in air blasting or sand blasting [24,25]. For example, the advancement in air blasting technologies employed primary microplastic products (i.e. acrylic sandblasting and polyester scrubbers) in the removal of rust and paint from the treatment sites [21,26]. [21] explained that the extensive use of these products led to the conjugation with heavy metals including cadmium, chromium, and lead, thus raising environmental concerns about the ecosystem from its combined harmful effects. In, addition, organic elements including oatmeal, ground almonds and pumice found in hand cleansers and body scrubs were substituted by microplastic "scrubbers" as a modern exfoliating alternative. Also, the extensive utilization of plastics-based exfoliating products in commercial industries was contributed by the microplastic scrubbers patented in the 1970s [27].

Few studies further explained these plastics as microbeads or micro-exfoliates, differing in their chemical compositions, sizes, and shapes adjusted to entertain the numerous interests in commercial products [23,28,29]. For instance, granules made of PP and PE with sizes smaller than 5 mm as well as PS components with sizes not bigger than 2 mm were reported in the beauty products [30]. [31] in different circumstances, acknowledged the spherical microbeads (vary from 60 to 800 μm) found in facial cleansers from some exclusive American brands. From the study, an estimation was made by them, indicating about 5 kg of these microbeads per year enter waste treatment management due to the high usage from the consumers [31]. However, to date, the utilization of PE microplastics in personal care and cosmetic products with a size smaller than 5 mm, was practised and yet reported by [28,32].

In general, secondary microplastics are tiny plastics that result from the fragmentation of larger plastic debris that existed on sea and land over time [21]. According to [33], approximately 75%–90% and 10%–25% of the plastics originated from terrestrial-based and marine-based sources, respectively. Although the mass production of synthetic plastics was about 60 years only, the high durability of plastics ranges from months to centuries, raising the adverse environmental threats to the polluted sites [34].

The natural breakdown of large plastic debris involves various physical, biological and chemical processes responsible for the deterioration of their structural integrity, leading to fragmentation processes [21]. The fragmentation of plastic debris under natural conditions (i.e. weathering & photodegradation) was influenced by different factors, including the surrounding temperatures, the exposure to sunlight, and the size and density of the plastics [34]. They further explained that sand beaches are the most effective site for mechanical and chemical weathering by providing the optimal factors (i.e. high solar UV, wave abrasion, high oxygen exposure) for plastic fragmentation.

The process of weathering was highlighted as it plays an important role in disintegrating plastics in marine environments. According to [35], chemical weathering was favored by the mechanically induced scratches in plastics, allowing deeper deterioration of the polymer surface and producing brittle plastics. This implies the efficient weathering of plastic debris on beaches as scratches were easily made by wave abrasion and water turbulence [36]. The sunlight-induced photodegradation also broke down the larger plastic debris into microplastics by oxidatively cleaving the bonds within the polymer matrix of plastics [37]. These tiny plastics eventually become brittle over time, making pits, and producing discoloration. The embrittlement in these plastics made them sink into marine water and their degradation process was rendered due to relatively low temperatures and low exposure to UV light in deeper water levels. These resulting activities led to the accumulation of tiny plastics in marine environments, hence increasing the possibility of accidental plastic ingestion by marine organisms due to its microscopic size [12].
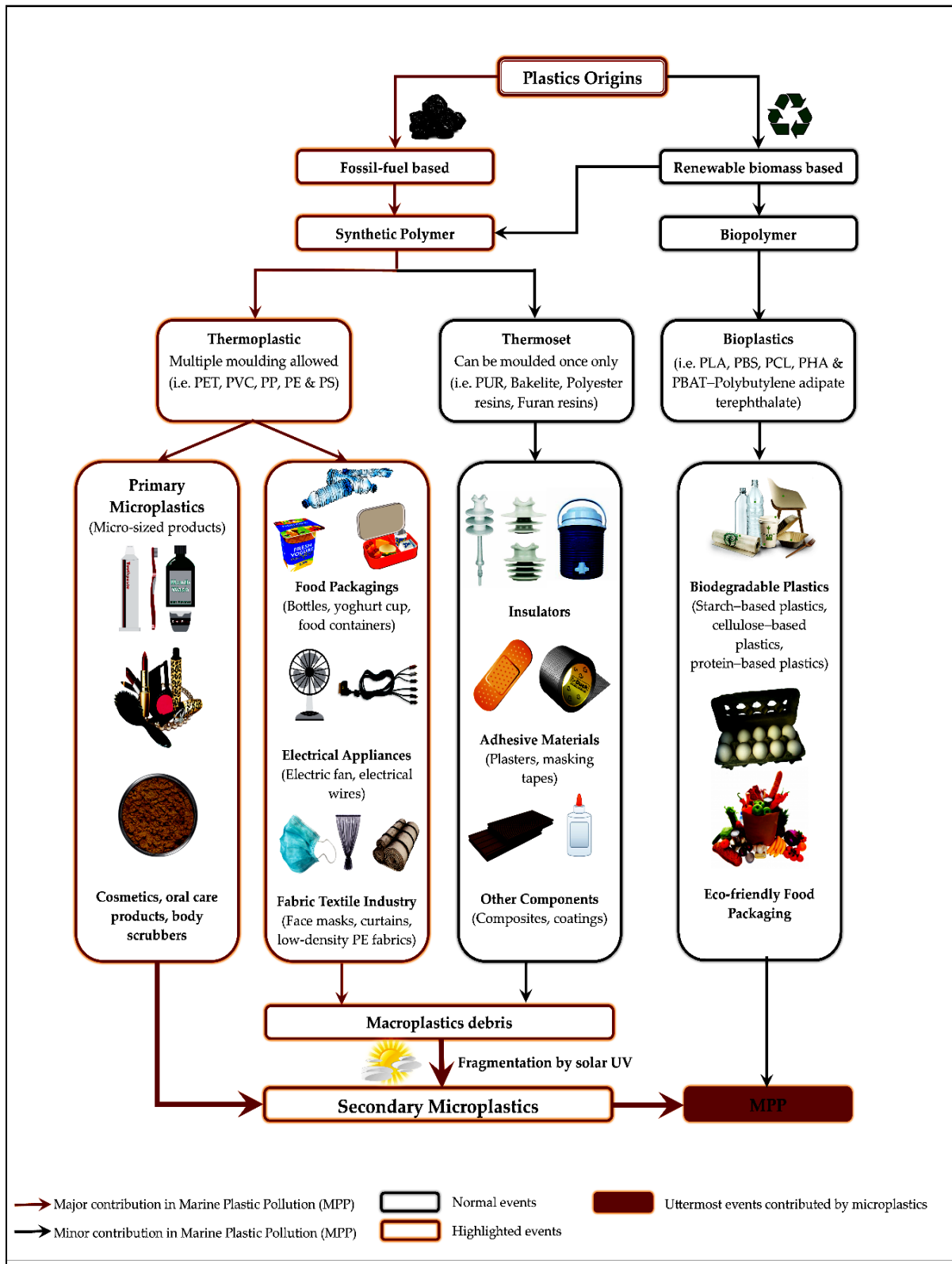
Fig. 1. The plastic origins and its contribution toward marine plastic pollution. Both synthetic (fossil fuel-derived) and natural polymers (renewable biomass-derived) were utilized for industrial profits, leading to various commercial plastic-based products available to the consumer markets. Marine plastic pollution was contributed by all these plastics under the influence of environmental factors, especially from primary and secondary microplastics.
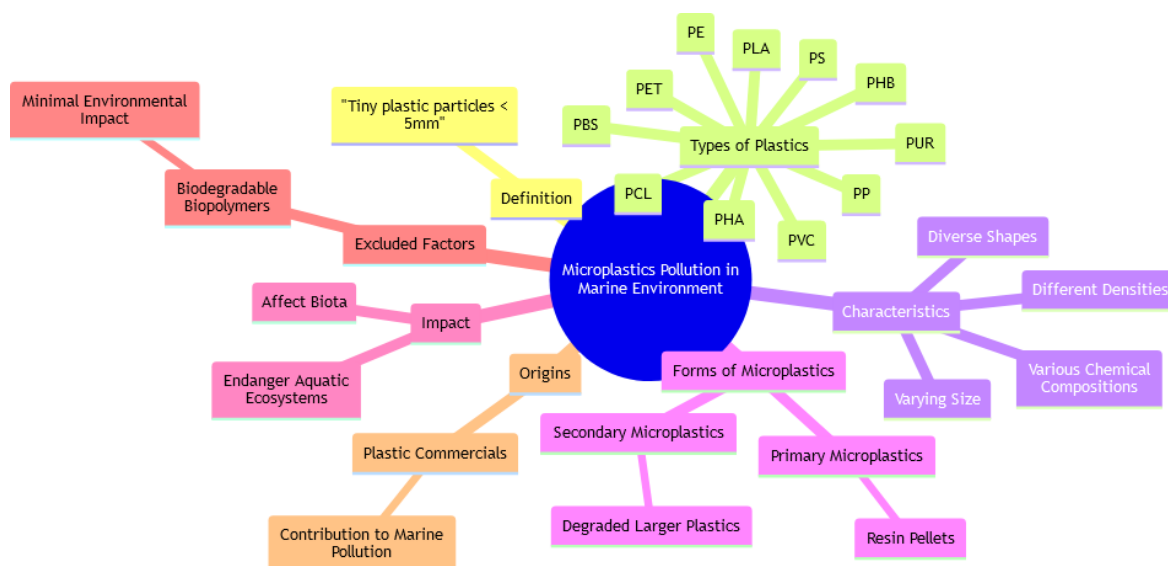
Fig. 2. A mindmap on the synthetic and natural polymers used industrially that create diverse plastic products and subsequently their pollution visualized and summarized using the Mermaid Chart software (v 10.6.1). .

The hazardous effects of microplastics on marine organisms

To date, the biological effects of tiny plastic particles on marine organisms are partially understood as those effects tend to be species-specific [38]. Few studies suggested that marine organisms ingest microplastics which then block and accumulate in their gastrointestinal tract to give a false signal of satiation that causes starvation, leading to bad growth and corrupted body conditions [39,40]. A study with mysid shrimp (*Neomysis japonica*), [39]) reported that PS microplastics were accumulated in several organs (i.e. brain, stomach, gastrointestinal tract and liver), leading to low food intake and causing insufficient nutrients as well as deaths due to disruptive hunting activities contributed by low swimming movements and toxins. Besides that, disruption of the internal digestive system, abnormal hormone levels and the reproduction capability of marine organisms were disrupted due to the toxic effects of the ingested microplastic [41]. For instance, adult zebrafish (*Danio rerio*) were reported to have several abnormal behavioural activities identified after exposure to virgin PE microplastics for 4 days, including erratic swimming and strange tail bending upward/downward that reduce the swimming abilities in zebrafish and raised survival concerns.

Other toxic effects in adult zebrafish were also recognized such as the deposition of toxic –product, sulfur oxide which damages the digestive guts due to the upregulated cytochrome P450 1A gene, while the compromised oogenesis activity which eventually changes all male zebrafishes to female zebrafishes due to overexpressed vitellogenin gene that interferes the endocrine hormone [41]. Microplastics can also induce inflammation in cells and organs by stimulating the production of reactive oxygen species (ROS) [40,42]. A study conducted by [42]reported significant oxidative stress found in clam gills after PET microplastic exposure. This event was due to the inhibited antioxidant enzyme (i.e. glutathione peroxidase, GPx gene) in gills, leading to severe lipid peroxidation on their cell membranes as well as other cellular components, and producing inflamed cells and organs at the end of treatments. On the other hand, few studies focused on the combined effect posed by different conjugated pollutants involving microplastics and toxic chemical additives (i.e. Polybrominated diphenyl ethers, oxybenzone, chlorpyrifos & glyphosate)

[43–45]. By referring to the actual marine plastic polluted sites, plastic particles tend to adsorb some persistent chemicals found in water environments, which are subsequently ingested by marine organisms, leading to more severe ecotoxicological effects on them as compared to the microplastic pollutant alone [14]. This concern has raised a research interest in elucidating the actual effect posed by the chemical additive and microplastic on marine organisms. A study done by [44] highlighted the potential high-density PE (HDPE) as a vector in enhancing the toxic effect of chlorpyrifos (CPF) in marine copepod (*Acartia tonsa*), in which they found out the toxicity of CPF increased by more than twenty–fold as compared to single treatment of CPF, leading to significant mortality rate (i.e. no survived species after 48 h). The exposure to HDPE–CPF also suppressed the feeding activities (i.e. little or no movements) and reproduction activities (i.e. slow hatching process) of marine copepods. Although there was a significant lethal effect observed from CPF on marine copepods, they stated the toxic effect could be species–specifically as marine copepods are susceptible to organophosphorus pollutants which might not be in the same case for other marine organisms. They further urged that toxicity study of CPF should be done on other marine organisms before making a consensus on the lethal effect of CPF for all marine organisms.

To date, most studies reported that the combination of microplastic and chemical additives led to toxic effects on marine organisms, however, a study challenged the combined toxicity of microplastics on aquatic organisms. For instance, [46] reported the toxicity of 4–n–nonylphenol (NP) was not influenced by PE microplastics on planktonic sea urchins as the EC_{50} (i.e. concentration needed to decrease species growth rate by half) of NP was greater than 2–fold as compared to the combined toxicity test in sea urchins, regardless the usage and concentration of PE microplastics. Nevertheless, the laboratory-based microplastic toxicity test with or without organic chemical pollutants still needs more clarification to elucidate the actual ecotoxicological effect in marine ecosystems. Few studies reported on the adverse effect of microplastic with or without chemical pollutants on aquatic organisms were documented in **Table 1** and **Table 2**, respectively.

Table 1. The ecotoxicological effects of microplastics on marine organisms reported from laboratory–based studies.

Organisms	Type	Microplastic (MP) Size (diameter)	Concentration	Exposure time	Toxic Effects	Reference
Mysid shrimp (*Neomysis japonica*)	PS	5 μm	10 mg/mL	2–4 days	Accumulated PS-MPs were observed in several organs (i.e. brain, stomach, and liver). Lethal effects (i.e. high mortality & low growth rate) and disruptive hunting activities (i.e. decreased swimming movements) were observed probably due to insufficient nutrients, respiratory stress by gill injuries and toxins in the brain.	[39]
Sea urchin (*Paracentrotus lividus*)	PS	10 & 45 μm	10 particles/mL	3 days	A significant increase in reactive oxygen species (ROS), reactive nitrogen species (RNS) and immune cells was observed in sea urchins. The elevated immune cells refer to the actual immune response to the toxic ingested microplastics due to proliferation. The high amount of ROS and RNS leads to the overexpression of free radicals that cause damage to protein, DNA, and lipid components.	[47]
Adult zebrafish (*Danio rerio*)	PE	10–600 μm	2 mg/L	4 days	Although no death was observed in this study MP accumulation in organs (i.e. intestine & fish gills) and abnormal behavioural activities were identified (i.e. erratic swimming & abnormal tail bending). –regulation of vitellogenin and cytochrome P450 gene were also recognized that lead to the overproduction of toxic sulfur oxides in intestines and feminization of male zebrafish.	[41]
Manila clam (*Ruditapes philippinarum*).	PET	8–1054 μm	0.125–12.5 μg/ml	7 days	A significant increase in oxidative stress was observed in clam gills. The overexpression of oxidation leads to lipid peroxidation in manila clams that cause damage to cellular components and the cell membranes, resulting in inflamed cells and organs.	[42]
6 stony coral species (*Acropora humilis* & etc.)	PE	37–163 μm	4000 particles/L	4 weeks	PE-MP was found on surface tentacles and mesenterial filaments in the gut-associated with mucus. Two bad conditions were observed, where necrosis covers about 40% of their surface area while coral bleaching probably increases the mortality rate of coral species by suppressing the growth rate.	[38]
Goldfish (Carassius carassius)	EVA, PS & PA	< 5000 μm	15–76 items/fish	6 weeks	Decreased in overall weight by 17.5–21.5% in goldfish after the MP exposure. The chewing activity causes severe damage in the oral cavity of goldfish for about 80% of the total species. The ingested MP with microorganisms penetrates the liver causing inflammatory reactions and inducing inflamed cells and organs.	[40]

Table 2. The adverse effects of microplastics combined with other toxic chemicals on marine organisms.

Organisms	Microplastic (MP) Size (diameter)	Concentration	Contaminant Type	Concentration	Exposure time	Toxic Effects	Reference
MP Type: PS							
Marine mussel (*Mytilus coruscus*)	2 μm	0–2.5 μg/L	Polybrominated diphenyl ethers, BDE–47	0–10 μg/L	21 days	The combined effect of MP and BDE-47 led to some events such as elevated respiration rate, higher expression rate for acid phosphatase, alkaline phosphatase and reactive oxygen species while the expression of lactate dehydrogenase and heat shock protein (Hsp70 & 90) was rendered. Overall MP has exaggerated the effect of BDE-47, mainly affecting the defence mechanisms and cellular metabolism.	[43]
MP Type: LDPE							
Shell clam (*Scrobicularia plana*)	11–13 μm	1 mg/L	Oxybenzone, BP–3	82 ng/g	14 days	Few organs (i.e. digestive gland & hemolymph) have been identified with the accumulated MP– BP3 while gills were the major affected site associated with abnormal biomarker modification. The adsorption of BP3 on MP caused a significant oxidative attack and damage when compared to the sole MP treatments. High genotoxic levels (i.e. DNA damage) are also contributed by the combination of BP3 and MP.	[48]
MP Type: High-Density PE, HDPE							
Marine copepod (*Acartia tonsa*)	2–10 μm	100 mg MP/L	Chlorpyrifos, CPF	100 mg CPF/L	24 h	HDPE served as a vector to increase the bioavailability of CPF to the marine copepod. Exposure to HDPE–CPF led to decreased feeding and reproduction activities where a slow hatching process was observed. Significant lethal effects were identified where the presence of HDPE–CPF has contributed to a great amount (i.e. > twenty–fold) of toxic effects as compared to a single treatment of CPF alone., leading to a high mortality rate.	[44]
MP Type: PE & PET							
Planktonic crustacean (*Daphnia magna*)	2.09 μm	0.01 mg dry weight/mL	Glyphosate, Gly	2.5 mg/L	7 days	In general, Gly–acid had the lowest mortality rate (12.5%) as compared to Roundup Gran (20%) and Gly–monoisopropylamine, Gly-IPA (23.3%). However, the exposure of MP has significantly increased the mortality rate in planktonic crustaceans contributed by Gly–acid (i.e. 40.8% for PE & 17.5% for PET) and Roundup Gran (i.e. 14% for PE & 10.7% for PET), respectively, while slightly decreased with Gly–IPA.	[45]

Marine microplastics: possible removal by biological approaches

Marine microplastic pollutions pose an emerging threat to wildlife and subsequently compromises the benefits of the human population as it gives rise to ecotoxicological and ecological risks. In addition, the rate of microplastics entering the environment succeeded the rate of removal due to enormous usage by the consumer annually [4]. Thus, the widespread of marine plastic pollutants leads to a huge research interest in exploring various applicable removal treatments to remedy plastic pollutants from water bodies, hence decreasing their bioavailability and toxic effects on marine organisms. Several methods have been proposed including membrane technology, advanced filtration systems, electrical–coagulation and chemical coagulants [49]. However, it was established that these tiny plastic particles generally are highly persistent in nature, smaller in size and have low visibility which contributes to the difficulty in manual–based treatment [14]. Besides that, chemical methods were expensive (i.e. frequently replaced cathode and anode due to passivation & high electricity cost) and may raise poisonous threats to the treatment site as toxic lead– and aluminium-based coagulants were used to coagulate the microplastic particles [49]. Therefore, a more feasible approach could be utilized by exploiting microorganisms that are capable of degrading microplastic polymers since it is environmentally friendly, low costs and highly applicable in different environments. Furthermore, to date, few animals and marine organisms also been suggested with their potential in removing the microplastic from marine environments. Thus, the microbial biodegradation and potential animal applications are discussed.

Possible plastic remediation by exploiting microorganisms

This process is acknowledged as biodegradation, in which microorganisms are used to break down synthetic plastic polymers. Biodegradation is feasible due to the possibility of plastic particles to serve as a sole carbon and energy supply to plastic degrative microbes [50,51]. Several studies highlighted the potential utilization of microbes in plastic remediation by showing a considerable decrease in the dry weight of microplastics and stimulating physiochemical alterations. These studies mainly focused on the frequently found microplastics including PE, PP & PS which were correlated to their abundance in current plastic-polluted sites. For instance, [50] reported the degradation of PP microplastic by *Bacillus* sp. strain 27 (i.e. 4.0% decrease in dry weight of PP after 40 days) and *Rhodococcus* sp. strain 36 (i.e. 6.4% decrease in dry weight of PP after 40 days) isolated from mangrove sediments. In addition, the deterioration half-life study (i.e. time to decrease the amount of PP by half) showed a shorter half–life of 346 days in *Rhodococcus* sp. strain 36 while isolates 27 recorded a longer half–life of 693 days.

Scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) in the study further supported the potential plastic degradation ability in these strains, in which they found damages in the form of irregular holes on PP surfaces followed by the colonisation of microbial communities while FTIR analysis reported successful degradation by examining different absorption peaks (i.e. 1456 cm^{-1} & 1376 cm^{-1} for bending of carbon and hydrogen bond) which provide information on bond splitting and chemical changes. At the end of the study, they concluded the possibility of *B. cereus*, *B. thuringiensis* and *R. ruber* as synthetic polymer degraders as they can utilise PP as the carbon source and display some degrative characteristics after treatment.

To date, several plastic degrative strains isolated from various sources have been proposed include *Pseudomonas aeruginosa* E7, *Streptomyces albogriseolus* LBX-2, *Acinetobacter* sp. and *Bacillus gottheilii*, highlighting their potential remediator for plastic pollutants especially on PP, PE, PS and PET, respectively (61–64). Although most studies focused on single-strain plastic degradation, few studies explored the plastic degrative ability in microbial consortium due to their emerging applications in environmental pollution research [51,52]. The emerging microbial consortium has been applied in petroleum hydrocarbon degradation due to its higher catabolic removal ability contributed by varied enzymatic responses which eventually enhance the diesel degradation as compared to the single bacterial strain [53]. Thus, the research opportunity by utilising microbial consortium has gained attention in the removal of various environmental pollutants, especially on microplastics. A study in Korea by [51] reported a relatively higher PE microplastic degradation was observed in a bacterial consortium (i.e. 14.7% decrease in dry weight of PE after 60 days & 22.8% decrease in PE microplastic diameter) retrieved from a landfill. In the study, the dominant species existed in the bacterial consortium was identified as *Bacillus* sp. and *Paenibacillus* sp., in which they found these significant colonized bacteria on PE surfaces that further deteriorated the microplastics supported by the result from SEM, FTIR and Gas Chromatography-Mass Spectrophotometry (GC-MS). Consequently, they acknowledged the presence of microbial consortium has enhanced the plastic degradation efficiency as they are relatively stable probably due to the collaboration between different microbes in remedying the plastic pollutant, especially on PE microplastic (i.e. 40–600 µm). Nonetheless, more scientific data are needed to understand the actual role played by the microbial consortium on each type of microplastic, before the usage of microbial consortia in field treatment of plastic-polluted sites.

Besides bacteria, fungus is also one of the potential plastics degrative microorganisms which has been proposed in recent times. For instance, [25] highlighted a marine fungus (*Zalerion maritimum*) that can serve as a tool for plastic bioremediation where it recorded more than 43% removal rate of PE microplastic after 14 days. They examined the biological compounds (i.e. higher carbohydrate level & lower protein concentration) gradually with time, in these results disclose a probability of *Z. maritimum* utilising PE microplastic as their carbon uptakes. In addition, both electron and optical microscopy in the study emphasized the potential degradation process by marine fungus *Z. maritimum* on PE surfaces as the presence of biological materials and irregular pits were observed on its surfaces. Meanwhile, in the study, FTIR assay further supported the plastic degradative ability in *Z. maritimum*, where several new peaks were recognized for the formation of carbonyl factions and double bonds due to oxidative deterioration of PE, an identical FTIR analysis reported from [54].

Similarly, [55] reported the fungus (*Aspergillus flavus* strain PEDX3) isolated from the intestines of wax moth (*Galleria mellonella*) displayed an efficient deterioration of HDPE microplastic, giving a mass loss of 3.90 ± 1.18% after 28 days. Both studies from [56] and [55] confirmed the PE microplastic can be utilized as a sole carbon nutrient for fungus and they have obtained an identical FTIR analysis (i.e. new peaks for carbonyl fractions & double bonds) implying fungus as the potential plastic bioremediation tool.

Noteworthily, the plastic degrative gene study from [55] suggesting the potential plastic bioremediation in *A. flavus* strain PEDX3 was contributed by the up-expression of two laccase-like multicopper oxidases (i.e. AFLA_006190 & AFLA_053930) which catalyze oxidative cleaving on plastic polymers and increase its eliminatory efficiency. Thus, fungus might be an interesting remediator of plastic pollutants, yet more clarifications are needed to understand the toxicity effects of these microplastic particles on fungus and the possible ecological concerns after the fungus bioremediation to the treated sites.

Possible plastic remediation by living organisms
Although there is little information regarding microplastic bioremediation by animals and most studies focus on bacteria and fungus biodegradation, it is one of the alternatives available for the possible removal of plastic pollutants. In general, few considerations should be made in deciding the appropriate animals for plastic remediation. Firstly, the mode of elimination (i.e. by ingestion, filtration & retention) on microplastics should be highly efficient, preferably those with little harmful effects caused and the toxic plastics are not returning to the surroundings. Secondly, indigenous species should be localized within their natural habitats as the geographical transfers were highly prohibited to conserve the biodiversity of the treatment sites, while these organisms normally were adapted to their natural habitat conditions and nutrient bioavailability which eventually eased the application of these animals [57].

Lastly, the use of animals should be simple in maintaining, controlling, and managing, hence the developments would be easier while high efficiency is confirmed. Many studies have reported minimal microplastic retention rates in active–feeding living organisms (i.e. gastropods & copepods), hence revealing its unsuitability of using them in plastic bioremediation. In the study, although both gastropods and copepods reported high survival rates after microplastic exposure, yet to in plastic bioremediation due to their significant egestion rates which eventually return the toxic plastic pollutants back to the environments in the form of fecal pellets [44,58]. These fecal pellets make available to the higher trophic level due to the accidental ingestion by bigger marine animals, subsequently endangering their health and survival [59,60]. On the other hand, filter feeder species seem to have high potential in microplastic bioremediation due to their high retention rates. For instance, epibenthic species *Ophiomusium lymani* (i.e. 1.30–4.78 microplastics/g) which exhibited filter feeding and facultative predation behavior were reported of high retention rate of microplastics especially on fragments and fibers, when compared to the sole predator benthic species, *Hymenaster pellucidus* (i.e. 0.48–13.31 microplastics/g). Furthermore, the filter feeder bivalves (*Mytilus* spp.) were proposed as one of the potential animals for the effective remediation of microplastics, highlighting their abundancy in sea waters, high ability to consume different microplastics (i.e. PE, PS, PP, PA, PET & PVC) and the retainment of ingested microplastic (i.e. for 2 days) in their circulatory systems [19,61]. However, the efficient gut maintenance (i.e. frequent egestion after 24 h) in *Mytilus* spp. and high toxicity effects of microplastic (i.e. upregulation of oxidative attacks lead to inflamed cells) on these species were reported, hence rendering its microplastic eliminatory efficiency [61].

In sea waters, coral reefs are essential for the marine environments as they provide nutrients to marine organisms and maintain biodiversity integrities [62]. Recently, filter feeder coral species (*Acropora hemprichii*, *Goniastrea retiformis* & *Pocillo-*

pora verrucosa) also received scientific attention in the microplastic bioremediation as the microplastic ingestion was reported in these corals conjugated with efficient microplastic adhesion [63]. In the study, they reported the combination of a relatively lower ingestion rate (i.e. 0.25×10^{-3}–14.8×10^{-3} microplastic particles/h) and significant adhesion rate (i.e. more than 40 times fold than ingestion) suggesting the potential use of these corals in plastic bioremediation, elucidating the actual reduction in plastic pollutants by accumulating in the coral sinks.

Another study with mushroom coral (*Danafungia scruposa*) by [62] further supported the previous result by highlighting their identical findings where *D. scruposa* removes PE microplastic in the water body actively through ingestions ($2.3 \pm 0.7\%$ of plastic pieces/h) as well as passively by adhesions ($97.7 \pm 0.7\%$ of plastic pieces/h), in which the former process was 40 times less efficient in the removal study. Both studies support that the adhesion process in coral reefs was an effective microplastic removal as these organisms provided them with a "sink" in the marine environments that contributed to their large polyp structures (i.e. 3–38 cm in diameter) [63]. However, few studies challenged the adverse effects contributed by the short-term microplastic exposure to these corals, including necrosis on the surfaces, discolouration by bleaching and stress on physiological responses [64]. Thus, the use of corals in plastic bioremediation is still challenging and information regarding the long-term microplastic exposure effects on corals is greatly needed before the field study.

Aside from these marine animals, snails and mealworms were also reported to play a potential role in plastic bioremediation. A study with land snails (*Achatina fulica*) by [65] suggested their potential use in plastic bioremediation due to the high ingestion rates (i.e. 18.5 ± 2.9 mg PE/snail after 28 days) facilitated by the plastic depolymerization in their guts and subsequently egested in the fecal pellets. In the study, they examined the polydispersity index (PDI) in the fecal pellets using two parameters (i.e. number average molecular mass, M_n & weight average molecular mass, M_w), in which a PDI of 2.01 was observed in the fecal pellets from the treated species and compared to the control with higher PDI of 2.55 after 28 days. The lower PDI from treated species revealed there was a significant change from low molecular weight compounds to higher molecular weight compounds, indicating successful depolymerization of PS microplastics due to chemical bond cleavages. Besides that, the FTIR and Proton Nuclear Magnetic Resonance analysis further supported the theory of plastic depolymerization in *A. fulica* by highlighting a few new peaks of 1075–1150 cm^{-1} & 1650 cm^{-1} attributed to CO and C=C bonds, respectively, indicating molecular alterations in PS microplastics into potential carbonyl groups.

The successful depolymerization activity in the guts of *A. fulica* was contributed by the significant growth of *Enterobacteriaceae* sp. (i.e. 52.5% increase in abundance on week 2) and *Sphingobacteriaceae* sp. (i.e. 18.8% increase in abundance on week 4) which are capable in catalyzing oxidative depolymerization on PE microplastics. An identical increase in *Enterobacteriaceae* sp. also was reported in PE & PS microplastic degradation study from [66] using larvae of *Zophobas atratus*, confirming the successful microplastic degradation theory in *A. fulica*. Similarly, a study in China by [66] reported both yellow (*Tenebrio molitor*) and dark (*Tenebrio obscurus*) mealworms consumed high amounts of PS microplastics, estimated as 24.30 ± 1.34 and 32.44 ± 0.51 mg per larvae per h, respectively. In the study, they also examined the M_n value in the fecal pellets from both treated species, in which they found efficient microplastic degradation in *T.*

obscurus (i.e. 26.03% decrease in M_n of PS left over in fecal pellet) when compared to the *T. molitor* (i.e. 11.6% decrease in M_n of PS left over in fecal pellet). Noteworthily, a similar FTIR analysis was observed, revealing new peaks attributed to the formation of carbonyl compounds, while the genetic sequencing finding showed the dominance of a few strains, namely *Enterobacteriaceae* sp., *Spiroplasmataceae* sp., and *Enterococcaceae* sp. Although these living organisms were mostly land–based, yet there is a potential use of these species in wastewater treatment plants as proposed by a review summarized by [67]. Since one of the main sources of marine microplastics originated from the treated effluent discharged by the wastewater treatment plant, thus implementing these plastic degradative organisms seems to be a good solution in the remedy of marine plastic pollution. In summary, epibenthic species *O. lymani* and land–based organisms (i.e. black mealworm, *T. obscurus* & land snails, *A. fulica*) seem to be an effective remediator tool for marine plastic pollution, yet further investigations should be conducted on the suitability in both actual seawater conditions and wastewater treatment plants, before a scientific consensus was made.

CONCLUSION

To sum up, marine ecosystems are facing serious problems as a result of the widespread use of plastics, especially microplastics. There has been an unprecedented surge in the worldwide production of plastics because of their widespread use and the ease with which they can be shaped to meet specific needs. Nevertheless, this has led to significant consequences for the environment. Marine ecosystems are severely impacted by microplastics, which can be classified as either primary or secondary pollutants. Microplastics, both primary (found in consumer goods) and secondary (produced by the breakdown of bigger plastic debris), are major sources of pollution in the ocean. Not only does this pollution harm marine life through accumulation and ingestion, but it also presents ecotoxicological risks as a result of the harmful chemicals that are absorbed. Microplastics pose a significant threat to marine life due to their wide-ranging and diverse harmful effects, which affect reproduction, health, and survival. These effects can range from physical blockages to chemical toxicity. These consequences become even more complicated and severe when microplastics interact with other contaminants. Innovative and effective solutions are necessary to address this crisis. Microorganisms and specific land and marine animals are examples of biological approaches that show potential for reducing microplastic pollution. These living organisms have the ability to break down or accumulate microplastics, which could lead to a decrease in their abundance in aquatic habitats. But we don't know much about these methods' effectiveness or environmental impacts just yet because we're in the early phases of research. All things considered, the assessment stresses how critical it is to have immediate plans to control plastic trash, boost recycling rates, and create eco-friendly substitutes for traditional plastics. To address the persistent problem of microplastic pollution in the ocean, we must find a way to satisfy both consumer and industrial demands while simultaneously protecting the environment.

REFERENCES

1. Ahmed T, Shahid M, Azeem F, Rasul I, Shah AA, Noman M, et al. Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ Sci Pollut Res Int. 2018 Mar;25(8):7287–98.
2. Andrady AL. The plastic in microplastics: A review. Marine pollution bulletin. 2017;119(1):12–22.
3. Heidbreder LM, Bablok I, Drews S, Menzel C. Tackling the plastic problem: A review on perceptions, behaviors, and interventions. Science of The Total Environment. 2019 Jun;668:1077–93.
4. Phillips C. Revealing Materials: plastics in alternative food economies. Australian Geographer. 2017 Apr 3;48(2):169–84.
5. PlasticsEurope. Plastics - the Facts 2019: An analysis of European plastics production, demand and waste data. [Internet]. 2019 p. 1–42. Available from: https://www.plasticseurope.org/application/files/1115/7236/4388/FINAL_web_version_Plastics_the_facts2019_14102019.pdf
6. Thompson RC, Swan SH, Moore CJ, Vom Saal FS. Our plastic age. Phil Trans R Soc B. 2009 Jul 27;364(1526):1973–6.
7. Austin HP, Allen MD, Donohoe BS, Rorrer NA, Kearns FL, Silveira RL, et al. Characterization and engineering of a plastic-degrading aromatic polyesterase. Proc Natl Acad Sci U S A. 2018 May 8;115(19):E4350–7.
8. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science. 2015;347(6223):768–71.
9. Van Cauwenberghe L, Claessens M, Vandegehuchte MB, Janssen CR. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. Environmental Pollution. 2015 Apr;199:10–7.
10. Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, et al. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science. 2016 Mar 11;351(6278):1196–9.
11. Critchell K, Bauer-Civiello A, Benham C, Berry K, Eagle L, Hamann M, et al. Plastic Pollution in the Coastal Environment: Current Challenges and Future Solutions. In: Coasts and Estuaries [Internet]. Elsevier; 2019 [cited 2024 Jan 5]. p. 595–609. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780128140031000344
12. Vince J, Hardesty BD. Plastic pollution challenges in marine and coastal environments: from local to global governance. Restoration Ecology. 2017 Jan;25(1):123–8.
13. Haward M. Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nat Commun. 2018 Feb 14;9(1):667.
14. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science. 2015 Feb 13;347(6223):768–71.
15. Carney Almroth B, Eggert H. Marine Plastic Pollution: Sources, Impacts, and Policy Issues. Review of Environmental Economics and Policy. 2019 Jul 1;13(2):317–26.
16. Schmidt C, Krauth T, Wagner S. Export of Plastic Debris by Rivers into the Sea. Environ Sci Technol. 2017 Nov 7;51(21):12246–53.
17. Isobe A, Uchiyama-Matsumoto K, Uchida K, Tokai T. Microplastics in the Southern Ocean. Marine Pollution Bulletin. 2017 Jan;114(1):623–6.
18. Lusher AL, Tirelli V, O'Connor I, Officer R. Microplastics in Arctic polar waters: the first reported values of particles in surface and subsurface samples. Sci Rep. 2015 Oct 8;5(1):14947.
19. Waller CL, Griffiths HJ, Waluda CM, Thorpe SE, Loaiza I, Moreno B, et al. Microplastics in the Antarctic marine system: An emerging area of research. Science of The Total Environment. 2017 Nov;598:220–7.
20. Andrady AL. The plastic in microplastics: A review. Mar Pollut Bull. 2017 Jun 15;119(1):12–22.
21. Shim WJ, Thomposon RC. Microplastics in the Ocean. Arch Environ Contam Toxicol. 2015 Oct;69(3):265–8.
22. Auta HS, Emenike CU, Fauziah SH. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. Environment international. 2017;102:165–76.
23. Kalogerakis N, Karkanorachaki K, Kalogerakis GC, Triantafyllidi EI, Gotsis AD, Partsinevelos P, et al. Microplastics Generation: Onset of Fragmentation of Polyethylene Films in Marine Environment Mesocosms. Front Mar Sci [Internet]. 2017 Mar 28 [cited 2024 Jan 5];4. Available from: http://journal.frontiersin.org/article/10.3389/fmars.2017.00084/full
24. Carr SA, Liu J, Tesoro AG. Transport and fate of microplastic particles in wastewater treatment plants. Water Res. 2016 Mar 15;91:174–82.

25. Guzzetti E, Sureda A, Tejada S, Faggio C. Microplastic in marine organism: Environmental and toxicological effects. Environ Toxicol Pharmacol. 2018 Dec;64:164–71.

26. Fendall LS, Sewell MA. Contributing to marine pollution by washing your face: microplastics in facial cleansers. Marine pollution bulletin. 2009;58(8):1225–8.

27. Sørensen L, Rogers E, Altin D, Salaberria I, Booth AM. Sorption of PAHs to microplastic and their bioavailability and toxicity to marine copepods under co-exposure conditions. Environ Pollut. 2020 Mar;258:113844.

28. Wang J, Peng J, Tan Z, Gao Y, Zhan Z, Chen Q, et al. Microplastics in the surface sediments from the Beijiang River littoral zone: Composition, abundance, surface textures and interaction with heavy metals. Chemosphere. 2017 Mar;171:248–58.

29. Gregory MR. Plastic 'scrubbers' in hand cleansers: a further (and minor) source for marine pollution identified. Marine pollution bulletin. 1996;32(12):867–71.

30. Arthur C, Bamford H, Bake J. The occurrence, effect and fate of small plastic debris in the ocean. White paper, National Ocean and Atmospheric Administration, Marine Debris Program, Silver Spring, Maryland, USA. 2008;1–16.

31. Jabeen K, Su L, Li J, Yang D, Tong C, Mu J, et al. Microplastics and mesoplastics in fish from coastal and fresh waters of China. Environ Pollut. 2017 Feb;221:141–9.

32. Thiel M, Luna-Jorquera G, Álvarez-Varas R, Gallardo C, Hinojosa IA, Luna N, et al. Impacts of Marine Plastic Pollution From Continental Coasts to Subtropical Gyres—Fish, Seabirds, and Other Vertebrates in the SE Pacific. Front Mar Sci. 2018 Jul 24;5:238.

33. Wang W, Ge J, Yu X. Bioavailability and toxicity of microplastics to fish species: A review. Ecotoxicol Environ Saf. 2020 Feb;189:109913.

34. Rochman CM, Hoh E, Kurobe T, Teh SJ. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci Rep. 2013 Nov 21;3(1):3263.

35. Barboza LGA, Dick Vethaak A, Lavorante BRBO, Lundebye AK, Guilhermino L. Marine microplastic debris: An emerging issue for food security, food safety and human health. Mar Pollut Bull. 2018 Aug;133:336–48.

36. Schwabl P, Köppel S, Königshofer P, Bucsics T, Trauner M, Reiberger T, et al. Detection of Various Microplastics in Human Stool: A Prospective Case Series. Ann Intern Med. 2019 Oct 1;171(7):453–7.

37. Toussaint B, Raffael B, Angers-Loustau A, Gilliland D, Kestens V, Petrillo M, et al. Review of micro- and nanoplastic contamination in the food chain. Food Addit Contam Part A Chem Anal Control Expo Risk Assess. 2019 May;36(5):639–73.

38. Lehtiniemi M, Hartikainen S, Näkki P, Engström-Öst J, Koistinen A, Setälä O. Size matters more than shape: Ingestion of primary and secondary microplastics by small predators. Food Webs. 2018 Dec;17:e00097.

39. Koelmans AA, Bakir A, Burton GA, Janssen CR. Microplastic as a Vector for Chemicals in the Aquatic Environment: Critical Review and Model-Supported Reinterpretation of Empirical Studies. Environ Sci Technol. 2016 Apr 5;50(7):3315–26.

40. Bhardwaj H, Gupta R, Tiwari A. Communities of Microbial Enzymes Associated with Biodegradation of Plastics. J Polym Environ. 2013 Jun;21(2):575–9.

41. Cole M, Lindeque P, Halsband C, Galloway TS. Microplastics as contaminants in the marine environment: a review. Marine pollution bulletin. 2011;62(12):2588–97.

42. Khan S, Nadir S, Shah ZU, Shah AA, Karunarathna SC, Xu J, et al. Biodegradation of polyester polyurethane by Aspergillus tubingensis. Environ Pollut. 2017 Jun;225:469–80.

43. Muenmee S, Chiemchaisri W, Chiemchaisri C. Enhancement of biodegradation of plastic wastes via methane oxidation in semi-aerobic landfill. International Biodeterioration & Biodegradation. 2016 Sep;113:244–55.

44. Paço A, Duarte K, da Costa JP, Santos PSM, Pereira R, Pereira ME, et al. Biodegradation of polyethylene microplastics by the marine fungus Zalerion maritimum. Sci Total Environ. 2017 May 15;586:10–5.

45. Sudhakar M, Priyadarshini C, Doble M, Sriyutha Murthy P, Venkatesan R. Marine bacteria mediated degradation of nylon 66 and 6. International Biodeterioration & Biodegradation. 2007 Jan;60(3):144–51.

46. Danso D, Chow J, Streit WR. Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. Drake HL, editor. Appl Environ Microbiol. 2019 Oct;85(19):e01095-19.

47. Jabeen K, Li B, Chen Q, Su L, Wu C, Hollert H, et al. Effects of virgin microplastics on goldfish (Carassius auratus). Chemosphere. 2018;213:323–32.

48. Parolini M, De Felice B, Gazzotti S, Annunziata L, Sugni M, Bacchetta R, et al. Oxidative stress-related effects induced by micronized polyethylene terephthalate microparticles in the Manila clam. Journal of Toxicology and Environmental Health, Part A. 2020;83(4):168–79.

49. Murano C, Agnisola C, Caramiello D, Castellano I, Casotti R, Corsi I, et al. How sea urchins face microplastics: Uptake, tissue distribution and immune system response. Environmental Pollution. 2020;114685.

50. Gu H, Wei S, Hu M, Wei H, Wang X, Shang Y, et al. Microplastics aggravate the adverse effects of BDE-47 on physiological and defense performance in mussels. Journal of Hazardous Materials. 2020;122909.

51. O'Donovan S, Mestre NC, Abel S, Fonseca TG, Carteny CC, Willems T, et al. Effects of the UV filter, oxybenzone, adsorbed to microplastics in the clam Scrobicularia plana. Science of the Total Environment. 2020;733:139102.

52. Bellas J, Gil I. Polyethylene microplastics increase the toxicity of chlorpyrifos to the marine copepod Acartia tonsa. Environmental Pollution. 2020;260:114059.

53. Zocchi M, Sommaruga R. Microplastics modify the toxicity of glyphosate on Daphnia magna. Science of the Total Environment. 2019;697:134194.

54. Beiras R, Tato T. Microplastics do not increase toxicity of a hydrophobic organic chemical to marine plankton. Marine pollution bulletin. 2019;138:58–62.

55. Wang X, Liu L, Zheng H, Wang M, Fu Y, Luo X, et al. Polystyrene microplastics impaired the feeding and swimming behavior of mysid shrimp Neomysis japonica. Marine Pollution Bulletin. 2020;150:110660.

56. Mak CW, Yeung KCF, Chan KM. Acute toxic effects of polyethylene microplastic on adult zebrafish. Ecotoxicology and environmental safety. 2019;182:109442.

57. Reichert J, Schellenberg J, Schubert P, Wilke T. Responses of reef building corals to microplastic exposure. Environmental Pollution. 2018;237:955–60.

58. Padervand M, Lichtfouse E, Robert D, Wang C. Removal of microplastics from the environment. A review. Environmental Chemistry Letters. 2020;1–22.

59. Auta HS, Emenike CU, Jayanthi B, Fauziah SH. Growth kinetics and biodeterioration of polypropylene microplastics by Bacillus sp. and Rhodococcus sp. isolated from mangrove sediment. Marine pollution bulletin. 2018;127:15–21.

60. Park SY, Kim CG. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere. 2019;222:527–33.

61. Jeon HJ, Kim MN. Functional analysis of alkane hydroxylase system derived from Pseudomonas aeruginosa E7 for low molecular weight polyethylene biodegradation. International Biodeterioration & Biodegradation. 2015;103:141–6.

62. Auta HS, Emenike CU, Fauziah SH. Screening of Bacillus strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. Environmental Pollution. 2017;231:1552–9.

63. Shao H, Chen M, Fei X, Zhang R, Zhong Y, Ni W, et al. Complete genome sequence and characterization of a polyethylene biodegradation strain, Streptomyces Albogriseolus LBX-2. Microorganisms. 2019;7(10):379.

64. Wang Z, Xin X, Shi X, Zhang Y. A polystyrene-degrading Acinetobacter bacterium isolated from the larvae of Tribolium castaneum. Science of The Total Environment. 2020;138564.

65. Pattanasuttichonlakul W, Sombatsompop N, Prapagdee B. Accelerating biodegradation of PLA using microbial consortium from dairy wastewater sludge combined with PLA-degrading bacterium. International Biodeterioration & Biodegradation. 2018;132:74–83.

66. Chaudhary DK, Kim J. New insights into bioremediation strategies for oil-contaminated soil in cold environments. International Biodeterioration & Biodegradation. 2019;142:58–72.

67. Paço A, Duarte K, da Costa JP, Santos PS, Pereira R, Pereira ME, et al. Biodegradation of polyethylene microplastics by the marine

fungus Zalerion maritimum. Science of the Total Environment. 2017;586:10–5.

68. Tofa TS, Kunjali KL, Paul S, Dutta J. Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods. Environmental Chemistry Letters. 2019;17(3):1341–6.

69. Zhang J, Gao D, Li Q, Zhao Y, Li L, Lin H, et al. Biodegradation of polyethylene microplastic particles by the fungus Aspergillus flavus from the guts of wax moth Galleria mellonella. Science of The Total Environment. 2020;704:135931.

70. Mainka SA, Howard GW. Climate change and invasive species: double jeopardy. Integrative Zoology. 2010;5(2):102–11.

71. Yu SP, Chan BK. Intergenerational microplastics impact the intertidal barnacle Amphibalanus amphitrite during the planktonic larval and benthic adult stages. Environmental Pollution. 2020;267:115560.

72. Desforges JPW, Galbraith M, Ross PS. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. Archives of environmental contamination and toxicology. 2015;69(3):320–30.

73. Setälä O, Fleming-Lehtinen V, Lehtiniemi M. Ingestion and transfer of microplastics in the planktonic food web. Environmental pollution. 2014;185:77–83.

74. Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC. Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L.). Environmental science & technology. 2008;42(13):5026–31.

75. Li J, Lusher AL, Rotchell JM, Deudero S, Turra A, Bråte ILN, et al. Using mussel as a global bioindicator of coastal microplastic pollution. Environmental pollution. 2019;244:522–33.

76. Corona E, Martin C, Marasco R, Duarte CM. Passive and active removal of marine microplastics by a mushroom coral (Danafungia scruposa). Frontiers in Marine Science. 2020;7:128.

77. Martin C, Corona E, Mahadik GA, Duarte CM. Adhesion to coral surface as a potential sink for marine microplastics. Environmental Pollution. 2019;255:113281.

78. Lanctôt CM, Bednarz VN, Melvin S, Jacob H, Oberhaensli F, Swarzenski PW, et al. Physiological stress response of the scleractinian coral Stylophora pistillata exposed to polyethylene microplastics. Environmental Pollution. 2020;114559.

79. Song Y, Qiu R, Hu J, Li X, Zhang X, Chen Y, et al. Biodegradation and disintegration of expanded polystyrene by land snails Achatina fulica. Science of the Total Environment. 2020;746:141289.

80. Peng BY, Li Y, Fan R, Chen Z, Chen J, Brandon AM, et al. Biodegradation of low-density polyethylene and polystyrene in superworms, larvae of Zophobas atratus (Coleoptera: Tenebrionidae): Broad and limited extent depolymerization. Environmental Pollution. 2020;266:115206.

81. Peng BY, Su Y, Chen Z, Chen J, Zhou X, Benbow ME, et al. Biodegradation of polystyrene by dark (Tenebrio obscurus) and yellow (Tenebrio molitor) mealworms (Coleoptera: Tenebrionidae). Environmental science & technology. 2019;53(9):5256–65.

82. Masiá P, Sol D, Ardura A, Laca A, Borrell YJ, Dopico E, et al. Bioremediation as a promising strategy for microplastics removal in wastewater treatment plants. Marine Pollution Bulletin. 2020;156:111252.