Chapter 12

Plastic Degradation and its Environmental Implications

Manviri Rani¹, Uma Shanker^{*2}

¹Department of Chemistry, Malaviya National Institute of Technology JLN Marg, Rajasthan-India

²Department of Chemistry, Dr B R Ambedkar National Institute of Technology Jalandhar, Punjab-India

manviri.chy@mnit.ac.in; shankeru@nitj.ac.in

Abstract

Extensive use of non-biodegradable plastic by anthropogenic activities is posing a severe threat to the global environment in the form of massive waste disposal and problems of closed-landfill sites and rising water and land pollution. Organisms are facing challenge to their lives once they consume plastic in the form of food. In addition, the plastic debris may have additive chemicals having possibility to leach out. Therefore, proper degradation of plastic to lessen negative environmental implications is necessary. Earlier the people were ignorant about this problem however, now-a-days, people are serious about its negative impact. Hence, biodegradable plastics are coming into the trend in the market. Interaction of plastic (adsorbing characteristics) with the environment results in new functional groups on its surface in a dynamic situation. In these circumstances, oxygenated, thermal, bio-based, and photocatalytic degradation of plastics is in high demand. Usually, different-rates along with diverse-pathways have been found in variable polymers like polyethylene, polypropylene, and polyethylene terephthalate. Polyethylene photo-degradation resulted in sharp infrared-peaks of ketones, esters, and acids due to oxidation reaction. Hydrogen peroxide is generated by oxidative action on methylene groups in the backbone of polyethylene terephthalate. The present chapter will provide compiled information about various polymers used in plastic as well as environmental concerns of plastic, finally the chapter concludes with comprehensive details about the degradation of various types of plastics. State-of-the-art on degradable plastics market with an emphasis on principle design for recyclable plastics and biodegradable plastics from renewable raw materials are also included. Factors affecting

plastic degradation and metabolic pathways including past and present scenarios have also been discussed in this chapter.

Keywords

Plastic Pollution, Polymer Degradation, Environment Conditions, Biodegradation

Contents

Plastic Degradation and its Environmental Implications	290
1. Introduction.....	291
1.1 Commodity polymers	295
2. Environmental degradation of polymers.....	295
3. Methods for plastic degradation	296
3.1 Biodegradation.....	298
3.2 Polyolefins	299
3.3 Degradation of polyethylene	299
3.4 Biodegradation of polyethylene.....	301
3.5 Degradation of polypropylene.....	304
4. Polyethylene terephthalate.....	306
4.1 Photo-thermal degradation of polyethylene terephthalate.....	307
4.2 Environmental concern of plastic	308
4.3 Biodegradable plastics.....	309
Conclusions	311
Acknowledgements.....	312
References	312

1. Introduction

Since their start in the 1950s, plastics with massive production as well as several applications is transforming human life for convenience and therefore, became an essential part of contemporary culture [1]. Life without it seems almost impossible credited to its versatile nature, molecular structure and additives. The global annual production of synthetic polymers is approaching to 140 metric tons [2]. However, the percentage of recycled or reused plastic is much less, only about 10%. The main reason

for such a low percentage is extremely limited disposal options and almost no attention towards solid waste management. Among commodity plastics, polyethylene (PE) with several forms like high density (HDPE), low density (LDPE) and linear low density (LLDPE) are mostly used. Polypropylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polycarbonate (PC), polyethylene terephthalate (PET), and poly(methyl methacrylate) (PMMA) are also in widespread use. These plastic polymers actually contribute nearly 98% share of consumed/produced products worldwide. The plastic consumption demand in Europe followed the order: PE (13,000 kiloton)> PP (8,000 kiloton)>PVC (5000kiloton) and for PET (3,000 kiloton) [3].

The high production along with large consumption of plastic is creating a lot of burden on the environment moreover, due to limited treatment and poor disposal methods also resulting plastic waste. In developing countries with inadequate engineered/planned landfill disposal sites, people used to burn these plastic wastes that leads to evolution of poisonous and destructive gases into the atmosphere. Improper disposal methods such as open-dumping, unrestrained incineration and intuitive composting as well as inappropriate landfill are frequently used in developing countries like India [4]. This practice has further caused concern and called attention for biodegradation of highly stable polyethylene and polystyrene polymers by advanced methods. Furthermore, due to the inert and non-biodegradable nature of plastic, its treatment and disposal is the main problem in urban solid waste management [5]. Plastic polymers release various contaminants and toxic additives once left unprotected in environmental-circumstances [6,7]. It has been reported that due to this 50–80% of debris causes distress in the oceanic environment around the globe [8]. Environment and biodiversity are being significantly affected by widespread and unrestrained usage and dumping of such harmful materials [9-11]. Plastics are obstinate in the environment and adsorb contaminants [12-14]. It has been found that microplastics sorb pollutants at a faster rate from environmental matrices (water, air, and soil) [15]. Ioakeimidis and co-workers [16] observed that plastics, with a percentage of 95%, are the major waste at the bottom of the oceans among the total oceanic litter matters. Additionally, plastic debris in the ocean comprises fairly high-levels of organic contaminants e.g., polystyrene having a large number of hexabromocyclododecanes, a flame retardant, and bisphenol A in polycarbonate plastics [17-21].

Polymer degradation is a change in the properties like tensile strength, color and shape of a polymer or polymer-based product under the influence of one or more environmental factors. These factors are heat, light or chemicals such as acids, alkalis and some salts. Such changes are usually undesirable like cracking and chemical disintegration of products or, more rarely, desirable as in biodegradation or deliberately lowering the

molecular weight of a polymer for recycling. Degradation of plastic by any methods can be useful in the implication of environment and recycling of plastic waste can be beneficial for further reducing pollution. Chemical structures of various types of plastics are presented in Fig. 1 and 2. Further details about the uses of synthetic and biodegradable plastics are given in Tables 1 and 2).

Table 1 Various types of synthetic plastics and their uses.

Plastic	Use
Polyethylene	Plastic bags, milk and water bottles, food packaging film, toys, irrigation, and drainage pipes, motor oil bottles
Polystyrene	Disposable cups, packaging materials, laboratory ware, certain electronic uses
Polyurethane	Tires, gaskets, bumpers, in refrigerator insulation, sponges, furniture cushioning, and life jackets
Polyvinyl chloride	Automobile seat covers, shower curtains, raincoats, bottles, visors, shoe soles, garden hoses, and electricity pipes
Polypropylene	Bottle caps, drinking straws, medicine bottles, car seats, car batteries, bumpers, disposable syringes, carpet backings
Polyethylene terephthalate (PET)	Carbonated soft drink bottles, processed meat packages peanut butter jars
Nylon	pillow and sleeping bag filling, textile fibers
	Polyamides or Nylon are used in small bearings, speedometer gears, windshield wipers, water hose nozzle, football helmets, racehorse shoes, inks, clothing
	parachute fabrics, rainwear, and cellophane
Polycarbonate	Nozzles on paper making machinery, street lighting, safety visors, rear lights of cars, baby bottles and for houseware. Skylights and the roofs of greenhouses, sunrooms and verandahs. Lens in glasses
Polytetrafluoroethylene (PTFE)	PTFE is used in various industrial applications such specialized chemical plant, electronics and bearings. It is met with in the home as a coating on non-stick kitchen utensils, such as saucepans and frying pans

Table 2 Various types of biodegradable plastics and their uses.

Plastics	Uses
Polyglycolic acid (PGA)	Specialized applications; controlled drug releases; implantable composites; bone fixation parts
Poly lactic acid (PLA)	Packaging and paper coatings; other possible markets include sustained release systems for pesticides and fertilizers, mulch films, and compost bags
Polycaprolactone (PCL)	Long-term items; mulch and other agricultural films; fibers containing herbicides to control aquatic weeds; seedling containers; slow-release systems for drugs
Polyhydroxybutyrate (PHB)	Products like bottles, bags, wrapping film, and disposable nappies, as a material for tissue engineering scaffolds and controlled drug release carriers
Polyhydroxyvalerate (PHBV)	Films and paper coatings; other possible markets include biomedical applications, therapeutic delivery of worm medicine for cattle, and sustained release systems for pharmaceutical drugs and insecticides
Polyvinyl alcohol (PVOH)	Packaging and bagging applications that dissolve in water to release Products such as laundry detergent, pesticides, and hospital washables
Polyvinyl acetate (PVAc)	Adhesives, the packaging applications include boxboard manufacture, paper bags, paper lamination, tube winding and remoistenable labels

Fig. 1 Structures of conventional plastics polyethylene.

Fig. 2 Chemical structure of poly(lactide)(PLA), poly(3-hydroxybutyrate)(PHB), poly(propiolactone)(PPL), poly(ε-caprolactone)(PCL), poly(ethylene succinate) (PES), poly(butylenes succinate)(PBS), poly(3-hydroxybutyrate-co-3-hydroxyvalerate)(PHBV) and poly(ester carbonate)(PEC).

1.1 Commodity polymers

Now a days, polyethylene, polypropylene, polyvinylchloride, polyethylene terephthalate, polystyrene, polycarbonate and poly (methyl)methacrylate represents the seven commodity polymers that are highly used. Such macromolecules have their styles of degradation pathway along with light, chemicals, and temperature-resistant. Some polymers like polyethylene, polypropylene and poly (methyl)methacrylate are highly sensitive to oxidation under UV radiation whereas polyvinylchloride changes its color at high temperature and becomes brittle due to loss of hydrogen chloride gas. Polyethylene terephthalate is affected by the action of water and strong acids, while strong alkalis depolymerize polycarbonates. Polyethylene typically degrades via unsystematic scission. On heating to a temperature above 450 °C, polyethylene is converted into a mixture of molecules similar to gasoline. Poly- α -methylstyrene showed breakage of the polymeric chain, which finally depolymerize into different essential monomers. Fig. 3 represents the worldwide production of various types of polyethylene.

2. Environmental degradation of polymers

On worldwide scale, limited reports are available on the assessment of degradation of polymers under environmental conditions. Scanning electron microscopic analysis of plastic samples collected from beaches (beached plastic pellets) revealed that relative inertness is generally emphasized but also some degradation and oxidative aging is evident in the plastic pellets. This finally led to complete disintegration of the plastic pellets and dispersal as dust. Further, it was also recommended partial degradation of floating plastic granules while complete degradation of stranded pellet granules of plastic occurs due to exposure of UV radiation [22].

Fig. 3 Production of various types of polyethylene worldwide.

Orhan and Buyukgungor [23] evaluated degradation of low-density polyethylene (that has been blended with starch) baggage in soil and reported that the presence of starch does not affect the degradation of plastic bags even after 90 days. Slight degradation was observed if the soil was injected with fungi. On soil burial for 5 months, such plastic polymers were converted into microplastics. Among the inspected polymeric films, polyethylene blended with starch lost most of the susceptibility followed by low-density polyethylene. Endo et al. [24] studying the sorption properties of plastic pellets suggested that the degree of discoloring can be an index of the residence time of the pellets in the seawater. One of the additives phenolic antioxidants is found responsible for discoloration. These phenolic antioxidants quench free radicals generated by exposure to UV light, high-temperature polymerization, nitrogen oxides in the air, and preventing the polymer from oxidation. Phenolic antioxidant degrades under vigorous conditions into byproducts with quinonoidal structures that impart yellow color. This study has significance while studying the photo-oxidation of polyethylene under UV-light exposure.

Weathering of plastic films of low and linear low-density polyethylene under natural scenario has been investigated by Basfar and Idriss Ali in 2006 [25]. The results showed that added UV-stabilizers and light absorbers protects the plastic films from degradation under UV-exposure. This was evident from analysis of tensile-strength of polymer in amount of 50% within thirty to five hundred ninety days.

Several forms of polyethylene (linear low and high density polyethylene) and polypropylene polymers films with varying film thickness (15 to 80 μm) were degraded under solar light [26]. A significant reduction in molecular weight and almost zero mechanical properties of the polymers was observed in a year. Weathering of plastic was also identified by the increased number of carbonyl groups especially in polypropylene that was having a rapid rate of oxidation than that of polyethylene. Overall, from the above discussion it was concluded that the degradation of plastics is very subjective to the local environmental conditions that are usually a combination of those simulated in laboratory conditions.

3. Methods for plastic degradation

Any change in the physical or chemical properties due to a change in structure is called degradation and it may be chemical, physicochemical, or biological processes. The polymer degradation mechanisms are mainly due to hydrolysis and oxidation [27]. Photo-degradation is the procedure of decay of the material under sunlight considered as one of the primary sources of damage exerted upon polymeric substrates at ambient conditions. The mechanism of plastic biodegradation under aerobic conditions has been presented as

Fig. 4. Usually, synthetic polymers are vulnerable to degradation started by ultraviolet (UV) and visible light. Generally, wavelength range 400–290 nm of near-UV radiations in the sunlight governs the lifespan of polymers in outdoor uses. The near-UV (400–290 nm) radiations have energies from 3.1 to 4.3 eV that corresponds to 72–97 kcal/mol. required for breaking the chemical bonds in polymers [28]. Generally, pathways induced by photo and thermal degradation are analogous [29]. Most of the polymers degraded under sunlight or UV irradiation yielded lower molecular weight fragments. Chain-growth polymers such as poly(methyl) methacrylate could be degraded at high temperatures $\sim 500\text{ }^{\circ}\text{C}$ under reduced pressure ~ 200 bars to yield precursors, like oils, gases, and water. The degradation takes place by hydrogenation and gasification process. Solvolysis was found efficient method for the degradation of step-growth polymers like polyesters, polyamides and polycarbonates to yield lower molecular weight fragments. The hydrolysis was prompted by water comprising an acid or an alkali as catalyst. Polyamides were found sensitive towards the acids. Table 3 summarized the different types of modes by which plastics usually undergo for degradations.

Fig. 4 General mechanism of plastic biodegradation under aerobic conditions.

Table 3 Various polymer degradation routes.

Factors (requirement/ activity)	Photo-degradation	Thermo-oxidative degradation	Biodegradation
Active agent	UV-light or high-energy radiation	Heat and oxygen	Microbial agents
Requirement of heat	Not required	Higher than ambient temperature required	Not required
Rate of degradation	Initiation is slow. But propagation is fast	Fast	Moderate
Other consideration	Environment friendly if high-energy radiation is not used	Environmentally not acceptable	Environment friendly
Overall Acceptance	Acceptable but costly	Not acceptable	Cheap and very much acceptable

(<http://www.envis-icpe.com>, Plastics recycling-Economic and Ecological

3.1 Biodegradation

Biodegradation is governed by various parameters like nature of pretreatment, polymer features, type of organisms, functional groups, mobility, tacticity, crystallinity, molecular weight, and substituents present in the polymer structure. Addition of plasticizers or additives also plays a significant role during degradation of plastics [30]. Physical and biological forces result in the initial degradation of a polymer [31]. There are various steps of biodegradation, which could be recognized by precise terminology [32]. Deterioration is an apparent degradation that adjusts the mechanical, physical, and chemical properties of a given polymers [33]. Depolymerization that identified by the breakage of polymers into oligomers, dimers, or monomers by catalytic-agents secreted by microorganisms is also a key step. The next step is the integration, and mineralization is the final step of this process. Integration discusses the addition of molecules transported in the cytoplasm in the microbial metabolism to yield energy, new biomass, storage vesicles, and numerous fragments. Mineralization means the secretion of simple and dissimilar salts and complex metabolites which reach the extracellular surroundings. Biodegradable plastics were initially industrialized to resolve precise waste issues of agricultural films or to the assemblage and parting of food waste. Biodegradation constantly follows photo-degradation and chemical degradation [34].

3.2 Polyolefins

These are polymers of simple olefins such as ethylene, propylene, and butenes constituting thermoplastic materials. Polyolefins consist of carbon and hydrogen atoms and they are nonaromatic. The most common polyolefins are polyethylene and polypropylene. The impurities like carbonyls and hydroperoxide groups generated during synthesis are mainly responsible for the photo-degradation of polyolefins [35]. The photodegradation is also dependent on the nature of absorbing impurities and wavelength. The oxidation vulnerability of polyolefins is as follows: (isostatic) polypropylene>low density polyethylene>linear low density polyethylene>high density polyethylene [36,37].

It has been concluded that there is a synergetic interaction between photo-oxidation and biodegradation during the degradation of polyolefins. Photo-oxidation of the polyolefins alters surface area, reduces molecular weight, challenges tensile strength, which helps the bio-degradation [38].

3.3 Degradation of polyethylene

Polyethylene is a thermoplastic polymer consisting of long hydrocarbon chains used in a number of applications including flexible film packaging produced by the blown film process. Substantial dissimilarities in physical properties have been witnessed in linear low-density polyethylene, low-density polyethylene, and high-density polyethylene blown films. The properties of polyethylene's are govern by structural parameters like density/ crystallinity, molecular weight, and its distribution, short-chain branching (SCB)/ long chain branching (LCB) length and amount, and crystalline morphology [39]. The intrinsic factors influencing polymer degradation are the number of branching of the polymer, the molecular weight, the hydrophobicity/hydrophilicity ratio, the crystallinity, and the morphology of the polymer [40]. Numerous reports of degradation of PE and the alteration of plastic surfaces in the laboratory or under controlled conditions in the field [41-47].

The pathway of photo-degradation polyethylene is well understood and can be summarized in Fig. 5 [48]. Light absorption by chromophoric defects consequences in the creation of radicals, that react by different pathways like removal of a hydrogen atom from the polymer chain, adding to an unsaturated group, or joining to oxygen [49]. Primary photoproducts are formed as hydroperoxides. As soon as they are generated, decomposes by the breaking of the weak O–O bond, yields a macro-alkoxy and a hydroxyl radical HO. The alkoxy macroradical can react by numerous pathways like scission with cleavage of the main chain to form aldehydes, abstraction of hydrogen without cleavage of the chain to form hydroxyls, cage reaction between the pair of the

radicals formed, i.e., macro-alkoxy radical and hydroxyl radical HO. Ketones reacts photochemically as per Norrish type I or type II reactions [50].

In photo-degradable plastics, the materials are built with a combination of light-sensitive additives or copolymers which weaken the bonds of the macromolecule under ultraviolet radiation. Such plastics are designed to become weak and brittle once exposed to sunlight for a long time. Photosensitizers used include diketones, ferrocene derivatives (aminoalkylferrocene), and carbonyl-containing species. Photodegradable plastics degrade in a two-stage process, with UV light firstly broking few bonds making it more brittle lower molecular weight compounds which further degrade from physical strains [51]. It appears that degradation does expedite the development of microplastics that originally the same polymer but with some of their degraded sides. The most harmful UV wavelength for a specific plastic is subject to which type of bonds present, and the maximum degradation therefore occurs at different wavelengths for various types of plastics, e.g., it is around 300 nm for polyethylene [52].

In most of the studies, photo-degradation results in sharper peaks in the bands which represent ketones, esters, acids, etc. on infrared spectrum. Table 4 [30,31,35, 39-44]., shows the main changes in the surface functional groups of polyethylene under different photo-degradation conditions as were observed using infrared spectrometer.

Fig. 5 Photo-degradation of polyethylene.

Table 4 Main changes in the surface functional groups on PE surface after exposure to different conditions [30,31,35, 39-44].

Type of PE	Wavenumber (cm ⁻¹)	Functional Group	Degradation mode	Reference
HDPE, LDPE, and LLDPE	1733–1743	Aldehydes or ester	UV-Xenon lamb	[31]
LLDPE		Carbonyl Band	Xenon lamb	[40]
HDPE		Ester	Electron beam and gamma	[30]
HDPE		Ketones and acid	Natural	[41]
LDPE and LLDPE		Aldehydes	Accelerated environmental conditions	[39]
PE with vinyl and t-vinylene groups		Esters and Lactones	Photo-oxidation thermo-oxidation	[35]
Environmentally beached PE pellets	1712–1723	Esters	Environment	[42]
HDPE, LDPE, and LLDPE		Ketones	UV-Xenon lamb	[31]
LLDPE		Acid	Xenon lamb	[40]
HDPE		Ketones	Electron beam and gamma	[30]
HDPE		Ketones and Acid	Natural	[41]
HDPE		Carbonyl	Natural	[43]
LDPE and LLDPE		Ketones	Accelerated environmental conditions	[39]
HDPE		Carbonyl	Natural	[44]
PE with vinyl and t-vinylene groups		Ketones and acid	Photo-oxidation thermo-oxidation	[35]
Environmentally beached PE pellets		Ketones	Environment	[42]

3.4 Biodegradation of polyethylene

Plastic-debris makes available a substrate for aquatic life that has a longer life than natural floating substrates and has been implicated as a vector for transportation of harmful algal species. Such biofilm development changes with the season, substrate, and location [53]. The high hydrophobic level and high molecular weight of polyethylene make it non-biodegradable [54]. Modification in crystalline level, molecular weight, and mechanical properties of polyethylene is needed for its biodegradation [55]. The same can be attained by enhancing the hydrophilic level of PE by shortening polymer chain

length via oxidation [56]. Hydro-biodegradation and oxo-biodegradation are the two main mechanisms for the biodegradation of polyethylene [57].

During the last few decades, numerous reports showing that various strains interact with different kinds of polyethylene initiating some kind of degradation. Microbes are capable to colonize the surfaces of polyethylene have diverse effects on its properties. Seven different features were typically examined for alteration to create the degree of biodegradation of the polymer: functional groups on the surface, hydrophobicity/hydrophilicity, crystallinity, surface topography, mechanical properties, molecular weight distribution, and mass balance [58].

Table 5 [25-28,49,51,52] shows the changes in the characteristics of different types of polyethylene. Generally, it is accepted that in the presence of microorganisms, the concentration of the surface functional groups will decrease, which is normally reported as a decrease in the carbonyl groups. Such a phenomenon occurs because microorganisms are normally attached to the carbonyl groups [59-62].

Table 5 Changes found in the literature for polyethylene after exposure to different biodegradation conditions [25-28, 49,51,52].

Type of Polyethylene	Environment	Parameter	Changes	Reference
Low density polyethylene after UV irradiation	LDPE mixed with natural soils for 10 years	Infrared spectrometer	UV irradiation increased carbonyl index, peak at 905–915 cm ⁻¹ due to biodegradation	[25]
Polyethylene with Totally Degradable Plastic Additive	Rhodococcus rhodochrous, Cladosporium cladosporioides, and Nocardia asteroides	Scanning electron microscopy Infrared spectrometer Molecular Weight	Surface physically weak, readily disintegrated under mild pressure Band at 1,088 cm ⁻¹ due to polysaccharides Increased carbonyl index, decreased molecular weight Reduction in molecular weight	[49]
Low density polyethylene with 60 marine Bacteria from Arabian sea	Monitor environment	Infrared spectrometer Crystallinity	Peak at 905–915 cm ⁻¹ Reduction in crystallinity	
Low density polyethylene mixed with different natural soils	Monitor environment	Infrared spectrometer Weight loss Tensile strength Elongation brake	Peaks at 1,448–1,470, 2,800–300 cm ⁻¹ Weight loss due to Biodegradation Tensile strength decreased elongation brake decreased	[25]
Low density polyethylene with	P. chrysosporium in soils with LDPE with	Infrared spectrometer	1,650–1,860 carbonyl Compounds; 900–1,200 peaks due to biodegradation	[26]

12% starch Low density polyethylene	12% starch Pseudomonas sp. AKS2	Atomic force microscopy Weight loss Tensile strength	Rough surface with cracks and grooves; Time dependent weight loss; Reduction in tensile strength	[51]
Polyethylene food plastic bags	Monitor environment (PE in 2 m depth in the sea)	Hydrophobicity	Decreased hydrophobicity	[27]
High density polyethylene and Low density polyethylene	Monitor environment	Hydrophobicity Atomic force microscopy Infrared spectrometer Weight loss	Decreased hydrophobicity Increased surface roughness; Decreased carbonyl; Index Weight loss with higher rates for LDPE	[28]
High density polyethylene, Low density polyethylene, and Linear low density polyethylene	Rhodococcus rhodochrous ATCC 29672 after UV irradiation	Molecular Weight Infrared spectrometer; Scanning electron microscopy	Reduction in molecular Weight Increased at 1,712 for pre-photo-oxidized samples HPDE film behaves differently than the LDPE and LLDPE and was not so favorable for microbial metabolism	[52]

Reports on microorganism attachment to polyethylene have recognized that the key drawback of the colonization process is the comparatively high hydrophobicity of the polymer contrary to the frequently hydrophilic surfaces of microorganisms [63]. It has been recommended that strains with more hydrophobic surfaces may have an important role in the initial colonization of the polymer. Since polyethylene surface is hydrophobic in nature, hence, the more hydrophobic bacterial cell on the surface, the greater will be the interaction with the polyethylene. Other metabolic version which will be key in polymer colonization is the creation of surfactants that can facilitate the attachment process of microorganisms to the hydrophobic surface. Harshvardhan and Jha [64] quantified that marine bacteria (*Kocuria palustris* M16, *Bacillus pumilus* M27, and *Bacillus subtilis* H1584), the microorganisms, usage the polyethylene surface as a carbon source. This is the first step of polyethylene biodegradation and due to which a decline in molecular weight occurs. Once the size of the molecule is contracted, oxidation is essential to convert the hydrocarbon into a carboxylic acid which finally metabolized by means of β -oxidation and the Krebs cycle.

3.5 Degradation of polypropylene

Polypropylene is a thermoplastic material used in numerous applications that includes packaging, labeling, and textiles. In view of high processability and low cost, polypropylene is one of the most widely manufactured polymers, particularly, for the auto industry. Pristine polypropylene is impervious to photo-oxidation and thermal oxidation at modest temperatures. Furthermore, polypropylene is sensitive to several external stimuli like temperature, light, and irradiation. When polypropylene is exposed to high temperatures or to an irradiation environment, the tertiary hydrogen atoms present in its chains are susceptible to be attacked by oxygen [65]. Oxidation of polypropylene depends on both light irradiation and temperature in outdoor aging circumstances. Polypropylene can also be photo-degraded because several molecular chains are affected in the wavelength range from 310 to 350 nm [66]. Polypropylene is resistant to photo-oxidation at low temperatures while sensitive to many external environments like heat, light, and radiation and hence has a comparatively lower service temperature. When polypropylene is irradiated to a high temperature, the tertiary hydrogen atoms present in its chains are susceptible to be attacked by oxygen [67]. The wavelengths of over 290 nm are sufficient to start the degradation and create discoloration, chalking, and embrittlement of polypropylene. Therefore, assessment of the service life of polypropylene in the natural environment is a well-established practice [68]. Under ultraviolet irradiation cause fast degradation of the polypropylene while the weakening of its strength occurs under sunlight. Numerous efforts have been made to examine the outcomes of photo-oxidation of polypropylene to deliver a good estimation of its continuing service performances. Outdoor weathering test and accelerated weathering test are two methods usually employed for this purpose [69]. Table 6 shows the studies for degradation of polypropylene under different accelerated or environmental conditions.

The photo-oxidation of polypropylene as described is presented in Fig. 3 [70-73]. For degradation of polyolefins in environmental implications, there should be either improvisation of hydrophilic characters or plummeting chain length of polymer, more favorable conditions to microbial degradation [74,75].

Oxidative degradation of polypropylene includes chemical methods, thermal procedures and UV exposure that may be responsible to generation of active functional groups ($>\text{C}=\text{O}$, $-\text{COOH}$ and ester) on surface of polymer. Formation of carbonyl, carboxyl, and functional groups decreases the hydrophobicity of the surface and hence favors biodegradation. Limited studies showing biodegradation of polypropylene under various conditions has been summarized (Table 6 [61-67] and 7 [68, 71-74]).

Table 6 Changes found in the literature for PP after exposure to different biodegradation conditions [61-67].

Environment	Parameters	Changes	Reference
Accelerated and outdoor weathering	Infrared spectrometer Molecular weight Scanning electron microscopy	Different carbonyl products formed during degradation Reduction in molecular weight Increasing cracks in the surface with increasing exposure	[62]
Thermal	Infrared spectrometer chemiluminescence spectroscopy	Initial peak wavelength of chemiluminescence emission at 490 nm remained constant during the early stages of thermal degradation. New emissions developed with time in the red spectral region (i.e., 490, 660, and 740 nm) over an extended oxidation period	[63]
Xisha tropical environment	Macroscopic morphology Chromatic aberration Tensile strength Elongation break	Macroscopic cracks observed after 9 months of exposure; Rapidly increasing chromatic aberration, the sample becomes darker with the exposure; Reduction in tensile strength due to oxidation; Dramatic decrease in elongation; break. The toughness of the polymer is more sensitive than the strength	[64]
Electron irradiated aging in autoclave	Weight and geometry Tensile strength Infrared spectrometer	No significant changes in geometry Reduction of tensile strength proportional to temperature; Ether and carbonyl species due to oxidation	[65]
Accelerated photo-thermal aging	Infrared spectrometer Molecular weight	Different carbonyl species, hydroperoxides, and hydroxyl species due to exposure Reduction in crystallinity, for samples containing nanocomposites increasing crystallinity; Reduction in molecular weight	[66]
Outdoor weathering and accelerated conditions	Tensile strength Intrinsic viscosity Infrared spectrometer	Reduction in tensile strength; Reduction in intrinsic viscosity; The carbonyl contents increased with increasing exposure	[61]
Outdoor weathering and accelerated conditions	Tensile strength Infrared spectrometer	Reduction in tensile strength Carbonyl concentration rose with the irradiation time and the increasing rate depends on UV content	[67]

Table 7 Changes found in the literature for PP after exposure to different biodegradation conditions [68, 71-74].

Environment	Parameter	Changes	Reference
polypropylene and thermally treated PP in soil consortia for 12 months	Infrared spectrometer Surface energy; Mechanical properties	Carbonyl index increased due to thermal treatment; Carbonyl index decreased due to biodegradation; Crystallinity increased, tensile strength decreased	[68]
polypropylene and UV irradiated PP in four different soil consortia	Infrared spectrometer Surface energy; Weight loss	Carbonyl index increased due to thermally treatment Carbonyl index decreased due to biodegradation; Decreased hydrophobicity, highest weight loss for UV irradiated samples	[72]
Thermal and photochemical treatment for PP and then mixed with <i>R. rhodochrous</i> ATCC 29672	Infrared spectrometer Molecular weight; Size exclusion chromatography	Increase in carbonyl index due to abiotic treatment. The loss in molecular weights is lower in the case of additive free polypropylene; <i>R. rhodochrous</i> cells were able to use the oxidized polymer films as carbon source	[73]
PP/starched based materials aged in soil	Thermogravimetry analysis	The kinetic parameters dependent on: (a) the influence of the atmosphere in which the experiment was carried out, (b) the composition of the blend, and (c) the process of degradation in soil	[71]
PP photo-degraded and then Biodegraded	Molecular weight 1H NMR	Decreased molecular weight Biodegradation occurred Anaerobically	[74]

4. Polyethylene terephthalate

(PET, aromatic polyesters) is a significant polymer class that has prevalent commercial uses in several fields in form of fibers, films, food packaging, and beverage containers due to brilliant material characteristics. Polyethylene terephthalate has a very high resistance to atmospheric and biological agents and frequently observed as substantial waste items on land and beaches [76]. Therefore, limited studies of degradation or microbial degradation are reported in literature on polyethylene terephthalate [77,78]. It can be synthesized in laboratory by reaction of ethylene glycol with terephthalic acid

(dimethyl terephthalate) followed by 2 or 3-step polymerization, dependent on the desired molecular weight [79,80]. In general, repeated units of PET have a length of about 1.09 nm and a molecular weight of ~200 [81]. Nevertheless, the ester-bond can be simply broken still the presence of an aromatic ring with a short aliphatic chain makes it stiffer in strength if we compare it with other aliphatic polymers (polyolefin and polyamide). Besides, moderately high thermal-stability is credited to the segmental flexibility of polymer chains.

A textile-grade polymer (100 repeating units/ molecule; 100 nm length; molecular weight of ~20,000) needs upper stages of polymerization to yield higher strength fibers. On the other hand, small moisture can affect melt viscosity along with melt-stability and may lead to hydrolytic degradation. The additions of heteroatoms in polymer backbone (e.g., polyesters and polyamines) also improve the susceptibility to microbial or oxidative degradation while inclusion of secondary qualifier in aromatic polymers can make them further tough to degradation [82].

4.1 Photo-thermal degradation of polyethylene terephthalate

On exposure to near-UV-light, polyethylene terephthalate undergoes photo-degradation that involve scission of polymeric chain via Norrish I and II reactions. It may also show further cross-linking if the reaction carried out in presence of linkers and gelling agents. A yellow or brown polyenes are formed when polyethylene terephthalate is thermally degraded that is indicated by discolored final polymer after that increase of more carboxyl terminated-species. Carboxyl groups catalyzed formation of vastly conjugated-species and more discoloration of polymer and hence, quick degradation [81]. Thermo-oxidative stability also decreased in presence of rich carboxyl content [83]. Venkatachalam et al. [81] suggested that the preliminary phase of thermal-degradation is a random scission of the in-chain ester linkage resultant of the generation of a vinyl-ester and carboxyl end groups. Trans-esterification of the vinyl ester yields the vinyl alcohol that converted instantaneously to acetaldehyde. Environmental degradation of polyethylene terephthalate has been scarcely reported till now. During the study of degradation of polyethylene terephthalate through irradiation by MeV He^+ , it was observed that the colorless samples turn brittle and yellow color was witnessed as a function of irradiation [84]. Hydrolytic degradation of polyethylene terephthalate was also reported for its copolymer-containing nitrated units [85,86]. It was observed that the polyethylene terephthalate copolymers having nitrated units degraded with fast rate than semi-crystalline and amorphous PET and the rate of degradation increased with nitrated units. During the study of hydrolytic degradation, significant changes occurred in the $\nu(\text{C-H})$ bond of polyethylene terephthalate. This might be due to influence of

environmental condition on the functional groups, extensive hydrogen-bonding along with aliphatic methyl groups; all factors also responsible for increasing the hydrophilic character as well as degradation of polyethylene terephthalate [85].

4.2 Environmental concern of plastic

There is a continuous enhancement in the production of plastic worldwide as reported in data from 1950 to 2014 (1.7 million tons to 311 million tons) [87]. Plastic has become a widespread and ubiquitous item of marine and land debris credited to extensive production, consumption, and stability [88-90]. Navigational safety and the aesthetic quality of beaches are damaging due to the accumulation of plastic debris and imparting adverse effects on the aquatic system. The estimated financial loss to fisheries, tourism, and time spent cleaning up beaches equal to \$13 billion to saline ecosystems caused by plastic pollution every year [91]. Several aquatic species such as marine mammals, birds, sea turtles, crustaceans, and bivalves (approximately 395 species) have been affected by the ingestion/entanglement of marine plastic debris [92].

Marine plastic debris has been acting as vehicle of noxious plastic additives in the environment is an emerging issue. Plastic contains additives and absorbed chemicals that may have possibility to leach into the surrounding environment [93,94]. To enhance the performance of plastics various additives chemicals are added during synthesis processes include antioxidants, plasticizers, etc. Many of them (phthalates and bisphenol A) contain endocrine disrupting properties that may affect the genetics and development of aquatic species [95]. Hydrophobic pollutants (e.g., polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and plastic additives) have the tendency of accumulation on the surface of the seawater. The magnitude of accumulation of persistent organic pollutants of plastics is six times higher in that of ambient seawater [96]. With the floating of plastics, these chemicals or additives may travel from one place to other or from polluted to out-of-the-way clean areas [97,98]. Marine organisms are exposed for those toxic chemicals when they ingested contaminated plastic debris, [99]. These additive chemicals have the ability of assimilation in the stomachs of seabirds via leaching through ingested plastics. In support of that, several controlled studies have been reporting that highlight the transfer of organic chemicals from microplastics and resulted in worsening of physiological functions and health of the targeted organisms [100-105]. Some contradictory studies indicated the negligible bio-accumulation of perilous chemicals by plastic [106,107]. Therefore, to confirm the actual role of plastic as the carrier of persistent organic pollutants, many field-evidence studies are on-going to understand marine microplastic pollution and its aftereffects. Concentration levels/ abundance and chemical profiles were compared in organisms (fish, whales, and birds) with that of

microplastics in nearby waters (or gut matters) [108-111]. In spite of this, limited information is available on statements that may say that plastic marine-debris is a vector to transfer dangerous compounds into marine organisms. Therefore, there is much need for plenty of data on this issue to further prove the field evidence.

4.3 Biodegradable plastics

During the biodegradation of recyclable plastics under aerobic conditions, microbes gained carbon and energy. Mechanism occurred during this process can be shown below:

Microorganisms integrated the carbon of the polymer (C_{polymer}) into biomass (C_{biomass}) followed by fast mineralization into CO_2 and H_2O . This biomass can also be used for development and reproduction (more C_{biomass}) which is further mineralized in the long-term because of the succeeding attack of the soil microbial community. Hence, it was observed for the bi-phasic pattern that includes rapid-phase for CO_2 production after that a slower secondary-phase for CO_2 evolution; seen by finally conversion into mineralization of organic-matter [112-114]. The reaction may be expressed as

Overall, there are two reactions with different kinetics 1) conversion of C_{polymer} into C_{biomass} and 2) conversion of obtained C_{biomass} into CO_2 . First one reaction is biodegradation that is indicated by either intake of the reagents or the appearance of the yields and the other one belongs to mineralization. Biodegradation could be monitored and quantified by measuring reagent of reactions (O_2) or the end-product (CO_2) of energy-metabolism. Biodegradation percentage can be defined as ratio of evolved CO_2 over theoretical CO_2 ($ThCO_2$) i.e. the quantities of CO_2 predictable for total-oxidation of the carbon existent in the plastic sample (C_{polymer}) acquaint within the reactor.

$$\text{Biodegradation \%} = \frac{C_{\text{evolved as } CO_2}}{\text{Available } C_{\text{polymer}}} \times 100 \quad (3)$$

Instead, oxygen intake can be measured with a similar method using the theoretic oxygen demand to designate the maximum-oxygen-uptake for the entire oxidation of the plastics.

Measurement of biomass accurately by a consistent method is still not offered. Accordingly, the assessment of biodegradation has been achieved by mineralization as presented in [Eq. (3)]. As per guidelines, the “ready biodegradable” compounds have to reach 60% (of the ThCO_2) in a 10-day window within a 28-day period of the test. The 10-day window begins when the degree of biodegradation has reached 10% and must end before day 28 of the test. This pass level is deliberated to demonstrate practically the complete degradation of the test samples, as the remaining portion of 40% of the test substance is presumed to be adjusted by the biomass or to be present as products of biosynthesis.

A “ready biodegradable” chemical is presumed to undergo quick and final biodegradation in the environment exposure and no supplementary examination of the biodegradability of the polymer, or the probable environmental effects of conversion products, is usually essential. Biodegradable plastics cannot be regarded as “readily biodegradable” as they do not show such fast rates of degradation. The heterogeneous reaction is believed to involve in the biodegradation of solid substances since it occurs on solid/liquid interface, where the microbial enzymes present in the liquid phase interact with the macromolecules accessible at the surface of the solid plastic samples subjected to biodegradation [115]. The polymers in the internal portions of the plastic sample are not involved in the reaction, as they are not available.

Basically:

$$C_{\text{polymer}} = \text{Available C} + \text{Unavailable C} \quad (4)$$

Where, “available C” stands for carbon present in the exterior part of plastics, effectively available to the enzymes in the liquid phase and to biodegradation, while the rest is buried in the core of the plastic. Therefore, Eq. (3) when applied to macromolecules rather than to chemicals should be rewritten as:

$$\text{Biodegradation \%} = \frac{C_{\text{evolved as CO}_2}}{\text{Available } C_{\text{polymer}}} \times 100 \quad (5)$$

The effect of the surface area of different plastics at laboratory scale under controlled composting conditions on their biodegradation behavior has been examined [116]. Comparison of the biodegradation of polycaprolactone, poly (butylene succinate-co-adipate), poly(L-lactic acid) and poly(butylene succinate) in film and powder form. It was concluded that the shape of the polymer affected the biodegradation [117-119]. The shape of the simply degradable plastics was reported to distress biodegradation only at

the commencement of the procedure, while the slowly degrading plastics during the biodegradation. Initial stages of the biodegradation, plastics with a larger surface area were biodegraded faster than the same plastic in film form. Though, at the later stages of biodegradation, the rate of easily biodegradable plastics became closely independent of the form of the samples, while the effect was constant for slowly degrading plastics [120].

Conclusions

From this chapter it was concluded that the most important apprehensions about the natural and synthetic plastics polymers, their kinds, applications, dumping methods, degradability and standards employed in evaluating polymer degradation and interest of biodegradation of new and old plastics. Enhancement in concentration of plastic in land, coastal shores and oceans are triggering their environmental unease. Polyethylene, polypropylene, polystyrene and polyethylene terephthalate are the chief constituents of plastic debris and are regularly employed in several applications, which include clothes and food packaging. Polyethylene terephthalate is extremely unaffected by environmental biodegradation and, therefore, causes several environmental concerns related to its accretion. Degradation of plastics is rarely reported, particularly under natural conditions. Till now, three plastic disposal methods (landfill, incineration, and recycling) are usually employed on an industrial scale with several drawbacks. Both the methods landfill and incineration discharges harmful secondary contaminants into the environment while the landfill method required large portions of land space. The recycling method rectifies such environmental concerns, however, this method is found incompetent and degrading the quality of the polymers. This process was found costly and consequently, less incentive for investment in recycling facilities. Biodegradation was reported as environmentally safe and effective for the disposal of plastic waste. Until now, there is no protocol developed to effectively dispose of polyethylene terephthalate by biodegradation on an industrial level. Though, considerable research & development is still being conducted in the area of biodegradation of polymers. Quantity of CO₂ released on exposure to microorganisms, compost or soil is determined with respirometry technique. Infrared spectroscopy, differential scanning calorimeter, nuclear magnetic resonance, scanning electron microscopy, atomic force microscopy and X-ray diffraction were several techniques used for characterization of plastic surface. Moreover, international standard methods are required to estimate the amount of biodegradation for comparison studies. In light of these, there is a requirement to regulate the parameters in standards to be used worldwide. It has also been observed that many of recalcitrant plastics may be destroyed to significant extent in the proper scenario at the optimum concentration. Although, the

prevention measures of the degradation of plastics have already been initiated still more efforts are needed to solve this issue.

Acknowledgments

One of the authors Dr Manviri Rani is grateful for the financial assistance from DST-SERB, New Delhi (Sanction order no. SRG/2019/000114) and TEQIP-III, MNIT Jaipur, Rajasthan, India. Authors are also thankful to TEQIP-phase -III NIT Jalandhar for financial support.

References

- [1] A.C. Albertsson, C. Barenstedt, S. Karlsson, Abiotic degradation products from enhanced environmentally degradable polyethylene, *Acta Polym.*, 45 (1994) 97-103. <https://doi.org/10.1002/actp.1994.010450207>
- [2] A.-C. Albertsson, S.O. Andersson, S. Karlsson, The mechanism of biodegradation of polyethylene, *Polym. Degradation Stab.*, 18 (1987) 73-87. [https://doi.org/10.1016/0141-3910\(87\)90084-X](https://doi.org/10.1016/0141-3910(87)90084-X)
- [3] A. Arkatkar, J. Arutchelvi, S. Bhaduri, P.V. Uppara, M. Doble, Degradation of unpretreated and thermally pretreated polypropylene by soil consortia, *Int. Biodeterior. Biodegrad.*, 63 (2009) 106-111. <https://doi.org/10.1016/j.ibiod.2008.06.005>
- [4] A. Arkatkar, J. Arutchelvi, M. Sudhakar, S. Bhaduri, P.V. Uppara, M. Doble, Approaches to enhance the biodegradation of polyolefins, *The Open Environmental Engineering Journal*, 2 (2009). <https://doi.org/10.2174/1874829500902010068>
- [5] A. Arkatkar, A.A. Juwarkar, S. Bhaduri, P.V. Uppara, M. Doble, Growth of *Pseudomonas* and *Bacillus* biofilms on pretreated polypropylene surface, *Int. Biodeterior. Biodegrad.*, 64 (2010) 530-536. <https://doi.org/10.1016/j.ibiod.2010.06.002>
- [6] T. Artham, M. Sudhakar, R. Venkatesan, C.M. Nair, K. Murty, M. Doble, Biofouling and stability of synthetic polymers in sea water, *Int. Biodeterior. Biodegrad.*, 63 (2009) 884-890. <https://doi.org/10.1016/j.ibiod.2009.03.003>
- [7] C.G. Avio, S. Gorbi, M. Milan, M. Benedetti, D. Fattorini, G. d'Errico, M. Pauletto, L. Bargelloni, F. Regoli, Pollutants bioavailability and toxicological risk from microplastics to marine mussels, *Environ. Pollut.*, 198 (2015) 211-222. <https://doi.org/10.1016/j.envpol.2014.12.021>

- [8] E. Besseling, A. Wegner, E.M. Foekema, M.J. Van Den Heuvel-Greve, A.A. Koelmans, Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *Arenicola marina* (L.), *Environ. Sci. Technol.*, 47 (2013) 593-600. <https://doi.org/10.1021/es302763x>
- [9] D.N. Bikiaris, G.P. Karayannidis, Effect of carboxylic end groups on thermooxidative stability of PET and PBT, *Polym. Degradation Stab.*, 63 (1999) 213-218. [https://doi.org/10.1016/S0141-3910\(98\)00094-9](https://doi.org/10.1016/S0141-3910(98)00094-9)
- [10] S. Bonhomme, A. Cuer, A. Delort, J. Lemaire, M. Sancelme, G. Scott, Environmental biodegradation of polyethylene, *Polym. Degradation Stab.*, 81 (2003) 441-452. [https://doi.org/10.1016/S0141-3910\(03\)00129-0](https://doi.org/10.1016/S0141-3910(03)00129-0)
- [11] G. Botelho, A. Queirós, S. Liberal, P. Gijsman, Studies on thermal and thermooxidative degradation of poly (ethylene terephthalate) and poly (butylene terephthalate), *Polym. Degradation Stab.*, 74 (2001) 39-48. [https://doi.org/10.1016/S0141-3910\(01\)00088-X](https://doi.org/10.1016/S0141-3910(01)00088-X)
- [12] M.A. Browne, S.J. Niven, T.S. Galloway, S.J. Rowland, R.C. Thompson, Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity, *Curr. Biol.*, 23 (2013) 2388-2392. <https://doi.org/10.1016/j.cub.2013.10.012>
- [13] E.M. Chua, J. Shimeta, D. Nugegoda, P.D. Morrison, B.O. Clarke, Assimilation of polybrominated diphenyl ethers from microplastics by the marine amphipod, *Allorchestes compressa*, *Environ. Sci. Technol.*, 48 (2014) 8127-8134. <https://doi.org/10.1021/es405717z>
- [14] M. Djebara, J. Stoquert, M. Abdesselam, D. Muller, A. Chami, FTIR analysis of polyethylene terephthalate irradiated by MeV He⁺, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 274 (2012) 70-77. <https://doi.org/10.1016/j.nimb.2011.11.022>
- [15] R.M. Donlan, Biofilms: microbial life on surfaces, *Emerging Infect. Dis.*, 8 (2002) 881. <https://doi.org/10.3201/eid0809.020063>
- [16] [16] R.E. Engler, The complex interaction between marine debris and toxic chemicals in the ocean, *Environ. Sci. Technol.*, 46 (2012) 12302-12315. <https://doi.org/10.1021/es3027105>
- [17] J.P. Eubeler, M. Bernhard, T.P. Knepper, Environmental biodegradation of synthetic polymers II. Biodegradation of different polymer groups, *TrAC, Trends Anal. Chem.*, 29 (2010) 84-100. <https://doi.org/10.1016/j.trac.2009.09.005>

- [18] P. Europe, *Plastics the facts 2014/2015: an analysis of European plastics production, demand and waste data*, Plastic Europe, Brussels, (2015).
- [19] M.C. Fossi, C. Panti, C. Guerranti, D. Coppola, M. Giannetti, L. Marsili, R. Minutoli, Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*), *Mar. Pollut. Bull.*, 64 (2012) 2374-2379. <https://doi.org/10.1016/j.marpolbul.2012.08.013>
- [20] K.N. Fotopoulou, H.K. Karapanagioti, Surface properties of beached plastics, *Environmental Science and Pollution Research*, 22 (2015) 11022-11032. <https://doi.org/10.1007/s11356-015-4332-y>
- [21] M. Funabashi, F. Ninomiya, M. Kunioka, Biodegradation of polycaprolactone powders proposed as reference test materials for international standard of biodegradation evaluation method, *J. Polym. Environ.*, 15 (2007) 7-17. <https://doi.org/10.1007/s10924-006-0041-4>
- [22] S.C. Gall, R.C. Thompson, The impact of debris on marine life, *Mar. Pollut. Bull.*, 92 (2015) 170-179. <https://doi.org/10.1016/j.marpolbul.2014.12.041>
- [23] D. Hadad, S. Geresh, A. Sivan, Biodegradation of polyethylene by the thermophilic bacterium *Brevibacillus borstelensis*, *J. Appl. Microbiol.*, 98 (2005) 1093-1100. <https://doi.org/10.1111/j.1365-2672.2005.02553.x>
- [24] K. Harshvardhan, B. Jha, Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India, *Mar. Pollut. Bull.*, 77 (2013) 100-106. <https://doi.org/10.1016/j.marpolbul.2013.10.025>
- [25] P.W. Hill, J.F. Farrar, D.L. Jones, Decoupling of microbial glucose uptake and mineralization in soil, *Soil Biol. Biochem.*, 40 (2008) 616-624. <https://doi.org/10.1016/j.soilbio.2007.09.008>
- [26] E. Huerta Lwanga, H. Gertsen, H. Gooren, P. Peters, T. Salánki, M. van der Ploeg, E. Besseling, A.A. Koelmans, V. Geissen, Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae), *Environ. Sci. Technol.*, 50 (2016) 2685-2691. <https://doi.org/10.1021/acs.est.5b05478>
- [27] D. Jeyakumar, J. Chirsteen, M. Doble, Synergistic effects of pretreatment and blending on fungi mediated biodegradation of polypropylenes, *Bioresour. Technol.*, 148 (2013) 78-85. <https://doi.org/10.1016/j.biortech.2013.08.074>

- [28] D.P. Kint, A.M.n. de Ilarduya, S. Muñoz-Guerra, Hydrolytic degradation of poly (ethylene terephthalate) copolymers containing nitrated units, *Polym. Degradation Stab.*, 79 (2003) 353-358. [https://doi.org/10.1016/S0141-3910\(02\)00299-9](https://doi.org/10.1016/S0141-3910(02)00299-9)
- [29] A.A. Koelmans, E. Besseling, E.M. Foekema, Leaching of plastic additives to marine organisms, *Environ. Pollut.*, 187 (2014) 49-54. <https://doi.org/10.1016/j.envpol.2013.12.013>
- [30] A.A. Koelmans, E. Besseling, A. Wegner, E.M. Foekema, Plastic as a carrier of POPs to aquatic organisms: a model analysis, *Environ. Sci. Technol.*, 47 (2013) 7812-7820. <https://doi.org/10.1021/es401169n>
- [31] L.R. Krupp, W.J. Jewell, Biodegradability of modified plastic films in controlled biological environments, *Environ. Sci. Technol.*, 26 (1992) 193-198. <https://doi.org/10.1021/es00025a024>
- [32] M. Kunioka, F. Ninomiya, M. Funabashi, Biodegradation of poly (lactic acid) powders proposed as the reference test materials for the international standard of biodegradation evaluation methods, *Polym. Degradation Stab.*, 91 (2006) 1919-1928. <https://doi.org/10.1016/j.polymdegradstab.2006.03.003>
- [33] E.H. Lwanga, H. Gertsen, H. Gooren, P. Peters, T. Salánki, M. van der Ploeg, E. Besseling, A.A. Koelmans, V. Geissen, Incorporation of microplastics from litter into burrows of *Lumbricus terrestris*, *Environ. Pollut.*, 220 (2017) 523-531. <https://doi.org/10.1016/j.envpol.2016.09.096>
- [34] E.H. Lwanga, B. Thapa, X. Yang, H. Gertsen, T. Salánki, V. Geissen, P. Garbeva, Decay of low-density polyethylene by bacteria extracted from earthworm's guts: A potential for soil restoration, *ScTEn*, 624 (2018) 753-757. <https://doi.org/10.1016/j.scitotenv.2017.12.144>
- [35] S. Maaß, D. Daphi, A. Lehmann, M.C. Rillig, Transport of microplastics by two collembolan species, *Environ Poll.*, 225 (2017) 456-459. <https://doi.org/10.1016/j.envpol.2017.03.009>
- [36] J.D. Meeker, S. Sathyanarayana, S.H. Swan, Phthalates and other additives in plastics: human exposure and associated health outcomes, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364 (2009) 2097-2113. <https://doi.org/10.1098/rstb.2008.0268>
- [37] T.J. Mincer, E.R. Zettler, L.A. Amaral-Zettler, Biofilms on plastic debris and their influence on marine nutrient cycling, productivity, and hazardous chemical mobility,

- in: Hazardous Chemicals Associated with Plastics in the Marine Environment, Springer, 2016, pp. 221-233. https://doi.org/10.1007/698_2016_12
- [38] R.-J. Mueller, Biological degradation of synthetic polyesters—enzymes as potential catalysts for polyester recycling, *Process Biochem.*, 41 (2006) 2124-2128. <https://doi.org/10.1016/j.procbio.2006.05.018>
- [39] R.J. Müller, Biodegradability of polymers: regulations and methods for testing, *Biopolymers Online: Biology• Chemistry• Biotechnology• Applications*, 10 (2005).
- [40] L. Nizzetto, S. Langaas, M. Futter, Pollution: Do microplastics spill on to farm soils?, *Nature*, 537 (2016) 488-488. <https://doi.org/10.1038/537488b>
- [41] E. Oburger, D. Jones, Substrate mineralization studies in the laboratory show different microbial C partitioning dynamics than in the field, *Soil Biol. Biochem.*, 41 (2009) 1951-1956. <https://doi.org/10.1016/j.soilbio.2009.06.020>
- [42] I.G. Orr, Y. Hadar, A. Sivan, Colonization, biofilm formation and biodegradation of polyethylene by a strain of *Rhodococcus ruber*, *Appl. Microbiol. Biotechnol.*, 65 (2004) 97-104. <https://doi.org/10.1007/s00253-004-1584-8>
- [43] X. Ramis, A. Cadenato, J. Salla, J. Morancho, A. Valles, L. Contat, A. Ribes, Thermal degradation of polypropylene/starch-based materials with enhanced biodegradability, *Polym. Degradation Stab.*, 86 (2004) 483-491. <https://doi.org/10.1016/j.polymdegradstab.2004.05.021>
- [44] M. Rani, S. Hong, W. Shim, G. Han, M. Jang, Leaching characteristics of hexabromocyclododecanes (HBCDs) from expanded polystyrene buoy in water, *Organohalogen Compd.*, 75 (2013) 691-694.
- [45] M. Rani, W.J. Shim, G.M. Han, M. Jang, N.A. Al-Odaini, Y.K. Song, S.H. Hong, Qualitative analysis of additives in plastic marine debris and its new products, *Arch. Environ. Contam. Toxicol.*, 69 (2015) 352-366. <https://doi.org/10.1007/s00244-015-0224-x>
- [46] M. Rani, W.J. Shim, G.M. Han, M. Jang, Y.K. Song, S.H. Hong, Benzotriazole-type ultraviolet stabilizers and antioxidants in plastic marine debris and their new products, *ScTEen*, 579 (2017) 745-754. <https://doi.org/10.1016/j.scitotenv.2016.11.033>
- [47] J.-M. Restrepo-Flórez, A. Bassi, M.R. Thompson, Microbial degradation and deterioration of polyethylene—A review, *Int. Biodeterior. Biodegrad.*, 88 (2014) 83-90. <https://doi.org/10.1016/j.ibiod.2013.12.014>

- [48] M.C. Rillig, Microplastic in terrestrial ecosystems and the soil?, in, ACS Publications, 2012. <https://doi.org/10.1021/es302011r>
- [49] M.C. Rillig, L. Ziersch, S. Hempel, Microplastic transport in soil by earthworms, *Sci. Rep.*, 7 (2017).
- [50] C.M. Rochman, M.A. Browne, B.S. Halpern, B.T. Hentschel, E. Hoh, H.K. Karapanagioti, L.M. Rios-Mendoza, H. Takada, S. Teh, R.C. Thompson, Classify plastic waste as hazardous, *Nature*, 494 (2013) 169-171. <https://doi.org/10.1038/494169a>
- [51] C.M. Rochman, C. Manzano, B.T. Hentschel, S.L.M. Simonich, E. Hoh, Polystyrene plastic: a source and sink for polycyclic aromatic hydrocarbons in the marine environment, *Environ. Sci. Technol.*, 47 (2013) 13976-13984. <https://doi.org/10.1021/es403605f>
- [52] P. Ryan, A. Connell, B. Gardner, Plastic ingestion and PCBs in seabirds: is there a relationship?, *Mar. Pollut. Bull.*, 19 (1988) 174-176.
- [53] C. Sammon, J. Yarwood, N. Everall, An FT-IR study of the effect of hydrolytic degradation on the structure of thin PET films, *Polym. Degradation Stab.*, 67 (2000) 149-158. [https://doi.org/10.1016/S0141-3910\(99\)00104-4](https://doi.org/10.1016/S0141-3910(99)00104-4)
- [54] R.R. Singhanian, G. Christophe, G. Perchet, J. Troquet, C. Larroche, Immersed membrane bioreactors: an overview with special emphasis on anaerobic bioprocesses, *Bioresour. Technol.*, 122 (2012) 171-180. <https://doi.org/10.1016/j.biortech.2012.01.132>
- [55] Y.K. Song, S.H. Hong, M. Jang, J.-H. Kang, O.Y. Kwon, G.M. Han, W.J. Shim, Large accumulation of micro-sized synthetic polymer particles in the sea surface microlayer, *Environ. Sci. Technol.*, 48 (2014) 9014-9021. <https://doi.org/10.1021/es501757s>
- [56] A. Steiner, Emerging issues in our global environment, UNEP Year Book; UNEP: Nairobi, Kenya, (2014).
- [57] Z. Steinmetz, C. Wollmann, M. Schaefer, C. Buchmann, J. David, J. Tröger, K. Muñoz, O. Frör, G.E. Schaumann, Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation?, *ScTEn*, 550 (2016) 690-705. <https://doi.org/10.1016/j.scitotenv.2016.01.153>

- [58] M. Sudhakar, M. Doble, P.S. Murthy, R. Venkatesan, Marine microbe-mediated biodegradation of low-and high-density polyethylenes, *Int. Biodeterior. Biodegrad.*, 61 (2008) 203-213. <https://doi.org/10.1016/j.ibiod.2007.07.011>
- [59] K. Tanaka, H. Takada, R. Yamashita, K. Mizukawa, M.-a. Fukuwaka, Y. Watanuki, Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics, *Mar. Pollut. Bull.*, 69 (2013) 219-222. <https://doi.org/10.1016/j.marpolbul.2012.12.010>
- [60] R.C. Thompson, S.H. Swan, C.J. Moore, F.S. Vom Saal, Our plastic age, in, *The Royal Society Publishing*, 2009.
- [61] P. Tribedi, A.K. Sil, Low-density polyethylene degradation by *Pseudomonas* sp. AKS2 biofilm, *Environmental Science and Pollution Research*, 20 (2013) 4146-4153. <https://doi.org/10.1007/s11356-012-1378-y>
- [62] M. van der Zee, Methods for evaluating the biodegradability of environmentally degradable polymers, in: *Handbook of Biodegradable Polymers*, Smither Rapra, 2014, pp. 1-28.
- [63] N. Wanasekara, V. Chalivendra, P. Calvert, Sub-micron scale mechanical properties of polypropylene fibers exposed to ultraviolet and thermal degradation, in: *MEMS and Nanotechnology*, Volume 2, Springer, 2011, pp. 275-281. https://doi.org/10.1007/978-1-4419-8825-6_40
- [64] H.K. Webb, J. Arnott, R.J. Crawford, E.P. Ivanova, Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate), *Polymers*, 5 (2013) 1-18. <https://doi.org/10.3390/polym5010001>
- [65] R. Yamashita, H. Takada, M.-a. Fukuwaka, Y. Watanuki, Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, *Puffinus tenuirostris*, in the North Pacific Ocean, *Mar. Pollut. Bull.*, 62 (2011) 2845-2849. <https://doi.org/10.1016/j.marpolbul.2011.10.008>
- [66] J. Yang, Y. Yang, W.-M. Wu, J. Zhao, L. Jiang, Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms, *Environ. Sci. Technol.*, 48 (2014) 13776-13784. <https://doi.org/10.1021/es504038a>
- [67] R. Yang, Y. Li, J. Yu, Photo-stabilization of linear low density polyethylene by inorganic nano-particles, *Polym. Degradation Stab.*, 88 (2005) 168-174. <https://doi.org/10.1016/j.polymdegradstab.2003.12.005>

- [68] A. Yano, N. Akai, H. Ishii, C. Satoh, T. Hironiwa, K.R. Millington, M. Nakata, Thermal oxidative degradation of additive-free polypropylene pellets investigated by multichannel Fourier-transform chemiluminescence spectroscopy, *Polym. Degradation Stab.*, 98 (2013) 2680-2686.
<https://doi.org/10.1016/j.polymdegradstab.2013.09.031>
- [69] C. Zarfl, M. Matthies, Are marine plastic particles transport vectors for organic pollutants to the Arctic?, *Mar. Pollut. Bull.*, 60 (2010) 1810-1814.
<https://doi.org/10.1016/j.marpolbul.2010.05.026>
- [70] H. Zhao, R.K. Li, A study on the photo-degradation of zinc oxide (ZnO) filled polypropylene nanocomposites, *Poly*, 47 (2006) 3207-3217.
<https://doi.org/10.1016/j.polymer.2006.02.089>
- [71] W. Zheng, M. Wen, Z. Zhao, J. Liu, Z. Wang, B. Zhai, Z. Li, Black plastic mulch combined with summer cover crop increases the yield and water use efficiency of apple tree on the rainfed Loess Plateau, *PLoS One*, 12 (2017).
<https://doi.org/10.1371/journal.pone.0185705>
- [72] Y. Zheng, E.K. Yanful, A.S. Bassi, A review of plastic waste biodegradation, *Crit. Rev. Biotechnol.*, 25 (2005) 243-250.
<https://doi.org/10.1080/07388550500346359>
- [73] A.-C. Albertsson, S.O. Andersson, S. Karlsson, The mechanism of biodegradation of polyethylene, *Polym. Degradation Stab.*, 18 (1987) 73-87.
[https://doi.org/10.1016/0141-3910\(87\)90084-X](https://doi.org/10.1016/0141-3910(87)90084-X)
- [74] A. Ammala, S. Bateman, K. Dean, E. Petinakis, P. Sangwan, S. Wong, Q. Yuan, L. Yu, C. Patrick, K. Leong, An overview of degradable and biodegradable polyolefins, *Prog. Polym. Sci.*, 36 (2011) 1015-1049.
<https://doi.org/10.1016/j.progpolymsci.2010.12.002>
- [75] T. Artham, M. Doble, Biodegradation of aliphatic and aromatic polycarbonates, *Macromol. Biosci.*, 8 (2008) 14-24. <https://doi.org/10.1002/mabi.200700106>
- [76] D.K. Barnes, F. Galgani, R.C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364 (2009) 1985-1998.
<https://doi.org/10.1098/rstb.2008.0205>
- [77] A. Basfar, K.I. Ali, Natural weathering test for films of various formulations of low density polyethylene (LDPE) and linear low density polyethylene (LLDPE),

- Polym. Degradation Stab., 91 (2006) 437-443.
<https://doi.org/10.1016/j.polymdegradstab.2004.11.027>
- [78] M.A. Browne, P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway, R. Thompson, Accumulation of microplastic on shorelines worldwide: sources and sinks, *Environ. Sci. Technol.*, 45 (2011) 9175-9179. <https://doi.org/10.1021/es201811s>
- [79] I. Carpentieri, V. Brunella, P. Bracco, M.C. Paganini, E.M.B. Del Prever, M.P. Luda, S. Bonomi, L. Costa, Post-irradiation oxidation of different polyethylenes, *Polym. Degradation Stab.*, 96 (2011) 624-629.
<https://doi.org/10.1016/j.polymdegradstab.2010.12.014>
- [80] S. Cheng, F. Dehaye, C. Bailly, J.-J. Biebuyck, R. Legras, L. Parks, Studies on polyethylene pellets modified by low dose radiation prior to part formation, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 236 (2005) 130-136.
<https://doi.org/10.1016/j.nimb.2005.03.272>
- [81] E. Chiellini, A. Corti, S. D'Antone, R. Baciú, Oxo-biodegradable carbon backbone polymers—Oxidative degradation of polyethylene under accelerated test conditions, *Polym. Degradation Stab.*, 91 (2006) 2739-2747.
<https://doi.org/10.1016/j.polymdegradstab.2006.03.022>
- [82] M. Edge, M. Hayes, M. Mohammadian, N. Allen, T. Jewitt, K. Brems, K. Jones, Aspects of poly (ethylene terephthalate) degradation for archival life and environmental degradation, *Polym. Degradation Stab.*, 32 (1991) 131-153.
[https://doi.org/10.1016/0141-3910\(91\)90047-U](https://doi.org/10.1016/0141-3910(91)90047-U)
- [83] S. Endo, R. Takizawa, K. Okuda, H. Takada, K. Chiba, H. Kanehiro, H. Ogi, R. Yamashita, T. Date, Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences, *Mar. Pollut. Bull.*, 50 (2005) 1103-1114. <https://doi.org/10.1016/j.marpolbul.2005.04.030>
- [84] M. Eriksen, The plastisphere-the making of a plasticized world, *Tul. Envtl. LJ*, 27 (2013) 153.
- [85] A. Francois-Heude, E. Richaud, E. Desnoux, X. Colin, Influence of temperature, UV-light wavelength and intensity on polypropylene photothermal oxidation, *Polym. Degradation Stab.*, 100 (2014) 10-20.
<https://doi.org/10.1016/j.polymdegradstab.2013.12.038>
- [86] M. Gardette, A. Perthue, J.-L. Gardette, T. Janecska, E. Földes, B. Pukánszky, S. Therias, Photo-and thermal-oxidation of polyethylene: comparison of mechanisms

- and influence of unsaturation content, *Polym. Degradation Stab.*, 98 (2013) 2383-2390. <https://doi.org/10.1016/j.polymdegradstab.2013.07.017>
- [87] B. Graca, M. Beldowska, P. Wrzesień, A. Zgrundo, Styrofoam debris as a potential carrier of mercury within ecosystems, *Environmental Science and Pollution Research*, 21 (2014) 2263-2271. <https://doi.org/10.1007/s11356-013-2153-4>
- [88] M.R. Gregory, Virgin plastic granules on some beaches of eastern Canada and Bermuda, *Mar. Environ. Res.*, 10 (1983) 73-92. [https://doi.org/10.1016/0141-1136\(83\)90011-9](https://doi.org/10.1016/0141-1136(83)90011-9)
- [89] J. Gulmine, P. Janissek, H. Heise, L. Akcelrud, Degradation profile of polyethylene after artificial accelerated weathering, *Polym. Degradation Stab.*, 79 (2003) 385-397. [https://doi.org/10.1016/S0141-3910\(02\)00338-5](https://doi.org/10.1016/S0141-3910(02)00338-5)
- [90] K. Harshvardhan, B. Jha, Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India, *Mar. Pollut. Bull.*, 77 (2013) 100-106. <https://doi.org/10.1016/j.marpolbul.2013.10.025>
- [91] H. Hirai, H. Takada, Y. Ogata, R. Yamashita, K. Mizukawa, M. Saha, C. Kwan, C. Moore, H. Gray, D. Laursen, Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches, *Mar. Pollut. Bull.*, 62 (2011) 1683-1692. <https://doi.org/10.1016/j.marpolbul.2011.06.004>
- [92] L.A. Holmes, A. Turner, R.C. Thompson, Interactions between trace metals and plastic production pellets under estuarine conditions, *Mar. Chem.*, 167 (2014) 25-32. <https://doi.org/10.1016/j.marchem.2014.06.001>
- [93] C. Ioakeimidis, C. Zeri, H. Kaberi, M. Galatchi, K. Antoniadis, N. Streftaris, F. Galgani, E. Papatthanassiou, G. Papatheodorou, A comparative study of marine litter on the seafloor of coastal areas in the Eastern Mediterranean and Black Seas, *Mar. Pollut. Bull.*, 89 (2014) 296-304. <https://doi.org/10.1016/j.marpolbul.2014.09.044>
- [94] P. Kandakatla, B. Mahto, S. Goel, Extent and rate of biodegradation of different organic components in municipal solid waste, *International Journal of Environment and Waste Management*, 11 (2013) 350-364. <https://doi.org/10.1504/IJEWPM.2013.054262>
- [95] H. Karapanagioti, S. Endo, Y. Ogata, H. Takada, Diffuse pollution by persistent organic pollutants as measured in plastic pellets sampled from various beaches in Greece, *Mar. Pollut. Bull.*, 62 (2011) 312-317. <https://doi.org/10.1016/j.marpolbul.2010.10.009>

- [96] I. Kyrikou, D. Briassoulis, M. Hiskakis, E. Babou, Analysis of photo-chemical degradation behaviour of polyethylene mulching film with pro-oxidants, *Polym. Degradation Stab.*, 96 (2011) 2237-2252.
<https://doi.org/10.1016/j.polymdegradstab.2011.09.001>
- [97] N. Lucas, C. Bienaime, C. Belloy, M. Queneudec, F. Silvestre, J.-E. Nava-Saucedo, Polymer biodegradation: Mechanisms and estimation techniques—A review, *Chemosphere*, 73 (2008) 429-442.
<https://doi.org/10.1016/j.chemosphere.2008.06.064>
- [98] Y. Mato, T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, T. Kaminuma, Plastic resin pellets as a transport medium for toxic chemicals in the marine environment, *Environ. Sci. Technol.*, 35 (2001) 318-324. <https://doi.org/10.1021/es0010498>
- [99] T. Muthukumar, A. Aravinthan, K. Lakshmi, R. Venkatesan, L. Vedaprakash, M. Doble, Fouling and stability of polymers and composites in marine environment, *Int. Biodeterior. Biodegrad.*, 65 (2011) 276-284.
<https://doi.org/10.1016/j.ibiod.2010.11.012>
- [100] T.-T. Nguyen-Boisse, J. Saulnier, N. Jaffrezic-Renault, F. Lagarde, Miniaturised enzymatic conductometric biosensor with Nafion membrane for the direct determination of formaldehyde in water samples, *Anal. Bioanal. Chem.*, 406 (2014) 1039-1048. <https://doi.org/10.1007/s00216-013-7197-2>
- [101] Y. Ogata, H. Takada, K. Mizukawa, H. Hirai, S. Iwasa, S. Endo, Y. Mato, M. Saha, K. Okuda, A. Nakashima, International pellet watch: global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs, *Mar. Pollut. Bull.*, 58 (2009) 1437-1446.
<https://doi.org/10.1016/j.marpolbul.2009.06.014>
- [102] T. Ojeda, A. Freitas, K. Birck, E. Dalmolin, R. Jacques, F. Bento, F. Camargo, Degradability of linear polyolefins under natural weathering, *Polym. Degradation Stab.*, 96 (2011) 703-707. <https://doi.org/10.1016/j.polymdegradstab.2010.12.004>
- [103] Y. Orhan, H. Büyükgüngör, Enhancement of biodegradability of disposable polyethylene in controlled biological soil, *Int. Biodeterior. Biodegrad.*, 45 (2000) 49-55. [https://doi.org/10.1016/S0964-8305\(00\)00048-2](https://doi.org/10.1016/S0964-8305(00)00048-2)
- [104] I.G. Orr, Y. Hadar, A. Sivan, Colonization, biofilm formation and biodegradation of polyethylene by a strain of *Rhodococcus ruber*, *Appl. Microbiol. Biotechnol.*, 65 (2004) 97-104. <https://doi.org/10.1007/s00253-004-1584-8>

- [105] G. Pastorelli, C. Cucci, O. Garcia, G. Piantanida, A. Elnaggar, M. Cassar, M. Strlič, Environmentally induced colour change during natural degradation of selected polymers, *Polym. Degradation Stab.*, 107 (2014) 198-209.
<https://doi.org/10.1016/j.polymdegradstab.2013.11.007>
- [106] J.E. Pegram, A.L. Andrady, Outdoor weathering of selected polymeric materials under marine exposure conditions, *Polym. Degradation Stab.*, 26 (1989) 333-345.
[https://doi.org/10.1016/0141-3910\(89\)90112-2](https://doi.org/10.1016/0141-3910(89)90112-2)
- [107] N. Priyanka, T. Archana, Biodegradability of polythene and plastic by the help of microorganism: a way for brighter future, *J Environ Anal Toxicol*, 1 (2011) 1000111.
<https://doi.org/10.4172/2161-0525.1000111>
- [108] B. Rånby, Photodegradation and photo-oxidation of synthetic polymers, *J. Anal. Appl. Pyrolysis*, 15 (1989) 237-247. [https://doi.org/10.1016/0165-2370\(89\)85037-5](https://doi.org/10.1016/0165-2370(89)85037-5)
- [109] M. Rani, W.J. Shim, G.M. Han, M. Jang, Y.K. Song, S.H. Hong, Hexabromocyclododecane in polystyrene based consumer products: an evidence of unregulated use, *Chemosphere*, 110 (2014) 111-119.
<https://doi.org/10.1016/j.chemosphere.2014.02.022>
- [110] J.-M. Restrepo-Flórez, A. Bassi, M.R. Thompson, Microbial degradation and deterioration of polyethylene—A review, *Int. Biodeterior. Biodegrad.*, 88 (2014) 83-90. <https://doi.org/10.1016/j.ibiod.2013.12.014>
- [111] L.M. Rios, C. Moore, P.R. Jones, Persistent organic pollutants carried by synthetic polymers in the ocean environment, *Mar. Pollut. Bull.*, 54 (2007) 1230-1237. <https://doi.org/10.1016/j.marpolbul.2007.03.022>
- [112] C.M. Rochman, E. Hoh, T. Kurobe, S.J. Teh, Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress, *Sci. Rep.*, 3 (2013) 3263.
<https://doi.org/10.1038/srep03263>
- [113] A.A. Shah, F. Hasan, A. Hameed, S. Ahmed, Biological degradation of plastics: a comprehensive review, *Biotechnol. Adv.*, 26 (2008) 246-265.
<https://doi.org/10.1016/j.biotechadv.2007.12.005>
- [114] M. Shimao, Biodegradation of plastics, *Curr. Opin. Biotechnol.*, 12 (2001) 242-247. [https://doi.org/10.1016/S0958-1669\(00\)00206-8](https://doi.org/10.1016/S0958-1669(00)00206-8)
- [115] B. Singh, N. Sharma, Mechanistic implications of plastic degradation, *Polym. Degradation Stab.*, 93 (2008) 561-584.
<https://doi.org/10.1016/j.polymdegradstab.2007.11.008>

- [116] R. Smith, Biodegradable polymers for industrial applications, CRC Press, 2005.
<https://doi.org/10.1533/9781845690762>
- [117] G. Swift, Requirements for biodegradable water-soluble polymers, Polym. Degradation Stab., 59 (1998) 19-24. [https://doi.org/10.1016/S0141-3910\(97\)00162-6](https://doi.org/10.1016/S0141-3910(97)00162-6)
- [118] S. Taniguchi, F.I. Colabuono, P.S. Dias, R. Oliveira, M. Fisner, A. Turra, G.M. Izar, D.M. Abessa, M. Saha, J. Hosoda, Spatial variability in persistent organic pollutants and polycyclic aromatic hydrocarbons found in beach-stranded pellets along the coast of the state of São Paulo, southeastern Brazil, Mar. Pollut. Bull., 106 (2016) 87-94. <https://doi.org/10.1016/j.marpolbul.2016.03.024>
- [119] E.L. Teuten, J.M. Saquing, D.R. Knappe, M.A. Barlaz, S. Jonsson, A. Björn, S.J. Rowland, R.C. Thompson, T.S. Galloway, R. Yamashita, Transport and release of chemicals from plastics to the environment and to wildlife, Philosophical Transactions of the Royal Society B: Biological Sciences, 364 (2009) 2027-2045. <https://doi.org/10.1098/rstb.2008.0284>
- [120] Y. Zheng, E.K. Yanful, A.S. Bassi, A review of plastic waste biodegradation, Crit. Rev. Biotechnol., 25 (2005) 243-250.
<https://doi.org/10.1080/07388550500346359>