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REVIEW ARTICLE

Biodegradation of plastics: current scenario and future prospects for environmental safety

Temoor Ahmed[1] · Muhammad Shahid[1] · Farrukh Azeem[1] · Ijaz Rasul[1] · Asad Ali Shah[1] · Muhammad Noman[1] · Amir Hameed[1] · Natasha Manzoor[2] · Irfan Manzoor[1] · Sher Muhammad[1]

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Abstract

Plastic is a general term used for a wide range of high molecular weight organic polymers obtained mostly from the various hydrocarbon and petroleum derivatives. There is an ever-increasing trend towards the production and consumption of plastics due to their extensive industrial and domestic applications. However, a wide spectrum of these polymers is non-biodegradable with few exceptions. The extensive use of plastics, lack of waste management, and casual community behavior towards their proper disposal pose a significant threat to the environment. This has raised growing concerns among various stakeholders to devise policies and innovative strategies for plastic waste management, use of biodegradable polymers especially in packaging, and educating people for their proper disposal. Current polymer degradation strategies rely on chemical, thermal, photo, and biological procedures. In the presence of proper waste management strategies coupled with industrially controlled biodegradation facilities, the use of biodegradable plastics for some applications such as packaging or health industry is a promising and attractive option for economic, environmental, and health benefits. This review highlights the classification of plastics with special emphasis on biodegradable plastics and their rational use, the identified mechanisms of plastic biodegradation, the microorganisms involved in biodegradation, and the current insights into the research on biodegradable plastics. The review has also identified the research gaps in plastic biodegradation followed by future research directions.

Keywords Biodegradation · Bio-based plastics · Fossil-based polymers · Microorganisms · Mechanisms · Environment

Introduction

Plastics are polymer products consisting of a wide range of synthetic or semi-synthetic organic and inorganic compounds (Saminathan et al. 2014). They are made substantially from petrochemical materials extracted from coal, oil, and natural gas. Many polymer materials such as polyethylene (PE), polycaprolactone (PCL), polyurethane (PUR), polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polybutylene succinate (PBS), polylactic acid or polylactide (PLA), polypropylene (PP), and polystyrene (PS) are commonly used for various purposes (Muhamad et al. 2015; Yoshida et al. 2016). Most of the fossil-based and bio-based plastics, used nowadays, are non-biodegradable, e.g., PE, PP, PS, and PVC. Thus, these non-biodegradable plastics have been accumulated in the environment in large quantities due to improper waste management and uncontrolled littering and, thus, posed a serious threat to our planet (Sharma and Dhingra 2016). The long-term accumulation of non-biodegradable polymers in the soil led to a decrease in soil fertility in addition to many other ecological and health problems. As per global estimation, about 57 million tons of plastics waste is generated annually (Vijaya and Reddy 2008). In addition, the amount of plastic polymers in the oceans has exceeded sixtimes compared to plankton, due to which aquatic birds and fishes are in danger. Plastics and their additives are also causing serious problems related to human health (Comăniţă et al. 2016). Therefore, scientists and other stakeholders have shown great concern to overcome the accumulation of non-biodegradable plastics in the environment (Tokiwa and Calabia 2008).

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✉ Muhammad Shahid
shahidmpg@yahoo.com

[1] Department of Bioinformatics and Biotechnology, Government College University, Faisalabad 38000, Pakistan

[2] Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

There is a growing role of bio-based biodegradable plastics mainly in packaging as well as health and agriculture industry, but still, their contribution in plastic industry is very low. Moreover, their environmental safety and applicability are based on proper waste management as well as community training plans (Rujnić-Sokele and Pilipović 2017). Many studies have reported the striking ability of certain microorganisms including bacteria and fungi in fast degradation of both bio-based and fossil-based biodegradable polymers under stress conditions by producing exoenzymes and their products (Mohanty et al. 2000; Sharma et al. 2003, Ghosh et al. 2013). Important microbial enzymes responsible for polymer biodegradation are proteases, lipases, and cutinases (Tokiwa et al. 2009; Muhamad et al. 2015). Moreover, enzymes like esterases and lipases, produced by *Rhizopus delemar*, *R. arrhizus*, *Achromobacter* sp., and *Candida cylindracea*, have been shown to work on complex polymers like poly(ethylene adipate) and PCL (Jin et al. 2000; Lam et al. 2009). The share of biodegradable plastic polymers for commercial applications is very low mainly due to their complex structure and lack of knowledge about optimized conditions for fast degradation (Rujnić-Sokele and Pilipović 2017). If strategies such as proper waste management, garbage control, community education, and the development of industrial biodegradation facilities are adopted, biodegradable plastics could replace non-biodegradable polymers in at least some applications such as packaging to guarantee environmental safety.

Microorganisms use various mechanisms to degrade the complex polymers including direct use of plastic fragments as nutritional source or indirect action of various microbial enzymes. For biodegradation of polymers, the most widely used bacterial and fungal strains are *Pseudomonas fluorescens*, *P. aeruginosa*, and *Penicillium simplicissimum* (Norman et al. 2002; Singh and Sharma 2008; Raziyafathima et al. 2016). This review is focused on the classification of plastics with special emphasis on biodegradable plastics and the known mechanisms of microbial degradation of polymers. The rationality of use of biodegradable polymers in terms of environmental safety is also discussed. Finally, the current insights into research on biodegradable plastics followed by prospects of plastic biodegradation are also covered.

Classification of plastics based on biodegradability

There are two groups of plastics on the basis of biodegradability, i.e., non-biodegradable plastics and biodegradable plastics. Chemical structures of some plastic polymers (biodegradable and non-biodegradable) and the reported mechanisms of their degradation in specific studies are presented in Table 1.

Non-biodegradable plastics

Non-biodegradable plastics include both fossil-based and bio-based polymers. Most of the conventionally used non-biodegradable plastics are fossil-based synthetic polymers, which are obtained from the derivatives of hydrocarbon and petroleum (petrochemicals). Their molecular weight is high due to the extensive repetition of small monomer units (Ghosh et al. 2013). These plastics are highly stable and do not readily enter into the degradation cycles of the biosphere (Vijaya and Reddy 2008). Most of the commodity polymers employed nowadays are either non-biodegradable or their degradation rate is too slow to be disintegrated completely. Non-biodegradable plastics include many of the routinely used plastics like PVC, PP, PS, PET, PUR, and PE. Due to poor waste management and littering, they have been accumulated in the environment in huge amounts and have become a threat to the earth (Krueger et al. 2015). Plastics derived from polyolefins, like PE, are currently used for making plastic films for various plastic items such as sheets used for packaging, carry and shopping bags, and mugs. Because of the longevity and stability in the environment, polyolefins cause concerns due to lack of waste management. Therefore, it is necessary to promote waste management systems of such non-biodegradable polymers (Shah et al. 2008). Moreover, the properties of inertness and resistance to microbial attack in some of these polymers are deliberately lessened by incorporating starch and pro-oxidants to facilitate fragmentation (Vijaya and Reddy 2008). Nevertheless, oxo-biodegradable plastics are considered to be non-biodegradable because of lack of conclusive evidences of degradation (Reddy 2008).

Biodegradable plastics

Both bio-based and fossil-based polymers can be included in biodegradable plastics depending upon the degree of biodegradability and microbial assimilation. Biodegradation of plastics involves enzymatic and non-enzymatic hydrolysis (Wackett and Hershberger 2001). Type of organism, nature of pretreatment, and polymer characteristics are some of the factors affecting the efficiency of biodegradation processes. In addition, mobility, crystallinity, type of functional groups, tactility, chemical components, molecular weight, and additives present in polymers are some of the important characteristics for the degradation of plastics (Artham and Doble 2008). During degradation, microorganisms secrete exoenzymes that disintegrate polymer complexes into smaller molecules like dimers and monomers. Thus, small molecules are much tinier

Table 1 Some non-biodegradable and biodegradable polymers, their chemical structures, applications, and microorganisms involved in specific biodegradation studies

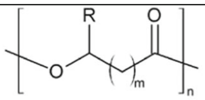
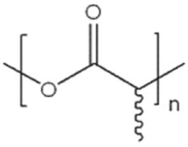
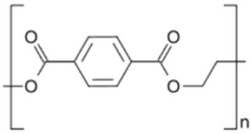
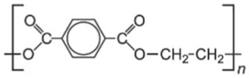
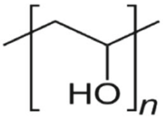
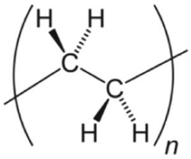
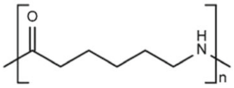
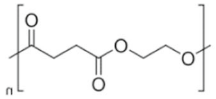
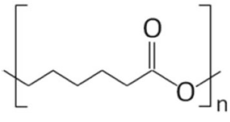
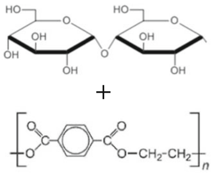
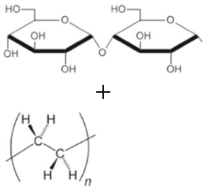
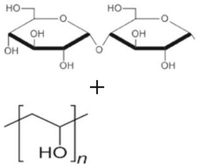
Plastics	Microorganism	Chemical Structure	Application	Reference
Biobased polymers				
Polyhydroxyalkanoates	*Pseudomonas stutzeri*		Packaging materials, disposable diapers, Food ware, Single-Medical devices, Paints	(Muhamad et al. 2015) (Flieger, Kantorova et al. 2003)
Polylactic acid	*Bacillus brevis*, *Amycolatopsis* sp., *Penicillium Roquefort*		Packaging paper, Coatings, Fertilizers, Films, Compost bags	(Kasirajan and Ngouajio 2012)
Fossil-based polymers				
Polyethylene terephthalate	*Ideonella sakaiensis*		Carpets, Shirts, Bags, Plastics bottles, Food packages, Container,	(Yoshida, Hiraga et al. 2016)
Polyester	*Streptomyces sp.* *Phanerochaete chyrsosporium*		Fibers, Textiles	(Shah et al. 2008).
Polyvinyl alcohol	*Pseudomonas O-3*		Adhesives coatings, Ceramics, Reprography, Photography, Medicine,	(Shimao 2001).
Polyethylene	*Brevibacillus borstelensis* *Rhodococcus rubber*		Bags, water bottles, Food packaging Film, Toys, Pipes, Motor oil Bottles	(Hadad et al. 2005; Sivan et al. 2006).
Nylon	*Flavobacterium sp* *Pseudomonas sp.*		Small bearings, Speedometer gears, windshield Wipers, Water hose nozzels, Football helmets	(Tokiwa et al. 2009).

Table 1 (conitnued)

Polyethylene succinate	*Pseudomonas* sp.		Plastics industry, Shopping bags, Agriculture films	(Tribedi and Sil 2014)
Polylcaprolactone	*Clostridium botulinum,* *C. acetobutylicum,* *Fusarium solani*		Long-term items, Agricultural films, Fibers, Aquatic weeds, Seedling containers	(Abou-Zeid et al. 2001).
Polymer blends				
Starch/polyester	*Streptomyces* *Phanerochaete chyrsosporium*		Present in fibers, Engineering thermoplastics	(Shah et al. 2008)
Starch/polyethylene	*Aspergillus niger* *Penicillium funiculosm* *Phanerochaete chrysosporium*		Highly susceptible to the environmental conditions	(Shah et al. 2008)
Starch/PVA Blends	*Alcaligenes feacalis*		Agricultural applications, Packaging materials	Tokiwa, Calabia et al. 2009)

to pass through semi-permeable membranes of a bacterial cell to be used as its energy as well as carbon source (Gu 2003; Jayasekara et al. 2005). Biodegradation reactions involve both aerobic and anaerobic mechanisms (Shah et al. 2008).

Classification of biodegradable plastics

Bio-based biodegradable plastics

Bio-based biodegradable plastics are derived from renewable resources. From the environmental point of view, bio-based biodegradable polymers are advantageous in certain industrial applications due to their ability to be completely degraded biologically (Kale et al. 2007). Bio-based biodegradable plastics such as cellulose, starch, and starch-based polymers are consumed directly by microorganisms, since their molecular weight is reduced extracellularly by the action of enzymes. Starch is the most commonly used bio-based polymer for the production of biodegradable plastics. The extensive use of starch to synthesize bio-based biodegradable plastics is due to its abundance, ready availability, inexpensiveness, and biodegradability under certain environmental conditions (Chattopadhyay et al. 2011; Kyrikou and Briassoulis 2007; Nanda et al. 2010). Starch is composed of amylopectin and amylase polymers making it a viable substitute. In addition to many other bio-based biodegradable materials used in packaging, starch-based polymers are classified into two types: (a) starch-filled polymer and (b) starch-based polymer (Jayasekara et al. 2005). The microorganisms (bacteria, fungi, and algae) and different environmental factors are able to completely decay these polymers (Kasirajan and Ngouajio 2012). Various microorganisms (*Variovorax paradoxus*, *Comamonas* sp., *Aspergillus fumigatus*, *Acidovorax faecilis*, and *P. lemoignei*), isolated from soil, are reported to degrade bio-based polymers under both anaerobic and aerobic conditions (Shah et al.

2008). The most common types of bio-based biodegradable plastics, PHA and PLA (Elbanna et al. 2004) (Table 1), are discussed under.

Polyhydroxyalkanoates

It is a bio-based biodegradable polyester and produced in nature by bacterial fermentation of sugars and lipids (Shimao 2001). The PHA polymers can be used in packaging, medical, and pharmaceutical industries due to their biodegradability (Philip et al. 2007). Other commonly used PHA-made items are fast food service materials, disposable medical tools, packaging materials, and some paints (Flieger et al. 2003). The microbial biodegradation of PHA varies under different soil and environmental conditions. Under limited energy and carbon sources, microorganisms can degrade PHA and utilize it as carbon and energy source (Chen and Patel 2011). Some representative bacterial genera for PHA biodegradation include *Bacillus*, *Burkholderia*, *Nocardiopsis*, and *Cupriavidus* (Boyandin et al. 2013). Similarly, fungal genera like *Mycobacterium* and *Micromycetes* are also known to assimilate PHA (Boyandin et al. 2013) by employing both aerobic and anaerobic mechanisms.

Polylactic acid

Polylactic acid is a bio-based biodegradable plastic and is made on a commercial level by NatureWorks in the USA (150.000 tons year^{-1}). It is derived from renewable resources like corn starch, tapioca roots, or sugarcane. It has been used extensively in the medicine because of the ability of the polymer to be incorporated into human and animal bodies (Ikada and Tsuji 2000). PLA is the most important among the bio-based biodegradable plastics because of its availability, biodegradability, and good mechanical attributes (Liu et al. 2000). It has been reported that the products of hydrolytic degradation of PLA can be digested by microorganisms completely (Fukushima et al. 2009). Recently, *Amycolatopsis* sp. And *B. licheniformis*, isolated from soil, were reported to degrade PLA (Anderson and Shive 2012; Fukushima et al. 2009). A lipase purified from a fungus, *Cryptococcus* sp. strain S-2, showed remote homology to proteins of cutinase family and exhibited effective biodegradation of PLA (Masaki et al. 2005). Poly(lactic-co-glycolic acid) is another bio-based biodegradable polymer used in drug and food delivery in host microorganisms (Anderson and Shive 2012).

Fossil-based biodegradable plastics

Fossil-based biodegradable plastics have been employed for several prospects, notably in the packaging industry. However, the majority of the fossil-based plastics are non-biodegradable and pose a serious problem for their waste control (Hoshino et al. 2003; Vert et al. 2002). The scrap of fossil-based non-biodegradable plastics in humus is a primary difficulty in the contamination control (Goldstein 2005). These plastics are broadly employed in the packaging of pharmaceutical products, different food items, makeup items, and different chemicals. The degradation of fossil-based non-biodegradable polymers is an extremely slow process. Different environmental agents including microbes and their enzymes are involved in the degradation process (Chen and Patel 2011; Shah et al. 2008; Chen 2010; Mir et al. 2017). Currently, the research on the degradation of plastics is focused on the characterization of microorganisms capable of degradation of fossil-based plastics in the atmosphere, development of new enzyme-based degradation strategies, and synthesis of copies of genes that encode biodegradation enzymes (Vijaya and Reddy 2008). Nevertheless, the microbe-based biodegradation processes need to be optimized for various environmental conditions for effective and speedy biodegradation. Moreover, waste management and littering control are also essential for better utilization of such polymers in terms of environmental safety. Some examples of fossil-based biodegradable polymers are reported below.

Polyethylene succinate

Polyethylene succinate (PES) is one of the thermoplastic polyesters and is made either through copolymerization of ethylene oxide and succinic anhydride or via ethylene glycol and succinic acid poly-condensation (Hoang et al. 2007). Plastic industry uses PES for the production of films for agriculture, as a paper coating agent, and for shopping bags. This polymer is reported to be degraded in an efficient manner by a mesophilic bacterial strain named as *Pseudomonas* sp. AKS2 (Tribedi and Sil 2014). There is a limited distribution of microbes that degrade PES in contrast to diversity of PCL-degrading microbes. Another PES-degrading thermophilic strain *Bacillus* sp. TT96 has been isolated from the soil (Tokiwa et al. 2009). Moreover, several mesophilic microbes, isolated with intrinsic ability to degrade PES, phylogenetically belong to *Bacillus* and *Paenibacillus* genera (Tezuka et al. 2004; Tokiwa et al. 2009).

Polycaprolactone

Polycaprolactone is a fossil-based biodegradable polymer that can easily be degraded by aerobic and anaerobic microorganisms. This partially crystalline polyester is mingled with other copolymers and used for making packaging material along with its use in biomedicals, catheters, and blood bags (Wu 2005). Despite being expensive, it has gained attention due to its flexibility and biodegradability (Wu 2005). PCL can be degraded by microbial lipases and esterases (Karakus 2016). The bacteria known for PCL degradation are widely found in

Table 2 Some bacterial and fungal enzymes/strains involved in biodegradation of both biodegradable and non-biodegradable plastics

Sources	Enzyme	Microorganisms	Plastics	Reference
Bacteria				
	Lipase	*Rhizopus delemar* *C. botulinum*	PCL	(Abou-Zeid et al. 2001; Tokiwa et al. 2009)
	Unknown	*Firmicutes*	PHB, PCL, and PBS	Tokiwa et al. (2009)
	Lipase	*R. arrizus*	PEA, PBS, and PCL	(Tokiwa et al. 2009)
	Serine hydrolase	*P. stutzeri*	PHA	(Muhamad et al. 2015)
	Unknown	*B. borstelensis*	PET	(Calabia and Tokiwa 2006)
	Unknown	*Pseudomonas fluorescens* B-22 *P. putida* *Ochrobactrum* TD	PVC	(Danko et al. 2004; Orr et al. 2004)
Fungi				
	Glycosidase	*A. flavus*	PCL	(Tokiwa et al. 2009)
	Unknown	*Penicillium funiculosum*	PHB	(Tokiwa et al. 2009)
	Catalase, protease	*A. niger*	PCL	(Tokiwa et al. 2009)
	Unknown	*Streptomyces*	PHB, PCL	(Tokiwa et al. 2009)
	Cutinase	*Fusarium*	PCL	(Muhamad et al. 2015)
	Manganese peroxidase	*Amycolaptosis* sp.	PLA, PE	(Muhamad et al. 2015)
	Serine hydrolase	*Pestalotiopsis microspore* *Curvularia senegalensis* *Fusarium solani*	PUR	(Howard 2002; Russell et al. 2011)

the atmosphere and some of them are presented in Table 2 (Shimao 2001). A fungal strain *Aspergillus* sp. ST-01 has been reported to efficiently degrade PCL into a wide range of products such as butyric, succinic, caproic, and valeric acids (Sanchez et al. 2000).

Biodegradable polymer blends

A cheaper and cost-efficient method to make the polymers biodegradable with desirable characteristics is to blend different materials. This method is easier, faster, and more economical as compared to copolymerization (Tokiwa et al. 2009). The degradation time of polymer blends is controlled by the element that is biodegradable immediately (Jayasekara et al. 2005). Due to their benefits on commercial scale, polymer blends are being considered more useful than fossil-based biodegradable polymers in certain applications (Garg and Jana 2007). There are various kinds of starch-based biodegradable polymer blends like starch/polyester blends and starch/PVA blends (Table 2). They are considered to be completely biodegradable due to the complete breakdown of each component. Polymer's structural integrity is collapsed by the primary process of degradation resulting in the increase of surface area for the action of enzymes. There has been an increasing trend of research on microbial degradation mechanisms of polymer blends and various degradation products (Jayasekara et al. 2005). The blends of starch and PVA are supposed to be totally biodegradable due to assimilation by various microbes. The characteristics related to processing of starch and PVA blends have been well-studied (Thakore et al. 2001).

Starch/polyester blends

Starch and polyester blends are biologically degradable due to the nature of their composition. Artificial polyester and starch blends are cost-effective since starch is affordable, renewable, and easily accessible (Tokiwa et al. 2009). Degradation speed of polyesters like PCL in the blend is increased by enhancing the starch concentration (Ratto et al. 1999). The addition of small amount of functionalized anhydride polyesters provides superior characteristics to straight chain polyester and starch blends (Mani and Bhattacharya 2001). With 70% level of starch by weight, these blends, carrying ductile intensities, are somewhat similar to the artificial polyester. Moreover, polyesters are also versatile polymers and most thermoplastics used in engineering are manufactured from polyesters (Fradet and Tessier 2003). Lipase enzymes secreted by several microbes, especially *R. arrhizus* and *R. delemar* strains, can hydrolyze polyester in blends (Tokiwa and Calabia 2007).

Starch/PVA blends

The PVA is a water-soluble fossil-based biodegradable polymer and its competitiveness is increased by blending starch with PVA. These blends have better film-forming property and are extensively used for agriculture and packaging purposes (Tang et al. 2008; Tudorachi et al. 2000). Several microbes have been reported to degrade the starch/PVA blends through enzymatic hydrolysis. For example, depolymerase secreted by *Alcaligenes feacalis* T1 is reported to efficiently degrade these blends (Tokiwa et al. 2009; Jayasekara et al. 2003).

Microbes and their mechanisms for plastic biodegradation

Microbes (mostly bacteria and fungi) often produce extracellular enzymes which help in degrading various types of bio- and fossil-based plastics (Shah et al. 2014). Bacteria and fungi act to degrade these polymers into CO_2 and H_2O through various metabolic and enzymatic mechanisms. The nature and catalytic activity of enzymes vary depending upon the microbial species and even within the strains. Due to this specificity, different enzymes are known to degrade various polymer types. For example, *Bacillus* spp. and *Brevibacillus* spp. produce proteases involved in degradation of various polymers (Sivan 2011). Fungi that biologically degrade the lignin frequently contain laccases to catalyze aromatic and non-aromatic compounds through an oxidation process (Mayer and Staples 2002). These microbial enzymes also influence the biodegradation rate of polymers in an efficient and environmentally sustainable manner. Both biodegradable and non-biodegradable polymers such as PHA, PLA, PET, PHB, PVC, PCL, and PBS are reported to be attached to various microbes and their enzymes (Muhamad et al. 2015). Microorganisms and their enzymes responsible for degradation of plastics of various groups have been listed in Table 1.

The primary mechanism involved in plastic biodegradation is sticking of microbes with polymers followed by surface colonization. Enzyme-based hydrolysis of plastics involves two steps: Firstly, the enzymes attach to the polymer substrate followed by hydrolytic division (Fig. 1). Degradation products of polymers like oligomers, dimers, and monomers are much low in molecular weight and are eventually converted to CO_2 and H_2O by mineralization (Tokiwa et al. 2009). Under aerobic conditions, oxygen is used as an electron acceptor by the bacteria followed by the synthesis of tinier organic compounds, and thus, CO_2 and water are produced as end products (Priyanka and Archana 2012). Under anaerobic conditions, polymers are crushed down in the absence of oxygen by microorganisms. Sulfate, nitrate, iron, carbon dioxide, and manganese are used as electron acceptors by anaerobic bacteria (Priyanka and Archana 2012). New microbial enzymes and pathways need to be explored to optimize conditions under which polymers can be degraded efficiently. Non-biodegradable polymers (fossil-based and bio-based) are so-called non-biodegradable since they might be completely biodegradable once new microbial strains and their pathways to degrade these polymers were completely described. There exists a great need to bring new polymers into the category of

Fig. 1 Mechanisms of plastic biodegradation under aerobic and anaerobic conditions

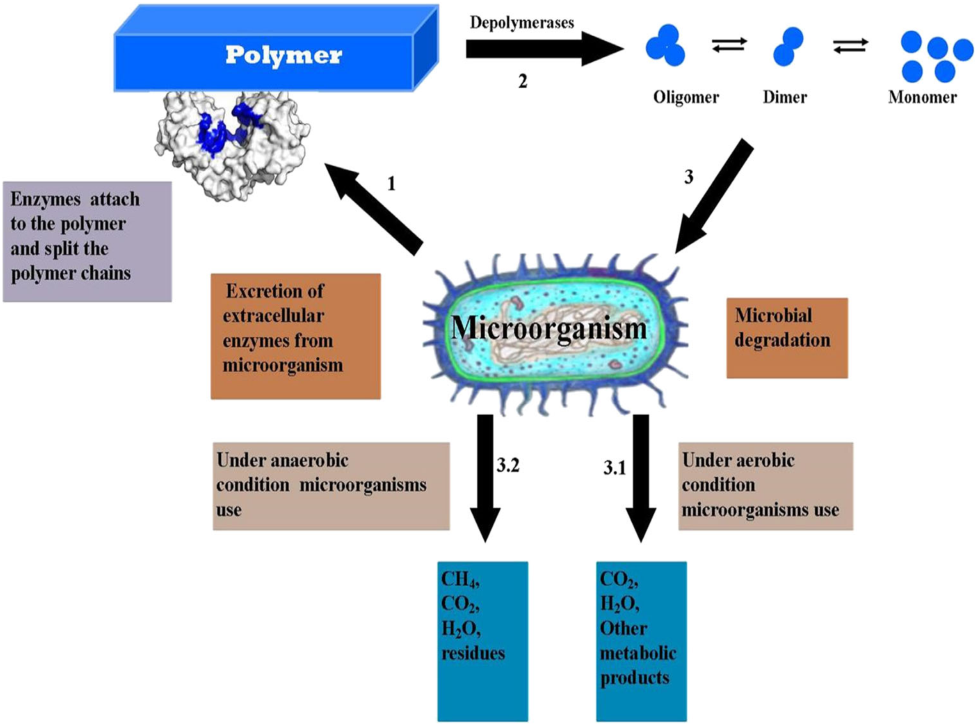
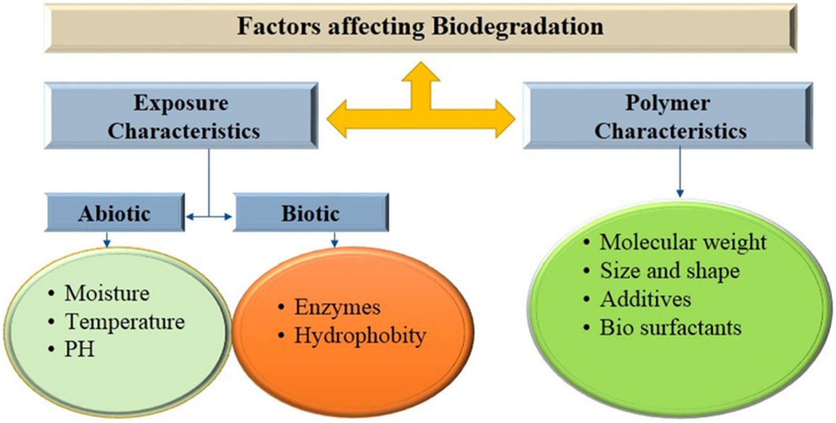


Fig. 2 Factors affecting the rate of biodegradation of plastics



biodegradable polymers for their utilization in packaging and health industry in an environment-friendly and sustainable manner.

Factors affecting plastic biodegradation

Several factors affect the biodegradation process including the polymer properties, the exposure conditions, and the enzyme characteristics (Fig. 2). Some of these factors are listed below.

Exposure conditions

Moisture

Moisture can influence polymer biodegradation in different ways due to the essential requirement of water for growth and multiplication of microbes. Hence, polymer degradation speed is enhanced in the presence of sufficient moisture due to swift microbial action (Ho et al. 1999). In addition, moisture-rich conditions support the process of hydrolysis by generating more chain scission reactions.

pH and temperature

The pH can modify the rate of hydrolysis reactions by changing the acidic or basic conditions. For example, at pH 5, the rate of hydrolysis of PLA capsules is optimal (Auras et al. 2004; Henton et al. 2005). Degradation products of various polymers alter the pH conditions followed by the rate of the degradation process and microbial growth. Similarly, enzymatic degradability is affected significantly by the polymer's softening temperature. Polyester with the higher melting point has less possibility of biodegradation. Potential enzymatic degradability decreases with the increase in temperature. For instance, purified lipase of *R. delemar* efficiently hydrolyzed polyesters like PCL showing low melting points (Tokiwa and Calabia 2004; Tokiwa et al. 2009).

Enzyme characteristics

Different enzymes possess unique active sites and have the ability to biodegrade various types of polymers. For instance, straight chain polyesters, obtained from diacid monomers with 6 to 12 C-atoms, have been degraded quickly by enzymes produced by fungal species *A. flavus* and *A. niger* as compared to straight chain polyesters produced from any other monomer (Kale et al. 2007). It was found that the extracellular enzymes, involved in the depolymerization of PHB (depolymerases), degrade PHB by distinct mechanisms depend on the specific microbially produced depolymerase (Yamada-Onodera et al. 2001). Plastics derived from the petrochemical sources, due to their hydrophobicity and 3D structure, cannot be readily degraded in the environment (Yamada-Onodera et al. 2001). Moreover, the hydrophobic nature of PE intervenes in the formation of a biofilm of microorganisms to reduce biodegradation rate (Hadad et al. 2005).

Polymer characteristics

Molecular weight

From the biodegradability point of view, molecular weight plays a very critical role in defining many polymer properties. Degradability is lowered with the increase in molecular weight. Higher molecular weight PCL (> 4000) was slowly degraded by lipase of a strain *R. delemar* as compared to low molecular weight polymer (Tokiwa et al. 2009). It becomes convenient for microbial enzymes to attack a substrate low in molecular weight (Auras et al. 2004).

Shape and size

The properties like shape and size of the polymer play an important role in the degradation process. The polymers having large surface area can be degraded quickly as compared to those with a small surface area (Kijchavengkul and Auras 2008; Stevens 2003). There is a standard criterion of shape and size for biodegradation of various kinds of plastics (ASTM 2004).

Additives

Non-polymeric contaminants such as dyes (waste or debris of catalysts used for the polymerization and additives conversion products) or filler affect the degradation ability. It has been said that when the lingo-cellulosic filler increases in the sample, the thermal stability is reduced followed by increase in the ash content. The dispersal and interfacial adhesion between the lingo-cellulosic filler and the thermoplastic polymer are the major factors influencing the thermal stability of the composite system (Yang et al. 2005). Similarly, metals serve as good pro-oxidants in polyolefin manufacturing of polymers sensitive to thermo-oxidative degradation.

Biosurfactants

Biosurfactants are amphiphilic compounds produced mostly on the living surfaces. Biodegradation of polymers (fossil-based and bio-based) is enhanced by the addition of a biosurfactant due to their low toxicity and high biodegradability (Orr et al. 2004). Biosurfactants facilitate the biodegradation process due to the presence of specific functional groups, and thus, they allow the activity under extreme temperature, pH, and salinity conditions (Kawai et al. 2002; Kawai et al. 2004).

Current insights of research on plastic biodegradation

There is an increasing trend in the utilization of environment-friendly biodegradable bio- and fossil-based plastics. The use of biodegradable plastics for specific applications to establish a sustainable community is a fruitful notion in the presence of proper waste management and littering control strategies (Iwata 2015). The PET, a non-biodegradable fossil-based polymer, has a global use in plastic products and its buildup in the environment has caught global attention. Recently, a novel bacterial strain, *Ideonella sakaiensis* 201-F6, has been isolated and found proficient in degrading PET by using it as an energy and carbon source. The strain produces two enzymes to hydrolyze the PET and its mono(2-hydroxyethyl) terephthalic acid into two environmentally harmless monomers, i.e., ethylene glycol and terephthalic acid (Yoshida et al. 2016). Thus, further optimization of the PET degradation process under industrial facilities or in cells is essentially required to find its many other eco-friendly applications. Another study illustrates that the microbial consortia composed of *Pantoea* spp. and *Enterobacter* spp. has a potential to degrade the LDPE (Skariyachan et al. 2016). Scientists have also recognized some microbes to convert the organic styrene (a waste material of industrial plastic processing) into PHA. A recently isolated strain, *P. putida* NBUS12, is an efficient styrene-degrading bacterium (Tan et al. 2015). Another recently characterized bacterial strain, *Achromobacter xylosoxidans*, was found to affect the structure of high-density polyethylene (Kowalczyk et al. 2016). Similarly, an innovative thermophilic bacterium, *Anoxybacillus rupiensis* Ir3 (JQ912241), was isolated from hydrocarbon-polluted soil in Iraq and demonstrated good capacity to utilize aromatic compounds as carbon sources followed by their degradation (Mahdi et al. 2016). So, extensive research efforts are being made around the globe to develop processes for degradation of fossil-based and bio-based polymers in order to find out their new environment-friendly applications and waste control plans.

Future prospects

To solve the problems related to the disposal of plastic waste produced from various sources, the most innovative and environmentally safe way is to use biodegradable plastics in certain applications like packaging, agriculture, and health industry. Bio- and fossil-based biodegradable polymers, if utilized, are efficiently degraded in the environment, cells, or under optimized industrial facilities. Currently, non-biodegradable petrochemical products, used for the manufacturing of plastics, are posing a great threat to the environment especially in the absence of waste management facilities and littering control. The demand for the environment-friendly polymers is increasing continuously in certain applications. Utilization of these materials should be focused in future especially for the manufacturing of packaging stuff, the food item packaging, and disposable medical items. It is also beneficial to use biodegradable plastics in the environment as agricultural films, fishery material (fishing nets), bio-absorbable materials in therapeutics, surgical frameworks, and sterile goods. Moreover, biodegradable plastics should be applied where diffusion into the environment is imminent or when it is challenging to separate the garbage. On the other hand, proper arrangement of their waste and littering control is essential to take advantage of such polymers in the community.

Next-generation bio-based biodegradable plastics will commit to building a more sustainable society for specific applications. Further, these plastics should be biodegraded and recycled in a balanced way to make their re-use possible. Consequently, we must have an in-depth understanding of biomass structure generated in nature to make new biodegradable plastic polymers by slight modifications in structure. Researchers related to biomass, synthetic chemists, process engineers, and microbiologists should make use of their expertise individually and in collaboration to make the society more sustainable by developing environment-friendly materials.

Conclusions

Based on literature survey, it can be concluded that the use of plastic materials is inevitable to meet our daily life needs. Demand and use of plastics is an ever-increasing process. This process needs to be positively correlated with waste management and littering control as well as utilization of bio-based and fossil-based biodegradable materials in certain applications for sustainable environmental safety. Different microbial communities have great potential to biologically convert certain plastic polymers into simpler products by aerobic and anaerobic mechanisms. There exists a great need to synthesize new bio-based biodegradable polymers and/or charactеrize new microbial strains and their mechanisms to degrade fossil-based polymers. Moreover, a share of biodegradable materials in certain industrial applications needs to be improved followed by the development of optimized industrial degradation facilities and littering control strategies in order to ensure environmental safety and sustainability.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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