

# Chapter 6

## Plastic Waste: Environmental Hazards, Its Biodegradation, and Challenges



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**Abstract** Plastics have become an indispensable part of the society. Lightweight, easy handling, durability, flexibility, resistance to water, and other microbial attacks have made them ubiquitously popular. The extensive use of the long-lived polymer has confronted the environment with a challenging plastic pollution problem. Plastics are the product of coal, natural gas, crude oil, cellulose, and salt manufactured through energy-intensive technology. From cradle to grave, plastics affect the environment in a multifaceted way. The hazardous and ecologically (terrestrial and marine) damaging threats necessitate its removal from the environment. Incineration, landfilling, recycling, and degradation are the four most available options to manage

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the plastic waste. However, to avoid long-term environmental damage, degradation of plastic is the most preferred option among the management options. Plastic degradation is carried out by photodegradation, thermooxidative degradation, hydrolytic degradation, and biodegradation. Among them, microbial degradation using bacteria and fungi is an emerging strategy to manage plastic waste. Hence, this chapter highlights the benefits, concerns, and threats surrounding the use of plastics. The different perspectives covered in this chapter include plastic production and plastic waste generation, environmental and health effects of plastic pollution, plastic waste management options, biodegradation of plastic polymers and the mechanism involved, biodegradable plastics, and challenges and constraints of plastic waste biodegradation.

**Keywords** Plastics · Environmental effects · Polymers · Biodegradation · Biopolymers

## 6.1 Introduction

Plastic is one of the commonly used, versatile substances of the twentieth century. The term “plastic” was coined by Baekeland in 1909. It is derived from the Greek word where 'Plastikos' means fit for molding and 'Plastics' means molded. They are synthetic or semisynthetic amorphous substances prepared from fossil fuel resources. They resemble the natural resins obtained from the trees and plants. Since its invention, it has replaced wood, glass, and metal. Though the history of plastics dates back to 100 years, the development of modern polymers started 50 years back. Plastics have almost invaded all the industries, namely, food, clothing, construction, shelter, medical, transportation, sports, and many more. The wide application of the plastics was due to its multiple properties: durability, stability, low cost, lightweight, and unbreakable nature. Plastics are a long chain of monomers prepared by polymerization through addition and condensation process. The process is energy intensive and requires a huge amount of fossil fuels for production. The versatility of the polymer has resulted in the generation of huge amount of plastic waste. The buoyant nature of plastics spreads them to a huge area for a long distance. Moreover, the material from which they are made of resists them from degrading in the environment. Resistance and nonbiodegradability make plastic waste management very critical. The plastics remain in perpetuity when disposed of in landfills or open dumps.

Plastic waste has started attracting public attention due to the various environmental and health hazards. They are hazardous to terrestrial and aquatic life. The marine environment is largely affected by the plastics. The persistent organic pollutants that are coated on the plastics might enter into the food chain and cause harm to the animals and human beings. Animals also die due to indigestion and stomach bloating problems when plastic was consumed along with food. Marine animals die of suffocation when they get tangled with plastics. Dioxins released during the burning of plastics lead to cancer. The deterioration caused by the plastic pollution

necessitates its removal from the environment. Microbial degradation can be one best option for its removal from the environment. Plastics are complex organic compounds and can be mineralized by microorganisms, unlike heavy metals. Henceforth, studies on plastic degradation using bacteria, fungi, and actinomycetes have generated a lot of interest among researchers.

Bacteria, fungi, and actinomycetes isolated from varied source, namely, soil, wastewater, sludge, mangrove soil, landfill soil, and plastic-accumulated soil, were efficient in degrading the natural and synthetic polymers. The microorganisms use intracellular and extracellular enzymes to cleave the polymer chain to oligomers, subsequent to which they are mineralized by aerobic and anaerobic metabolism. Weight loss, change in the structure of the polymers, and cracks in the polymers indicated the efficiency of microorganisms in degrading the polymers. However, the process of biodegradation was limited and challenged by factors such as polymer structure, composition, chemical bonding, stress, and environmental conditions (pH, temperature). Pretreatment of polymer with light, heat, oxygen, and UV enhances the biodegradation of polymers. This chapter will through light on plastic production, plastic waste generation, and its environmental and health effects. Biodegradation of plastic waste, factors influencing its degradation, and the various challenges associated are also discussed.

## 6.2 Plastic Production

Plastics are polymers that are manufactured chemically by polymerization of monomers of various synthetic and semisynthetic organic compounds. Monomers are a group of atoms that constitute unit cells. The monomers are made of elements such as carbon, hydrogen, sulfur, silicon, nitrogen, and chlorine. According to the type of polymers, the composition of monomers shall vary. For, example, polyethylene polymer consists of repeated units of carbon and hydrogen atoms. Other monomers include ethylene (ethene), propylene (propene), butene, and others. The monomers possess a double bond between carbon atoms such that it can react to form polymers. Polymerization of monomers occurs through two mechanisms: addition reaction and condensation. A catalyst is used to link one monomer to the other in an addition reaction, while in condensation reaction, the catalyst is used to fuse all monomers to adjacent monomers. This results in the formation of dimers and a by-product. The by-product has to be removed to avoid the release of environmental contaminants (American Chemistry Council 2005).

At the industrial level, the production of plastic began in the 1940s. Presently, huge quantity of plastics is manufactured annually due to their application in the household, packing, agriculture, toys, and many more (Al-Salem et al. 2009). In the 1950s, the annual production of plastics was 1.5 million tones which have increased dramatically to 299 million tons in 2013 (Plastics Europe 2015). Natural products such as cellulose, natural gas, salt, coal, and petroleum derived from crude oil are used as polymers for the synthesis of plastics. Today, around 4% of crude oil is used

as a feedstock for manufacturing plastics, and additional 4% of petrochemical products are used in energy-intensive process for plastic prototype or refined goods (Wu et al. 2013). During the distillation process of crude oil, different hydrocarbon products get separated into different fractions. One of such fraction includes naphtha which is a very crucial element for the production of plastics (Kalia et al. 2000). The most abundant plastic polymers produced include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), expanded polystyrene (EPS), polypropylene (PP), and polyvinyl chloride (PVC) (Li et al. 2016). In order to improve the performance of plastics, various additives along with polymer resins are mixed during polymerization of plastic polymers. These include inorganic fillers, phthalate plasticizers, bisphenol A (BPA), thermal and UV stabilizers, colorings, carbon, silica, and flame retardants which provide various range of plastic products (Thompson et al. 2009). Generally, plastics are divided into two basic categories: (i) thermo-softening plastics and (ii) thermosetting plastics. Thermo-softening plastics are those which can be recycled and remolded into different shapes, whereas thermosetting plastics cannot be recycled and remolded (Singh et al. 2017). The polymers are processed into finished products through a different process. Extrusion, blow molding, film blowing, calendaring, expanded bead blowing, injection and rotational molding, casting, thermoforming, and compression folding are finishing steps in plastic production (American Chemistry Council 2005).

### 6.3 Plastic Waste Generation

Rapid growth and urbanization have led to the increased demand for plastics around the globe due to its multiple advantages such as lightweight, strength, durability, and low cost. Plastic waste generation depends on increasing population, lifestyle, socioeconomic background, and developmental activities. Since 1990 the demand for plastics has increased at an annual rate of 5% (Kunwar et al. 2016). Increase in plastic production leads to higher consumption which in turn results in more plastic waste generation. Plastic is used widely in various sectors such as household, agriculture, packaging, and industrial areas. So, the plastic waste generated can be categorized into municipal and industrial plastic waste. Industrial waste is homogenous which get generated during manufacturing of plastic products, packaging, and processing. Municipal waste is heterogeneous waste which includes plastic bags, wrappers, toys, wires, vending cups, CD, disposable cups, and few more. They are discarded as household waste (Panda et al. 2010). Some plastics products are prepared for single use which gets disposed off. According to Indian government's Plastic Waste Management Rules (2016), it is estimated that everyday approximately 15,000 tons of plastic waste is generated, out of which 60% is collected. Globally, around 32 billion tons of plastic waste is generated every day, out of which 65% of total plastic waste generated ends life in landfills. As mentioned earlier, plastics are categorized into two types: thermoset plastics and thermoplastics. Thermoplastics are recyclable plastics and they constitute 80% of plastic waste. The

**Table 6.1** Resins used in manufacturing of plastics

Sr. no.	Thermoplastic	Thermoset plastic
1.	Polyethylene terephthalate (PET)	Bakelite
2.	Polypropylene (PP)	Epoxy
3.	Polyvinyl acetate (PVA)	Melamine
4.	Polyvinyl chloride (PVC)	Polyester
5.	Polystyrene (PS)	Polyurethane
6.	Low-density polyethylene (LDPE)	Urea-formaldehyde
7.	High-density polyethylene (HDPE)	

Source: CPCB (2011)

**Table 6.2** Status of plastic waste generation

Sr. no.	Description	World	India
1.	Per capita per year consumption of plastic (kg)	24	6–7
2.	Recycling (%)	15–20	60
3.	Plastics in solid waste (%)	7	9

Source: Atulesh (2017)

resins produced for the preparation of varied types of plastics are summarized in Table 6.1. Plastic waste does not degrade unlike other municipal wastes such as paper, organic waste, etc. because it accumulates and remains there for longer periods of time (Sarker et al. 2011). Moreover, lack of awareness and unavailability of effective collection mechanism plastic waste generation are increasing day by day. In India, the per capita plastic waste generation is estimated as 5.7 kg/annum.

Recycling is the only means by which plastic waste generation is reduced or minimized. According to reports, the generation of plastic waste in India is comparatively lesser than the rest of the world (Table 6.2). Moreover, the recycling rate is also higher in India (60%) than the rest of the world (15–20%). The recycling is done only for a specific group of plastic. The mechanical recycling is done only for plastic bottles and PVCs. Polythene bag recycling is still facing issues. Segregation and cleaning are other factors that affect recycling.

## 6.4 Environmental Hazards of Plastic Waste

Plastics are extensively scattered in the general public and the environment due to their diverse chemical composition, properties, and applications. The higher the utilization, the more will be the generation of waste, and in case of plastics which are persistent in nature, the waste generation would be much higher (Thompson et al. 2009). Aesthetic problems get originated due to plastic debris. Plastics are very hazardous for both terrestrial and marine life. Conventional plastics are non-biodegradable and require very long time for degradation. They also show high resistance to aging, get converted to smaller debris, and accumulate in the environment (O'Brine and

Thompson 2010). Hazardous by-products or unbound monomers from plastics get released into the aquatic environment through the migration of plastic waste and landfill leachate to both freshwater and marine waters (Huang et al. 2012). In mid-oceans, plastic bags resemble prey to fishes. Fishes, mammals, turtles, and other sea animals consume these plastics along with their food, which gets accumulated in the gut of the sea animals. The plastics in the gut damage the inner lining of the stomach, block the digestive tract, and minimize the feed drive of animals (Laist 1987). Moore (2008) reported that around 267 marine species including mammals, fishes, turtles, seabirds, and invertebrates are affected by plastic waste. Marine animals get tangled in floating plastic debris which inhibits or limits their movement resulting in their drowning. Evidence of plastic debris in the guts of fishes have been reported by many researchers. Fragments of plastic enter the filter feeding organisms through which it enters the food chain and bioaccumulates in higher marine organisms. Plastics also destroy the habitat by acting as transportation agent for invasive species (Fergusson 1974). Microorganisms and other diatoms start growing over the plastics and create biofouling over the plastic material. Biofouling makes the plastic heavy and they eventually sink to the floor of the water body. Due to the buildup of plastic waste on the sea floor, hypoxia conditions may develop due to inhibition of gas exchange between pore waters of accumulated plastic debris and overlying waters. Hypoxia condition results in improper functioning of the normal marine ecosystem (Derraik 2002). Plastics floating in water suffocate marine animals to death. Plastic ingestion could increase the buoyancy of fish making it difficult for mesopelagic fish to return to deeper waters (Boerger et al. 2010).

A number of chemicals used for the manufacturing of plastics, unbounded monomers, additives, and their degradation products may get released into the environment during the lifecycle of plastic product which may have hazardous properties for biological life and environment. Bisphenol A (BPA), phthalates, polyhalogenated flame retardants, polyfluorinated compounds, nonylphenol, and antibacterial compounds such as triclosan pose serious threats to human health and other organisms (Halden 2010). Polybrominated diphenyl ethers (PBDEs) used in electrical and some non-electrical plastics as fire retardants are persistent in nature. In May 2009, Stockholm convention declared penta- and octa-BDE as persistent organic pollutants (POPs). The United States and the European Union have banned the use of these PBDEs (Tang et al. 2014). Bisphenol A and phthalates are of major concern due to their biological effects in humans as well as animals.

### **6.4.1 Bisphenol A (BPA)**

Bisphenol A (BPA) is a monomer chemical that is used for the manufacturing of polycarbonate plastics and PVC and can leach into the environment (Schechter et al. 2010). During polymerization, some of the monomers remain unbound which get released and are commonly found in the leachate of the landfill where plastic waste is dumped (Halden 2010). It potentially results in ecosystem disruption of the region

receiving leachates. Each year about 100 tons of BPA is released into the environment during synthesis alone (Vandenberg et al. 2009). BPA is of great concern because it poses some serious threats to humans. It has been recognized as potential endocrine disruptor which disrupts the normal hormonal functioning. Various other health effects associated with BPA are cardiovascular disease, heart attacks, male sexual dysfunction, and angina (Schechter et al. 2010).

### 6.4.2 *Phthalates*

Phthalates are diesters of phthalic acid used for flexibility of PVC, pliability, softening, and elasticity of rigid plastics. More than 25 different phthalate esters are used in plastic manufacturing. Phthalates do not bond covalently to polymer matrix due to which these are more prone to leaching into the environment (Halden 2010). Di(2-ethylhexyl) phthalate (DEHP) is associated with various health concerns for humans. On entering human body, DEHP is converted to mono-(2-ethylhexyl) phthalate (MEHP) by lipases and gets absorbed by the body (Singh and Li 2012). Dibutyl phthalate (DBP), benzyl butyl phthalate (BBP), di-isononyl phthalate (DINP), etc. are other important phthalate additives. Dibutyl phthalate and benzyl butyl phthalate produce toxic metabolite mono-butyl phthalate (Sathyanarayana 2008; Latini 2005). Adverse health effects of phthalates include hormone disruption, asthma, genital malformations, development of some cancers, and developmental and reproductive problems (Singh and Li 2012).

### 6.4.3 *Land Pollution*

The plastics when dumped in the open areas or landfills affect the aesthetics of the location. The wind carries the plastics and spreads them over a wide area. Improper segregation of plastics from other food wastes results in consumption of plastic by street animals. The animals die due to bloating of stomach and indigestion problems. In many places, especially in open dumpsites and landfills, the rag pickers set afire in the waste piles to segregate the materials. This results in burning of plastics along with other materials. According to NEERI (2010), burning of plastics results in the emission of 10,000 g of dioxins/furans every year to the atmosphere. Incomplete combustion of plastics results in the release of carbon monoxide (CO), dioxins, furans, polychlorinated biphenyls, soot, carbon black, aromatics (pyrene and chrysene), and heavy metals (chromium, copper, cobalt, selenium, lead, and cadmium). The burning of plastic waste causes headache, nausea, heart diseases, respiratory illness like asthma and emphysema, and neurological, respiratory, and reproductive diseases. It also damages the lungs, thyroid gland, eyes, and mucous membrane. Dioxins and its intermediate 2,3,7,8 tetrachlorodibenzo-*p*-dioxin (TCDD) are categorized under carcinogens and mutagens. Heavy metals released



during burning interfere with plant process and accumulate in the tissues of organisms. Chlorine released from polyvinyl chlorides forms hydrochloric acid. Hydrochloric acid increases the acidity of the soil in addition to respiratory diseases (Verma et al. 2016).

## 6.5 Plastic Waste Management

Natural degradation or decomposition of plastics is very slow and takes about hundreds of years to get mineralized. Slow degradation has increased or necessitated the management of plastic waste throughout the world (Puncochar et al. 2012). Integrated waste management approaches should be followed effectively for better plastic waste management. Conventional approaches along with new technological methods are being used for better management of plastic waste which includes land-filling, incineration, recycling, and degradation (Panda et al. 2010). The conventional and most common method for managing waste is landfill. But there are certain long-term problems associated with this method of plastic waste management such as breakdown products of plastics, and leachate produced during degradation may pollute soil and groundwater (Hopewell et al. 2009). Plastic has high volume to weight ratio and, therefore, requires more space. Nowadays constructing a suitable landfill is costly, and space scarcity for landfill site is a major concern due to which other unconventional methods of plastic waste management are required to reduce the ultimate volume of plastic waste reaching landfill (Panda et al. 2010). In order to effectively manage or reduce plastic waste quantity, three Rs, reduce, reuse, and recycle, strategy should be opted (Hopewell et al. 2009). Reusing plastics is the best approach for managing plastic waste as it requires less energy. Plastic waste recycling is the process of recovering plastics. Recycling of plastic waste can be categorized into four major types: re-extrusion, mechanical recycling, chemical recycling, and energy recovery (Al-Salem et al. 2009). Re-extrusion or primary recycling is the use of plastic scrap for the manufacturing of new product both having similar features. Mechanical recycling is the process of recovering plastic waste that has been used in the manufacturing of new plastic products. Mechanical recycling involves various treatment and preparation steps such as shredding or cutting, floating, milling, washing, drying, etc. to yield high-quality end products (Singh et al. 2017). Heterogeneous plastic waste recycling is very difficult or cannot be performed in mechanical recycling which limits its usage to only homogenous or single polymer plastic waste. Chemical recycling also is known as tertiary recycling, where the plastics are depolymerized into smaller polymers due to alteration in the chemical structure of plastics. They are further used as feedstock for manufacturing of new plastics (Arena and Mastellone 1999). Chemical recycling is attained by three main approaches: depolymerization, partial oxidation, and cracking. Cracking is further categorized into thermal cracking, catalytic cracking, and hydrocracking (Panda et al. 2010). Energy recovery or quaternary recycling includes thermal decomposition, pyrolysis, gasification, and incineration of plastic waste.



Cost-effective and adequate infrastructure is required for the plastic waste collection, makeover to new product, and marketing of recycled goods for the success of plastic waste recycling (Rebeiz and Craft 1995). Incineration is another way of managing plastic waste which significantly reduces the need for landfilling of plastics. In this process the waste material is exposed to high temperatures (900–2000 °C) which leads to controlled and complete combustion of plastics and energy recovery, thereby reducing the volume by 80–90% (Sharholly et al. 2008). Generation of greenhouse gases and other toxic gases such as polychlorinated dibenzo-*para*-dioxins and polychlorinated dibenzofurans during incineration has led to its restriction in many countries especially for plastic waste (Panda et al. 2010).

Other than the conventional processes, some new technologies such as liquid fuel, plasma pyrolysis, coprocessing in cement kiln, and polymer-blended bitumen roads are being efficiently used in plastic waste management (Siddique et al. 2008). Thermal decomposition of plastics is done to convert plastics into liquid fuel produced through condensation of volatile liquid vapors, carbonized char, and synthetic gas. This thermal cracking or pyrolysis of plastic waste is done at 2700–3000 °C temperature by both non-catalytic and catalytic methods (Almeida and Marques 2016; Kumar and Singh 2013). Few studies have reported the thermal decomposition of polyethylene, polypropylene, polymethyl methacrylate, polyurethane, and polystyrene to liquid fuel. Gasoline-range liquid fuels having low octane value have been produced through thermal decomposition. The fuel produced requires further refining for usage which adds extra cost (Panda et al. 2010). Plasma pyrolysis technology is a fresh innovative technology that has been used to transform waste into valuable high calorific synthetic gas (syngas). In plasma pyrolysis, the high calorific plastic waste is exposed to very high temperature under oxygen-deficient conditions. High temperature decomposes plastics into syngas, which is used for energy production. Tar is produced along with syngas which is composed of CO, H<sub>2</sub>, and low concentration of hydrocarbons, but the syngas produced in plasma pyrolysis has high heating value and low tar content in comparison with simple pyrolysis of plastic waste (Puncochar et al. 2012; Nema and Ganeshprasad 2002). Tang et al. (2003) used nitrogen plasma reactor for decomposition of polypropylene, which resulted in 96% of solid decomposition and 2160 mL/g of syngas production. Coprocessing means the use of waste material as a source of energy along with primary fuel. Plastic waste is used as alternative fuel in kilns to reduce the consumption of fossil fuel used in cement industry. Plastics used as fuel in coprocessing are known as an alternative fuel. Reduction in plastic waste volume along with energy recovery took place in coprocessing (De Queiroz Lamas et al. 2013). Another technology that has gained popularity in plastic waste management is polymer-based bitumen roads. In this, the plastic waste shredded into small pieces was blended with bitumen and used as alternative road material (Gawande et al. 2012). In Bangalore, India, the bitumen blended with shredded plastic waste was used for laying of the road (Khullar 2009).

Degradation is the best way of managing plastic waste as it provides a solution for longer periods of time. Any alteration in the chemical structure of a plastic polymer due to a physical, chemical, or biological constituent that leads to transformation is

degradation of plastics. Physical, mechanical, and chemical properties of plastics get changed due to degradation (Pospisil and Nespurek 1997). Photo, thermal, and biological factors contribute to the degradation of plastics. Plastics absorb UV radiations from the sun which leads to photodegradation and further thermo-degradation of plastics. Degradations begin with the integration of oxygen atom to plastic polymers. Both the processes make polymer delicate and break into smaller pieces until microbes start metabolizing. Microbes such as bacteria and fungi first transform low molecular weight polymers to monomers, and then microbial cells transform monomers to minerals. Four methods, photodegradation, thermooxidative degradation, hydrolytic degradation, and biodegradation by microorganisms, lead to complete degradation of plastics in sequence (Shah et al. 2008a, b; Singh and Sharma 2008). Biodegradation of plastics is far better than other plastic waste management processes as it is environment-friendly and completely mineralizes or transforms plastic waste, thus providing a sustainable solution to plastic waste.

## 6.6 Biodegradation of Natural and Synthetic Plastics

Bioremediation is the use of living organisms such as bacteria and plants or their enzymes to degrade and detoxify the environmental contaminants for environmental safety and public health protection (Saxena et al. 2018; Bharagava et al. 2017a, b; Saxena and Bharagava 2016, 2017; Chandra et al. 2015). In an environment, depending on the factors, plastic undergoes either abiotic or biotic degradation. Biotic degradation or biodegradation is a process by which the microorganisms bring about a change in the physical or chemical structure of the material (Paco et al. 2017). Bacteria, fungi, and actinomycetes are involved in the degradation of the polymers. Biodegradation results in the decomposition products such as carbon dioxide, methane, water, and inorganic compounds (nitrogen, sulfur, phosphorus). The microorganisms can perform degradation under both aerobic and anaerobic condition (Alshehrei 2017). The degree of degradation by the microorganisms depends on the molecular weight of the polymers. The higher the molecular weight, the lesser the solubility of the polymers. The microorganisms find it difficult to attack, break down, and metabolize the polymers of increased thickness. Precisely, the mechanism the microorganism follows to degrade the polymers includes the following:

1. The microorganisms secrete extracellular enzymes to breakdown the complex polymers into small oligomers, dimers, or monomers. This process is also termed as depolymerization. If the polymer is hydrophilic, then the microorganism attaches itself to the polymer, secretes the enzyme, and cleaves the polymers via hydrolysis (Schink et al. 1992). During hydrolysis, a nucleophilic attack occurs on the carbonyl carbon atom. The cleavage occurs at ester, peptide linkage, and glycosidic bonds.

2. The degraded substance is water soluble and can easily pass through the semi-permeable cell membrane.
3. The monomers on entering into the cell are used as a source of carbon and energy. The biodegradation process is favored by three processes such as hydrolysis, photooxidation, and physical disintegration. These processes weaken the surface of the polymer and decrease the molecular weight of the polymer (Muthukumar and Veerappapillai 2015).

### 6.6.1 Biodegradation of Plastics by Bacteria

Numerous bacteria have shown the ability to degrade natural and synthetic polymers (Table 6.3). In addition to degradation, bacteria also synthesize natural biopolymers. Polyhydroxyalkanoates (PHAs), a natural polymer, are synthesized during bacterial fermentation. Under starvation or nutrient-limited conditions, the PHAs are metabolized and degraded. Another important natural polymer that is produced from the low-cost feedstock is polyhydroxybutyrate (PHB). Aerobic and anaerobic bacteria isolated from different sources, namely, activated sludge, soil, anaerobic sludge, and seawater, were used for natural polymer degradation. *Pseudomonas lemoignei*, *Comamonas* spp., *Variovorax paradoxus*, *Streptovorticillium kashmeriense* AF1, *Bacillus megaterium* AF3, and *Ilyobacter delafieldii* are some of the strains reported for PHA and PHB degradation (Lee 1996a, b; Shah et al. 2007). Molitoris et al. (1996) and Sang et al. (2002) observed grooves and erosion pits on the polymer subjected to bacterial degradation.

Biodegradation of polyethylene glycol (PEG) has been widely studied due to multiple reasons such as huge application, long biodegradation time, fear of entry into the environment, water solubility, and availability in different molecular weights (200–50000 Åg/mol). Aerobic and anaerobic bacteria have been used for PEG degradation. Inoculum such as aerobic and anaerobic sludge, seawater, municipal sewage, and wetland sediments was used for PEG degradation. However, seawater showed just 40% PEG degradation. The degradation pathway followed by the bacteria to degrade PEG differed with the environment. *Desulfovibrio desulfuricans* DG2, *Bacteroides* sp., *Pseudonocardia* sp. strain K1, *Sphingomonas*, *Acetobacterium*, and *Pseudomonas* sp. were among those bacteria reported for PEG degradation (Kawai et al. 1978; Dwyer and Tiedje 1983; Zgola-Grzeskowiak et al. 2006). According to Kawai et al. (1978), PEG degradation was better when the synergistic mixed culture of *Flavobacterium* and *Pseudomonas* sp. was used. PEGs pretreated with ozone showed accelerated degradation (Suzuki et al. 1978).

Recently, a novel bacteria *Ideonella sakaiensis* 201-F6 isolated from the debris of PET bottle recycling site were used to degrade poly(ethylene terephthalate) (PET) polymer popularly used in the manufacturing of bottles. The bacteria degraded 75% of PET film at 30 °C within 6 weeks of incubation. Carbon dioxide evolution was observed during degradation which indicated the mineralization of the polymer (Yoshida et al. 2016). Polythene bags and plastic cups were buried in

**Table 6.3** Bacteria degrading different types of plastics

S. No.	Polymers	Microorganisms	References
1.	Polyethylene	LDPE	
		<i>Rhodococcus ruber</i> C208	Chandra and Rustgi (1997)
		<i>Pseudomonas stutzeri</i>	Sharma and Sharma (2004)
		<i>Brevibacillus borstelensis</i>	Hadad et al. (2005)
		<i>Rhodococcus ruber</i> C208	Sivan et al. (2006) and Gilan et al. (2004)
		<i>Bacillus</i> sp., <i>Micrococcus</i> sp., <i>Listeria</i> sp. and <i>Vibrio</i> sp.	Kumar et al. (2007)
		<i>Rhodococcus rhodochrous</i> ATCC 29672	Fontanella et al. (2009)
		<i>Staphylococcus epidermidis</i>	Chatterjee et al. (2010)
		<i>Bacillus cereus</i> CI	Balasubramanian et al. (2011)
		<i>Bacillus cereus</i> , <i>Bacillus megaterium</i> , <i>Bacillus subtilis</i> and <i>Brevibacillus borstelensis</i>	Abrusci et al. (2011)
		<i>Pseudomonas aeruginosa</i> PAO1 (ATCC 15729), <i>Pseudomonas aeruginosa</i> (ATCC 15692), <i>Pseudomonas putida</i> (KT2440 ATCC 47054) and <i>Pseudomonas syringae</i> (DC3000 ATCC 10862)	Kyaw et al. (2012)
		<i>Stenotrophomonas parvumii</i>	Mehmood et al. (2016)
		<i>Aneurinibacillus aneuriniyiticus</i> bDSC01, <i>Brevibacillus agri</i> bDSC02, <i>Brevibacillus</i> sp. bDSC03 and <i>Brevibacillus brevis</i> bDSC04	Skariyachan et al. (2018)
		LDPE powder	
LLDPE			
<i>Pseudomonas</i> sp., <i>Staphylococcus</i> sp. and <i>Bacillus</i> sp.	Usha et al. (2011)		
<i>Rhodococcus rhodochrous</i> ATCC 29672	Fontanella et al. (2009)		
<i>Bacillus cereus</i> , <i>Bacillus megaterium</i> , <i>Bacillus subtilis</i> and <i>Brevibacillus borstelensis</i>	Abrusci et al. (2011)		
<i>Serratia marcescens</i>	Odusanya et al. (2013)		
HDPE			
<i>Bacillus</i> sp., <i>Micrococcus</i> sp., <i>Listeria</i> sp. and <i>Vibrio</i> sp.	Kumar et al. (2007)		

		<i>Rhodococcus rhodochrous</i> ATCC 29672	Fontanella et al. (2009)
		<i>Arthrobacter</i> sp. and <i>Pseudomonas</i> sp.	Balasubramanian et al. (2010)
		<i>Aneurinibacillus aneuriniyiticus</i> bDSCE01, <i>Brevibacillus agri</i> bDSCE02, <i>Brevibacillus</i> sp. bDSCE03 and <i>Brevibacillus brevis</i> bDSCE04	Skariyachan et al. (2018)
	Degradable polyethylene	<i>Rhodococcus rhodochrous</i> ATCC 29672 and <i>Nocardia steroids</i> GK911	Bonhomme et al. (2003)
		<i>Bacillus mycoides</i>	Seneviratne et al. (2006)
	Polyethylene bags and plastic cups	<i>Streptococcus</i> sp., <i>Staphylococcus</i> sp., <i>Micrococcus</i> sp., <i>Moraxella</i> sp. and <i>Pseudomonas</i> sp.	Kathiresan (2003)
	Polyethylene carry bags	<i>Bacillus cereus</i> , <i>Pseudomonas</i> sp.	Aswale and Ade (2008)
		<i>Serratia marcescens</i>	Aswale and Ade (2009)
		<i>Serratia marcescens</i> 724, <i>Bacillus cereus</i> , <i>Pseudomonas aeruginosa</i> , <i>Streptococcus aureus</i> (B-324) and <i>Micrococcus lysae</i> (B-429), <i>Arthrobacter</i> sp. and <i>Pseudomonas</i> sp.	Aswale (2010)
		<i>Pseudomonas aeruginosa</i> , <i>Pseudomonas putida</i> and <i>Bacillus subtilis</i>	Obidi et al. (2010)
	Polyethylene and cups	<i>Bacillus</i> sp., <i>Staphylococcus</i> sp., <i>Streptococcus</i> sp., <i>Diplococcus</i> , <i>Micrococcus</i> sp., <i>Pseudomonas</i> sp. and <i>Moraxella</i> sp.	Reddy (2008)
	Natural and synthetic polyethylene	<i>Pseudomonas</i> sp. (P1, P2 and P3)	Nanda et al. (2010)
	Polyethylene	<i>Brevibacillus</i> , <i>Pseudomonas</i> and <i>Rhodococcus</i> spp.	Nanda and Sahu (2010)
		<i>Bacillus subtilis</i>	Vimala and Mathew (2016)
	Polyethylene terephthalate (PET)	<i>Serratia plymuthica</i>	Janczak et al. (2018)

(continued)

Table 6.3 (continued)

S. No.	Polymers	Microorganisms	References
2.	Polythene	<i>Pseudomonas</i> sp.	Sinosh et al. (2015)
3.	Polyurethane	<i>Staphylococcus</i> sp., <i>Bacillus</i> sp., <i>Pseudomonas</i> sp.	Singh et al. (2016)
		<i>Aeromonas salmonicida</i> ; <i>Alcaligenes denitrificans</i>	Kay et al. (1991) and Akutsu et al. (1998)
		<i>Arthrobacter globiformis</i>	
		<i>Comamonas acidovorans</i> TB-35	
		<i>Corynebacterium</i> sp.; <i>Enterobacter agglomerans</i> ; <i>Pseudomonas aeruginosa</i> ; <i>Serratia rubidaea</i>	
		<i>Comamonas acidovorans</i>	Nakajima-Kambe et al. (1995)
		<i>Acinetobacter calcoaceticus</i> ; <i>Arthrobacter globiformis</i> ; <i>Pseudomonas cepacia</i> ; <i>Pseudomonas</i> sp.	Halim et al. (1996)
		<i>Methanotrix</i> sp.	Varesche et al. (1997)
		<i>Bacillus</i> sp.	Blake and Howard (1998)
		<i>Pseudomonas fluorescens</i>	Howard and Blake (1999)
		<i>Pseudomonas chlororaphis</i>	Howard and Hilliard (1999)
		<i>Pseudomonas chlororaphis</i>	Zheng et al. (2005)
		<i>Pseudomonas</i> sp.	
		<i>Rhodococcus equi</i>	Akutsu-Shigeno et al. (2006)
		<i>Alicyclophiltus</i> spp.; <i>Alicyclophiltus denitrificans</i>	Oceguera-Cervantes et al. (2007)
<i>Bacillus pumilus</i>	Nair and Kumar (2007)		
<i>Corynebacterium</i> sp.	Shah et al. (2008a)		
<i>Micrococcus</i> sp.	Shah et al. (2008b)		
<i>Acinetobacter gernerii</i> P7	Howard et al. (2012)		
<i>P. Aeruginosa</i> strain MZA-85	Shah et al. (2013)		
<i>Pseudomonas putida</i>	Peng et al. (2014)		
<i>Bacillus subtilis</i>	Nakkabi et al. (2015)		
Polyurethane film	<i>Bacillus</i> sp. AF8, <i>Pseudomonas</i> sp. AF9, <i>Micrococcus</i> sp. 10, <i>Arthrobacter</i> sp. AF11 and <i>Corynebacterium</i> sp. AF12	Shah et al. (2008a)	

4.	Polypropylene	Isotactic polypropylene	<i>Pseudomonas chlororaphis</i> , <i>Pseudomonas stutzeri</i> and <i>Vibrio</i> sp.	Cacciari et al. (1993)
		Polypropylene films and pellets	<i>Aneurinibacillus aneurinilyticus</i> bDSC01, <i>Brevibacillus agri</i> bDSC02, <i>Brevibacillus</i> sp. bDSC03 and <i>Brevibacillus brevis</i> bDSC04	Skariyachan et al. (2018)
5.	Polyvinyl chloride	PVC powder	<i>Pseudomonas aeruginosa</i>	Peculyte (2002)
		PVC	<i>Pseudomonas fluorescens</i> B-22, <i>P. putida</i> AJ, <i>P. chlororaphis</i> , <i>Ochrobactrum</i> TD, <i>Aspergillus niger</i>	Dussud and Ghiglione (2014) and Shah et al. (2008a)
6.	Polylactic acid		<i>Penicillium roqueforti</i> , <i>Amycolatopsis</i> sp., <i>Bacillus brevis</i> , <i>Rhizopus delemar</i>	Shah et al. (2008a)
			<i>Serratia plymuthica</i>	Janczak et al. (2018)
7.	Polystyrene		<i>Rhodococcus zopfii</i> stoecker, <i>Enterococcus faecalis</i> , <i>Pseudomonas putida</i> and <i>Salmonella</i>	Savoldelli et al. (2017)
8.	Polyesteramides		<i>Pseudomonas aeruginosa</i>	Novotný et al. (2015)
9.	Plastic bags		<i>Aneurinibacillus migulanus</i>	Chaisu (2016)
10.	Degradable plastic		<i>Pseudomonas</i> sp., <i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Streptococcus lactis</i> , <i>Proteus vulgaris</i> and <i>Micrococcus luteus</i>	Priyanka and Archana (2011)
11.	Milk covers		<i>Pseudomonas putida</i>	Saminathan et al. (2014)
12.	UV-treated microplastics from polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and polystyrene (PS)		<i>Bacillus cereus</i> and <i>Bacillus gothelii</i>	Auta et al. (2017)

Source: Adapted and updated from Devi et al. (2016); Pathak and Navneet (2017)



mangrove soil to assess in situ degradation. It was observed that in a span of 9 months, polythene bags and plastic cups showed 4.21% and 0.25% degradation. The inoculum showed the presence of gram-positive and gram-negative bacteria. The species that were predominant were *Streptococcus*, *Staphylococcus*, *Micrococcus* (Gram-positive), *Moraxella*, and *Pseudomonas* (Gram-negative). *Bacillus*, *Listeria*, and *Vibrio* are bacteria observed in mangrove soil of Fiji in addition to the abovementioned bacteria. The bacteria generated hydrolytic enzymes such as amylases, lipases, and gelatinases for high-density and low-density polythene (Kumar et al. 2007). Garbage and garden soil, when used as an inoculum, showed 13.6% weight loss of polythene. *Staphylococcus arlettae* that was responsible for the weight loss altered the chemical properties of the polythene (Divyalakshmi and Subhashini 2016). *Staphylococcus aureus* and *Pseudomonas aeruginosa* also showed polythene and plastic degradation when incubated for a period of 1 month (Kannahi and Sudha 2013).

Synthetic polymers such as polyester, polycaprolactone, and polyurethane were also degraded by bacteria isolated from soil, activated sludge, and other sources. The bacteria utilized polymer as carbon and nitrogen source. *Comamonas acidovorans* and *Alcaligenes faecalis* degraded polyester polyurethane and polycaprolactone (Nakajima-Kambe et al. 1999; Oda et al. 1997). *Alcaligenes faecalis* produced polycaprolactone depolymerase enzyme to degrade polycaprolactone.

### 6.6.2 Biodegradation of Plastics by Fungi

Fungi like other microorganism have gained huge attention among researchers due to its biodegradation potential. The degradation ability of fungi is attributed to the enzymes they produce. Moreover, the hyphal structure of fungi through which it can penetrate into the contaminated sites has made it more advantageous for bacteria. Fungi are explored for the degradation of different types of natural and synthetic polymers such as low-density polyethylene, high-density polyethylene, polyvinyl chloride, polyurethane, polyolefins, poly(vinyl alcohol), and polyhydroxyalkanoates (Table 6.4). Irrespective of the type of polymer, genera *Aspergillus*, *Penicillium*, and *Phanerochaete* are popularly reported for plastic degradation. Polyvinyl chloride is a strong plastic used in pipes and fittings, flooring material, synthetic leathers, insulation wires, textiles, shoes, etc. It has low moisture and resists biodegradation. However, thermal and photodegradation are effective for PVC degradation. In fact, they serve as pretreatment, thereby facilitating better biodegradation by fungi. White rot fungi can degrade low molecular weight PVCs. According to Kirbas et al. (1999), Kitamoto (2008), and Ali et al. (2014), *Phanerochaete chrysosporium*, *Lentinus* spp., *Aspergillus niger*, *Penicillium janthinellum*, and *Doratomyces* spp. can degrade PVC. Many yeast strains, namely, *Rhodotorula aurantiaca* and *Kluyveromyces* spp., and other fungi *Aureobasidium pullulans* also degraded PVCs (Webb et al. 2000).

**Table 6.4** Fungi involved in plastic degradation

S. No.	Polymers	Microorganisms	References
1.	Polyethylene	<i>Penicillium simplicissimum</i>	Yamada et al. (2001)
		<i>Brevibacillus borstelensis</i> and <i>Rhodococcus ruber</i>	Hadad et al. (2005)
		<i>Trichoderma harzianum</i>	Sowmya et al. (2014)
		<i>Laccaria laccata</i>	Janczak et al. (2018)
	Polyethylene terephthalate (PET)	<i>Aspergillus niger</i>	Obidi et al. (2010)
		<i>Phanerochaete chrysosporium</i> , <i>Pleurotus ostreatus</i> , <i>Aspergillus niger</i> and <i>Aspergillus glaucus</i>	Aswale (2010)
	Polyethylene carry bags	<i>Aspergillus niger</i>	Aswale and Ade (2008)
		<i>Aspergillus niger</i> and <i>Aspergillus glaucus</i>	Kathiresan (2003)
		<i>Aspergillus niger</i> , <i>Aspergillus ornatus</i> , <i>Aspergillus nidulans</i> , <i>Aspergillus cremeus</i> , <i>Aspergillus flavus</i> , <i>Aspergillus candidus</i> and <i>Aspergillus glaucus</i>	Reddy (2008)
		<i>Penicillium pinophilum</i> and <i>Aspergillus niger</i>	Volke-Sepulveda et al. (2002)
		<i>Aspergillus niger</i> , <i>Penicillium funiculosum</i> , <i>Chaetomium globosum</i> , <i>Glilotadium virens</i> and <i>Pullularia pullulans</i>	Gilan et al. (2004)
LDPE	<i>Fusarium</i> sp. AF4	Shah et al. (2009)	
	<i>Aspergillus oryzae</i>	Konduri et al. (2011)	
	<i>Mucor circinelloides</i> and <i>Aspergillus flavus</i>	Pramila and Vijaya Ramesh (2011)	
	<i>Aspergillus</i> sp.	Raaman et al. (2012)	
	<i>Aspergillus</i> spp.	Kumar et al. (2013)	
	<i>Rhizopus oryzae</i> NS 5	Awasthi et al. (2017)	
	<i>Penicillium oxalicum</i> NS4 (KU559906) and <i>Penicillium chrysogenum</i> NS10	Ojha et al. (2017)	

(continued)

Table 6.4 (continued)

S. No.	Polymers	Microorganisms	References
	LDPE powder	<i>Aspergillus nidulans</i> and <i>Aspergillus flavus</i>	Usha et al. (2011)
	HDPE	<i>Aspergillus versicolor</i> and <i>Aspergillus</i> sp. <i>Phanerochaete chrysosporium</i> ME-446 and <i>Trametes versicolor</i> (IFO 7043, IFO 15413) <i>Aspergillus niger</i> , <i>Aspergillus oryzae</i> and <i>Aspergillus flavus</i> <i>Aspergillus terreus</i> MF12 <i>Penicillium oxalicum</i> NS4 (KU559906) and <i>Penicillium chrysogenum</i> NS10 <i>Cladosporium cladosporioides</i> <i>Penicillium frequentans</i>	Pramila and Vijaya Ramesh (2011) Liyoshi et al. (1998) Konduri et al. (2010) Balasubramanian et al. (2014) Ojha et al. (2017)
2.	Polyurethane	<i>Chaetomium globosum</i> and <i>Aspergillus terreus</i> <i>Curvularia senegalensis</i> , <i>Fusarium solani</i> , <i>Aureobasidium pullulans</i> and <i>Cladosporium</i> sp. <i>Polyporus versicolor</i> , <i>Pleurotus sajor-caju</i> , <i>Phanerochaete chrysosporium</i> ME 446, <i>Pleurotus ostreatus</i> , <i>Pleurotus sapidus</i> , <i>Pleurotus eryngii</i> , <i>Pleurotus florida</i> <i>Aureobasidium pullulans</i> , <i>Geotrichum candidum</i> , <i>Alternaria alternaria</i> , <i>Cladosporium</i> sp., <i>Aspergillus</i> sp., <i>Penicillium</i> sp. and <i>Ulocladium atrum</i>	Bonhomme et al. (2003) Seneviratne et al. (2006) Boubendir (1993) Crabbe et al. (1994)
3.	PVC	<i>Phanerochaete chrysosporium</i> PV1, <i>Lentinus tigrinus</i> PV2, <i>Aspergillus niger</i> PV3 and <i>Aspergillus sydowii</i> PV4 <i>Aureobasidium pullulans</i> , <i>Rhodotorula aurantiaca</i> and <i>Kluyveromyces</i> spp. <i>Aspergillus versicolor</i> , <i>Aspergillus niger</i> , <i>Aspergillus flavus</i> , <i>Chrysonilia sitophila</i> and <i>Penicillium</i> sp.	Kirbas et al. (1999) Pectulyte (2002) Ali et al. (2014) Webb et al. (2000) Sachin and Mishra (2013)
	Plasticized PVC		

4.	Polyesteramides		Yeast <i>Candida guilliermondii</i> and micromycete <i>Aspergillus fumigatus</i>	Novotný et al. (2015)
5.	Disposable plastic films		<i>Aspergillus flavus</i> and <i>Mucor rouxii</i> NRRL 1835	El-Shafei et al. (1998)
6.	Degradable plastic	Degradable plastic	<i>Phanerochaete chrysosporium</i> <i>Aspergillus niger</i> , <i>Aspergillus nidulans</i> , <i>Aspergillus lavus</i> , <i>Aspergillus glaucus</i> and <i>Penicillium</i> sp.	Lee et al. (1991) Priyanka and Archana (2011)

Source: Adapted and updated from Devi et al. (2016); Pathak and Navneet (2017)

Four fungal species, namely, *Curvularia senegalensis*, *Fusarium solani*, *Aureobasidium pullulans*, and *Cladosporium* sp., are soil fungi with potential to degrade ester-based polyurethane. These fungi produce extracellular enzymes such as ureases, proteases, and esterases in the presence of polyurethane. The release of ammonia is indicated in the degradation of polyurethane (Pathirana and Seal 1985; Howard et al. 2012). According to Cosgrove et al. (2007), *Geomyces pannorum* and *Phoma* species dominated the soil involved in polyurethane degradation.

Polyethylene is hydrophobic high molecular weight polymers which are difficult to degrade by fungi. The low-density polyethylene is degraded by genus *Penicillium*, *Aspergillus*, *Chaetomium*, *Pullularia*, and *Gliocladium*. Likewise, the high-density polymers are degraded by *Trametes versicolor* and *Phanerochaete chrysosporium* using lignocellulosic enzymes (Iiyoshi et al. (1998). Around 0.2% loss in weight of polymers was observed in 10 years. To facilitate better degradation, the high molecular weight polyethylene is pretreated with UV light and nitric acid. Pretreatment weakens the structure of polymers making it easy for fungi to act on the polymers. The biodegradation of polymers can be confirmed by the presence of oxidation products. The structural changes can be confirmed with an electron microscope and FTIR (Hasan et al. 2007). According to Friedrich et al. (2007), polyamide-6 also termed as nylon-6 is also degraded by white rot fungi and other species (*Fusarium* spp., *Phanerochaete chrysosporium*, *Aspergillus* spp., *Penicillium* spp., *Cladosporium* spp., *Ulocladium* spp., *Trichoderma* spp., *Gliocladium roseum*, *Pithomyces chartarum*, *Trichothecium roseum*, and *Mucor hiemalis*). Aliphatic polyester resin Bionolle and aliphatic-aromatic co-polyester Ecoflex (BASF) degradation were also assessed. No significant weight loss was observed in the polymer except for structural changes (279). *Phanerochaete chrysosporium* and *Talaromyces wortmannii* are also reported to degrade natural polymer poly(hydroxybutyrate-hydroxyvalerate) which is a biodegradable and biocompatible thermoplastic (Coelho et al. 2008). Polyhydroxyalkanoates are another natural polymer that showed 93% weight loss when inoculated with *Aspergillus fumigatus* (Bhatt et al. 2008). Other natural polymers that were degraded by fungi strains include poly(caprolactone) (PCL), poly(butylene succinate) (PBS), poly(butylene succinate and adipate) (PBSA), and poly(lactide) (PLA), poly(butylene succinate), and poly(alkaline succinate). The hydrolytic degradation products obtained during polymer degradation did not affect the diversity of other organisms in the soil. Incidence of marine and mangrove bacteria accumulating polyhydroxyalkanoates on the mid-west coast of India has been reported by Rawte et al. (2002).

### 6.6.3 Biodegradation of Plastics by Actinomycetes

Actinomycetes are organisms that possess characteristics of a bacteria and fungi. These unicellular organisms with nonseptate mycelium possess the ability to degrade plastics. Table 6.5 summarizes the various actinomycetes species involved in plastic biodegradation. Species of genera *Streptomyces* and *Acinetobacter* are

**Table 6.5** Actinomycetes and plastic degradation

S. No.	Types of plastic used		Microorganisms	References
1.	Polyethylene	Polyethylene	<i>Streptomyces</i> sp.	Méndez et al. (2007)
			<i>Streptomyces</i> sp., <i>Pseudonocardia</i> , <i>Actinoplanes</i> , <i>Sporichthya</i>	Sathya et al. (2012)
		Starch polyethylene-prooxidant degradable polyethylene	<i>Streptomyces badius</i> 252	Lee et al. (1991)
			<i>Streptomyces setonii</i> 75Vi2 and <i>Streptomyces viridosporus</i> T7A	Pometto et al. (1992)
		LPDE powder	<i>Streptomyces</i> KU8, <i>Streptomyces</i> KU5, <i>Streptomyces</i> KU1 and <i>Streptomyces</i> KU6	Usha et al. (2011)
<i>Streptomyces</i> sp.	Madhuri (2015)			
2.	Polyurethane		<i>Acinetobacter calcoaceticus</i>	Halim et al. (1996)
			<i>Acinetobacter gernerii</i> P7	Howard et al. (2012)
3.	Disposable plastic films		<i>Streptomyces</i> spp. (8 strains)	El-Shafei et al. (1998)
4.	Poly(tetramethylene succinate) (PTMS)		<i>Microbispora rosea</i> , <i>Excelsopora japonica</i> and <i>E. viridilutea</i>	Jarerat and Tokiwa (2001)

Source: Adapted and modified from Devi et al. (2016)

popularly reported to degrade polyethylene, polyurethane, plastic films, and LPDE powder. Other genera such as *Actinoplanes*, *Pseudonocardia*, and *Sporichthya* are also used in plastic degradation. Similar to bacteria, the actinomycetes too attacked the polymers using enzymes. The change in the polymer structure and weight confirms the polymer degradation by actinomycetes.

### 6.6.4 Factors Affecting Biodegradation of Plastics

The process of biodegradation is associated to certain drawbacks and is influenced by various factors. Some of them are discussed below.

#### 6.6.4.1 Anaerobic/Aerobic Condition

The process of biodegradation is greatly influenced by the presence or absence of oxygen. Aerobic condition is more favorable and efficient than anaerobic condition. The biodegradation under aerobic condition was found to be faster than anaerobic condition. Moreover, the aerobic process released only CO<sub>2</sub>, while anaerobic

process produced more harmful  $\text{CH}_4$  and  $\text{CO}_2$ . Microbial degradation of plastics is carried anaerobically in the landfills and results in the generation of methane having global warming potential of 56 in 20 years. According to Kumar et al. (2011), aerobic condition is elemental for the biodegradation of plastics by fungi.

#### 6.6.4.2 Chemical Composition of the Plastics

The chemical composition of plastics is crucial in deciding the fate of plastic degradation. The microbes decomposing the plastics feed and thrive on it by consuming it as nutrient source; therefore, starch-based polymers are preferred by the microbes as the hydrolytic enzymes released by them act on the polymer matrix and hence reduce plastic into simpler form. The polymers derived from flax fibers or starch is inclined to relatively easy biodegradation. Polymers based on petroleum such as polyolefins are photodegraded by microbes (Sen and Raut 2015). Molecular weight of the polymers is one of the important factors which determine the biodegradation. Low molecular weight is suitable for biodegradation as the rate of enzymatic hydrolysis is rapid in case of smaller molecular weight (Tokiwa and Suzuki 1977). The melting point of the polymer too influences the enzymatic biodegradability. A polymer with higher melting temperature tends to have lower biodegradability. The enzymatic activity is also observed to decrease with time.

#### 6.6.4.3 Pretreatment

Nowadays, during manufacturing or processing of polymers/biopolymers, some additives such as benzophenone are used to avoid or minimize the photodegradation of the plastics. These additives affect the thermal sensitivity and UV absorption capacity of the polymer. It is observed that chemically/thermally sensitive polymers have better biodegradation rate. The thermal exposure prior to subjecting microbes to the plastics leads to the breakdown of the polymer into simpler form on which bacteria can easily attack. An alkaline substance known as nodax is also added to alter the chemical structure of the polymer to make it available for the microbes (Augusta et al. 1993). According to Moore (2008), the natural conditions such as the hydrolytic properties of sea water, atmosphere's oxidative properties and solar radiation help in breaking polymers into fragile and simpler substrate for the microbes.

#### 6.6.4.4 Intrinsic Parameters

Factors such as temperature, pH, humidity, sunlight, water stress, culture conditions, and sunlight predominantly affect microbial community and enzymatic activity for polymer degradation (Gu 2003). Soil bacteria are known to reduce plastics in the presence of optimal water and temperature. Fungus when grown at lowest pH showed maximum  $\text{CO}_2$  evolution and efficient lignolytic activity (Glass and Swift 1990).



### 6.6.4.5 Microbial Population

The quality and quantity of microbial population determine the efficiency of biodegradation. Irrespective of the source, many bacteria have shown their potential in plastic degradation. Bacteria, algae, and fungi isolated from various resources such as plastic and soil at the dumping sites, rhizosphere soil of mangroves, marine water, polythene buried in the soil have been reported to degrade plastics (Rutkowska et al. 2002). Low density polythene was found to be effectively degraded using *Mucor circinelloides* and *Aspergillus flavus* isolated from municipal landfill area (Pramila and Vijaya Ramesh 2011). The microbial population use the plastics as a source of energy and carbon. Fuhs in 1961 reported several microorganisms that fed on paraffin as a carbon source. Jen-hou and Schwartz (1961) showed bacteria consumed polyethylene as carbon source.

## 6.7 Alternate to Plastics

### 6.7.1 Biodegradable Plastics

The invention of plastic has been a boon to the population to lead a sophisticated life. Excessive usage, improper disposal, and poor management practices have necessitated the synthesis of alternate, eco-friendly biodegradable or bio-based plastics (BDPs) that should possess properties of conventional plastic with a high degree of biodegradability. Such plastics are known as bioplastics which are synthesized from the polymers derived from renewable carbon sources. According to the literature, bioplastics consist of either biodegradable plastics (i.e., synthesized using fossil materials) or bio-based plastics (i.e., plastics synthesized from renewable resources or biomass) (Tokiwa et al. 2009). Biodegradable plastics or bioplastics are nonpersistent in the environment and get degraded naturally on exposure to sunlight, air, and microorganisms. Under aerobic conditions, they are degraded to CO<sub>2</sub>, inorganic compounds, and H<sub>2</sub>O and under anaerobic conditions to CH<sub>4</sub>, CO<sub>2</sub>, and H<sub>2</sub>O (Lee 1996a, b). The principal mechanism involved in degradation of bioplastics includes the enzymatic action of microorganisms. Renewable raw materials such as agricultural/animal resources like cellulose, starch, collagen, casein, soy protein polyesters, and triglycerides are used for the production of bioplastics. The composition of the final product and the chemical structure of the material used decide the biodegradability of plastics. The bioplastics are manufactured using natural or synthetic resins. Natural biodegradable plastics can be naturally created or either synthesized from renewable resources. Synthetic biodegradable plastics are a petroleum-based nonrenewable resource. Naturally biodegradable plastics are unified with synthetic polymers to produce plastics to meet the properties of the conventional plastics (Demirbas 2007).

The different types of biodegradable or bioplastics are listed below. Some of the polymers used as bioplastics include polylactic acid (PLA), poly- $\beta$ -hydroxybutyric

acid (PHB), and polyhydroxyalkanoate (PHA). They are produced using natural polymers, polymers derived from microbes, and conventional chemical or fermentation process for bio-based monomer polymerization (Harding et al. 2007; Kalia et al. 2000).

**Plant-based bioplastics:** Bioplastics are derived from plant raw materials such as corn, soy, and potato starch. They are degraded by composting and more than 60% of it gets degraded within 180 days. Biodegradation of these plastics requires water, air, and sunlight. These plastics meet the American society for testing and material standards. The biggest disadvantage of the plant-based bioplastics is that they are not economical and cannot be recycled. Spudware is one example of plant-based bioplastics prepared from potato starch and used in the manufacturing of spoons, forks, and plates.

**Oil-based bioplastics:** They are manufactured from nonrenewable sources such as crude oil. Oil-based bioplastics are produced using energy-intensive techniques.

**Thermal-based film:** These are bioplastics with a specific additive which helps the plastic to degrade when exposed to high temperature. They include two types of film plastics, namely, oxo- and hydro-biodegradable. The medium of destruction differentiates oxo- and hydro-biodegradable plastics. The former requires oxygen for degradation and the latter requires moisture. Hydro-biodegradable plastics degrade much faster than oxo-degradable plastics. Oxo-biodegradable plastics are less expensive. The major disadvantage of these plastics is they start to degrade when stored in hot place.

**Additive-based film combo:** It is another type of film with additives. During degradation, they convert into humus and then to carbon dioxide and water. The advantage of these types of plastic is they can degrade with and without oxygen, can be recycled, and possess a long expiration date, for example, green film.

BAK is a 100% biodegradable polyester amide plastic that is developed by Bayers. They are recyclable and possess excellent properties. According to reports, these degrade at a temperature as low as 0.5 °C. Moisture is another important factor for degradation of BAK. Preservation is required for BAK which is the major drawback of the product.

**Degradable polyethylene:** These plastics are manufactured with the purpose of degrading them within 60 days to 5 years of incubation according to the requirement. They are degraded by light and moisture. Within 55 days of incubation, it gets converted to mulch. The additive used in the plastic is less toxic and can be safely disposed off in landfills.

The waste management option for the bioplastics or biodegradable plastics is domestic and municipal composting (Davis and Song 2006). Anaerobic digestion is also popularly used in bioplastic degradation (Murphy and Bartle 2004). Under mesophilic conditions, the material gets degraded within a maximum period of 24 months (Briassoulis and Dejean 2010). The advantage of biodegradable plastics over conventional plastics is that carbon emissions are eight times lesser for biodegradable plastics. Conventional plastic manufacturing process requires more energy in comparison with bioplastics. Bioplastics can be decomposed by composting on a regular basis, and the compost can be used as valuable soil additive (Song et al. 2009).

### 6.7.2 *Compostable Plastics*

Compostable plastics are new generation plastics that are degraded by composting. Cornstarch, potato starch, cellulose, and soy resin are the polymers used for the production of compostable plastics. They possess most of the properties of conventional plastics such as tensile strength, oxygen barrier, and resistance to heat and impact or shock. Compostable plastics are degraded in a composting facility within 90–180 days. However, the thickness and composition of the compostable plastics determine the degradation efficiency and time. A compostable plastic should possess three characteristics, namely, biodegradability, disintegration, and toxicity. The compostable plastic should not produce any toxic intermediates.

## 6.8 Challenges in Plastic Degradation

Most of the polymers are biologically inert and recalcitrant due to high molecular weight, hydrophobic nature, and absence of functional groups which are compatible with the microbial enzymatic system. Degradation of the polymer is characterized by discoloration, phase separation, cracking, erosion, and delamination. One of the biggest challenges remains high molecular weight of the synthetic polymers as the rate of biodegradability is directly dependent on the molecular weight of the polymer. The other limiting factors which need to be explored are breakage of bonds, transformation due to chemicals, and synthesis of new functional groups which are responsible for the variation in the structure of the polymer to make it easy for degradation. Moreover, since biodegradation involves microorganisms, the type and nature of organisms, availability, size of the inoculum, and environmental conditions are also important challenges that need more attention in polymer biodegradation. The challenges of the polymer biodegradation are discussed below in detail:

- (a) **Chemical composition:** The chemical composition of the polymers plays a crucial role in polymer degradation. The long carbon chain in the thermoplastic makes the polymers resistant to biodegradation. The strength of the polymer chain is affected by assimilation with heterogroups such as  $O_2$ . Unsaturated portions and amorphous regions are susceptible to oxidation. The rate of oxidation depends on the reactivity of the peroxy radicals formed and on the dissociation energies of available carbon-hydrogen bonds in the polymer substrate.
- (b) **Molecular weight:** Molecular weight determines the rate of degradation of plastics. The higher the molecular weight, the lower the rate of degradation. It has been reported that some microorganisms utilize polyolefins with low molecular weight faster as compared to high molecular weight polyolefins. Lower molecular weight polymers support the growth of microorganisms.
- (c) **Hydrophobicity:** Hydrophobicity interferes with the formation of microbial biofilm, and hence degradation gets limited.

- (d) Size of the molecules: Degradation (mechanical, thermal, and biological) is influenced by the size of the molecules. The smaller the size of the molecule, the higher the rate of degradation.
- (e) Introduction of functionality: Addition of carbonyl groups or chromophores to the polymers increases its photodegradation capacity. This might be due to the availability of more sites to absorb photons to initiate degradation. The carbonyl chromophore absorbs near-UV radiation and forms radicals by the Norrish Types I and II and H-abstraction processes for photochemical degradation. Reagents based on sulfuric acid help in slow sulfonation and oxidative degradation of polyolefins. In certain cases, starch is used to modify the polymer. Addition of starch helps in bacterial and fungal degradations in the soil.
- (f) Additives: Addition of fillers, pigments, photostabilizers, and other polymerization catalysts makes the polymer susceptible to degradation. Lignocellulosic fillers and metals decrease the thermal stability of the polymer. Heating in the presence of oxygen changes the properties of the polymer via oxidation. The extent of oxidation determines the structure and chemical properties of the polymer.
- (g) Chemical bonding: Linkage between the monomer units determines the resistance of the plastics. During polymerization, the head-to-head addition of monomer units and the tail-to-tail addition of monomer units create weaker portions of the polymer favoring degradation. Likewise branching increases degradation, and cross-linking reduces the rate of degradation. Cross-linking locks the polymer structure and prevents lamellar unfolding.
- (h) Methods of synthesis: Polymer preparation method too determines the rate of biodegradation.
- (i) Effect of substituents: The addition of substituents in the polymer backbone influences the stability of the plastics. For example, hydrogen, phenyl group, and hydrochloric acid affect the thermal stability, while fluorine and aromatic compounds increase the stability of polymers.
- (j) Effect of stress: Polymers face two types of stress, namely, tensile and compressional stress. The former favors degradation and the latter retards it. A structural or morphological change is observed in the polymers exposed to stress. Stressed polymers are more susceptible to degradation. During stress, polymer strains are straightened, stretched, and cleaved by light.
- (k) Environmental conditions: Polymer biodegradation depends upon environmental conditions such as moisture, temperature, oxygen, and a suitable population of microorganisms. In warm climates when the relative humidity exceeds above 70%, the rate of polymer degradation by the microorganisms increases. High temperature and high humidity enhance hydrolytic degradation of the polymers. Moisture and temperature do some primary degradation and weaken the polymer, thereby facilitating the microbial attack. Briefly, the photostabilizers become active when exposed to light and leach out of the polymer matrix in the presence of moisture. After a preliminary breakage in the polymer chain, it is easy for the microorganisms to attack the polymer chain. Tropical regions are more favorable for degradation. It is a general rule that at an increase of temperature by 10 °C, the rate of the reaction doubles. Oxygen in the air due to its scavenging property also facilitates polymer attack at ambient temperature.

## 6.9 Conclusion

Plastics are ubiquitous due to their multiple advantages. They are part of our day today's life. Improper management and disposal practices have ended up in the accumulation of plastic waste in the terrestrial and aquatic environment. The harmful effects caused by plastic waste accretion are drastically increasing day by day. Henceforth, their removal from the environment is very vital. Among thermal, photooxidative, ozone-induced, mechanochemical, and catalytic degradation methods, biodegradation is considered as the best option for plastic waste degradation due to low cost and eco-friendly nature. Also, they do not release any secondary pollutants. The microorganisms (bacteria, fungi, and actinomycetes) degrade the polymers through secretion of extracellular and intracellular enzymes. The complexity of the polymer limited the degradation by the microorganisms. Polymer pretreatment enhanced the biodegradation efficiency of the microorganisms. Henceforth, plastic biodegradation can be successful when biodegradation is combined with pretreatment. Further, bioprospecting of the isolated microorganism is essential to obtain efficient plastic-degrading bacteria. Although biodegradation can be one of the solutions, still more research is required to develop biodegradable alternate plastics that can degrade naturally without causing any harm to the environment.

## 6.10 Future Outlook

As mentioned earlier, plastics have become an indispensable part of our society. It is highly impossible to ban it from the society. Henceforth, to minimize the problems of conventional plastics, it is vital for us to focus on the preparation of polymers from natural sources. Further, the modifications or additives used in synthetic polymers to strengthen them can be minimized or replaced with alternate sources that can cause minimum damage to the environment. In recent times, the focus is also shifted to the preparation of bioplastics from waste materials such as organic wastes, agricultural wastes, paper wastes, and many more. Reusability can be another best option for minimizing plastic pollution. Hence, more research should be focused on the preparation of durable materials that can be reused again and again.

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