

Review

Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate)

Hayden K. Webb, Jaimys Arnott, Russell J. Crawford and Elena P. Ivanova *

Faculty of Life and Social Sciences, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia; E-Mails: hkwebb@swin.edu.au (H.K.W.); jaimys.arnott@gmail.com (J.A.); rcrawford@swin.edu.au (R.J.C.)

* Author to whom correspondence should be addressed; E-Mail: eivanova@swin.edu.au; Tel.: +61-3-9214-5137; Fax: +61-3-9819-0834.

Received: 30 November 2012; in revised form: 18 December 2012 / Accepted: 19 December 2012 / Published: 28 December 2012

Abstract: With increasing global consumption and their natural resistance to degradation, plastic materials and their accumulation in the environment is of increasing concern. This review aims to present a general overview of the current state of knowledge in areas that relate to biodegradation of polymers, especially poly(ethylene terephthalate) (PET). This includes an outline of the problems associated with plastic pollution in the marine environment, a description of the properties, commercial manufacturing and degradability of PET, an overview of the potential for biodegradation of conventional polymers and biodegradable polymers already in production.

Keywords: biodegradation; polymers; poly(ethylene terephthalate); environment

1. Introduction

Due to plastic's resilience against degradation and its proliferation in industry, the issue of plastic pollution has evolved to become a threat to global ecology. Plastic pollution arises from both terrestrial and marine sources. The continual stream of pollutant plastic is maintained via two means: purposefully, through illegal or inappropriate dumping of domestic and industrial refuse; and inadvertently, through poorly contained static and transported waste. Directed by the elements, land-based plastic debris migrates to waterways, where it is further added to by the disposal or loss

borne from marine vessels and offshore petroleum platforms. Such pollution results in a number of deleterious repercussions.

2. Plastics in the Environment

2.1. Environmental Impacts of Plastic Pollution

Plastic pollution in the marine environment is the cause of several hazardous and ecologically damaging effects. Plastic debris poses a direct threat to wildlife, with many and varied species documented as being negatively impacted by plastic items. The main dangers associated with plastic objects for most species surround entanglement in and ingestion of said items [1]. Juvenile animals in particular often become entangled in plastic debris, which can result in serious injury as the animal grows [2,3], not to mention restriction of movement, preventing animals from properly feeding and, in the case of mammals, breathing [4]. A wide variety of species have been reported to be negatively impacted by plastic debris: marine birds [5,6], sea turtles [7], cetaceans [8], fur seals [2], sharks [3] and filter feeders [9] are just some of those documented. Marine birds are particularly susceptible to ingestion of plastic objects that they mistake for food [5,6]. Plastic ingested by these animals persists in the digestive system and can lead to decreased feeding stimuli, gastrointestinal blockage, decreased secretion of gastric enzymes and decreased levels of steroid hormones, leading to reproduction problems [5].

Plastic particles in the ocean have been shown to contain quite high levels of organic pollutants. Toxic chemicals, such as polychlorinated biphenyls (PCBs), nonylphenol (NP), organic pesticides, such as dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs) and bisphenol A (BPA) have been consistently found throughout oceanic plastic debris [10–12]. The presence of these compounds further increases the risks associated with ingestion of plastic debris by wildlife, and additionally, many of these compounds can undergo significant biomagnification and may potentially pose a direct risk to human health [12]. These toxic agents have been linked to and are associated with many health problems, including developmental impairment (neurological impairment, growth abnormalities and hormonal imbalances), cancer, endocrine disruption, neurobehavioral changes, arthritis, breast cancer, diabetes and DNA hypomethylation [13–16].

Plastic debris also provides increased opportunity for potentially invasive and destructive fauna to migrate to new environments [4,17–20]. Colonisation and subsequent dispersal of marine species is common, with many reports of barnacles [4,20], bryozoans [4,20], polychaetes [4,20], dinoflagellates [17], algae [4] and molluscs [4] found to adhere to plastic debris in the environment. Terrestrial animals are also capable of riding marine debris to new areas. Ants have been reported to ride debris from the Brazilian mainland to San Sebastian Island, several kilometres away [18], and there are even examples of animals as large as iguanas riding flotsam to new islands in the Caribbean [19].

2.2. Levels of Plastic in the Marine Environment

There have been many efforts at quantifying the level of plastic pollution in marine environments, the vast majority of which focus on the deposition of debris on beaches [21–25]. This is probably due

to the fact that plastics typically float and, therefore, tend to accumulate on beaches [25]. The bulk of debris washed onto the beaches studied, in terms of numbers, is composed of plastic items; often three quarters of all debris washed ashore are made of plastic [24,25]. Such high levels of plastic debris in the environment can be attributed to the high availability of plastic products and its ability to persist in the environment [21,26].

Plastic particles collected in purpose-built trawl nets have been shown to exceed zooplankton levels during sampling from the neustonic layer of open ocean waters in parts of the North Pacific [9]. In terms of the number of particles, zooplankton outnumbered plastic particles approximately five to one; however, the total plastic collected outweighed zooplankton by approximately six-times. Other studies have reported similar abundances of plastic pollution: During an expedition in the Atlantic Ocean, the total floating marine debris, including naturally occurring debris, such as kelp, was characterised from as far south as the Southern Ocean, all the way north to the high Arctic [20]. In most samplings, plastic was the most abundant type of debris, reaching as high as 92% of items collected in one sampling, and plastic was recovered in every 10° latitudinal belt. A separate study monitoring plastic debris in the Atlantic over a period of 22 years found that 62% of all net tows contained plastic items large enough to be easily detected and, in some regions, reaching an average of more than 20,000 pieces km⁻² [27]. It has been reported that in the North Pacific subtropical gyre, plastic levels reach up to 335,000 plastic items km⁻², or 5.1 kg km⁻² [28].

2.3. Degradation

As a rule, widely used plastics do not naturally degrade to a large degree when released into the environment [29–32]. This is perhaps unsurprising, as one of the primary reasons for the popularity and widespread application of many polymers is their exceptionally high stability and durability [29,30]. There are four mechanisms by which plastics degrade in the environment: photodegradation, thermooxidative degradation, hydrolytic degradation and biodegradation by microorganisms [33]. Generally speaking, natural degradation of plastic begins with photodegradation, which leads to thermooxidative degradation. Ultraviolet light from the sun provides the activation energy required to initiate the incorporation of oxygen atoms into the polymer [33,34]. This causes the plastic to become brittle and to break into smaller and smaller pieces, until the polymer chains reach sufficiently low molecular weight to be metabolised by microorganisms [30,33]. These microbes either convert the carbon in the polymer chains to carbon dioxide or incorporate it into biomolecules [29,33]. However, this entire process is very slow, and it can take 50 or more years for plastic to fully degrade [35]. This is not aided by the fact that the photodegradative effect is significantly decreased in seawater due to the lower temperature and oxygen availability and that the rate of hydrolysis of most polymers is insignificant in the ocean [33].

3. Poly(ethylene terephthalate)

3.1. Properties and Applications

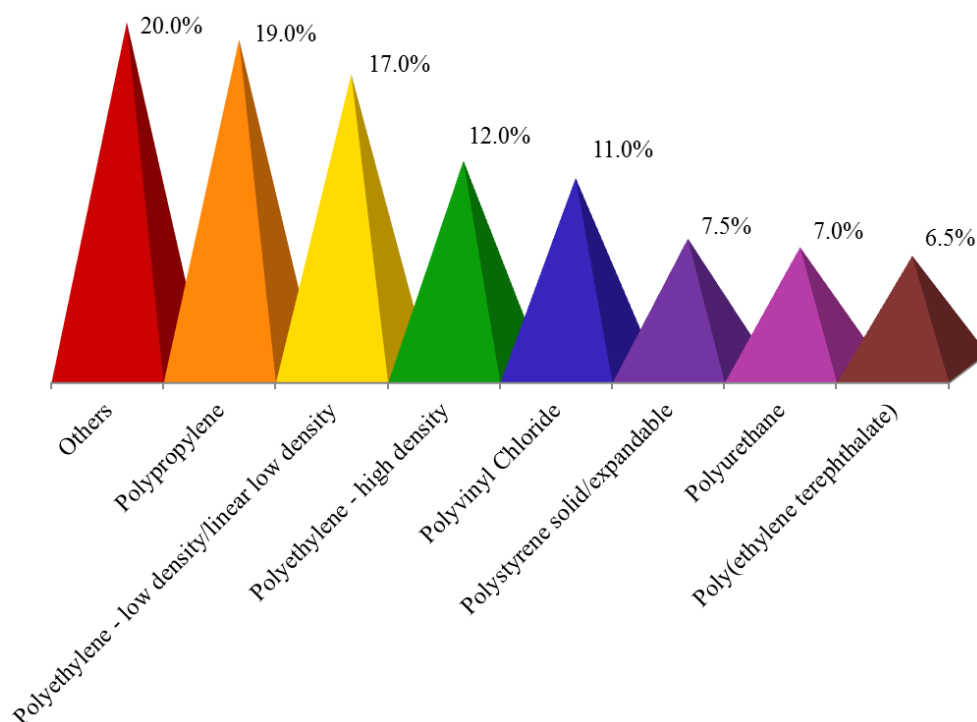
Poly(ethylene terephthalate) (PET) is a semicrystalline, thermoplastic polyester [36–39]. It is manufactured by a number of separate companies, under different trade names (Table 1). PET is strong

and durable, chemically and thermally stable, has low gas permeability and is easily processed and handled [38,39]. This combination of properties makes PET a desirable material for a wide range of applications and a significant component of worldwide plastic consumption. PET comprises 6.5% of European plastic demand—an excess of over 3,000 tonnes (see Figure 1) [40]. More than 50% of synthetic fibres produced around the world consist of PET, and global consumption of PET has been reported to exceed \$17 billion per year [41].

Table 1. Manufacturers and commercial names of poly(ethylene terephthalate) (PET).

Manufacturer	Commercial name
DSM Engineering Plastics	Arnitel [®]
Du Pont De Nemours & Co., Inc.	Mylar [®]
Du Pont De Nemours & Co., Inc.	Rynite [®]
Eastman Chemical Company	Eastapac [®]
ENKA-Glazstoff	Diolen [®]
Farbwerke Hoescht AG	Hostadur [®]
Imperial Chemical Industries Ltd.	Melinex [®]

Figure 1. European plastic demand by resin type for the year 2011 [40].



PET is primarily used as fibres, sheets and films, and more specifically, it is used in food and beverage packaging (especially, soft-drink and water bottles), electronics, automotive parts, houseware, lighting products, power tools, sports goods, photographic applications, X-ray sheets and textiles [38,39,41]. Depending on the intended application and desired properties, PET can be manufactured to specification by controlling the polymerisation conditions. Some of the specific properties of PET are summarised in Table 2.

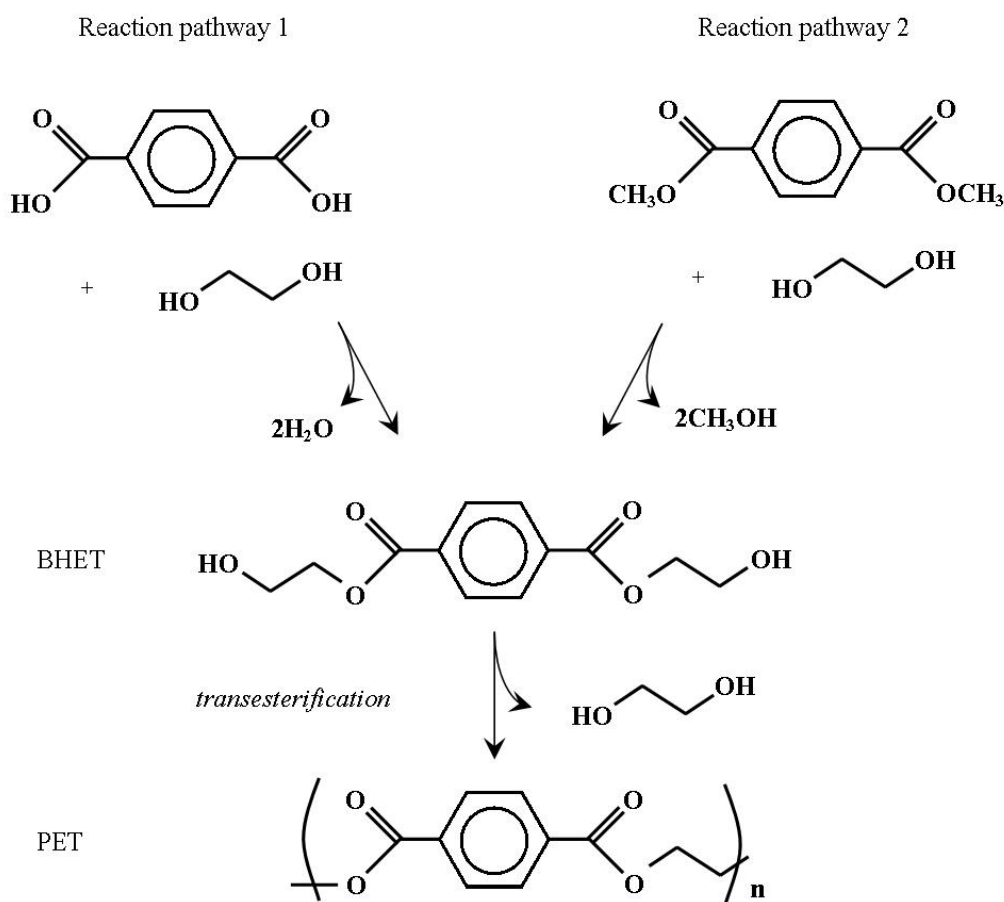
Table 2. Intrinsic properties of PET polymers.

Property	Value *
Average molecular weight	30,000–80,000 g mol ^{−1}
Density	1.41 g cm ^{−3}
Melting temperature	255–265 °C
Glass transition temperature	69–115 °C
Young's modulus	1700 MPa
Water absorption (24 h)	0.5%

* Values taken from Awaja and Pavel [38]. Values with ranges indicate properties, which vary depending on crystallinity and degree of polymerisation.

3.2. Chemistry, Synthesis and Manufacture

Commercial synthesis of PET begins with one of two chemical reactions: Ethylene glycol (EG) is reacted with either (1) terephthalic acid or (2) dimethyl terephthalate (DMT) [38,39]. Reaction 1 is performed at 240–260 °C and 300–500 kPa, while reaction 2 is performed at 140–220 °C and 100 kPa, and both yield bis(hydroxyethyl) terephthalate (BHET) [38,39]. After the initial reaction, two or three polymerisation steps are then performed, depending on the required molecular weight (Figure 2).

Figure 2. Chemical reactions of PET manufacturing.

The first polymerisation step is transesterification between BHET molecules, displacing EG, at 250–280 °C and 2–3 kPa [38,42]. The resulting oligomers are then polycondensed at 270–280 °C and

50–100 kPa [38,39]. At this stage, the polymer is suitable for applications that do not require high molecular weight chains, however if higher molecular weight is required, the polymer is subjected to a third, solid state polymerisation, at 200–240 °C and 100 kPa [38,39,41]. After synthesis of the raw polymer, it can then be processed into the required form, via extrusion, injection moulding or blow moulding [38].

Atmospheric CO₂ emissions for PET production, from cradle to gate, equate to approximately 2440 kg per 1000 kg of PET resin produced [43]. Advances in the catalytic synthesis of p-xylene, however, may work to reduce this environmental cost. P-xylene is an important constituent used in the production of terephthalic acid, with recent research showing that p-xylene has the potential to be produced from renewable sources, such as cellulose and hemicellulose biomass [44].

4. Plastic Disposal Methods

Currently, there are three main methods for plastic waste handling: burying in landfill, incineration and recycling [45]. Each has its own inherent limitations.

4.1. Landfill

The first drawback associated with disposal of plastic waste is the fact that landfill facilities occupy space that could be utilised for more productive means, such as agriculture [45]. This is compounded by the slow degradability of most plastics, as this means the occupied land is unavailable for long periods of time. Plastic components of landfill waste have been shown to persist for more than 20 years [46]. This is due to the limited availability of oxygen in landfills; the surrounding environment is essentially anaerobic [47,48]. The limited degradation that is experienced by many plastics is largely due to thermooxidative degradation [33], and the anaerobic conditions in landfills only serves to further limit degradation rates.

Plastic debris in landfill also acts as a source for a number of secondary environmental pollutants [45]. Pollutants of note include volatile organics, such as benzene, toluene, xylenes, ethyl benzenes and trimethyl benzenes, released both as gases and contained in leachate [49] and endocrine disrupting compounds, in particular BPA [50–52]. In addition to its endocrine disruption properties, BPA released from plastics in landfill has also been shown to lead to an increase in production of hydrogen sulphide by sulphate-reducing bacteria in soil populations [52]. High concentrations of hydrogen sulphide are potentially lethal [52].

4.2. Incineration

Another technique routinely used for disposal of plastic waste is incineration [45]. Plastic incineration overcomes some of the limitations placed on landfill in that it does not require any significant space, and there is even the capability for energy recovery in the form of heat [41]. However, there is a significant trade-off in that incineration of plastics leads to the formation of numerous harmful compounds, most of which are released to the atmosphere [45]. PAHs, PCBs, heavy metals, toxic carbon- and oxygen-based free radicals, not to mention significant quantities of greenhouse gases, especially carbon dioxide, are all produced and released when plastics are

incinerated [53–57]. The significant environmental drawbacks of plastic disposal via both landfill and incineration were the driving force behind the development of plastic recycling processes.

4.3. Recycling

There are two approaches currently in widespread use for the recycling of PET: chemical and mechanical processing [38]. Chemical processing of PET is performed by carrying out chemolysis with one of a number of compounds, resulting in depolymerisation of the plastic [38]. Depolymerisation can be carried out by hydrolysis (using water), methanolysis (methanol), glycolysis (EG) or aminolysis (e.g., methylamine,) [38,41]. Each results in different monomer units that can be recovered, but all of the monomers can be used as polymerisation materials to produce new plastic. Mechanical processing, however, is generally preferred to chemolysis, because even though it is a complicated process, it has the advantage of being much more cost effective [38].

Mechanical recycling of PET consists of several individual steps [38], the first of which is the removal of as much contaminating material as possible. The minimum requirements for PET flakes to undergo mechanolytic recycling are listed in Table 3.

Table 3. Minimum requirements of PET flakes to undergo mechanical recycling.

Property	Requirement
Flake size	0.4–8 mm
Melting temperature	>240 °C
Viscosity (η)	>0.7 dL g ⁻¹
Water content	<0.02%
Dye content	<10 ppm
PVC content	<50 ppm
Polyolefin content	<10 ppm
Metal content	<3 ppm
Yellowing index *	<20

* Yellowing index is a measure of the tendency of polymers to turn yellow through photodegradation.

There are a number of contaminants that can significantly inhibit the recycling process and result in severe deterioration of the recovered plastic [38]. These contaminants will be discussed later in this section. The first step in contamination removal is sorting of plastic waste in order to separate the PET from other plastics. It is of particular importance that PVC be removed from the PET to be recycled, and this is typically done manually [38]. After sorting, the PET is ground into flakes and washed, either using 2% NaOH and detergent at 80 °C followed by rinsing in cold water, or using tetrachloroethylene [38]. After washing, the PET must be dried, usually under desiccation at ~170 °C for six hours [38]. Washed and dried flakes are then ready to be melted down and extruded into new forms; however, it is at this step that the practical limitations of mechanolysis arise. Contaminants still reside within the PET flakes, and under high extrusion temperatures, they lead to hydrolytic and thermal degradation and subsequent decreases in both the molecular weight and intrinsic viscosity of the plastic [38].

There are a number of contaminants that can significantly limit the effectiveness of PET recycling processes. The first class of contaminants is acids and acid-producing contaminants, for example,

PVC, which produces hydrochloric acid [38,58]. Acids act as catalysts for chain cleavage reactions [59,60]. Similarly, elevated water content can lead to chain breakage through hydrolysis. Most water contamination arises from the washing process and can be removed by proper drying [38]. Dyes and colouring agents can lead to undesirable colours in recycled plastic [38]. Finally, contaminants, such as acetaldehyde (a natural degradation product of PET) and other contaminants arising from misuse of PET by consumers (such as storage of fuel, pesticides, and other dangerous materials) are potential health hazards in recycled PET products [61,62].

While recycling processes address the environmental shortcomings of both landfill and incineration, it is a relatively expensive and inefficient process [29,45]. The presence of additives and impurities can complicate the recycling procedure and decrease both the yield and quality of the recovered product [38,45].

4.4. Biodegradation

The metabolic diversity of bacteria makes them a useful resource for remediation of pollution in the environment [63]. Bacteria have been utilised in the clean-up of oil spills [64–67], PCBs [68] and heavy metals, such as arsenic, mercury, cadmium and lead [69,70]. There are sufficient examples to suggest there are few if any substances that cannot be utilised at least in part by microbes for metabolic activities [63]. Biodegradation is an attractive alternative to current practices for waste disposal, as it is generally a cheaper process, potentially much more efficient and does not produce secondary pollutants, such as those associated with incineration and landfill [63,64,68,70,71]. In some cases, it may even be possible to obtain useful end products with economic benefit from bacterial metabolism of pollutants, for example, ethanol for use in biofuels [63].

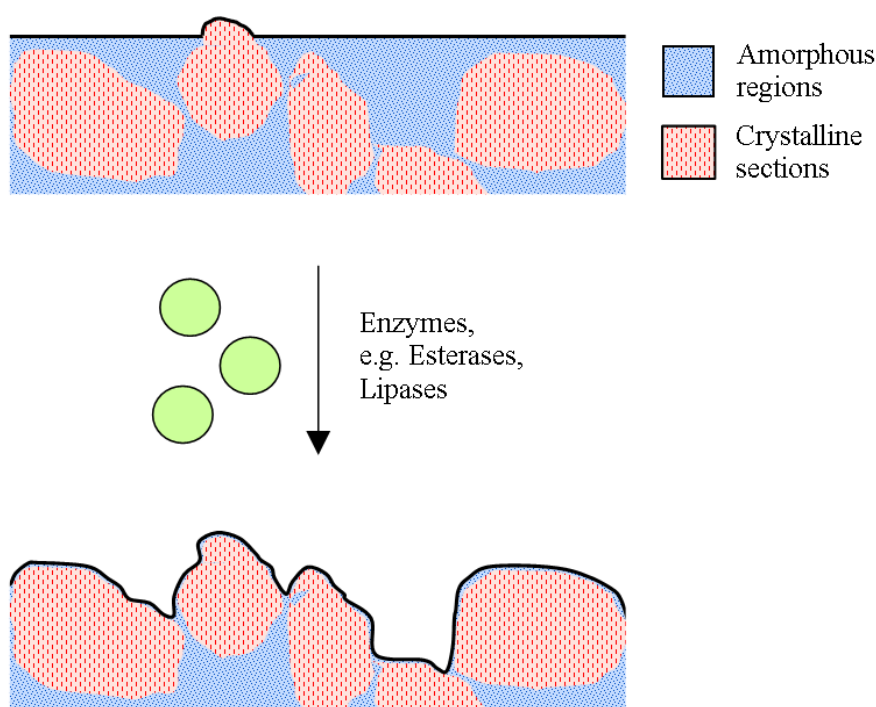
Bioremediation of hydrocarbons, crude oil, for example, poses a number of practical difficulties. Bacteria prefer aqueous nutrients [63] and hydrocarbons are often immiscible with water. Also, hydrocarbons are largely deficient in certain essential elements, namely nitrogen, potassium and phosphorus [63,65]. It has been shown in the literature that manually adding these elements in the form of fertiliser or ammonium sulphate can significantly aid the degradation of hydrocarbons by bacteria [65]. Hydrocarbons also actively interfere with cell membranes, accumulating within and disrupting the phospholipid bilayer [71], however, some bacteria have even been isolated that resist organic solvents [71].

Many studies have investigated the degradability of a wide range of polymers [29,32,45,72–75]. Zheng *et al.* [30] observed that in most cases, polymers with pure carbon backbones are particularly resistant to most methods of degradation, but polymers that include heteroatoms in the backbone (e.g., polyesters, polyamines) show higher susceptibility to degradation. While this is often true, there is, however, a secondary qualifier in the latter case; aromatic polymers tend to be resistant to degradation, despite the presence of bonds that are normally readily hydrolysed [30,35]. PET is a classic example of such a polymer; the ester bonds that form part of the polymer chain could normally be quite easily broken by a number of mechanisms, however, due to its aromatic groups, the polymer is essentially non-degradable under normal conditions.

While the PET polymer is particularly stable and durable, it has been shown that microbial communities are capable of utilising diethylene glycol terephthalate (DTP), a subunit of PET, as a sole

carbon and energy source [45]. This suggests that the reason for the extreme stability arises from being in a polymeric state. There have been a few studies that have established a link between plastic degradability and the degree of crystallisation of the polymer [39,72,73,75–77]. Increased crystallisation limits chain movement and decreases the availability of polymer chains for degradative agents, such as microbial lipases or other ester lysing molecules (Figure 3). Evidence for this can be seen in the lipase-catalysed degradation of poly(hydroxybutyrate-co-valerate) (PHBV), which has been shown to occur preferentially in the amorphous regions, exposing the polymer crystals [78]. Efforts to increase the biodegradability of PET have focussed on modifications of the polymer to decrease the intermolecular cohesion [31,75,79,80]; however, this approach dictates the need to find a compromise between optimum biodegradability and the mechanical and chemical stability for which PET is chosen for so many applications.

Figure 3. Schematic representation of the effect of polymer crystallinity on enzymatic degradation. Microbial enzymes are only able to degrade amorphous regions of the polymer, and the depth of degradation is limited by the adjacent crystalline regions.



4.5. Biodegradable Polymers

Over the last ten years, there has been a shift away from investigation of the degradability of traditional plastics, with more and more emphasis placed on the development of novel biodegradable polymers, some of which are listed in Table 4, below. Many biodegradable polymers currently exist, both natural and synthetic, however, the two major barriers to their incorporation in current plastic-based applications are increased production costs and inferior material properties, e.g., decreased durability [30,81]. Production costs can be minimised through the continued development of manufacturing protocols and increasing efficiency, but substantial research is still required to produce biodegradable polymers with comparable physical properties to conventional plastics. Regardless,

some progress has been made in the field of biodegradable plastics, and a number of strategies have emerged for their development.

Table 4. Biodegradation rate and ^{Ed}K of a range of biodegradable polymers (values taken from Guo *et al.* [82].)

Polymer	Biodegradation rate (%) ^a	^{Ed}K ^b
starch	78.34 ± 1.74	100.00 ± 0.00
pullulan	73.77 ± 1.35	94.22 ± 3.74
curdlan	64.60 ± 1.79	82.50 ± 3.13
Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), PHBHHx	62.12 ± 0.88	79.36 ± 1.28
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate), PHBV	53.47 ± 0.67	68.29 ± 2.28
Poly(ester amide), PEA	36.29 ± 1.84	46.34 ± 2.58
Poly(e-caprolactone), PCL	25.68 ± 0.7	32.77 ± 0.21
cellulose	25.00 ± 0.6	31.93 ± 1.36
chitosan	14.86 ± 0.42	18.98 ± 0.71
Poly(ethylene glycol), PEG	11.97 ± 0.39	15.28 ± 0.42
Poly(vinyl alcohol), PVA	5.02 ± 0.44	6.41 ± 0.53
Poly(ethylene oxide), PEO	3.76 ± 0.26	4.81 ± 0.43
Poly(propylene carbonate), PPC	3.38 ± 0.26	4.31 ± 0.27
Poly(butylenes succinate-co-adipate), PBSA	2.90 ± 0.26	3.70 ± 0.32
Poly(butylenes succinate), PBS	1.93 ± 0.10	2.47 ± 0.16
Poly(lactic acid), PLA	0.97 ± 0.26	1.23 ± 0.32
Polyethylene, PE	0.00 ± 0.00	0.00 ± 0.00

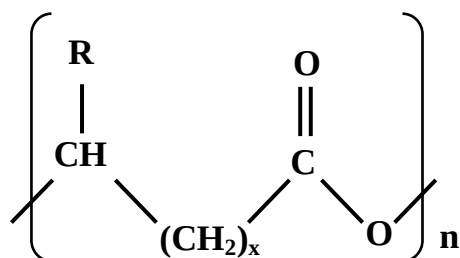
^a Biodegradation rate: calculated as the CO₂ released during analysis, divided by the theoretical CO₂ contained in the sample; ^b ^{Ed}K : Used to quantitatively evaluate the potential biodegradability of biodegradable polymers in the natural environment. Natural soil samples were inoculated into bioreactors, and rates of biodegradation of reference materials were determined over a 2-week period. Starch and polyethylene were used as reference materials to define the ^{Ed}K values of 100 and 0, respectively. Values determined using the ISO 14852 method, detecting the evolved carbon dioxide as an analytical parameter.

One approach for production of biodegradable plastics is to produce materials based on conventional plastics with enhanced degradability, without compromising the material properties. For example, polymers with additional functional groups on the polymer chains have been produced by both post-polymerisation treatments [29,74] and copolymerisation with equivalent functionalised monomers [31]. The rationale behind this is to create increased opportunities for microbial enzymes to attack the polymer chains. However, biodegradation of these polymers is still relatively limited, and for degradation to occur, there is a requirement for substantial energy input, especially for the post-polymerisation treated materials. Better degradation rates have been achieved when producing block copolymers of conventional plastics with readily hydrolysable polymeric molecules. Common examples are starch, lactic acid, ethylene glycol and caprolactone [34,39,83–85]. Unfortunately, these types of polymers are significantly less durable than many conventional plastics, and in many cases, it is unclear whether these polymers are truly biodegraded or whether they simply disintegrate into small pieces.

Development of plastics based on biological molecules has been a popular area of research. Polymers have been produced based partially or entirely on starch [34,83,84,86], lactic acid [87,88],

caprolactone [89], proteins [90], cellulose acetate [91] and other polysaccharides [92], and in many cases, the mechanical durability of these polymers has been improved through addition of plasticisers [90,92] or nanoparticles [89] or by carefully controlling production conditions [84]. One of the most significant groups of biopolymers is poly(hydroxyalkanoates) (PHAs). PHAs are polymeric materials naturally produced by many bacteria and some archaea, which can be processed into a number of forms suitable for packaging, coatings and biomedical applications [93]. The general structure of PHAs is given below in Figure 4. PHAs are produced commercially through bacterial fermentation, although quantities are somewhat limited due to inflated production expenses in comparison to conventional plastics and the lack of high-value applications [94–96]. Manufacturers have been able to decrease expenses to some degree by utilising cheaper foodstocks for metabolism by bacteria; PHAs can be produced from waste materials, such as whey, wheat and rice bran, molasses, vegetable oil and even carbon dioxide [95], however, the main prohibitive expense remains the extraction procedure for recovery of the polymer [96]. Extraction methods include solvent extraction, chemical digestion, enzymatic treatment, mechanical disruption, supercritical fluid disruption, flotation, gamma irradiation and two-phase systems, however, as of yet, no sufficiently inexpensive extraction technique has been developed to allow PHAs to truly compete with conventional plastics in terms of market share [96].

Figure 4. General molecular structure of poly(hydroxyalkanoates) (PHAs). R side chains consist of alkyl groups up to 13 carbon atoms in length, and the number of consecutive CH₂ groups in the polymer backbone (x) ranges from 1 to 4.



Despite the significant work that has been conducted into the development of biodegradable polymers, it seems unlikely that any polymer that undergoes significant environmental degradation will ever be able to compete with conventional synthetic plastics in terms of material properties and widespread application. The very reason conventional plastics are popular across a wide range of applications is their physical and chemical stability, which is also the cause of their lack of degradability. Therefore, any attempt to increase biodegradability is highly likely to compromise the physical properties of the material to some degree. There is, however, potential for case-by-case compromises between degradability and durability on the basis of the intended application.

5. Conclusions and Summary

Plastic accumulation, particularly in the world's oceans, is of increasing environmental concern. One of the major components of plastic waste is poly(ethylene terephthalate) (PET), a polymer frequently used in many applications, including textiles and food packaging. PET is highly resistant to environmental biodegradation and, thus, causes many and varied environmental concerns associated

with its accumulation, including, but not limited to, absorption and concentration of organic pollutants, hazardous effects on marine wildlife and dissemination of potentially invasive species to new environments. To date, only three plastic disposal methods are routinely used on a large scale: landfill, incineration and recycling. Each technique has disadvantages and drawbacks. Landfill and incineration both lead to the release of dangerous secondary pollutants into the environment, and landfill also has an additional drawback in the requirement of large portions of land space. Recycling addresses the environmental concerns of landfill and incineration, however, the process is relatively inefficient and the diminishing quality of the polymer yielded is a limiting factor. The process is also less cost-effective, and subsequently, there is less incentive for investment in recycling facilities. Biodegradation is an attractive option for environmentally friendly and efficient disposal of plastic waste. To date, no protocol has yet been developed to feasibly dispose of PET by biodegradation on a commercial scale; however, substantial research is still being conducted in the field of biodegradation of polymers, and given the vast metabolic potential of microorganisms, it is expected that it is simply a matter of time before viable biodegradation processes are developed.

References

1. Derraik, J.G.B. The pollution of the marine environment by plastic debris: A review. *Mar. Pollut. Bull.* **2002**, *44*, 842–852.
2. Pemberton, D.; Brothers, N.P.; Kirkwood, R. Entanglement of Australian fur seals in man-made debris in Tasmanian waters. *Wildl. Res.* **1992**, *19*, 151–159.
3. Sazima, I.; Gadig, O.B.F.; Namora, R.C.; Motta, F.S. Plastic debris collars on juvenile carcharhinid sharks (*Rhizoprionodon lalandii*) in southwest Atlantic. *Mar. Pollut. Bull.* **2002**, *44*, 1147–1149.
4. Gregory, M.R. Environmental implications of plastic debris in marine settings—Entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philos. Trans. R. Soc. B* **2009**, *364*, 2013–2025.
5. Azzarello, M.Y.; van Vleet, E.S. Marine birds and plastic pollution. *Mar. Ecol. Prog. Ser.* **1987**, *37*, 295–303.
6. Blight, L.K.; Burger, A.E. Occurrence of plastic particles in sea-birds from the eastern north pacific. *Mar. Pollut. Bull.* **1997**, *34*, 323–325.
7. Barreiros, J.P.; Barcelos, J. Plastic ingestion by a leatherback turtle *Dermochelys coriacea* from the Azores (NE Atlantic). *Mar. Pollut. Bull.* **2001**, *42*, 1196–1197.
8. Baird, R.W.; Hooker, S.K. Ingestion of plastic and unusual prey by a juvenile harbour porpoise. *Mar. Pollut. Bull.* **2000**, *40*, 719–720.
9. Moore, C.J.; Moore, S.L.; Leecaster, M.K.; Weisberg, S.B. A comparison of plastic and plankton in the north Pacific central gyre. *Mar. Pollut. Bull.* **2001**, *42*, 1297–1300.
10. Mato, Y.; Isobe, T.; Takada, H.; Kanehiro, H.; Ohtake, C.; Kaminuma, T. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ. Sci. Technol.* **2001**, *35*, 318–324.
11. Rios, L.M.; Moore, C.; Jones, P.R. Persistent organic pollutants carried by synthetic polymers in the ocean environment. *Mar. Pollut. Bull.* **2007**, *54*, 1230–1237.

12. Hirai, H.; Takada, H.; Ogata, Y.; Yamashita, R.; Mizukawa, K.; Saha, M.; Kwan, C.; Moore, C.; Gray, H.; Laursen, D.; Zettler, E.R.; Farrington, J.W.; Reddy, C.M.; Peacock, E.E.; Ward, M.W. Organic micropollutants in marine plastic debris from the open ocean and remote and urban beaches. *Mar. Pollut. Bull.* **2011**, *62*, 1683–1692.
13. Schecter, A.; Colacino, J.; Haffner, D.; Patel, K.; Opel, M.; Pöpke, O.; Birnbaum, L. Perfluorinated compounds, polychlorinated biphenyls, and organochlorine pesticide contamination in composite food samples from Dallas, Texas, USA. *Environ. Health Perspect.* **2010**, *118*, 796–802.
14. Trudel, D.; Scheringer, M.; von Goetz, N.; Hungerbühler, K. Total consumer exposure to polybrominated diphenyl ethers in North America and Europe. *Environ. Sci. Technol.* **2011**, *45*, 2391–2397.
15. Chung, S.Y.; Yettella, R.R.; Kim, J.S.; Kwon, K.; Kim, M.C.; Min, D.B. Effects of grilling and roasting on the levels of polycyclic aromatic hydrocarbons in beef and pork. *Food Chem.* **2011**, *129*, 1420–1426.
16. Zhou, Q.; Gao, Y.; Xie, G. Determination of bisphenol A, 4-*n*-nonylphenol, and 4-*tert*-octylphenol by temperature-controlled ionic liquid dispersive liquid-phase microextraction combined with high performance liquid chromatography-fluorescence detector. *Talanta* **2011**, *85*, 1598–1602.
17. Masó, M.; Garcés, E.; Pagès, F.; Camp, J. Drifting plastic debris as a potential vector for harmful algal bloom (HAB) species. *Sci. Mar.* **2003**, *67*, 107–111.
18. Wheeler, W.M. Ants carried in a floating log from the Brazilian mainland to San Sebastian Island. *Psyche* **1916**, *23*, 180–183.
19. Censky, E.J.; Hodge, K.; Dudley, J. Over-water dispersal of lizards due to hurricanes. *Nature* **1998**, *395*, 556.
20. Barnes, D.K.A.; Milner, P. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Mar. Biol.* **2005**, *146*, 815–825.
21. Frost, A.; Cullen, M. Marine debris on northern New South Wales beaches (Australia): Sources and the role of beach usage. *Mar. Pollut. Bull.* **1997**, *34*, 348–352.
22. Walker, T.R.; Reid, K.; Arnould, J.P.Y.; Croxall, J.P. Marine debris surveys at Bird Island, South Georgia 1990–1995. *Mar. Pollut. Bull.* **1997**, *34*, 61–65.
23. Martinez-Ribes, L.; Basterretxea, G.; Palmer, M.; Tintoré, J. Origin and abundance of beach debris in the Balearic Islands. *Sci. Mar.* **2007**, *71*, 305–314.
24. Morishige, C.; Donohue, M.J.; Flint, E.; Swenson, C.; Woolaway, C. Factors affecting marine debris deposition at French Frigate Shoals, northwestern Hawaiian islands marine national monument, 1990–2006. *Mar. Pollut. Bull.* **2007**, *54*, 1162–1169.
25. Santos, I.R.; Friedrich, A.C.; Ivar do Sul, J.A. Marine debris contamination along undeveloped tropical beaches from northeast Brazil. *Environ. Monit. Assess.* **2008**, *148*, 455–462.
26. Ivar do Sul, J.A.; Costa, M.F. Marine debris review for Latin America and the wider Caribbean region: From the 1970s until now, and where do we go from here? *Mar. Pollut. Bull.* **2007**, *54*, 1087–1104.

27. Law, K.L.; Morét-Ferguson, S.; Maximenko, N.A.; Proskurowski, G.; Peacock, E.E.; Hafner, J.; Reddy, C.M. Plastic accumulation in the North Atlantic subtropical gyre. *Science* **2010**, *329*, 1185–1188.
28. Ryan, P.G.; Moore, C.J.; van Franeker, J.A.; Moloney, C.L. Monitoring the abundance of plastic debris in the marine environment. *Philos. T. Roy. Soc. B* **2009**, *364*, 1999–2012.
29. Yamada-Onodera, K.; Mukumoto, H.; Katsuyaya, Y.; Saiganji, A.; Tani, Y. Degradation of polyethylene by a fungus, *Penicillium simplicissimum* YK. *Polym. Degrad. Stabil.* **2001**, *72*, 323–327.
30. Zheng, Y.; Yanful, E.K.; Bassi, A.S. A review of plastic waste biodegradation. *Crit. Rev. Biotechnol.* **2005**, *25*, 243–250.
31. Marqués-Calvo, M.S.; Cerdà-Cuellar, M.; Kint, D.P.R.; Bou, J.J.; Muñoz-Guerra, S. Enzymatic and microbial biodegradability of poly(ethylene terephthalate) copolymers containing nitrated units. *Polym. Degrad. Stabil.* **2006**, *91*, 663–671.
32. Bonhomme, S.; Cueur, A.; Delort, A.-M.; Lemaire, J.; Sancelme, M.; Scott, G. Environmental degradation of polyethylene. *Polym. Degrad. Stabil.* **2003**, *81*, 441–452.
33. Andrady, A.L. Microplastics in the marine environment. *Mar. Pollut. Bull.* **2011**, *62*, 1596–1605.
34. Raquez, J.-M.; Bourgeois, A.; Jacobs, H.; Degée, P.; Alexandre, M.; Dubois, P. Oxidative degradations of oxodegradable LDPE enhanced with thermoplastic pea starch: thermo-mechanical properties, morphology, and UV-ageing studies. *J. Appl. Polym. Sci.* **2011**, *122*, 489–496.
35. Müller, R.-J.; Kleeberg, I.; Deckwer, W.-D. Biodegradation of polyesters containing aromatic constituents. *J. Biotechnol.* **2001**, *86*, 87–95.
36. Levchik, S.V.; Weil, E.D. A review on thermal decomposition and combustion of thermoplastic polyesters. *Polym. Adv. Technol.* **2004**, *15*, 691–700.
37. Bergeret, A.; Ferry, L.; Ienny, P. Influence of the fibre/matrix interface on ageing mechanisms of glass fibre reinforced thermoplastic composites (PA-6,6, PET, PBT) in a hygrothermal environment. *Polym. Degrad. Stabil.* **2009**, *94*, 1315–1324.
38. Awaja, F.; Pavel, D. Recycling of PET. *Eur. Polym. J.* **2005**, *41*, 1453–1477.
39. Kint, D.; Muñoz-Guerra, S. A review on the potential biodegradability of poly(ethylene terephthalate). *Polym. Int.* **1999**, *48*, 346–352.
40. PlasticsEurope. Plastics—The Facts 2012. Available online: <http://www.plasticseurope.org/Document/plastics-the-facts-2012.aspx?FolID=2> (accessed on 24 December 2012).
41. Sinha, V.; Patel, M.R.; Patel, J.V. PET waste management by chemical recycling: A review. *J. Polym. Environ.* **2010**, *18*, 8–25.
42. Amari, T.; Ozaki, Y. Real-time monitoring of the initial oligomerization of bis(hydroxyethyl) terephthalate by attenuated total reflection/infrared spectroscopy and chemometrics. *Macromolecules* **2001**, *34*, 7459–7462.
43. Franklin Associates. *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*; The Plastics Division of the American Chemistry Council: Prairie Village, KS, USA, 2011.
44. Williams, C.L.; Chang, C.C.; Do, P.; Nikbin, N.; Caratzoulas, S.; Vlachos, D.G.; Lobo, R.F.; Fan, W.; Dauenhauer, P.J. Cycloaddition of biomass-derived furans for catalytic production of renewable p-xylene. *ACS Catal.* **2012**, *2*, 935–939.

45. Zhang, J.; Wang, X.; Gong, J.; Gu, Z. A study on the biodegradability of polyethylene terephthalate fiber and diethylene glycol terephthalate. *J. Appl. Polym. Sci.* **2004**, *93*, 1089–1096.
46. Tansel, B.; Yildiz, B.S. Goal-based waste management strategy to reduce persistence of contaminants in leachate at municipal solid waste landfills. *Environ. Dev. Sustain.* **2011**, *13*, 821–831.
47. Massardier-Nageotte, V.; Pestre, C.; Cruard-Pardet, T.; Bayard, R. Aerobic and anerobic biodegradability of polymer films and physico-chemical characterization. *Polym. Degrad. Stabil.* **2006**, *91*, 620–627.
48. Tollner, E.W.; Annis, P.A.; Das, K.C. Evaluation of strength properties of polypropylene-based polymers in simulated landfill and oven conditions. *J. Environ. Eng.* **2011**, *137*, 291–296.
49. Urase, T.; Okumura, H.; Panyosaranya, S.; Inamura, A. Emission of volatile organic compounds from solid waste disposal sites and importance of heat management. *Waste Manag. Res.* **2008**, *26*, 534–538.
50. Xu, S.-Y.; Zhang, H.; He, P.-J.; Shao, L.-M. Leaching behaviour of bisphenol A from municipal solid waste under landfill environment. *Environ. Technol.* **2011**, *32*, 1269–1277.
51. Svenson, A.; Sjöholm, S.; Allard, A.-S.; Kaj, L. Antiestrogenicity and estrogenicity in leachates from solid waste deposits. *Environ. Toxicol.* **2009**, *26*, 233–239.
52. Tsuchida, D.; Kajihara, Y.; Shimidzu, N.; Hamamura, K.; Nagase, M. Hydrogen sulfide production by sulfate-reducing bacteria utilizing additives eluted from plastic resins. *Waste Manag. Res.* **2011**, *29*, 594–601.
53. Astrup, T.; Møller, J.; Fruergaard, T. Incineration and co-combustion of waste: Accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* **2009**, *27*, 789–799.
54. Khoo, H.H.; Tan, R.B.H. Environmental impacts of conventional plastic and bio-based carrier bags: Part 2: End-of-life options. *Int. J. Life Cycle Assess.* **2010**, *15*, 338–345.
55. Shen, C.; Tang, X.; Yao, J.; Shi, D.; Fang, J.; Khan, M.I.; Cheema, S.A.; Chen, Y. Levels and patterns of polycyclic aromatic hydrocabons and polychlorinated biphenyls in municipal waste incinerator bottom ash in Zhejiang province, China. *J. Hazard. Mater.* **2010**, *179*, 197–202.
56. Simoneit, B.R.T.; Medeiros, P.M.; Didyk, B.M. Combustion products of plastics as indicators for refuse burning in the atmosphere. *Environ. Sci. Technol.* **2005**, *39*, 6961–6970.
57. Valavanidis, A.; Iliopoulos, N.; Gotsis, G.; Fiotakis, K. Persistent free-radicals, heavy metals and PAHs generated in particulate soot emissions and residue ash from controlled combustion of common types of plastics. *J. Hazard. Mater.* **2008**, *156*, 277–284.
58. Paci, M.; La Mantia, F.P. Influence of small amounts of polyvinylchloride on the recycling of polyethyleneterephthalate. *Polym. Degrad. Stabil.* **1999**, *63*, 11–14.
59. Cardi, N.; Po, R.; Giannotta, G.; Occhiello, E.; Garbassi, F.; Messina, G. Chain extension of recycled poly(ethylene terephthalate) with 2,2'-Bis(2-oxazoline). *J. Appl. Polym. Sci.* **1993**, *50*, 1501–1509.
60. Paci, M.; La Mantia, F.P. Competition between degradation and chain extension during processing of reclaimed poly(ethylene terephthalate). *Polym. Degrad. Stabil.* **1998**, *61*, 417–420.
61. Villain, F.; Coudane, J.; Vert, M. Thermal degradation of polyethylene terephthalate: Study of polymer stabilization. *Polym. Degrad. Stabil.* **1995**, *49*, 393–397.

62. Demertzis, P.G.; Johansson, F.; Lievens, C.; Franz, R. Studies on the development of a quick inertness test procedure for multi-use PET containers—Sorption behaviour of bottle wall strips. *Packag. Technol. Sci.* **1997**, *10*, 45–58.
63. Iranzo, M.; Sainz-Pardo, I.; Boluda, R.; Sánchez, J.; Mormeneo, S. The use of microorganisms in environmental remediation. *Ann. Microbiol.* **2001**, *51*, 135–143.
64. Head, I.M.; Swannell, R.P.J. Bioremediation of petroleum hydrocarbon contaminants in marine habitats. *Curr. Opin. Biotechnol.* **1999**, *10*, 234–239.
65. Rosa, A.P.; Triguís, J.A. Bioremediation process on Brazil shoreline. Laboratory experiments. *Environ. Sci. Pollut. Res.* **2007**, *14*, 470–476.
66. Piedad Díaz, M.; Boyd, K.G.; Grigson, S.J.W.; Burgess, J.G. Biodegradation of crude oil across a wide range of salinities by an extremely halotolerant bacterial consortium MPD-M, immobilized onto polypropylene fibers. *Biotechnol. Bioeng.* **2002**, *79*, 145–153.
67. Hazen, T.C.; Dubinsky, E.A.; DeSantis, T.Z.; Andersen, G.L.; Piceno, Y.M.; Singh, N.; Jansson, J.K.; Probst, A.; Borglin, S.E.; Fortney, J.L.; Stringfellow, W.T.; Bill, M.; Conrad, M.E.; Tom, L.M.; Chavarria, K.L.; Alusi, T.R.; Lamendella, R.; Joyner, D.C.; Spier, C.; Baelum, J.; Auer, M.; Zemla, M.L.; Chakraborty, R.; Sonnenthal, E.L.; D'haeseleer, P.; Holman, H.-Y.N.; Osman, S.; Lu, Z.; van Nostrand, J.D.; Deng, Y.; Zhou, J.; Mason, O.U. Deep-sea oil plume enriches indigenous oil-degrading bacteria. *Science* **2010**, *330*, 204–208.
68. Luigi, M.; Gaetano, D.M.; Vivian, B.; Angelina, L.G. Biodegradative potential and characterization of psychrotolerant polychlorinated biphenyl-degrading marine bacteria isolated from a coastal station in the Terra Nova Bay (Ross Sea, Antarctica). *Mar. Pollut. Bull.* **2007**, *54*, 1754–1761.
69. De, J.; Ramaiah, N.; Vardanyan, L. Detoxification of toxic heavy metals by marine bacteria highly resistant to mercury. *Mar. Biotechnol.* **2008**, *10*, 471–477.
70. Takeuchi, M.; Kawahata, H.; Gupta, L.P.; Kita, N.; Morishita, Y.; Ono, Y.; Komai, T. Arsenic resistance and removal by marine and non-marine bacteria. *J. Biotechnol.* **2007**, *127*, 434–442.
71. Pieper, D.H.; Reineke, W. Engineering bacteria for bioremediation. *Curr. Opin. Biotechnol.* **2000**, *11*, 262–270.
72. Müller, R.-J.; Schrader, H.; Profe, J.; Dresler, K.; Deckwer, W.-D. Enzymatic degradation of poly(ethylene terephthalate): rapid hydrolyse using a hydrolase from *T. fusca*. *Macromol. Rapid Comm.* **2005**, *26*, 1400–1405.
73. Herzog, K.; Müller, R.-J.; Deckwer, W.-D. Mechanism and kinetics of the enzymatic hydrolysis of polyester nanoparticles by lipases. *Polym. Degrad. Stabil.* **2006**, *91*, 2486–2498.
74. Artham, T.; Doble, M. Biodegradation of physicochemically treated polycarbonate by fungi. *Biomacromolecules* **2009**, *11*, 20–28.
75. Kondratowicz, F.L.; Ukielski, R. Synthesis and hydrolytic degradation of poly(ethylene succinate) and poly(ethylene terephthalate) copolymers. *Polym. Degrad. Stabil.* **2009**, *94*, 375–382.
76. Marten, E.; Müller, R.-J.; Deckwer, W.-D. Studies on the enzymatic hydrolysis of polyesters I. Low molecular mass model esters and aliphatic polyesters. *Polym. Degrad. Stabil.* **2003**, *80*, 485–501.
77. Asakuma, Y.; Nakagawa, K.; Maeda, K.; Fukui, K. Theoretical study of the transesterification reaction of polyethylene terephthalate under basic conditions. *Polym. Degrad. Stabil.* **2009**, *94*, 240–245.

78. Mueller, R.-J. Biological degradation of synthetic polyesters-enzymes as potential catalysts for polyester recycling. *Process Biochem.* **2006**, *41*, 2124–2128.
79. La Mantia, F.P.; Botta, L.; Morreale, M.; Scaffaro, R. Effects of small amounts of poly(lactic acid) on the recycling of poly(ethylene terephthalate) bottles. *Polym. Degrad. Stabil.* **2012**, *97*, 21–24.
80. Rwei, S.-P.; Lin, W.-P.; Wang, J.-F. Synthesis and characterization of biodegradable and weather-durable PET/PEG/NDC copolymers. *Colloid Polym. Sci.* **2012**, *290*, 1381–1392.
81. Amass, W.; Amass, A.; Tighe, B. A review of biodegradable polymers: Uses, current developments in the synthesis and characterization of biodegradable polyesters, blends of biodegradable polymers and recent advances in biodegradation studies. *Polym. Int.* **1998**, *47*, 89–144.
82. Guo, W.; Tao, J.; Yang, C.; Song, C.; Geng, W.; Li, Q.; Wang, Y.; Kong, M.; Wang, S. Introduction of environmentally degradable parameters to evaluate the biodegradability of biodegradable polymers. *PLoS ONE* **2012**, *7*.
83. Russo, M.A.L.; O'Sullivan, C.; Rounsefell, B.; Halley, P.J.; Truss, R.; Clarke, W.P. The anaerobic degradability of thermoplastic starch: Polyvinyl alcohol blends: Potential biodegradable food packaging materials. *Bioresour. Technol.* **2009**, *100*, 1705–1710.
84. Brandelero, R.P.H.; Grossmann, M.V.E.; Yamashita, F. Effect of the method of production of the blends on mechanical and structural properties of biodegradable starch films produced by blown extrusion. *Carbohydr. Polym.* **2011**, *86*, 1344–1350.
85. Kim, S.H.; Tan, J.P.K.; Fukushima, K.; Nederberg, F.; Yang, Y.Y.; Waymouth, R.M.; Hedrick, J.L. Thermoresponsive nanostructured polycarbonate block copolymers as biodegradable therapeutic delivery carriers. *Biomaterials* **2011**, *32*, 5505–5514.
86. Canché-Escamilla, G.; Canché-Canché, M.; Duarte-Aranda, S.; Cáceres-Farfán, M.; Borges-Argáez, R. Mechanical properties and biodegradation of thermoplastic starches obtained from grafted starches with acrylics. *Carbohydr. Polym.* **2011**, *86*, 1501–1508.
87. Nampoothiri, K.M.; Nair, N.R.; John, R.P. An overview of the recent developments in polylactide (PLA) research. *Bioresour. Technol.* **2010**, *101*, 8493–8501.
88. Ye, R.-R.; Wang, Z.-Y.; Wang, Q.-F.; Yang, K.; Luo, S.-H. Synthesis of biodegradable material poly(lactic acid-co-aspartic acid) via direct melt polycondensation and its characterization. *J. Appl. Polym. Sci.* **2011**, *121*, 3662–3668.
89. Neppalli, R.; Causin, V.; Marega, C.; Saini, R.; Mba, M.; Marigo, A. Structure, morphology and biodegradability of poly(ϵ -caprolactone)-based nanocomposites. *Polym. Eng. Sci.* **2011**, *51*, 1489–1496.
90. Verbeek, C.; van den Berg, L.E. Extrusion processing and properties of protein-based thermoplastics. *Macromol. Mater. Eng.* **2010**, *295*, 10–21.
91. Puls, J.; Wilson, S.A.; Höltzer, D. Degradation of cellulose acetate-based materials: A review. *J. Polym. Environ.* **2011**, *19*, 152–165.
92. Ghasemlou, M.; Khodaiyan, F.; Oromiehie, A.; Yarmand, M.S. Development and characterisation of a new biodegradable edible film made from kefir, an exopolysaccharide obtained from kefir grains. *Food Chem.* **2011**, *127*, 1496–1502.

93. Nitschke, M.; Costa, S.G.V.A.O.; Contiero, J. Rhamnolipids and PHAs: Recent reports on *Pseudomonas*-derived molecules of increasing industrial interest. *Process Biochem.* **2011**, *46*, 621–630.
94. Chen, G.-Q. A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. *Chem. Soc. Rev.* **2009**, *38*, 2434–2446.
95. Akaraonye, E.; Keshavarz, T.; Roy, I. Production of polyhydroxyalkanoates: The future green materials of choice. *J. Chem. Technol. Biotechnol.* **2010**, *85*, 732–743.
96. Kunasundari, B.; Sudesh, K. Isolation and recovery of microbial polyhydroxyalkanoates. *Express Polym. Lett.* **2011**, *5*, 620–634.

© 2013 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/>).