Heliyon 9 (2023) e15104

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Microplastics and their interactions with microbiota

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ARTICLE INFO

Keywords:
Microplastics
Toxicological effects
Microbiota
Biodegradation
Actinobacteria

ABSTRACT

As a new pollutant, Microplastics (MPs) are globally known for their negative impacts on different ecosystems and living organisms. MPs are easily taken up by the ecosystem in a variety of organisms due to their small size, and cause immunological, neurological, and respiratory diseases in the impacted organism. Moreover, in the impacted environments, MPs can release toxic additives and act as a vector and scaffold for colonization and transportation of specific microbes and lead to imbalances in microbiota and the biogeochemical and nutrients dynamic. To address the concerns on controlling the MPs pollution on the microbiota and ecosystem, the microbial biodegradation of MPs can be potentially considered as an effective environment friendly approach. The objectives of the presented paper are to provide information on the toxicological effects of MPs on microbiota, to discuss the negative impacts of microbial colonization of MPs, and to introduce the microbes with biodegradation ability of MPs.

1. Introduction

The term “microplastics” (MPs) refers to plastic particles smaller than 5 mm (5 mm) in size that are found in a variety of ecosystems. MPs are now widely distributed in all types of ecosystems (i.e., terrestrial, aquatic, soil, arctic and antarctic), and negative impacts of MPs are alarmingly reporting by increase in worldwide plastics productions [1]. Evidence shows that MPs have direct (primary MPs) and indirect (secondary MPs) sources. Primary MPs are directly released into our ecosystems mainly from personal care products, synthetic textiles, tires, and marine coatings. On the other hand, the source of secondary MPs is from larger plastic, such as debris from trash dumps, fishing nets, and tire wears that are degraded into minute particles by mechanical or UV abrasion [2,3].

MPs transport to our ecosystem through biotic (i.e., soil invertebrates, and terrestrial vertebrates), and abiotic (i.e., overland flow and erosions) pathways. In this context, both horizontal and vertical transfer of MPs by springtails and earthworms (biotic pathway) in different layers of soil, and significant transportation of MPs to the maritime environment by fluid dynamics and wind transmissions (abiotic pathway) have been reported by scientists (Fig. 1) [4,5]. Undeniable evidence demonstrates in their impacted ecosystems, MPs have a deleterious influence on the cycling of nitrogen and carbon, oxygen production, and the productivity of floral and animal biomass [5]. According to data, plastics started entering the ocean in greater quantities in the 1950s, and every year, more than 8 million tons of plastics from land and sea-based sources end up in the seas, and plastic contamination accounts for 80 to 85% of marine litter [6,7]. It has been recorded that chemical leaching from plastic increases the amount of dissolved organic Carbon and produces greenhouse gases like ethylene and methane in marine environments. According to estimates, rivers carry between 1.15 and 2.41 million tons of plastic each year into the coastal area and the ocean [8]. MPs potentially can uptake the harmful compounds from the

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https://doi.org/10.1016/j.heliyon.2023.e15104
Received 29 September 2022; Received in revised form 16 March 2023; Accepted 27 March 2023
Available online 31 March 2023
2405-8440/

nearby aquatic systems and transfer them to the food chain [9]. Persistent organic pollutants, heavy metals (HMs), and chemicals (i.e., phthalates and bisphenol A), among others, have been reported to be leached from the surface of plastics or become absorbed in them, leading to persistence and bioaccumulation in marine food webs. The chemical additives (i.e., dibutyl phthalate, hexabromocyclododecane, and polybrominated diphenyl ethers) of MPs have adverse impacts on the ecosystem since they are not chemically bond to the MPs structure and can be easily release to the ecosystem [10].

In the impacted ecosystems, some specific autotrophic, and heterotrophic microbes capable of colonization on the MP surfaces employ the MPs as a means of passage through various habitats [11]. Pollution from MPs may also impact microbiota and disrupt essential ecological, biogeochemical cycling, or bioremediation processes.

Evidence indicates that MPs have negatively impacted 700 aquatic species globally, including sea turtles, penguins, and different crustaceans (Table 1). Following intake, MPs could either stay in the digestive system or go through the gut leading to pathogenic stresses, illusory sense of satiation, genetic abnormalities, enzymes activity, slowed development, inflammatory response, cytotoxicity, imbalance in intracellular uptake, immunological response, cell membrane alterations, gene expression changes, embryotoxicity, and hemolysis in micro and macro-organisms [12–14].

The consequences of MPs differ depending on the organism species, MPs type, concentrations, and leaching of additives [15,16]. These proofs of MPs' detrimental impact on our ecology aroused curiosity and made it necessary to write this review paper. This study aims to present current knowledge on the 1. Toxicological effects of microplastics on microbiota, 2. Negative impacts of microbial colonization of microplastics, 3. Microbes mediated biodegradation of microplastics, 4. *Actinobacteria*: a promising microorganism against microplastics.

2. Toxicological effects of microplastics on microbiota

Healthy and stable ecosystems rely on well-functioning microbiota, and amount and the varieties of microbes living in a healthy microbiota are assumed to be relatively stable [17]. Microbiota consists of microbes that are symbiotic, pathogenic, or commensal, and in multicellular organisms, the intestinal microbiota can directly prevent illnesses by forming a barrier to prospective pathogens and promote the gastrointestinal physiology and mucosal immunity.

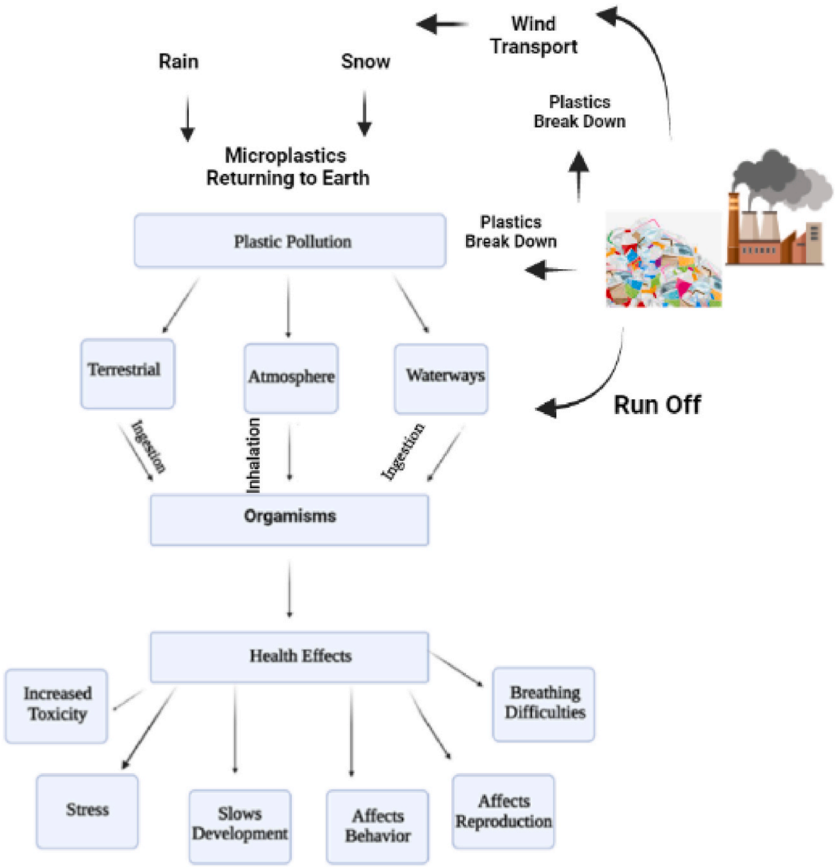

Fig. 1. Impacts of plastic contamination in different settings. Note: Plastic contamination is a broad umbrella term used for the accumulation of plastic particles as well as plastic objects that adversely affect many organisms and their habitat. These plastics can be categorized by size into micro-, meso-, or macro debris pollution.

Table 1
Toxicity effect of microplastics on different organisms.

Organism	MPs type	Size	Toxicity Mode of Action	References
Gentoo Penguin	Microfibers	<1 dtex	Affects reproductivity, immune systems, feeding habits, and productivity	84
Sharks	Microfibers	0.3 mm - 14.4 mm		85
Daphnia magna	Micro-sized			86
Oysters	PS	0.2 μm		
Zooplankton	Microfibers polystyrene Microbeads	1.7–3.6 μm		
Mussels	PE	50–570 μm	Disturbs metabolism, immune defenses, induces toxicity, and tissue changes	87
Springtail	Microbeads	0.47–0.53 μm 27–32 μm, 250–300 μm	Modifies gut microbiomes Alters development and reproduction	88
Zebrafish	Microbeads	300–355 μm	Intestinal inflammation oxidative stress Produce microbial dysbiosis	89
Turtle	Microbeads, Microfibers	144–240 μm <100 μm	Alters membranes, causes oxidative stress, gene changes, mild embryotoxicity, and hemolysis	90
Humans	Microfibers	<5 mm	Physiological damage (nutritional, toxicological, immunological, or developmental)	91
Mice	–	<5 mm	Intestinal damage Alters metabolism	92
C. neogracile,	Microbeads	0.5 and 2 μm	Affects chlorophyll, esterase activity, cell growth	93
B. koreanus,	Microbeads	0.05, 0.5, and 6 μm	Reduces fertilization rate and development ability	86
A. franciscana,	Microbeads	0.1 μm	Impairs feeding, behavioral and physiological conditions	94
C. finmarchicus	Microfibers	10 × 30 μm	Alters behavior, growth, and development	95

Note: PA = Polyamide, MP = Microplastic, PS = Polystrene, NP = Nanoplastic. PE= Polyethylene. dtex = mass in grams for every 10,000 m of fiber or filament.

Toxicological records show, contamination with MPs leads to immunological, neurological, and respiratory diseases in a wide range of multicellular organisms (Table 1). Additionally, the polymeric components and chemical additives, such as copper ions in MPs, might act as endocrine disruptors [4]. Using mice as a model for studying the impacts of MPs on microbiota in organisms demonstrated the uptake of polyethylene MPs increase the inflammatory factor (i.e., IL-1β, IL-6, IL-8, and IL-10), decrease the colon mucin expression, disrupt the lipopolysaccharide metabolism, and increase the microflora amino acid metabolism pathway through altering the intestine microflora composition [18]. The exclusion of new strains of bacteria from the external environment via colonization is a vital function of the microbiome, and disturbance of this barrier might enable disease colonization (Table 2). For example, the exposure of Chinese mitten crab (*Eriocheir sinensis*) to MPs resulted in activation of immune-related genes and decrease of *Firmicutes* and *Bacteroidetes* population as the two most important bacterial phyla in the gastrointestinal tract [19]. MPs have also been identified to cause gut microbiota dysbiosis and intestinal inflammation through increasing the population of *Proteobacteria* and more production of lipopolysaccharides in *Danio rerio* (zebra fish) as a prominent aquatic model organism [20]. Additionally, MPs can increase the concentration of reactive oxygen species (ROS) in different organisms (i.e., *Danio rerio* and *Sparus aurata* Linnaeus) through the alternation bacterial population (i.e., *Proteobacteria, Bacteroidetes, Fusobacteria* and *Firmicutes* in the microbiota [21,22]. Researchers have also reported the MPs negative impacts on the epithelial cell proliferation and renewal in the vertebrate intestine of *Danio rerio* by

Table 2
Microbes colonized on bioplastics in different ecosystems.

Region	Ecosystem	Microplastic Size	Name of the Colonized Microbes	References
Atlantic	Sargasso Sea	MPs (<5 mm)	Hyphomonadaceae, Erythrobacteraceae	38
				96
Global	Deep Ocean	MSP (~ 9.3	Crenarchaeota, Cyanobacteria Proteobacteria, Bacteroidetes,	97
Mediterranean	Mediterranean Sea	mm)	Firmicutes	98
Atlantic	North Seas	MPs (<5 mm)	Ascomycota, Basidiomycota	99
North Atlantic	Baltic Seas		Fungal filaments, Spores	52
Southeastern Brazil	Vitoria Bay Estuarine			53
Atlantic	New Jersey (Raritan River)	MPs (<5 mm)	*Limnobacter thiooxidans*	49
Eastern Asia	East Asian Seas	MPs (<5 mm)	Proteobacteria	100
United Kingdom	Coast of North Sea,	PET, PE, PP, PS		38
		–	*Tenacibaculum* sp., and *Crocinitomix* sp.	
			Leptolyngbya sp., *Pleurocapsa* sp., *Scytonema* sp., *Alteromonas* sp., *Pelagibacter* sp.	
Northwest Mediterranean Sea	Banyuls Bay			

Note: PE = Polyethylene, MPs = Microplastics, MSP = Mesoplastic, *PET: polyethylene terephthalate, PP:* polypropylene, polystyrene: PS.

lowering the populations of *Pseudomonas* and *Aeromonas* [23].

In marine ecosystems the sediments are presenting the most organic carbon source on the earth and the microbiota of the marine sediments are playing a major role in biogeochemical and nutrients dynamic of ecosystem. Alarming records are demonstrating the MPs are destabilizing the balance of microbiota in marine sediments. Seeley et al. [8] reported MPs possess antibacterial characteristics that favor some taxa (i.e., sulfate reducers) while inhibiting others (i.e., nitrifiers), meantime assessments of potential denitrification activity imply that MPs may function as an organic C source for some sediment microbial populations (i.e., *Bacteroidetes, Acidobacteria,* and *Chloroflexi*) [24]. Microalgae in aquatic ecosystems play a vital role since they are the food and energy base for all organisms. However, the balance of the microalgal population could also be disrupted by MPs through MPs' negative impacts on the growth, photosynthetic activity, and morphological changes. A study by Rummel et al. [25] demonstrates that MPs derived from electronic waste and computer keyboards cause greater effects on the growth of the microalgae *Scenedesmus vacuolatus.* In this study, the authors explained the strong toxicity could be due to the presence of mono - and dicarboxylic acids molecules because of photo-oxidation of MPs.

Microorganisms as decomposers dynamically circulate the organic compounds and energy in the soil ecosystem, however once MPs enter the soil ecosystem, they cause an imbalance in the bacterial populations. Evidence shows, although MPs can be taken up and processed into energy by some bacteria (i.e., *Rhodococcus ruber*, and *Actinomadura* sp.) but during the degradation toxic compounds, such as phthalates with negative impacts on soil biota will be released [21,26]. Furthermore, due to MPs' high hydrophobicity, some environmental contaminants, such as HMs, and antibiotics, become adsorbent on their surface. These MPs-hazardous compound mixtures may significantly impact microbiota more than the microplastic itself. A recent study shows the heavy metal concentrations in MPs particles are 10–100 times greater than in the local environment [27]. Moreover, the composition, shape, and the concentration of MPs influences the microbiota balance. In this regard, Sun et al. [16] investigated the effects of various concentrations and types of spherical MPs (150 μm) on the soil bacterial community. Their findings showed the composition of the polymer structure is a crucial determinant of the bacterial responses in the soil. As a result, the Gemmatimonadetes were prevalent (Linear Discriminant Analysis = 2.0) in soil treated with polyethylene (PE), polystyrene (PS), and polypropylene (PP) MPs. At the same time, Cyanobacteria were more prevalent in soil treated with PS. Additionally, the bacterial populations affected by PE and PP particles follow a similar response but differ from soils treated with PS.

Evidence shows the imbalance caused by MPs in microbiota affects the dynamics of the nutrients and eventually threat the soils health. A study by Zhu and his team [28] revealed under the impact of polyvinyl chloride (PVC)-MPs the microbiota of the soil will be shaped into a population of more nitrogen-fixers and urea decomposers and less nitrifiers leading to enhance in NH_4^+-N and decrease in NO3-¯N contents.

3. Negative impacts of microbial colonization of microplastics

Plastisphere is a phrase that describes the new biological niche established by introducing plastic waste into the environment. The plastisphere microorganisms exhibit a wide spectrum of phenotypic diversity, including motility, oxygen dependence, and extremophilia [29]. The plastisphere's structure has been shaped by plastic polymer type, topography, and seasonality [30,31]. The plastisphere produces an environment that encourages bacterial adhesion and subsequent biofilm development, they also act as a vector (carrier) facilitating the transportation of the MPs in the impacted ecosystem. Being a quick bioavailable carbon source, plastispheres after degradation leach toxic compounds into their surrounding environment leading to increase of the toxicity of MPs on the ecosystem [32]. The condition of being affected by contaminants while being secured by a biofilm matrix may result in a shift in the distribution of specific microbial species which eventually impacts their surrounding environment [33]. For example, biofilms on mesoplastics (MSP) (≃9.3 mm) recovered from the Mediterranean Sea reveal more variety than free-living bacterial populations. Bacteroidetes, Proteobacteria, and Firmicutes are reported to be the most found phyla on the studied MPs [34]. Acting as a vector and being a persistent pollutants MPs are known for spreading multi-drug resistant microbes in different ecosystems [35]. Reports are showing the biodegradability levels of MPs are associated to spreading of antibiotic resistance genes in ecosystem. In this regard, a metagenomic analysis by Sun et al. [16] on the biofilm - developed MPs revealed a higher abundance of multidrug resistant genes on PET as a nondegradable MP in comparison to poly hydroxy alkanoate as a biodegradable MP. Pham et al. [36] also reported the biofilms containing sulfonamide resistance genes (sul1 and sul2) and the associated mobile genetic element (intI1) can be formed on both PE and PS at municipal wastewater treatment plants. Further studies using 16S rRNA analysis showed the MPs have more tendency to host the pathogenic and antibiotic-resistant taxa (i.e., *Raoultella ornithinolytica* and *Stenotrophomonas maltophilia*). These results were also confirmed by Wu et al. [37], reporting that the biofilms formed on the MPs host *Pseudomonas monteilii*, and *Pseudomonas mendocina* as the opportunistic human pathogens. Certain bacteria commonly associated with antibiotic resistance were also found on MPs in the oligotrophic Sargasso Sea. Researchers also reported that PE and PS-MPs attracted high quantities of microbes from the *Hyphomonadaceae* and *Erythrobacteraceae* families [38].

Moreover, it is frequently reported the biofilm-developed microplastics has more resistance and survivability to harmful environmental elements, such as UV irradiation, heat, dryness, or HMs which this characteristic could essentially help them to become dominant species in their living microbiota [39–42]. Antibiotic- and hazardous metal-resistant genes were also reported to be more prevalent in MPs-biofilms than in the surrounding water, suggesting that the MPs may act as a repository for these microorganisms [43]. In the stable ecosystems the biofilms are metabolic hotspots and the important sources of the breakdown of dissolved organic carbon (DOC) and nutrients dynamics [44,45]. DOC is incorporated into the biomass of microbes, which is then consumed by phagotrophic protozoa. Protozoans are then devoured by zooplankton, and preyed upon by creatures at higher trophic levels, promoting nutrient cycling and energy transmission across the aquatic food web. MPs biofilms have different bacterial populations than natural particles (i.e., wood pellets, cellulose, and glass beads) which potentially can interact with the microbial community [46,47] A recent study by Ya et al. [48] revealed that when the soil microbial community is alerted under the influence of PE-MPs, the activity of urease and fluorescein diacetate hydrolase (FDAse) will be higher in soil microbiota. A concentration-dependent trend on the microbial type is also reported, as 1% (w/w) PE-MPs considerably affect the relative population of *Gemmatimonadaceae,* and *Arthrobacter*, while PE-MPs at 5% (w/w) concentration, meaningfully decreased the relative population of *Bacillus*, *Blastococcus, Arthrobacter*, and *Nocardia*. This imbalance in microbial population caused by MPs potentially influences the stability of nutrients and minerals movements and affect the food chain metrics and dynamics in the impacted ecosystem [25,46].

Physical environmental factors (i.e., temperature and pH) and environmental nutrient factors (i.e., NO_3–N, CODcr, NH_4–N, NO_2–N) *impact the biofilm formation and colonization of the MPs. In this context, a study by Qiang* et al. [49] *found that the type of MPs and salinity concentration both affect the growth of biofilms and the colonization of microbial communities.* Limnobacter thiooxidans *has been discovered as one of the most prevalent MPs colonizing bacteria on PS, high-density polyethylene (HDPE), and polyethylene terephthalate (PET). Using 16S-rDNA high-throughput sequencing on different types of MPs derived from tires showed the essential roles of* contribution rate of nutrients (i.e., Nitrite nitrogen, Nitrate nitrogen, and Ammonium nitrogen) and physical environmental conditions (i.e., pH and temperature) on microbial colonization of MPs were 63%, and 50%, respectively [50].

MPs colonization by photosynthesizing microorganisms has also been seen in aquatic ecosystems. Autotrophic species, such as the *bacterivorous ciliates,* appeared to have roles in transporting organic matters from MPs to the higher trophic levels [51]. This result was also confirmed during another study on the biofilm-developed MPs from aquatic ecosystems in the Mediterranean Sea, where the blue-green algae (Cyanobacteria) were the most prevalent photoautotrophic microbes in biofilm-developed MPs, and the two fungi phyla Basidiomycota and Ascomycota were the most common identified microorganisms on the MPs in the Baltic Seas. Additionally, biofilm-developed MPs formed in the estuarine sediments of Vitória Bay contained fungi filaments and spores [52,53]. Evidence also shows, when the MPs are accumulated in sediment layers, the increased heterotrophic activity may aid in creating hypoxic areas (dead zones), such as those seen on the shoreline and seabed. MPs in these systems promote the development of heterotrophic microbes with diverse growth efficiency and community structure under varying nutrient circumstances. Heterotrophic microbial communities coexisting with autotrophic microbes will impact the overall MPs biofilm respiration [54].

4. Microbes for biodegradation of microplastics

Biodegradation is the process by which microorganisms degrade materials into environmentally acceptable products (i.e., water, carbon dioxide, and biomass). For example, Oleophilic microbes can do bioremediation by decomposing petroleum hydrocarbon contaminants using their enzymes [55]. During biodegradation, process enzymes are essential in cell function and regulation and break down the emerging pollutants due the human activities, such as MPs.

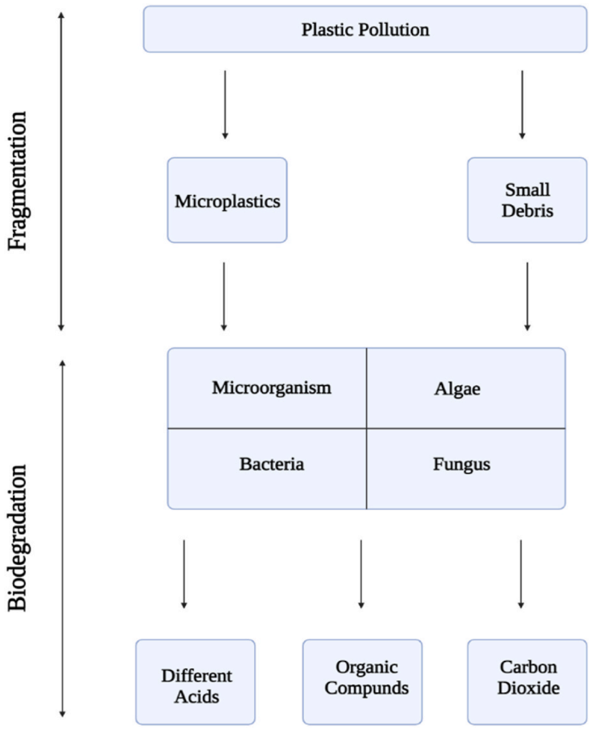

Fig. 2. Microbial degradation of Microplastics. **Note:** Several variables influence the microbial decomposition of microplastics/plastics. There are two types: variables linked to microorganism development and factors connected to MP properties and the external environment.

Degrading enzyme (i.e., Laccase, Amylases, and Lipase) produced by microorganisms may target the polymer chains of MPs and break it down into its monomer, which is then used as a carbon source in the microorganism energy cycle (Fig. 2) [56]. Several microbial enzymes are known to be capable of degrading polymers into monomers. For example, enzymes, such as phenylacetaldehyde dehydrogenase, styrene monooxygenase, styrene-oxide isomerase, and serine hydrolase have been linked to PS breakdown, with acetyl-CoA serving as the last monomer in the tricarboxylic acid (TCA) cycle [57,58]. Extracellular and intracellular depolymerizes are involved in polymers' biological breakdown during the depolymerization process [59]. Exo-enzymes from microorganisms degrade complex polymers to smaller molecules, such as monomers and dimers. These molecules are small enough to enter microbes' semi-permeable outer membranes and get consumed as a source of carbon and energy by the livings in ecosystem (Fig. 3) [60]. The capacity to degrade plastic polymers has been discovered in several bacterial species from the genera *Pseudomonas*, *Escherichia*, *Arthrobacter*, and *Bacillus* which have been found in various biological settings, such as landfills, recycling facilities, dumps, cold-water coral, and insect guts [61]. According to studies, bacteria's intrinsic ability to break down long-chained fatty acids is the basis for their capability to break down plastic particles. As a result, it is not surprising that *Pseudomonas* is the very well-recognized and extensively studied bacterial genus in terms of breaking down polymeric polymers [62].

Records are showing microbial specificity in MPs degradation. In this regard, *Bacillus cereus*, *Phanerochaete chrysosporium*, and *Trarnetes versicolor* were identified to be responsible for breaking down the PE through the production of laccase and manganese peroxidase enzymes, while *Rhodococcus* sp., *Sphingobacterium* sp., *Vibrio* sp., *Xanthomonas* sp., and *Pseudomonas* sp., are reported to be potent for the degradation of PS and PP [63,64]. Other microbes that have been found to degrade PVC include *Pseudomonas citronellolis*, *Pseudomonas putida*, *Bacillus fexus*, *Aspergillus* sp., *P. chrysosporium* [55]. Evidence shows the process of MP biodegradation is affected by microbial characteristics and environmental factors. For example, it was found that bacteria in mangrove soil degraded the plastics particles at a slower time frame, and the microbiota population associated with the biodegradation process was primarily formed of Staphylococcus, Streptococcus, Micrococcus, Pseudomonas, Moraxella, and Aspergillus genera [65].

One of the valuable recent findings in plastic biodegradation is the ability of *Ideonella sakaiensis*, a special species isolated from a

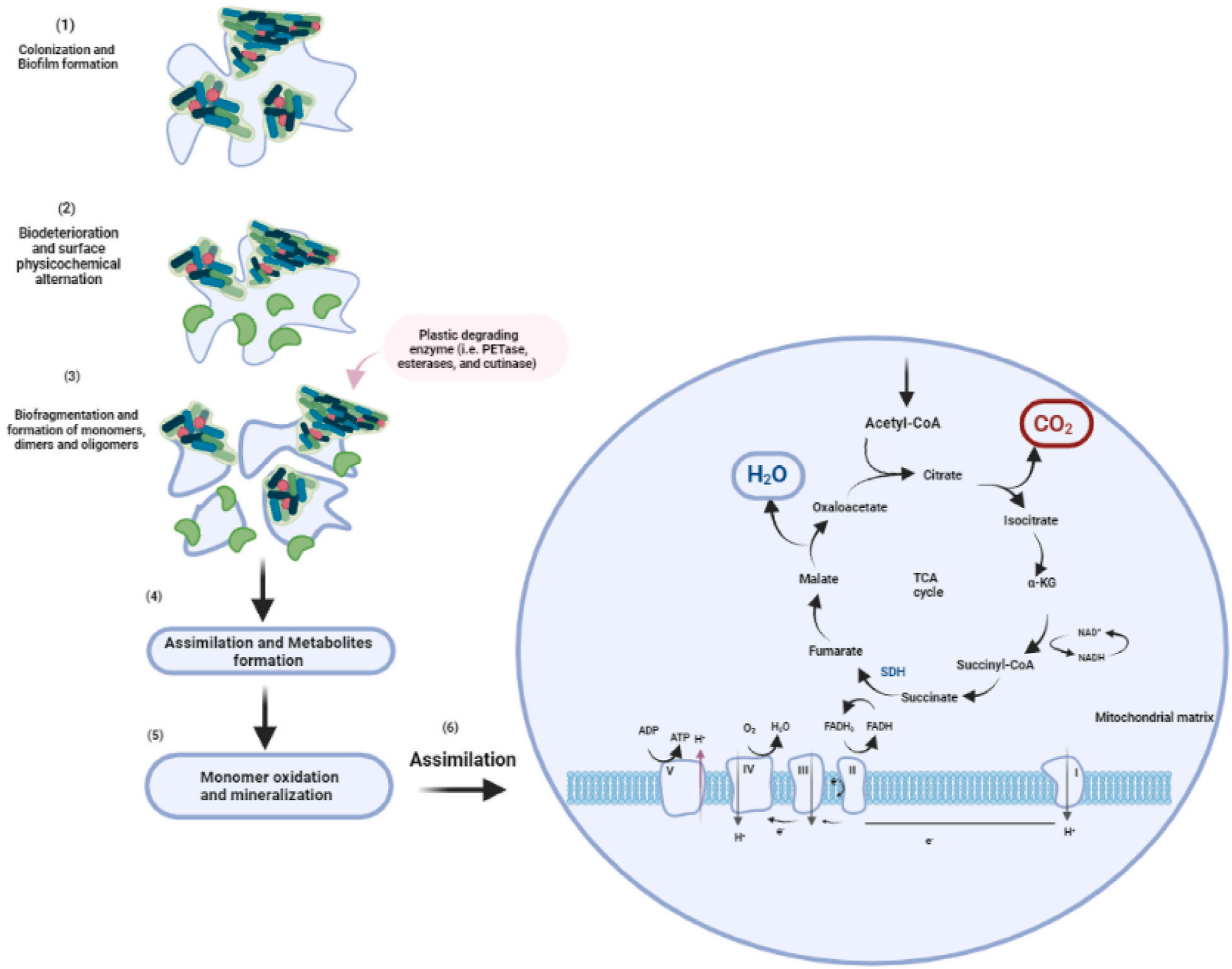

Fig. 3. The General Mechanism of microbial degradation of MPs.

group of bacteria from a recycling facility. This bacterium is capable to biodegrade the amorphous PET which is extensively used for food packing to its building blocks by utilizing two hydrolytic enzymes (PET hydrolase and mono(2-hydroxyethyl) terephthalate hydrolase). Actinomycetes are a diverse group of filamentous bacteria that can be grown in different ecosystems. They are well recognized for their metabolic diversity and biotechnological applications in bioremediation and waste treatments. Reports demonstrate that Actinomycetes, such as *Streptomyces fulvissimus*, *Streptomyces antibioticus*, *Actinomadura* sp., *Rhodococcus ruber,* and *Thermoactinomyces* have strong plastic biodegradative properties [66,67]. *Streptomyces scabies,* with the ability to synthesize laccases, was also shown to break down PET to terephthalic acid and other polymers [68].

The capacity of fungal species to degrade plastics has also been the subject of several investigations. Various studies have shown fungi' ability to break down plastics (Table 3). A recent study show, several species of Aspergillus, Cobetia, Fusarium, Exiguobacterium, and Alcanivorax, which were isolated from the MPs polluted marine ecosystem have the capability to biodegrade low-density polyethylene (LDPE) Additionally, it has been shown that PE-MPs are rapidly degraded by the fungal species, such as *Fusarium falciforme*, *Fusarium oxysporum*, and *Purpureocillium lilacinum*, which were isolated from landfill soil [69–71]. The biodegradability of the fungal species is also confirmed by Ekanayaka et al. [72], demonstrating that eleven classes within the fungal phyla, including Ascomycota (Dothideomycetes, Eurotiomycetes, Leotiomycetes, Saccharomycetes, and Sordariomycetes), Basidiomycota (Agaricomycetes, Microbotryomycetes, Tremellomycetes, Tritirachiomycetes (Mucoromycetes) have the capability to degrade plasticsAlgae are also under close attention for their biodegradation ability of plastics. in this regard, vidence shows that algal species can use the MPs surface for their colonization, and some microalgae are potent to break down the polymers and use MPs as carbon sources for their growth. Currently, algal species, such as *Anabaena spiroides* (Cyanophyceae), *Scenedesmus dimorphus* (Chlorophyceae), and *Navicula pupula* (Bacillariophyceae) are identified for the ability for biodegradation of both high and low-density PE, while other species, like *Spirulina* sp., (Cyanophyceae) are identified for the ability to biodegrade PET and PP- MPs [73].

Table 3
List of Microorganisms and Enzymes reported to degrade different types of plastics.

Enzyme	Source	Type of MPs	Obtained product	References
Esterase	*Aspergillus japonicus*	PE	Acetic acid, Formic acid	65
Lipase	*Aspergillus terreus*	PP, PVC	polycaprolactone depolymerase	71
	Aspergillus niger	PCL		
	Alcaligenes faecalis			
Esterase	*Streptomyces scabies*	PET, PS, PC	Terephthalic acid	68
Amylases	*Pseudomonas aeruginosa*	PS	DOC	88
Hydrogenase	*Lentinus tigrinus*	PE, LDPE, HDPE	Bisphenol A	102
Glycosidases	*Nocardiopsis* sp.	PP, PET	Acetic acid, Formic acid	103
Nitrate reductase	*Scenedesmus dimorphus*	PET	Acetic acid, Formic acid	104
Hydrolase	*Anabaena spiroides*	PE	Terephthalic acid	105
Hydrolytic	*Navicula pupula*	PHB	Acetic acid, Formic acid	106
Lipase	*Spirulina* sp.	PS, PC	Acetoacetic acid	107
Coagulase	*I. sakaiensis*	PE	DOC	108
Peptidase	*Burkholderia seminalis*	PS, PC	Bisphenol A	109
	Actinomadura sp.		Acetic acid, Formic acid	110
	Serratia marcescens		DOC	11
	Stenotrophomonas pavanii		Bisphenol A	112
	Staphylococcus aureus			
	Streptococcus pyogenes			
Laccase	*Rhodococcus ruber,*	PE	Acetic acid, Formic acid	113
	Bacillus cereus,			114
	Phanerochaete chrysosporium,			71
	Trametes versicolor			
Hydrolytic	*Fusarium falciforme*	PS	DOC	115
Cellulase	*Sphingobacterium* sp.	PE	Carbon dioxide	116
Oxidoreductase	*Fusarium oxysporum*	PS	Acetic acid, Formic acid	117
Fibrinolytic	*Purpureocillium lilacinum*		DOC	116
	Xanthomonas sp.			118
Lipase	*Penicillium*	PCL, PES, PUR	Polycaprolactone depolymerase,	119
	Aspergillus		Diethylene glycol, Adipic acid,	120
			Terephthalic acid	
PHB depolymerase	*Thermoactinomyces*	PHB	Acetoacetic acid	121
	Bacillus megaterium	PS, PC, PHB	DOC	122
			Bisphenol A	
Hydrolases	*Pseudomonas*	P	Nitrous oxides	122
Lipase			Organic compounds	
Esterases	*Bacillus* sp	PS	DOC	66
				120
Styrene oxide isomerase	*Pseudomonas* sp	PS	DOC	123

Note: PE = Polyethylene, PCL = Polycaprolactone, PET = polyethylene terephthalate, PS = polystyrene, PC = polycarbonate, LDPE = low-density polyethylene, HDPE = high-density polyethylene, PP = Polypropylene, PHB = Poly (3-hydroxybutyrate), PES = Polyester, PUR = polyurethane, PVC = Polyvinyl-chloride, P = polymer, dissolved organic carbon = DOC.

5. Actinobacteria: a promising microorganism against microplastics

Actinobacteria are filamentous Gram-positive bacteria with aerobic, facultatively anaerobic, or anaerobic metabolism with incredible metabolic flexibility capable of cleaning up harmful chemicals [74,75]. *Actinobacteria* are the biggest taxonomic groupings among the Bacteria domain's 18 major lineages, including five subclasses, six orders, and 14 suborders. This phylum's genera are highly diverse in anatomy, physiology, and metabolic capabilities [76]. Studies show *Actinobacteria* are prevalent under harsh conditions and can be found in a broad range of environments, such as soil and aquatic dwellers (i.e., *Streptomyces, Rhodococcus, Micromonospora*, *Thermactinomyces, Dietzia, Marinophilius, Nocardiaform,* and *Strptoverticillum*), plant or animal pathogens (i.e., *Mycobacterium,* and *Corynebacterium*), gastrointestinal commensals (i.e., *Bifidobacterium* sp.), and plant symbionts (i.e., *Frankia* sp.) [76,77].

Actinobacteria can synthesize a range of enzymes, enzyme inhibitors, and antibiotics, such as aureomycin and streptomycin. *Actinobacteria* can synthesize a diverse range of hydrolytic enzymes and bioactive compounds, which gives them the capacity to grow on various polymers (Table 3) [78]. Recent studies show that *Actinobacteria* have solid polymer breakdown capabilities and they play critical roles in the breakdown or decomposition of organic molecules, such as polysaccharides, organic acids, proteins, and lipids in their environment [77]. Moreover, *Actinobacteria* are one of the few microorganisms that can have excellent biodegradation capacity for various MPs (i.e., PP, polylactic acid polymer, polyurethane, and PE). In the phylum of *Actinomycetota*, the genera *Actinomadura, Amycolatopsis, Kibdelosporangium, Micromonospora, Nonomuraea, Pseudonocardia, Saccharothrix, Streptoalloteichus, Streptomyces, Thermomonospora,* and *Thermopolyspora* can degrade the polylactic acid polymer (PLA)-MPs [79]. Actinomycetota's PLA-MPs biodegradable activity is ~~a~~ beneficial for the environment, given that commercially accessible PLA is one of the most extensively utilized bioplastics as a replacement for biodegradable polymers.

Studies show that in the phylum of *Actinomycetota*, the *Amycolatopsis orientalis* bacterium synthesized a potent extracellular PLA-degrading enzyme that denatures the PLA powder within 8 h. Moreover, *Kibdelosporangium aridum* strain also showed excellent biodegradability, decreasing almost 97% of the starting polymer [80,81].

Evidence shows, the tendency for PET degradation is restricted to a small number of bacterial phyla, while Actinobacteria accounting for the most isolated bacterial with an efficient ability forbiodegradation of polyethylene-derived MPs. For example, the *Rhodococcus ruber* strain C208 isolated from the Waxworms showed the first MPs degradation symptoms just after 16 days. *Rhodococcus ruber* was able to develop biofilm on the PE surface. After 12–15 h of incubation, microcolonies began to organize and differentiate, increasing their size, structure, and frequency, resulting in the production of three-dimensional multicellular structures. Over 56 days, *Rhodococcus ruber* degraded 7.5% of the microplastic's initial mass, using PE as the sole carbon source [43].

Moreover, microbial consortium containing *Actinomycetes* demonstrated unique potential for MPs degradation. For example, the microbial consortium containing *Actinomycetes* and several *Bacillus* species demonstrated a high biodegradation ability of MPs, and aside from weight loss, during incubation, the MPs exhibited structural, physical, and chemical changes. Since the species *Bacillus* has excellent biodegradative powers, this consortium of *Actinomycetes* and *Bacillus* may have facilitated the enhanced polymer degradation [82]. The majority of plastics used today are made from hydrocarbons, and bacteria that break down hydrocarbons, such as *Alcanivorax*, *Marinobacter*, and *Arenibacter*, have been identified as potential agents in the breakdown of plastics, with *Alcanivorax borkumensis* being a key player in LDPE breakdown [83]. As the polymer mass fell, actinobacterial strains could also grow on PP-MPs. For instance, after 40 days of incubation, *Rhodococcus* sp. treated with PP, a thermoplastic polymer, lost 6.4% of its weight, while *Bacillus* sp. treated with PP lost 4.0% of its weight.

6. Conclusion

MPs are transporting through biotic and abiotic pathways and are threating the stability of our ecosystems with their negative impacts on the living organisms, microbiota, and nutrients dynamics. The composition, shape, and the concentration of MPs are the MPs key characteristics for their negative influence in their surrounding environments. Moreover, the leaching of additives from the MPs have more negative influence than MPs since they are not chemically bond to the MPs molecular structure and can be easily release to the ecosystem. MPs can potentially disrupt the balance of microbiota by hosting and transporting specific microbes. These microbes can form biofilms on the surface of MPs and use them as a carbon source for becoming the predominant species in the impacted microbiota. Microbial biodegradation is considered as an effective approach to address the global concerns on the MPs control. However, to avoid any negative impacts on the stability of microbiota and ecosystem this approach should be used in closed and controlled waste wastewater treatment systems, and in this regard *Actinobacteria* should be considered as one of the best options owing to their high biodegradation ability of MPs.

The future perspectives of MPs interactions with the microbiota lies in strengthening the following areas (1) studies on the compositions of the plastics products, (2) improving the current technical studies on the cost-effective detection of MPs, (3) deep understanding on the source, sink, and vectors of the MPs, (4) studies on the impacts of the MPs size, (5) studies on the interactions of the MPs and their surrounding environment, and (6) global awareness in the MPs hazards. It is worth mentioning that, the essential sectors, such as governments, the public, manufacturers, and scientists, should work closely with each other, and each sector must take responsibility to limit excessive plastic manufacture and wastes.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

No data was used for the research described in the article.

Declaration of competing interest

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

Acknowledgements

This project is funded by NSF EPSCOR WICCED Program Grant No. 1757353 and the State of Delaware.

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