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Microbes and Persistent Organic Pollutants in the Marine Environment

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Abstract:	Marine pollution has increased reaching the entire marine environment, from the surface to the deepest sediment and has become more concerning in the last seventy years. Persistent Organic Pollutants (POPs) are a fraction of ocean waste that includes, among the others, Polycyclic Aromatic Hydrocarbons (PAHs) and plastic polymers. These chemicals have an extremely long half-life, (bio)accumulate and damage the marine flora and fauna and, ultimately, human health. Some organisms have evolved enzymes to attack POPs in the environment and transform them into biomass and CO_2. Several microorganisms degrade many POPs in relatively short time. A wide variety of bacteria has been isolated with different techniques, and key catabolic enzymes used to degrade the most persistent oil hydrocarbon fractions have been identified. For plastic waste there is less evidence of microbial degradation, but a few recent studies are revealing that a biodegradation potential exists for some of the most recalcitrant plastic polymers as well. The scientific community is focusing on microorganisms and their enzymes for POPs uptake and removal from the environment, while searching novel biopolymers (also from microbiological origin) to substitute oil-derived plastics.
Response to Reviewers:	Dear Editor, We appreciate the opportunity to revise and resubmit our paper . We would like to thank the reviewers for the carefull reading of this manuscript. We also greatly appreciate the complimentary comments and suggestions, which help to improve the quality of this manuscript. We have revised the manuscript accordingly. Please find bellow a point-by-point response to the concerns. We hope that you will find our responses satisfactory. Sincerely, The corresponding author Paola Quatrini Rebuttal Reviewer #1: The type of this is review article and this work enhanced our understanding about pollutant in marine environment and Minor revisions need. I read this article carefully. information about plastic pollution in the marine environment is limited and this review can have enhanced our information about this problem. some minor edition need as follow:

	- some information about interaction of fungi and plastics must be added Authors: Thanks for your comments . Several information of the original paper already addressed the role of fungi in plastic degradation. However we agree to strengthen this point and added new information about interaction of fungi and plastics and the fungal key enzymes of the biodegradation pathway. We added various sentences in the paragraphs « The Plastisphere » (lines 158-161) and « Promising microbial Taxa and Enzymes for Plastic Attack » (167-168; 176-178; 188-195; 197-201; 211-220) ; . Having further added information on fungi and plastics, we changed the title « Promising bacterial taxa and enzymes for plastic attack » in « Promising microbial taxa and enzymes for Plastic Attack »). New references and new abbreviations have been added as well. Reviewer #1: - some information about environment assessment of this pollution needed Authors: Thanks for your suggestion. Indeed the text was missing this information, we added a part in the introduction dedicated to environmental assessment needs and methods (lines 68-83). New references have been added as well. (Tickner et al., 2019; Wu et al., 2008; Borah et al., 2020) Reviewer #1- References: This three reference is related to your work and you can use this references Abarian, M., Hassanshahian, M., Esbah, A. Degradation of phenol at high concentrations using immobilization of Pseudomonas putida P53 into sawdust entrapped in sodium-alginate beads. Water Science and Technology. 2018. 79 (7): 1387-1396. Bayat, Z., Hassanshahian, M., Cappello, S. Immobilization of Microbes for Bioremediation of Crude Oil Polluted Environments: A Mini Review. Open Microbiol J. 2015; 9: 48-54. Hassanshahian, M. Amini, N. 2016. Enrichment and identification of naphthalene-degrading bacteria from the Persian Gulf. Marine Pollution Bulletin. 107, 59-65. Ghanavati, H., Emtiazi, G., Hassanshahian, M., 2008. Synergism effects of phenol degrading yeast and ammonia oxidizing bacteria for nitrification in coke wastewater of Esfahan steel company. Waste Manage. Res. 26 (2), 203-208. Hassanshahian, M. 2014. Isolation and characterization of biosurfactant producing bacteria from Persian Gulf (Bushehr provenance). Marine Pollution Bulletin. 86, 361-366 Karimi, M, Hassanshahian, M. 2016. Isolation and characterization of phenol degrading yeasts from wastewater in the coking plant of Zarand, Kerman. Brazilian Journal of Microbiology. 4 7, 18-24. Authors: Thanks for the suggestions. We added the references suggested limited to those related to POPs. Reviewer #2: Dear Author the manuscript submitted is interesting and can be published in this form. Authors: no answers are given to reviewer 2, we only thank him for the revision of our paper.
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Microbes and Persistent Organic Pollutants in the Marine Environment

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Keywords

POPs, pollution, PAHs, plastisphere, marine biodegraders, bioplastics.

Abstract

Marine pollution has increased reaching the entire marine environment, from the surface to the deepest sediment and has become more concerning in the last seventy years. Persistent Organic Pollutants (POPs) are a fraction of ocean waste that includes, among the others, Polycyclic Aromatic Hydrocarbons (PAHs) and plastic polymers. These chemicals have an extremely long half-life, (bio)accumulate and damage the marine flora and fauna and, ultimately, human health. Some organisms have evolved enzymes to attack POPs in the environment and transform them into biomass and CO_2. Several microorganisms degrade many POPs in relatively short time. A wide variety of bacteria has been isolated with different techniques, and key catabolic enzymes used to degrade the most persistent oil hydrocarbon fractions have been identified. For plastic waste there is less evidence of microbial degradation, but a few recent studies are revealing that a biodegradation potential exists for some of the most recalcitrant plastic polymers as well. The scientific community is focusing on microorganisms and their enzymes for POPs uptake and removal from the environment, while searching novel biopolymers (also from microbiological origin) to substitute oil-derived plastics.

POPs Ocean Contamination

In recent decades, oceanic pollution by anthropogenic litter, mainly Persistent Organic Pollutants (POPs), has been recognized as a serious global environmental concern for its multiple implications on the environment, wildlife and human health (Andrady, 2011). POPs are chemical substances that are retained in the environment, even in the deepest marine sediments up to 10,000 meters of depth (Jamieson et al., 2017), causing the risk of adverse effects to the ecosystem (Islam et al., 2018). Their effects are exacerbated by bioaccumulation through the food web (Matthies et al., 2016) and by the outcomes of climate change (Nadal et al., 2015). Among POPs, Polycyclic Aromatic Hydrocarbons (PAHs) and plastic polymers at sea are of major concern (González-Gaya et al., 2019).

PAHs contamination results from activities related to the petrochemical industry, combustion and oil spill accidents (Ghosal et al., 2016). The amount of crude oil that is introduced from anthropogenic or natural sources into the marine environment is estimated to be more than 800 million liters per year (Kleindienst et al., 2015). Due to their complex structure among hydrocarbons, PAHs are highly resistant to degradation and remain persistent in the ecosystem, they have a natural potential for bioaccumulation in food chains they are hazardous environmental pollutants being highly toxic, genotoxic, mutagenic and carcinogenic (Abdel-Shafy & Mansour, 2016). PAHs, like other Hydrocarbons (HCs) such as long chain *n*-alkanes (Lo Piccolo et al., 2011), are ultimately degraded by environmental microorganisms that have been recognized as key players in cleanup events (Restrepo- Flórez et al., 2014; Catania et al., 2015, , Hassanshahian, 2014; Hassanshahian et al., 2016). However, we still need to expand the knowledge on microbial degradation mechanisms and conditions to fully exploit their catabolic potentialities (Ghosal et al., 2016).

Since the 1940s, the annual global demand for plastics consistently increased and presently stands at about 245 million tons per year, the variety and amount of POPs in the marine environment has consequently increased (Thompson et al., 2009; Cole et al., 2011). Plastic polymers are among the most recalcitrant substances and include Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyethylene Terephthalate (PET) and Polyvinyl Chloride (PVC) (Kale et al., 2015). Plastic is subject to deterioration by biotic and abiotic factors that reduce it into small fragments (microplastics) which are then mixed by waves and distributed to all habitats (Do Sul., et al., 2014). Ingestion of microplastics by the marine biota has probable negative consequences for its health (Browne et al., 2011). Moreover, some of the additives used to modify the properties of plastics are biologically active, potentially affecting development and reproduction (Oehlmann et al., 2009; Savoca et al., 2018). In addition, hydrophobic POPs in seawater are adsorbed onto plastic items (Mato et al., 2001; Teuten et al., 2009) and can accumulate toxins (Andrady, 2011).

Microbes tackle plastic polymers with direct and indirect action, by deteriorating the plastic itself or producing bioproducts that influence the polymer structure (Caruso, 2015). Both actions, enzymes and microbial products affecting plastic polymers are to be studied in the nearest future.

The use of microbial enzymes in coupled biotic-abiotic technologies for POPs degradation is starting to attract both the engineering and scientific world as a worthwhile and environmental-friendly solution (Jeon et al., 2013).

Due to growing concentration of persistent organic pollutants in the marine environment, combined with an increasing knowledge of their toxicity, in the last years extensive studies and monitoring programs have been carried out to determine POPs concentrations in water, sediment, and more recently, in biota; focusing increasingly on ‘‘possible biological effects” to assess the public health risk, environmental and ecological risk. An ecological and environmental risk assessment approach should be adopted for measuring POPs in the marine environment; routine monitoring and reporting of abiotic and biotic concentrations currently are the main methods used for environmental assessment risk (Jacobs et al., 2016; Tickner et al., 2019).

The primary objectives of most monitoring surveys consist in the comparisons of spatial changes to identify sources and ‘‘hot spots” containing great contaminant concentrations; comparisons of temporal changes to detect deterioration or improvement of contaminant concentrations in the environment, or checks on compliance according to governmental standards and established guidelines alternatives (Wu et al., 2008)

The environmental assessment of marine POPs require rigorous and expensive chemical analysis; the conventional techniques performed to evaluate usually the presence assessment in the marine environment of POPs are Gas or Liquid Chromatography, Mass Spectrometry and tandem Mass Spectrometry (MS/MS) or analytical techniques such as UV-Vis Spectroscopy and Surface-Enhanced Raman Scattering (Borah et al., 2020).

PAHs Biodegradation: Taking Over Persistent Organic Pollutants

Crude oil consists of many fractions, including the highly persistent and toxic (poly)aromatic compounds (Varjani, 2017). PAHs biodegradation by microorganisms has been demonstrated and widely described (Jeon and Madsen 2013; Ghosal et al., 2016), in pure-culture isolates (Oyehan et al., 2017, Djahnit et al., 2019) and in contaminated field sites (Vila et al., 2015; Catania et al., 2016; Dombrowski et al., 2016).

Laboratory experiments with pure bacterial cultures showed that low-molecular weight (LMW, two or three rings) PAHs reach complete degradation within 20 to 24 days of incubation (Dandie et al., 2004, Darmawan et al., 2015). High-molecular weight (HMW, more than three rings) PAHs can be degraded up to more than 95% in 16 days (Darmawan et al., 2015).

Many bacterial PAH-degrading genera, pathways and key enzymes involved in the biodegradation of PAHs have been characterized (Peng et al., 2008). The aerobic PAHs biodegradation is accomplished by monooxygenase or dioxygenase enzymes that incorporate oxygen atoms into the aromatic ring leading to the formation of intermediates that are ultimately converted to tricarboxylic acid cycle (TCA) cycle intermediates (Ghosal et al, 2016; Gupte et al., 2016). In anaerobic degradation pathways, the demolition of the aromatic ring is based on reductive reactions catalyzed by dehydrogenases, which lead to formation of aromatic central intermediates, which are then dearomatized and channeled to the central metabolism of the cell (Carmona et al., 2009).

A high proportion of PAH-degrading bacteria belong to the sphingomonads, mainly to the genera *Sphingomonas*, *Sphingobium* and *Novosphingobium*, (Ghosal et al., 2016). In contaminated marine environments PAH-degraders are either obligate HC-degrading bacteria such as *Cycloclasticus*, that results as the dominant species in contaminated surface sediment, or non-obligate PAHs degraders such as *Halomonas*, *Thalassospira*, and *Lutibacterium* genera (Gutierrez et al., 2015; Catania et al., 2018).

Halophilic archaea, fungi and algae can also mediate PAHs degradation and transformation (Sharma et al., 2018), but only with the advancement in genetic, genomic, proteomic and metabolomic studies, bioremediation is going to be a valid alternative for pollution management (Ghosal et al., 2016). Effort has been put in studying the most efficient environment for the bacteria to perform biodegradation: while oxygen concentration was at first considered the limiting factor, new pathways have been studied, using sulfate-reducing, denitrifying, methanogen or metal-ion-reducing bacteria (Nzila, 2018). *In situ* PAHs biodegradation can be achieved by biostimulation (Dell'Anno et al., 2018), or bioaugmentation (by the addition of selected microbes able to degrade the specific organic contaminants) that allow maintaining low costs and low environmental impacts (Dell'Anno et al., 2018).

Assessing Plastic Biodegradation

Studies on the biodegradation of plastics and factors that affect their biodegradability are now of great interest for the scientific community. Petroleum-based plastics have generally been considered highly recalcitrant to biodegradation, and data on the biodegradability of synthetic plastics have rarely been reported (Cacciari et al., 1993; Shah et al., 2008; Restrepo-Flórez et al., 2014; Alshehrei, 2017). The evaluation of plastics' biodegradability by microorganisms is mainly based on their chemical structure and physical properties which affect the efficiency of enzymes (Tokiwa et al., 2009), and the environmental conditions that encourage microbial growth (Gu, 2003). Abiotic factors such as UV irradiation, oxygen and temperature play a crucial role in the degradation of PE and PP in the environment (Bonhomme et al., 2003; Jakubowicz, 2003).

Biodegradation of plastic polymers consists of three important steps: (1) biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the growth of microorganisms on or inside its surface; (2) biofragmentation, which is the conversion of polymers to oligomers and monomers by microbial action and (3) assimilation, where microorganisms are supplied by necessary carbon, energy and nutrient sources from the fragmented polymers and convert plastic carbon to CO_2 and biomass (Lucas et al., 2008).

Different methods are used to assess polymer degradation. Biotic degradation and biodeterioration are mainly associated to physical tests (e.g. thermal transitions and tensile changes, tensile strength-elongation at fail and modulus of the polymer via Dynamic Mechanical Analysis), while biofragmentation is revealed by the identification of fragments of lower molecular weight using chromatographic methods; microcracks are revealed via Scanning Electron Microscopes, density with the contact angle, viscosity, and molecular weight distribution via High Temperature Gel Permeation Chromatography. The melting and glass transition temperature is detected via thermogravimetric analyses, and the crystalline and amorphous region with X-diffraction, small- and wide-angle-X-ray-scattering (Restrepo- Flórez et al., 2014; Kale et al., 2015).

Biodegradation can also be assessed measuring assimilation by microorganisms or monitoring the development of microbial biomass on plastic surface by microscopic observations, by testing the concentration of Adenosine Triphosphate and Fluorescein Diacetate, and protein analysis in general (Lucas et al., 2008; Kale et al., 2015); The microbiological characterization of the biofilm formed on plastic surface can be carried out using a wide range of cultural and culture-independent techniques (Dussud et al., 2018).

The Plastisphere

Any biotic and abiotic surface in the marine/aquatic environment can be colonized by micro- and macroorganisms that can form biofilms (Pinto et al., 2019). As expected, also plastic marine debris (PMD) hosts a diverse microbial community that exploits its hydrophobic surface forming a biofilm recently defined as the "plastisphere" (Zettler et al., 2013; Quero et al., 2017). The plastisphere is a unique consortium that differs from the surface water one, as plastics have a longer half-life than most of other floating substrates (Quero et al., 2017). Variation within plastisphere communities on different polymer types was observed, suggesting that polymer composition could shape the biofilm community structure (Oberbeckmann et al., 2014). This new colonized habitat hosts typical biofilm-forming bacteria and fungi, opportunistic pathogens, cyanobacteria and, interestingly, several hydrocarbon-degrading bacteria (Zettler et al., 2013). Similarly, PMD trapped in the sediment hosts bacterial genera affiliated with HC contaminant mineralization in cold ecosystems, supporting the possibility that these microbes play a role in degrading PMD (Harrison et al. 2014). However, the role of plastic surface colonizers in polymer biodegradation is still unclear, and especially fungal communities still represent an unexplored component of the plastisphere. The knowledges on fungi-plastic interaction mechanisms, especially in marine habitat are limited, although numerous fungal strains was reported for the capability to biodegrade plastic (Shah et al., 2008,; Jacquin et al., 2019).

Promising Microbial Taxa and Enzymes for Plastic Attack

Among plastic polymer biodegraders, the most active species are considered fungi and Actinobacteria (Tosin et al., 2012).

Fungi and Actinobacteria are an ecologically significant group, possessing unique metabolic and physical characteristics and are considerate of special interest due to their vast metabolic potential and ability to degrade plastics and recalcitrant molecules making them good candidates for bioremediation (Olajuyigbe & Ehiosun, 2016; Chen et al., 2016, Rogers et al., 2020). Actinobacteria play a role in several biological processes and are capable of producing pharmaceutically, industrially and clinically important bioactive compounds or enzymes (Ramírez & Calzadíaz, 2016). Theyare known to decompose a large number of biomolecules (lignin, cellulose, and hemicellulose) and to metabolize recalcitrant polymers such as long chain *n*-alkanes (Lo Piccolo et al., 2011), xenobiotics (Borozan et al., 2013), pesticides (Alvarez et al., 2017), and rubber (Shivlata & Tulasi, 2015). The Actinobacterium *Rhodococcus ruber*, for example, is reported as plastic (Andrady, 2011) and PS (Mor and Sivan, 2008) degrader, producing biofilm which helps to improve degradation (Auta et al., 2017). Saprophytic fungi are known to biodegrade PE and PS, they belong mainly to the phyla Chytridiomycota, Cryptomycota and Ascomycota and dominate fungal degrading communities in aquatic ecosystems (Kettner et al., 2017)

The pathways involved in plastic polymer degradation have been tentatively characterized and the key enzymes of the biodegradation pathway resulted to be plant polymer-degrading enzymes such as laccases, cutinases, hydrolases, and other enzymes such as esterase, protease and urease (Pathak, 2017). Polymers with hydrolysable chemical bonds in their backbone such as PET (Webb et al., 2013) and polyurethane (PUR) (Cregut et al., 2013) are more susceptible to biodegradation than PE, PS, PP and PVC (Zheng et al., 2005). Microbial laccases from *Trametes versicolor* and *Rhodococcus*, *Bacillus cereus* have been described as able to strongly reduce the molecular weight of a PE membrane (Singh et al., 2016). Manganese peroxidase from the fungi *Phanerochaete chrysosporium, Penicillium simplicissimum* and the bacterium *Bacillus cereus* have been reported to be involved in the biodegradation of PE, such as the lignin peroxidases detected in lignocellulose- degrading *Streptomyces* species (Wei & Zimmermann, 2017). Recently the marine fungus *Zalerion maritimum* has been isolated and his ability to degrade polyethylene microplastics in 14 days has been described (Paco et al., 2017). *Aspergillus* spp. Species showed good growth in medium supplemented with both low-density polyethylene (LDPE) (Pramila et al 2011) and high-density polyethylene (HDPE) (Devi et al. 2015) as unique carbon source. Degradation pathway involved in the biodegradation of LDPE comprise hydrophobic proteins and degrading enzymes that can attach to the polymer surface (Pramila et al 2011). Other strains of *Aspergillus*, together with *Phanerochaete* and *Lentinus* species, show significant potential also for biodegradation of PVC plastics (Devi et al., 2016).Several microorganisms capable of growing and degrading PUR were isolated and the enzymes related to polyurethane biodegradation have been described (Schmidt et al., 2017). *Pseudomonas* spp. degrades PUR using proteases, esterases and impranilases (Loredo-Treviño et al., 2012). Various species of fungi, including, *Curvularia senegalensis*, *Fusarium solani*, *Aureobasidium pullulans* and *Cladosporium* sp, have been isolated as polyurethane-degrading microbes from environment (Devi et al., 2016). Key enzymes of the biodegradation pathway include an endopolyurethanases that hydrolyze the PUR molecule at random locations, and exoenzymes that remove monomer units from the chain ends (Howard et al., 2002). *Pseudomonas* and *Vibrio* degrade PP by oxidative degradation causing a decrease in viscosity and the formation of carbonyl and carboxyl groups during the biodegradation (Alshehrei, 2017). A number of lipases, esterases, cutinases, carboxylesterases from fungi (*Fusarium oxysporum* and *F. solani*) has been isolated (Nimchua et al., 2007). Key enzymes for PET biodegradation from Actinobacteria (*Thermobifida fusca*) and Firmicutes (*Bacillus licheniformis*, *B. subtilis*) were found to change its crystalline structure (Wei & Zimmermann, 2017).

Recently, a newly discovered bacterium, *Ideonella sakaiensis* 201-F6, was shown to exhibit the rare ability to grow on PET as a major carbon and energy source (Son et al., 2019). Central to its PET biodegradation capability is a secreted polyester hydrolase called PETase (PET-digesting enzyme) that shows features common to both cutinases and lipases (Yoshida et al., 2016). This enzyme was also engineered for improved PET degradation capacity (Austin et al., 2018). Several fungal strains are also known to biodegrade PET, such as *Humicola insolens*, *Fusarium* spp., and *Penicillium citrinum* (Ribitsch et al., 2012); PET-colonizing fungal communities that have adapted to plastics as a surface for colonization and degradation, constituted mainly to Ascomycota, Basidiomycota, Chytridiomycota have been identified and characterized (Oberbeckmann et al., 2016). In fungal PET biodegradation, the strategy proposed suggests that fungi adhere to the PET surface and secrete extracellular enzymes PETase (hydrolase) and MHETase. PETase hydrolyze PET to mono-(2-hydroxyethyl) terephthalate (MHET), terephthalic acid (TPA), and bis (2-hydroxyethyl) terephthalate (BHET) (Taniguchi et al., 2019). The MHETase hydrolyzes MHET to TPA and ethylene glycol (EG) (Jacquin et al., 2019). P. citrinum hydrolyze PET with a polyesterase that increases PET surface hydrolysis (Liebminger et al., 2007)

Weathered polystyrene (PS) films incubated under simulated marine developed convergent biofilm communities enriched with hydrocarbon and xenobiotics degradation genes that efficiently reduced the weight of PS films and decreased the number-average molecular weight of films (Syranidou et al., 2017).

These recently obtained results suggest that marine microbial populations carry a plastic biodegradation potential that is still largely unexplored.

Future Directions

POPs continue to be produced and spread in the environment despite the worldwide efforts to reduce their impact by recycling, reusing and substituting them with less toxic and less persistent molecules (Nadal et al., 2015).

The platisphere has been object to many studies to assess microbial polymer biodegradation at sea, but new and combined monitoring parameters have yet to be defined and confirmed with *in situ* experiments, to define the steps of biofilm formation and bacterial colonization, the impact on global biogeochemical cycles and the spread of invasive species to both the animal and human world (Jacquin et al., 2019).

While great efforts are devoted to reducing the huge amount of plastic waste in the environment, the focus of research is to substitute petroleum-based plastics with bio-based plastics and to discover mechanisms that can make plastics degradable by acting on their chemical structure (Iwata, 2015). Additives, such as pro-oxidants and starch, are applied in synthetic materials to modify and make plastics biodegradable (Zheng et al., 2005) and promote microbial colonization (Fontanella et al., 2010). Both routes lead ultimately to plastic removal by biodegradation carried out by microorganisms in the environment.

Bioplastics, bio-based plastics synthesized from biomass and renewable resources (Scaffaro et al., 2017), should prevent the disposal of recalcitrant plastic waste in the environment because of their biodeteriorabilty/biodegradability (Tosin et al., 2012; Accinelli et al., 2012). Bioplastics can be exploited for various applications and are a good alternative to petroleum-based plastics due to their similar properties (Spierling et al., 2018). However, biodegradation rates are strongly dependent on the manufacturing procedure of the materials (Chinaglia et al., 2018). Higher surface roughness and/or the presence of humidity in the polymer matrix and high temperatures can sensibly increase the biodegradation rates (Lo Re et al., 2013). Microorganisms are also able to synthesize biopolymers as intracellular, structural, and extracellular polymers for their function and survival (Sukan et al., 2015). The polyhydroxyalkanoates (PHAs) and exopolysaccharides (EPS) are gaining importance over the other biopolymers (de Jesus Assis et al., 2016) in several applications including drug delivery, food, pharmaceutics, paper industry, textile printing, cosmetics and agriculture (Vijayendra, 2015).

Finally, microorganisms appear the only organisms able to turn plastic polymers into less complex chemical constituents facilitating their mineralization thanks to their enzymes (Kanaly et al., 2010). PAHs-biodegradation pathways, genes, enzymes and molecular mechanisms are the major study-areas selected until this moment: efficiency in high salinity or anaerobic environments and factors enhancing bioremediation like oxygen concentration, pH, temperature, and nutrient availability are to be analyzed (Ghozal et al., 2016). In an attempt to develop an efficient pathway of anaerobic biodegradation, PAHs-degrading bacteria have been used in sulfate-, nitrate-, and metal-ion-reducing conditions as well as methanogenic conditions, that has highlighted the need to develop biosurfactants to ease access to hydrophobic molecules via biochemical and molecular methods (Nzila, 2018). Biosurfactants with different characteristics and efficiency are produced by many microbial taxa: production and effectiveness are to be studied in order to develop eco-friendly *in situ* applications to increase the availability of oil and plastic compounds lessening eco-toxicological risks (Dell'Anno et al., 2018).

The development of environmental friendly and sustainable solutions to manage the waste of plastics mixtures in the environment could rely on the use of indigenous consortia tailored for the degradation of plastic polymers in the marine environment (Syranidou et al., 2017) or microorganisms with a set of complementary enzymes either native or engineered using state of the art biotechnologies (Kelwick et al., 2017). Controlled degradation in immobilized conditions can be used for cleaning up environments and wastewaters to perfect survival and performance of bacterial cells (Bayat et al., 2015; Abarian et al., 2019). With modern means of biotechnology, genes involved in pollutant degradation extracted from metagenomic libraries can be inserted into strains with strong fecundity and high adaptability, and overexpressed by plasmids, creating consortia of cooperating bacteria to further enhance biodegradation potential (that can ultimately be coupled with nitrification) (Ghanavati et al., 2008; Liu et al., 2019).

Abbreviations

EPS	Exopolysaccharides
HC	Hydrocarbon

HDPE	High-density polyethylene
HMW	High-Molecular Weight
LDPE	Low density polyethylene
LMW	Low-Molecular Weight
PAH	Polycyclic Aromatic Hydrocarbons
PE	Polyethyelene
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PMD	Plastic Marine Debris
POP	Persistent Organic Pollutant
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
TCA	Tricarboxylic Acid Cycle

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