Biodeterioration of Polyethylene

Subjects: Materials Science, Biomaterials
Contributor: David Levin

Polyethylene (PE) is the most abundant synthetic, petroleum-based plastic materials produced globally, and one of the most resistant to biodegradation, resulting in massive accumulation in the environment. Although the microbial degradation of polyethylene has been reported, complete biodegradation of polyethylene has not been achieved, and rapid degradation of polyethylene under ambient conditions in the environment is still not feasible.

Keywords: low-density polyethylene ; abiotic degradation ; biodegradation ; microbial degradation

1. Introduction

Five types of petroleum-based polymers are the most commonly used to make single-use plastic materials, namely low-density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). LDPE, mainly used to make plastic carry bags and food packaging materials, is the most abundant petroleum-polymer on earth, and represents up to 64% of single-use plastics that are discarded within a short period after use, resulting in massive and rapid accumulation in the environment [1][2]. Despite recycling and energy recovery efforts, the harmful impacts of virtually "non-biodegradable" LDPE waste accumulation in landfill and in the oceans are increasing [3][4][5][6]. There is mounting evidence that micro-plastics are now found everywhere on the planet, including snow in the arctic [7]. Hence, a suitable method for disposal that is eco-friendly must be found [1][2][8].

Unlike organic wastes discarded by humans, polyethylene (PE), and other petroleum-based plastics, are extremely recalcitrant to natural biodegradation processes. The scientific literature contains a considerable number of reports on the biodegradation of synthetic plastics, and on PE in particular. Thirteen review articles on microbial and physical biodegradation mechanisms and microorganisms involved have been published since 2008 (**Table 1**). Although many studies have reported microbial degradation of PE, significant degradation of PE wastes has not yet been achieved at real scales. The lack of a working definition for biodegradation for polyethylene that can lead to testable hypotheses has limited our ability to develop a biochemically-based understanding of the mechanisms and processes involved in PE degradation.

Table 1. Published review articles on plastic biodegradation.

Authors	Year of Publication	Topic	References
Shimao	2001	Biodegradation of plastics	[9]
Koutny et al.	2006	Biodegradation of polyethylene films with prooxidant additives	[10]
Arutchelvi et al.	2008	Biodegradation of polyethylene and polypropylene	[11]
Shah et al.	2008	Biological degradation of plastics	[12]
Lucas et al.	2008	Polymer biodegradation: Mechanisms and estimation techniques	[13]
Tokiwa et al.	2009	Biodegradability of Plastics	[14]

Authors	Year of Publication	Topic	References
Sivan	2011	New perspectives in plastic biodegradation	[15]
Ammala et al.	2011	An overview of degradable and biodegradable polyolefin	[16]
Restrepo-Flórez et al.	2014	Microbial degradation and deterioration of polyethylene	[17]
Sen and Raut	2015	Microbial degradation of low density polyethylene	[18]
Raziyafathima et al.	2016	Microbial Degradation of Plastic Waste: A Review	[19]
Emadian et al.	2017	Biodegradation of bioplastics in natural environments	[20]
Harrison et al.	2018	Biodegradability standards for carrier bags and plastic films in aquatic environments: A critical review	[21]

Early microbial biodegradation experiments attempted to demonstrate that microbial activity could result in changes in the physical characteristics of plastics, such as tensile strength, water uptake, and crystallinity [22]. Microbial biodegradation of plastics was first reviewed by Pirt (1980) [23]. A decade later, Albertsson and Karlsson (1990) reported a 0.2% weight loss of PE after 10 years [22]. Otake et al. (1995) surveyed changes on the surface of PE polymers that had been buried in soil for 10 to 32 years [24]. A high degree of degradation was observed for thin films of LDPE. Although areas of the PE films with severe deterioration were characterized by whitening with small holes, overall rate of degradation was very low, even after years of exposure to soil microbes.

Some scientists have surveyed the aerobic biodegradation of treated polyethylene and/or polyethylene modified by the addition of additives ("addivitated") PE in simulated soil burial and mature compost [25][26], in natural aqueous environments in laboratory condition [27][28], or in different type of soil contain microbial consortia in real condition [29]. Others tested the biodegradation of LDPE in soil and identified the microorganisms involved [30]. Abrusci et al. [31] isolated microorganisms adsorbed on the surface of PE films buried in agricultural soil and then tested the biodegradability of thermal and photo degraded addiviated LDPE films by those organisms.

Microbial degradation assay experiments usually include isolation of microorganisms from different sources by use of conventional, culture-dependent methods to find best potential microbial power to degrade polymeric PE chain. Some researchers have isolated potential microorganisms from different type of soil (garden soil, forest soil, garbage soil, mangrove soil, soil containing agricultural PE films for soil mulching) [32][33][34][35][36]. Plastic debris, solid waste dumps sites, or landfill areas (municipal solid soil) [8][37][38][39][40][41][42], water [2][43], waste water or sewage sludge [44], oil contaminated soil [45][46], and even from Waxworm larvae [47] were the other sources for the isolation of high potential PE-degrading bacteria.

The culture method involved parameters such as same constant incubation temperature (usually 30 °C) and aerobic culture condition over 3 to 10 days [33][39]. In these experiments, a large number of bacteria were identified as belonging to a limited number of genera (**Table 2**), but not all of them were responsible for PE degradation. Following the initial isolation of the bacteria, the ability of individual isolates to utilize treated and/or untreated polyethylene was investigated in pure shake-flask cultures over various periods of times. These bacteria were mostly identified by the use of sequencing 16S ribosomal RNA genes after amplification by polymerase chain reaction (PCR). In the final step, biodegradation assays with PE-degrading bacteria on polyethylene particles or films was estimated by different methods and techniques discussed in Section 6.3.

Table 2. Bacteria used in biodegradation studies of polyethylene (PE) degradation. The bacteria are listed alphabetically by genus.

Genus (and Species)	Source	Experiment Duration	Experiment Condition	Biodegradation Result	Reference
Acinetobacter bumannii	Municipal landfill	30 days	37 °C Non-pretreated PE	Biomass production	[42]
Arthobacter defluvii *Bacillus amyloliquefaciens* *Bacillussubtilis*	Dumped soil area	1 month	PE bags	20%–30% W.L. *	[48]
Bacillus pumilus *Bacillus subtillis*	Pelagic waters	30 days	PE bags	1.5%–1.75% W.L.	[2]
Bacillus ssp.	Waste coal, a forest and an extinct volcano crater	225 days	Modified PE	Reduction of mechanical properties by 98% No W.L. detected	[29]
Bacillus sphericus	Shallow waters of ocean	1 year	HDPE and LDPE; Untreated and Heat treated	3.5% and 10% 9% and 19%	[43]
Bacillus megaterium *Bacillus subtilis* *Bacillus cereus (MIX together)*	Soil	90 days	45 °C photo-degraded oxobiodegradable PE	7%–10% mineralization	[31]
Bacillus amyloliquefaciens	Solid waste dumped	60 days	LDPE	11%–16%	[49]
Bacillus subtilis	MCC No. 2183	30 days	Adding Biosurfactant Unpretreated 18 µm thickness PE	9.26% W.L.	[50]
Bacillus pumilus M27 *Bacillus subtilis H1584*	Pelagic waters	30 days	PE bags	1.5–1.75 W.L. %	[2]
Brevibacillus borstelensis	DSMZ	90 days	50 °C Irradiated LDPE	17% W.L.	[51]
Brevibacillus	Waste disposal site	3 weeks	Pretreated PE	37.5% W.L.	[41]

Genus (and Species)	Source	Experiment Duration	Experiment Condition	Biodegradation Result	Reference
Chryseobacterium gleum	Waste water activated sludge soil	1 month	UV-radiated LLDPE	-	[44]
Comamonas sp.	Plastic debris in soil	90 days	Non-treated LDPE	Changing in chemical properties	[8]
Delftia sp.	Plastic debris in soil	90 days	Non-treated LDPE	Changing in chemical properties	[8]
Kocuria palustris M16,	Pelagic waters	30 days	PE bags	1%	[2]
Microbacterium paraoxydans	Having Gene bank ID	2 months	Pretreated LDPE	61% W.L.	[52]
Pseudomonas sp.	Mangrove soil	1 month	PE	20.54% W.L.	[30]
Pseudomonas aeroginosa	Petroleum contaminated beach soil	80 days	LMWPE	40.8% W.L.	[45]
Pseudomonas sp.	Beach soil contaminated with crude oil	80 days	37 °C LMWPE	4.9%–28.6% CO_2 production	[46]
Pseudomonas sp.	Garbage soil	6 months	PE bags	37.09% W.L.	[34]
Pseudomonas citronellolis	Municipal Landfill	4 days	LDPE	17.8% W.L.	[38]
Pseudomonas sp.	Having Gene bank ID	2 months	Pretreated LDPE	50.5% W.L.	[52]
Pseudomonas aeroginosa *Pseudomonas putida* *Pseudomonas siringae*	ATCC	120 days	Untreated PE	9%–20%	[53]
Pseudomonas sp.	Waste disposal site	3 weeks	Pretreated PE	40.5% W.L.	[41]
Rhodococcus ruber	PE agricultural waste in soil	4 weeks	Treated LDPE	Up to 8% W.L.	[36]

Genus (and Species)	Source	Experiment Duration	Experiment Condition	Biodegradation Result	Reference
Rhodococcus ruber	PE agricultural waste in soil	60 days	LDPE	0.86% W.L./week	[54]
Rhodococcus ruber	PE agricultural waste in soil	30 days	LDPE	1.5%–2.5% W.L. Reduction of 20%.in Mw and 15%.in Mn	[55]
Rhodococcus rhorocuros	ATCC	6 months	27 °C Degradable PE	60% mineralization	[56]
Rhodococcus rhorocuros	ATCC 29672	6 month	PE containing prooxidant additives	Different amount of mineralization	[57]
Rhodococcus sp.	Waste disposal site	3 weeks	Pretreated PE	33% W.L.	[41]
Rhodococcus sp.	Three forest soil	30 days	LDPE containing prooxidant additives	Confirmation of Adhering	[35]
Staphylococcus arlettae	Various soil environments	30 days	PE	13.6% W.L.	[32]
Stentrophomonas sp.	Plastic debris in soil	90 days	Non-treated LDPE	Changing in chemical properties	[8]
Stentrophomonas pavanii	Solid waste dump site	56 days	Modified LDPE	Confirmed by FTIR	[40]
Streptomyces spp.	Nile River Delta	1 month	30 °C Heat treated degradable PE bags	3 species showed slight W.L.	[58]

* W.L., Weight loss report as %.

Because of the great variety of PE materials used and the wide-range of culture conditions, comparisons of the various results of biodegradation are not meaningful. This underscores the need for standardized methods and protocols to systematically study the biodegradation of synthetic plastics.

2. Abiotic Deterioration of PE

The complete process of biodegradation has been divided into four stages: biodeterioration, biofragmentation, bioassimilation, and mineralization. However, before microorganisms can begin to attack PE, they need access points in the PE structure to start fragmentation. Thus, initially, oxidation of PE polymers occurs through abiotic process, such as exposure to ultraviolet (UV) irradiation [59] in combination with heat [60] and/or chemicals in the environment [61], without the action of microbes.

That oxidation of PE, especially oxidation induced by UV-irradiation, is usually accompanied by thermal aging, is well-established and the mechanisms of polymer transformation have been well demonstrated [59][62][63]. Previous research has reported the exposure of PE to UV-light or oxidizing agents generates carbonyl-groups in the alkane chains of PE, which are subsequently further hydrolyzed by microorganisms that catabolize the shorter PE chain reaction products (fragmentation). In this mechanism, initially, UV-radiation is absorbed by the polymer chain, which leads to radical formation. Eventually, oxygen is absorbed and hydroperoxides are formed, resulting in the production of carbonyl groups (**Figure 1**). Additional exposure to UV-radiation causes the carbonyl groups to undergo Norrish Type I and/or Type II degradation. Also, photo-oxidation can be initiated by impurities or pro-oxidants. UV-degradation can also begin at locations of trace hydroperoxide or ketone groups, introduced during the manufacturing process or fabrication.

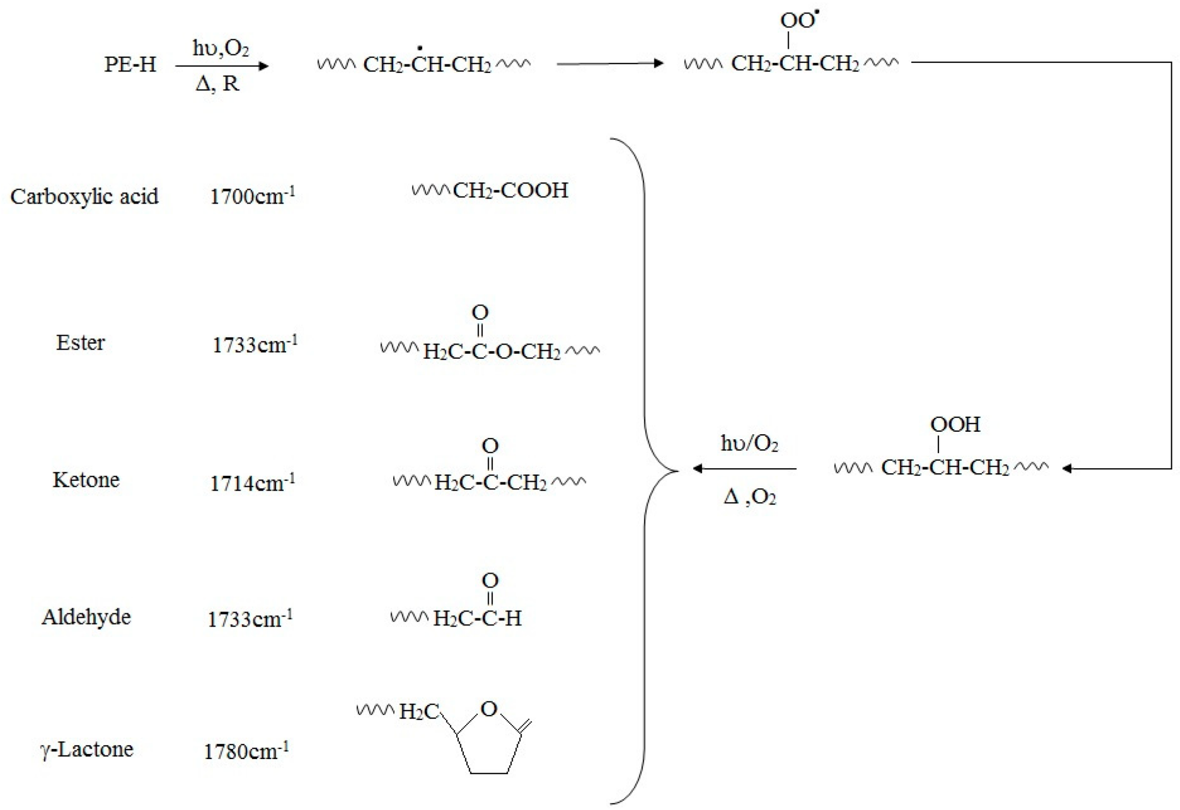

Figure 1. Degradation pathways of polyethylene containing pro-oxidant additives.

The oxidative degradation of polyolefins can be followed by measuring the level of carbonyl group adsorption by infra-red spectroscopy (IR). The measured carbonyl groups are usually expressed as a carbonyl index (C.I.), defined as the ratio of carbonyl and methylene absorbances, was used to express the concentration levels of carbonyl compounds measured by ATR-FTIR. The ratio of the absorbance of the carbonyl peak at 1714 cm^{-1} [64] and that of the methylene absorption band at 1435 cm^{-1} (CH_2 scissoring peak) taken as an internal thickness band (CI = A1714/A1435). The formation of carbonyl groups is increased by photo-oxidation, but also by increasing stress even after storage in an abiotic environment. Functional groups that can be identified by FTIR analysis are shown in **Table 3**.

Table 3. Characterization peaks in FT-IR [50].

SI No.	Wave Number (cm^{-1})	Bond	Functional Group
1	3000–2850	–C–H stretch	Alkanes
2	2830–2695	H–C = O: C–H stretch	Aldehyde
3	1710–1665	–C = O stretch	Ketones, Aldehyde
4	1470–1450	–C–H Bend	Alkanes
5	1320–1000	–C–O stretch	Alcohol, Carboxylic acid, esters, ethers

SI No.	Wave Number (cm^{-1})	Bond	Functional Group
6	1000–650	=C–H Bond	Alkenes

If Norrish Type I or Type II degradation (or both) occur, additional peaks are observed in the IR spectrum of the polymer. For example, a terminal double-bond appears at 905–915 cm^{-1}, and it is also possible to trace ester formation. Norrish Type I cleavage yields a carbonyl radical that can react with an alkoxy radical on the PE chain. A peak appears at 1740 cm^{-1} in the IR spectrum if this ester formation occurs. The plot of 1640–1850 cm^{-1} range of carbonyl groups, as determined by the overlapping bands corresponding to acids (1710–1715 cm^{-1}), ketones (1714 cm^{-1}), aldehydes (1725 cm^{-1}), ethers (1735 cm^{-1}), and lactones (1780 cm^{-1}) can reveal the presence of different oxidized products. Yamada-Onodera et al. [65], Gilan et al. [36], Hassan et al. [33], Yashchuck et al. [26], Abrusci et al. [61], and Vimala and Mathew [50] all report UV-light as the most applicable method of photo-oxidation in PE biodegradation experiments. **Figure 1** shows degradation pathways of polyethylene and production of different carbonyl group.

3. Biodeterioration of PE

In addition to the abiotic deterioration of PE materials, some microorganisms can initiate the oxidation process on their own, via the process of "hydroperoxidation". This has been termed "biodeterioration". However, the question as to whether PE oxidized in this manner can be ultimately degraded by microorganisms still remains to be clarified [10]. In some studies of microbial degradation of PE, different pro-oxidation additives (prodegradants) have been incorporated to the structure of polyethylene products to make them "oxo-degradable". PE polymers containing products that render them oxo-degradable are referred to as "addiviated" polymers. Materials used to make addiviated PE polymers oxo-degradable include polyunsaturated compounds, transition metals like iron, cobalt, manganese, and calcium [31][44][57], totally degradable plastic additives (TDPA) with different commercial names [25][26][27], natural polymers (e.g., starch, cellulose, or chitosan), food grade dyes [40][43], or synthetic polymers containing ester, hydroxyl or ether groups [29] that are prone to hydrolytic cleavage by microorganisms.

In some comparative studies of the microbial degradation of PE, the deterioration of crude and addiviated PE polymers is initiated by abiotic parameters like sun-light [40][50], heat [43][56][58], or both [35][57], as well as the addition of oxidizing chemical agents like nitric acid [33][51], as forms of PE pretreatment to render the plastic more susceptible to microbial degradation. The effects of these treatments on PE structure, and subsequently microbial degradation, were then investigated and compared with samples that were not pretreated.

During the process of deterioration, a transformation in the basic structure of PE leads to the formation of oxidized oligomers and modification of the polymer. Deterioration by physical, biological, or chemical agents makes the PE fragile and sensitive to further oxidation by enzymes secreted by the microorganisms. In this stage, the structure of PE changes, but there is no fragmentation of the polymer, or reduction in molecular structure. Overall, the deterioration phase is characterized by an increase in access points for enzymes secreted by microorganisms, and a reduction of mechanical or other physical properties of the polymer.

4. General Overview of Biodegradation Processes

The biodegradation process usually includes biofragmentation of the PE polymers by secreted enzymes, followed by bioassimilation of small cleavage fragments (molar mass must be less than 500 g/mol) by the microorganisms [56][66]. Many of the species shown to degrade PE are also able to consume linear n-alkanes like paraffin ($C_{44}H_{90}$, M_w = 618). The linear paraffin molecules were found to be consumed by several microorganisms within 20 days [58][67].

Microbial oxidation of n-alkanes is well understood and hexadecane, whose basic chemical structure is identical to that of PE, has been employed as a model compound for the investigation of the PE biodegradation and the relevant genes [46]. The initial step involves hydroxylation of C-C bonds to generate primary or secondary alcohols, which are further oxidized to aldehydes or ketones, and then to carboxylic acids. Thus, microbial oxidation decreases the number of carbonyl-groups due to the formation of carboxylic acids. Carboxylated n-alkanes are analogous to fatty acids, which can be catabolized by bacteria via the β-oxidation system pathway (**Figure 2**). However, neither cleavage of C-C bonds within the backbone of PE polymers, nor the generation of long carbon chain carboxylic acids hydrolysis products have been reported [45][46][68][69][70].

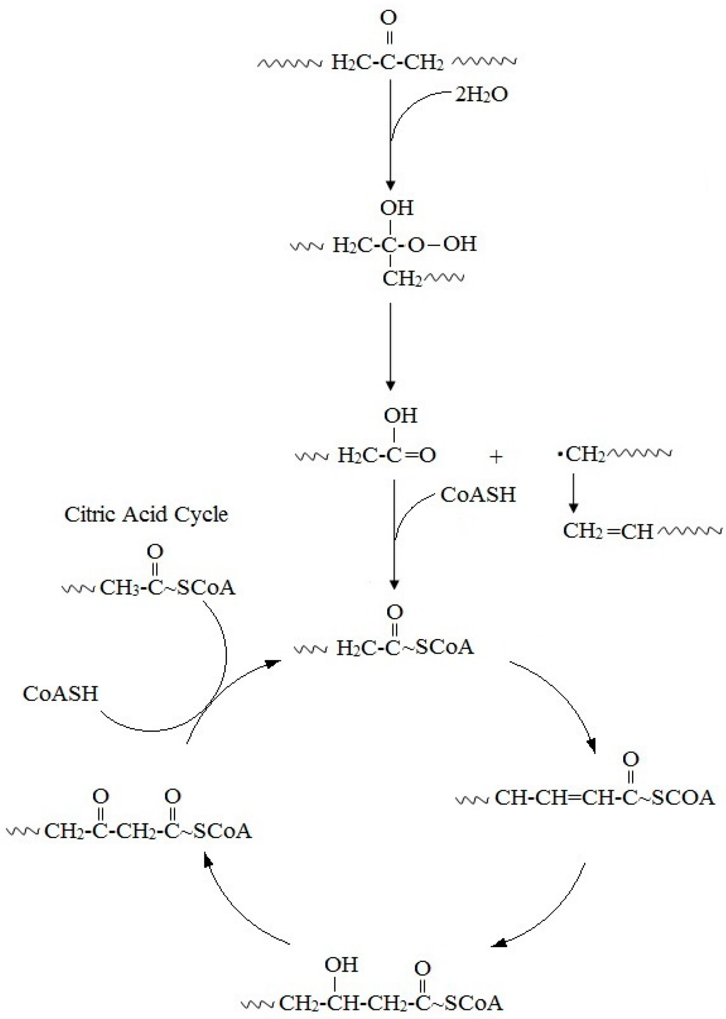

Figure 2. Proposed mechanism for the biodegradation of PE.

Studies of the genetic mechanisms associated with PE degradation are extremely scarce. However, it has been reported that Alkane hydroxylases (AlkBs), enzymes involved in the alkane hydroxylase system pathway, are known to degrade linear alkanes and are the best known enzymes involved in PE degradation in β-oxidation pathway [45]. The key enzymes of interest in the alkane hydroxylase system are monoxygenases. The number and types of Alkane hydroxylases vary greatly in different bacteria, in which the induction condition and amount of goal carbon in the alkane chain are completely different [71].

The *P. aeruginosa* genome encodes two Alkane hydroxylases, *alk*B1 and *alk*B2, while the *Rhodococcus sp.* TMP2 genome encodes 5 Alkane hydroxylases (*alk*B1, *alk*B2, *alk*B3, *alk*B4, and *alk*B5) [72]. The Alkane hydroxylase system has been investigated studied best in *P. putida* GPo1, which expressed an Alkane hydroxylase that participates in the first step of the n-alkane oxidation pathway by hydroxylating of the terminal carbon [73]. Yoon et al. [46] have shown that AlkB of *Pseudomonas aeruginosa* strain E7 actively degraded low molar mass PE and played a central role in the mineralization of LMWPE into CO_2 [46]. Also, AlkB cloned and expressed in *Pseudomonas* sp. E4 was active in the early stage of in LMWPE biodegradation, even in the absence of the other specific enzymes like rubredoxin and rubredoxin reductase. Laccase enzymes (phenol oxidases) expressed by *Rodococcus rubber* are multi-copper enzymes that have also been shown to play a major role in PE biodegradation [55].

References

1. Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 2017, 69, 24–58.
2. Harshvardhan, K.; Jha, B. Biodegradation of low-density polyethylene by marine bacteria from pelagic waters Arabian Sea, India. Mar. Pollut. Bull. 2013, 77, 100–106.
3. Álvarez-Hernández, C.; Cairós, C.; López-Darias, J.; Mazzetti, E.; Hernández-Sánchez, C.; González-Sálamo, J.; Hernández-Borges, J. Microplastic debris in beaches of Tenerife (Canary Islands, Spain). Mar. Pollut. Bull. 2019, 146, 26–32.

4. Foley, C.J.; Feiner, Z.S.; Malinich, T.D.; Hook, T.O. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci. Total Environ. 2018, 631, 550–559.
5. Rochman, C.M.; Browne, M.A.; Underwood, A.J.; Van Franeker, J.A.; Thompson, R.C.; Amaral-Zettler, L.A. The ecological impacts of marine debris: Unraveling the demonstrated evidence from what is perceived. Ecology 2016, 97, 302–312.
6. Shen, M.; Zhang, Y.; Zhu, Y.; Song, B.; Zeng, G.; Hu, D.; Wen, X.; Ren, X. Recent advances in toxicological research of nanoplastics in the environment: A review. Environ. Pollut. 2019, 252, 511–521.
7. Bergmann, M.; Mützel, S.; Primpke, S.; Tekman, M.B.; Trachsel, J.; Gerdts, G. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 2019, 5, eaax1157.
8. Peixoto, J.; Silva, P.L.; Krüger, R.H. Brazilian Cerrado soil reveals an untapped microbial potential forunpretreated polyethylene biodegradation. J. Hazard. Mater. 2017, 324, 634–644.
9. Shimao, M. Biodegradation of plastics. Curr. Opin. Biotechnol. 2001, 12, 242–247.
10. Koutny, M.; Lemaire, J.; Delort, A.M. Biodegradation of polyethylene films with prooxidant additives. Chemosphere 2006, 64, 1243–1252.
11. Arutchelvi, J.; Sudhakar, M.; Arkatkar, A.; Doble, M.; Bhaduri, S.; Uppara, P.V. Biodegradation of polyethylene and polypropylene. Indian J. Biotechnol. 2008, 7, 9–22.
12. Shah, A.A.; Hasan, F.; Hameed, A.; Ahmed, S. Biological degradation of plastics: A comprehensive review. Biotechnol. Adv. 2008, 26, 246–265.
13. Lucas, N.; Bienaime, C.; Belloy, C.; Queneudec, M.; Silvestre, F.; Nava-Saucedo, J.E. Polymer biodegradation: Mechanisms and estimation techniques. Chemosphere 2008, 73, 429–442.
14. Tokiwa, Y.; Calabia, B.P.; Ugwu, C.U.; Aiba, S. Biodegradability of plastics. Int. J. Mol. Sci. 2009, 10, 3722–3742.
15. Sivan, A. New perspectives in plastic biodegradation. Curr. Opin. Biotechnol. 2011, 22, 422–426.
16. Ammala, A.; Bateman, S.; Deana, K.; Petinakis, E.; Sangwan, P.; Wong, S.; Yuan, Q.; Yu, L.; Patrick, C.; Leong, K.H. An overview of degradable and biodegradable polyolefins. Prog. Polym. Sci. 2011, 36, 1015–1049.
17. Restrepo-Flórez, J.M.; Bassi, A.; Thompson, M.R. Microbial degradation and deterioration of polyethylene: A review. Int. Biodeterior. Biodegrad. 2014, 88, 83–90.
18. Sen, S.; Raut, S. Microbial degradation of low density polyethylene (LDPE): A review. J. Environ. Chem. Eng. 2015, 3, 462–473.
19. Raziyafathima, M.; Praseetha, P.K.; Rimal Isaac, R.S. Microbial degradation of plastic waste: A review. J. Pharm. Chem. Biol. Sci. 2016, 4, 231–242.
20. Emadian, S.M.; Onat, T.T.; Demirel, B. Biodegradation of bioplastics in natural environments. Waste Manag. 2017, 59, 526–536.
21. Harrison, J.P.; Boardman, C.; O'Callaghan, K.; Delort, A.M.; Song, J. Biodegradability standards for carrier bags and plastic films in aquatic environments: A critical review. R. Soc. Open Sci. 2018, 5, 171792.
22. Albertsson, A.C.; Karlsson, S. The Influence of biotic and abiotic environments on the degradation of polyethylene. Prog. Polym. Sci. 1990, 15, 177–192.
23. Pirt, S.J. Microbial degradation of synthetic polymers. J. Chem. Technol. Biotechnol. 1980, 30, 176–179.
24. Otake, Y.; Kobayashi, T.; Asabe, H.; Murakami, N. Biodegradation of low density polyethylene, polystyrene, polyvinyl chloride, and urea formaldehyde resin buried under soil for over 32 years. Appl. Polym. Sci. 1995, 56, 1789–1796.
25. Chiellini, E.; Cortia, A.; Swift, G. Biodegradation of thermally-oxidized, fragmented low-density polyethylenes. Polym. Degrad. Stab. 2003, 81, 341–351.
26. Yashchuk, O.; Portillo, F.S.; Hermida, E.B. Degradation of polyethylene film samples containing oxodegradable additives. Procedia Mater. Sci. 2012, 1, 439–445.
27. Chiellini, E.; Corti, A.; D'Antone, S. Oxo-biodegradable full carbon backbone polymers biodegradation behaviour of thermally oxidized polyethylene in an aqueous medium. Polym. Degrad. Stab. 2007, 92, 1378–1383.
28. Veethahavya, K.S.; Rajath, B.S.; Noobia, S.; Kumar, M.B. Biodegradation of low density polyethylene in aqueous media. Procedia Environ. Sci. 2016, 35, 709–713.
29. Nowak, B.; Pajak, J.; Drozd-Bratkowicz, M.; Rymarz, G. Microorganisms participating in the biodegradation of modified polyethylene films in different soils under laboratory conditions. Int. Biodeterior. Biodegrad. 2011, 65, 757–767.
30. Kathiresan, K. Polythene and plastics-degrading microbes from the mangrove soil. Rev. Biol. Trop. 2003, 51, 629–633.

31. Abrusci, C.; Pablos, J.L.; Corrales, T.; López-Marín, J.; Marín, I.; Catalina, F. Biodegradation of photo-degraded mulching films based on polyethylenes and stearates of calcium and iron as pro-oxidant additives. Int. Biodeterior. Biodegrad. 2011, 65, 451–459.

32. Divyalakshmi, S.; Subhashini, A. Screening and isolation of polyethylene degrading bacteria from various soil environments. IOSR J. Environ. Sci. Toxicol. Food Technol. 2016, 10, 1–7.

33. Hassan, F.; Shah, A.A.; Hameed, A.; Ahmed, S. Synergistic effect of photo and chemical treatment on the rate of biodegradation of low density polyethylene by Fusarium sp. AF4. J. Appl. Polym. Sci. 2007, 105, 1466–1470.

34. Usha, R.; Sangeetha, T.; Palaniswamy, M. Screening of polyethylene degrading microorganisms from garbage soil. Libyan Agric. Res. Cent. J. Intern. 2011, 2, 200–204.

35. Koutny, M.; Amato, P.; Muchova, M.; Ruzicka, J.; Delort, A.M. Soil bacterial strains able to grow on the surface of oxidized polyethylene film containing prooxidant additives. Int. Biodeterior. Biodegrad. 2009, 63, 354–357.

36. Gilan, I.; Hadar, Y.; Sivan, A. Colonization, biofilm formation and biodegradation of polyethylene by a strain of Rhodococcus ruber. Appl. Microbiol. Biotechnol. 2004, 65, 97–104.

37. Montazer, Z.; Habibi-Najafi, M.B.; Mohebbi, M.; Oromiehei, A. Microbial degradation of UV-pretreated low-density polyethylene films by novel polyethylene-degrading bacteria isolated from plastic-dump soil. J. Polym. Environ. 2018, 26, 3613–3625.

38. Bhatia, M.; Girdhar, A.; Tiwari, A.; Nayarisseri, A. Implications of a novel Pseudomonas species on low density polyethylene biodegradation: An in vitro to in silico approach. SpringerPlus 2014, 3, 497.

39. Das, M.P.; Kumar, S. An approach to low-density polyethylene biodegradation by Bacillus amyloliquefaciens. 3 Biotech 2015, 5, 81–86.

40. Mehmood, C.T.; Qazi, I.A.; Hashmi, I.; Bhargava, S.; Deepa, S. Biodegradation of low density polyethylene (LDPE) modified with dye sensitized titania and starch blend using Stenotrophomonas pavanii. Int. Biodeterior. Biodegrad. 2016, 113, 276–286.

41. Nanda, S.; Sahu, S.S. Biodegradability of polyethylene by Brevibacillus, Pseudomonas, and Rhodococcus spp. N. Y. Sci. J. 2010, 3, 95–98.

42. Pramila, R.; Ramesh, K.V. Potential biodegradation of low-density polyethylene (LDPE) by Acinetobacter bumannii. Afr. J. Bacteriol. Res. 2015, 7, 24–28.

43. Sudhakar, M.; Doble, M.; Sriyutha Murthy, P.; Venkatesan, R. Marine microbe-mediated biodegradation of low- and high-density polyethylenes. Int. Biodeterior. Biodegrad. 2008, 61, 203–213.

44. Jeon, H.J.; Kim, M.N. Degradation of linear low density polyethylene (LLDPE) exposed to UV-irradiation. Eur. Polym. J. 2014, 52, 146–153.

45. Jeon, H.J.; Kim, M.N. Functional analysis of alkane hydroxylase system derived from Pseudomonas aeruginosa E7 for low molecular weight polyethylene biodegradation. Int. Biodeterior. Biodegrad. 2015, 103, 141–146.

46. Yoon, M.G.; Jeon, J.H.; Kim, M.N. Biodegradation of polyethylene by a soil bacterium and AlkB cloned recombinant cell. J. Bioremed. Biodegrad. 2012, 3, 145.

47. Yang, J.; Yang, Y.; Wu, W.M.; Zhao, J.; Jiang, L. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ. Sci. Technol. 2014, 48, 13776–13784.

48. Thakur, P. Screening of Plastic Degrading Bacteria from Dumped Soil Area. Ph.D. Thesis, National Institue of Technology of Rourkela, Odisha, India, 2012.

49. Das, M.P.; Kumar, S. Influence of cell surface hydrophobicity in colonization and biofilm formation on LDPE biodegradation. Int. J. Pharm. Pharm. Sci. 2013, 4, 690–694.

50. Vimala, P.P.; Mathew, L. Biodegradation of polyethylene using Bacillus subtilis. Procedia Technol. 2016, 24, 232–239.

51. Hadad, D.; Geresh, S.; Sivan, A. Biodegradation of polyethylene by the thermophilic bacterium Brevibacillus borstelensis. J. Appl. Microbiol. 2005, 98, 1093–1100.

52. Rajandas, H.; Parimannan, S.; Sathasivam, K.; Ravichandran, M.; Yin, L.S. A novel FTIR-ATR spectroscopy based technique for the estimation of low-density polyethylene biodegradation. Polym. Test. 2012, 3, 1094–1099.

53. Kyaw, B.M.; Champakalakshmi, R.; Sakharkar, M.K.; Lim, C.S.; Sakharkar, K.R. Biodegradation of low-density polythene (LDPE) by Pseudomonas species. Indian J. Microbiol. 2012, 52, 411–419.

54. Sivan, A.; Santo, M.; Pavlov, V. Biofilm development of the polyethylene-degrading bacterium Rhodococcus ruber. Appl. Microbiol. Biotechnol. 2006, 72, 346–352.

55. Santo, M.; Weitsman, R.; Sivan, A. The role of the copper-binding enzyme, laccase, in the biodegradation of polyethylene by the actinomycete Rhodococcus ruber. Int. Biodeterior. Biodegrad. 2013, 84, 204–210.

56. Bonhomme, S.; Cuer, A.; Delort, A.M.; Lemaire, J.; Sancelme, M.; Scott, C. Environmental biodegradation of polyethylene. Polym. Degrad. Stab. 2003, 81, 441–452.

57. Fontanella, S.; Bonhomme, S.; Koutny, M.; Husarova, L.; Brusso, J.M.; Courdavault, J.P.; Pitteri, S.; Pichon, S.G.; Emaire, G.J.; Delort, A.M. Comparison of the biodegradability of various polyethylene films containing pro-oxidant additives. Polym. Degrad. Stab. 2010, 95, 1011–1021.

58. El-Shafei, H.; EI-Nasser, N.H.A.; Kansoh, A.L.; Ali, A.M. Biodegradation of disposable polyethylene by fungi Streptomyces species. Polym. Degrad. Stab. 1998, 62, 361–365.

59. Ranjan, V.P.; Goel, S. Degradation of Low-density polyethylene film exposed to UV radiation in four environments. J. Hazard. Toxic Radioact. Waste 2019, 23, 04019015.

60. Celina, M.; Linde, E.; Brunson, D.; Quintana, A.; Giron, N. Overview of accelerated aging and polymer degradation kinetics for combined radiation-thermal environments. Polym. Degrad. Stab. 2019, 166, 353–378.

61. Kelkar, V.P.; Rolsky, C.B.; Pant, A.; Green, M.D.; Tongay, S.; Halden, R.U. Chemical and physical changes of microplastics during sterilization by chlorination. Water Res. 2019, 163, 114871.

62. Albertsson, A.C.; Anderson, S.O.; Karlsson, S. Mechanism of biodegradation of polyethylene. Polym. Degrad. Stab. 1987, 18, 73–87.

63. Abrusci, C.; Pablos, J.L.; Marín, I.; Espí, E.; Corrales, T.; Catalina, F. Comparative effect of metal stearates as pro-oxidant additives on bacterial biodegradation of thermal- and photo-degraded low density polyethylene mulching films. Int. Biodeterior. Biodegrad. 2013, 83, 25–32.

64. Reddy, M.M.; Deighton, M.; Gupta, R.K.; Bhattacharya, S.N.; Parthasarathy, R. Biodegradation of montmorillonite filled oxo-biodegradable polyethylene. J. Appl. Polym. Sci. 2009, 113, 826–832.

65. Yamada-Onodera, K.; Mukumoto, H.; Katsuyama, Y.; Saiganji, A.; Tani, Y. Degradation of polyethylene by a fungus, Penicillium simplicissimum YK. Polym. Degrad. Stab. 2001, 72, 323–327.

66. Montazer, Z.; Habibi-Najafi, M.B.; Levin, D.B. Microbial degradation of low-density polyethylene and synthesis of polyhydroxyalkanoate polymers. Can. J. Microbiol. 2019, 65, 1–11.

67. Haines, J.R. Microbial degradation of high-molecular-weight alkanes. Appl. Microbiol. 1975, 28, 1084–1085.

68. Álvarez, H.M. Relationship between β-oxidation pathway and the hydrocarbon-degrading profile in actinomycetes bacteria. Int. Biodeterior. Biodegrad. 2003, 52, 35–42.

69. Eubeler, J.P.; Bernhard, M.; Knepper, T.P. Environmental biodegradation of synthetic polymers: Biodegradation of different polymer groups. Trends Analyt. Chem. 2010, 29, 84–100.

70. Gewert, B.; Plassmann, M.M.; MacLeod, M. Pathways for degradation of plastic polymers floating in the marine environment. Environ. Sci. Process. Impacts 2015, 17, 1513–1521.

71. Jeon, H.J.; Kim, M.N. Comparison of the functional characterization between alkane monooxygenases for low-molecular-weight polyethylene biodegradation. Int. Biodeterior. Biodegrad. 2016, 114, 202–208.

72. Takei, D.; Washio, K.; Morikawa, M. Identification of alkane hydroxylase genes in Rhodococcus sp. strain TMP2 that degrades a branched alkane. Biotechnol. Lett. 2008, 30, 1447–1452.

73. Rojo, F. Degradation of alkanes by bacteria. Environ. Microbiol. 2009, 11, 2477–2490.