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## Review Article

# Usage of Potential Micro-organisms for Degradation of Plastics

## Abstract

Plastics are high molecular weight organic source materials. It is necessary to devise systems to decompose plastic polymers because their disruptive effects are threatening the ecosystem. Biotic and abiotic strategies are being employed to convert plastics into monomers. The objective of both techniques is to reduce polymers to monomers. Microbes act on monomers for their degradation by releasing enzymes on polymers. The rate of microbial degradation is affected by both the environmental conditions as well as by polymer characteristics. Different methods are used to check the rate of biological degradation. However, some plastics oppose microbial action. The environment condition and polymer characteristics affect the rate of degradation. Different approaches are used to check the rate of biological degradation. The need of the time is to generate bio based plastics material which can be degraded efficiently. These polymers can be recycled by degradation to monomers and then convert back to petrochemical products. This will contribute to fulfill the increasing demand of organic fuels and may serve as next generation fuel. There is no effective technique that can degrade plastics with efficacy, so scientists are struggling to develop techniques which not only degrade these polymers but also results into beneficial products. This review is an attempt to organize some of the most common strategies for degradation of various types of polymers along with a list of potential microbes capable of feeding on them.

## Abbreviations

PE: Polyethylene; PP: Polypropylene; PVC: Polyvinyl Chloride; PS: Polystyrene; PUR: Poly Urethane; PET: Poly Ethylene Tetrathalate; PEA: Polyethylene Adipate; PCL: Polycaprolactone; PES: Polyethylene Succinate; PLA: Poly Lactic Acid; PHB: Poly Hydroxyl Butyrate; PBS: Poly Butylenes Succinate; PBSA: Poly Butylenesuccinate-co-adipate; PHA: Polyhydroxy Alkanoate; PVA: Polyvinyl Alcohol; PEG: Polyethylene Glycol; PES: Polyethersulfone

## Introduction

Plastics are vital hydrocarbons occurring both in natural as well as in synthetic forms. "Plastic" word comes from "plastikos" having Greek origin and implies to any material which can be molded in any shape. Generally the chemical structure of plastics comprises high molecular weight and long chains of hydrocarbon polymers [1].

Plastics have wide range of applications ranging from industrial, agricultural to domestic market. Examples include common use of polyethylene soil mulching in the agriculture sector [2]. The use and demand of polymers is growing day by day due to its applications in every field of life. Large scale synthetic plastic production initiated in 1950. There is a 20-

fold increase in plastic production over five decades since 1964 [3]. Synthetic polymer production has enormously progressed for the last 60 years. This time period allowed polymeric materials to step into every domain of human life [4]. A global estimate suggested plastics production up to three hundred and eleven million tons in 2014 [3,5] and reached up to three hundred and thirty five million tons by 2015 which clearly depicts its enormously rapid production which will become twice in the next two decades whereas will reach nearly four-folds by 2050 [3].

Plastics are actually the polymers derived from carbon source including fossil fuels and renewable resources. The discovery of the chemical process leading to the production of long chain, high molecular weight synthetic polymers from organic sources was the novel advancement in the field of chemical sciences. These long chain polymers are notorious for their distinguished features such as strength, malleability, low-weight, easy and inexpensive production [2]. Moreover, the polymeric materials can be categorized into natural polymers, synthetic polymers and blends of polymers, whereas the petrochemical compounds extracted from coal, oil and natural gas are the prime sources of these polymers [6]. These organic and inorganic raw materials are substantially composed of carbon, hydrogen, silicon, nitrogen, oxygen and chloride [7]. About 80% of the global plastic usage is of synthetic origin which includes polyethylene (PE), polypropylene (PP),

polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR) and polyethylene terephthalate (PET) [8].

The division of plastics is majorly based on two class's i.e. biodegradable and non-biodegradable plastics. Biodegradable plastics are known for some major advantages (1) they help in enriching the soil by returning to the soil through the process of composting with organic wastes (2) it causes the abatement of injuries to wild animals which occurs mainly by dumping of conventional plastics (3) as they are degraded naturally in the environment so, it reduces the need for labor and ultimately labor cost for removal of plastic waste from the environment (4) this feature also enhances the durability and stability of landfills by decreasing the amount of waste. (5) Effective microbial and enzymatic activity reduces them to monomers and oligomers [9]. There are various non-biodegradable polymers which are well documented and mainly includes PE, PP, PS and PVC [6]. However, high accumulation of non-biodegradable plastics in the environment due to inappropriate waste management practices and uncontrolled waste disposals are the cause of destruction on earth [6,10].

Extensive production of synthetic non-biodegradable plastics which initiated in the last century is contributing about 10% of the total waste disposed of either properly or improperly [11]. Non-biodegradable plastic waste is wreaking havoc for terrestrial and marine environments as large scale pollution [11,12]. A study suggested that China is the largest plastic waste producing country in the world with 8.82 million metric tons per year (Figure 1). An estimate indicated that 10 to 20 million tons of plastics find their way into the oceans annually [3]. Also, plastic debris has not spared Greenland and Barant Seas having hundreds of thousand pieces per square kilometers [3,13]. In addition, the Antarctic Ocean has also been affected by plastic litter. These regions are mainly inhabited by microplastics (< 5 mm) and mesoplastics (< 5 cm) [3,14]. In addition, the level of plastics has escalated six folds in the oceans compared to plankton which poses a serious threat to aquatic life [6]. It is estimated that about 1 million seabirds and 100 thousand marine mammals perish each year, where 44% of all seabirds, 86% of all sea turtles and 43% of all marine mammals and many fish are harmed by swallowing of plastic waste [5].

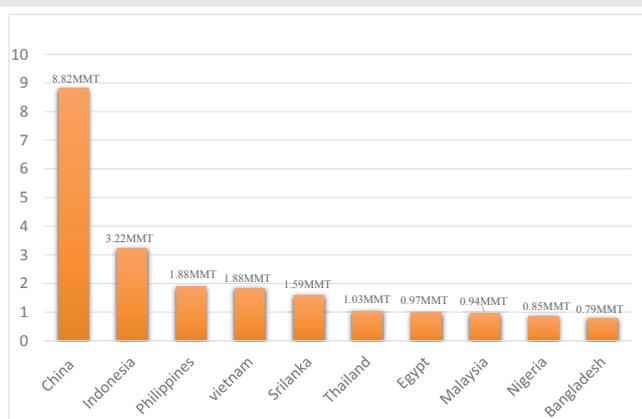


Figure 1: An estimate suggesting top 10 plastic waste (in units of millions of metric tons/year) producing countries of the world [12].

From the last 40 years, scientists are struggling hard to discover viable remedies to alter the destruction caused by plastics in the environment. Although the plastics have 300 million tons worldwide production each year [5], only a fraction of it is recycled. Various physicochemical factors and microbial communities in the environment are efficient in breaking the resistance of polymers [8,15] besides its profound longevity. Polymer fragments further decompose themselves until microplastics of size less than 5 millimeters are achieved [8]. Further degradation of microplastics is carried out by microorganisms [8]. Many studies have demonstrated the potential of microorganisms including bacteria and fungi capable of producing exoenzymes and their products under stress conditions, effectively degrades biodegradable polymers [6]. Several mechanisms have been adopted by the microorganisms for the breakdown of high molecular weight plastics including either the exploitation of microplastics for the fulfillment of their nutritional requirements by microbes or the action of microbial enzymes indirectly [6]. The ubiquitous strains of bacteria and fungi for degradation of plastic includes *Pseudomonas fluorescence*, *P. aeruginosa* and *Penicillium simplicissimum* [6,16,17]. However, certain enzymes e.g. esterases, lipases, and cutinases have the striking ability of hydrolysis of polymers [8] such as poly (ethylene adipate) (PEA) and poly (caprolactone) (PCL) [6]. The sources of enzymes such as esterases and lipases are fungal species i.e. *Rhizopus delemar*, *R. arrhizus*, *Achromobactr sp.* and *Candida cylindracea* [6,18,19]. This review will report the procedures of biodegradation with various classes of polymers. It will cover the biodiversity and occurrence of microbes having the potential of effective degradation of plastics. Moreover systematic overview of the mechanism of biodegradation will be reported and the factors that govern microbial degradation will be discussed. Also, the current scenario with future prospects will be highlighted.

### Classification of polyesters on the basis of biodegradation

On the basis of biodegradation polyesters are divided into two types which consist of non-biodegradable polyesters and biodegradable polyesters.

**Non-Biodegradable Polyesters:** Non-biodegradable polyesters include both fossil based polyesters and biobased polyesters. Most non-biodegradable plastics are fossil based synthetic plastics that are obtained by processing of petrochemicals [1]. These plastics are highly stable and do not undergo degradation because of extensive repetition of monomers [6]. Due to poor degradation, they have been accumulated in the environment and have become a threat to the environment [11]. There are certain oxo-biodegradable plastics which are considered to be nonbiodegradable as there is no evidence found for their degradation [20]. Therefore it is necessary to devise a system to degrade such polyesters. Pro-oxidants and starch are incorporated in these polyesters to reduce their resistance to bacterial attack [20].

### Biodegradable polyesters

**Fossil-based biodegradable polyesters:** Fossil-based

plastics are both biodegradable and non-biodegradable. These polyesters are used widely in the packaging industry. Microbes and their enzymes are involved in the degradation of fossil-based plastics but their rate of degradation is extremely slow [7,21]. The main focus of research on the degradation of plastics is on characteristics of micro-organisms that degrade plastics, degradation of fossil-based plastics by employing various enzyme based strategies, cloning of genes that encode biodegradation enzyme [20]. There is a need to optimize the biodegradation process for fossil-based biodegradation in order to make process fast and speedy. Some examples of fossil-based biodegradation polymers are discussed.

**Polycaprolacton:** PCL is fossil-based biodegradable polyester and it can be degraded by both aerobic and anaerobic microorganisms. It is used in blood bags formation, catheters and packaging materials [22]. The microbes that degrade PCL are found abundantly in the atmosphere. *Aspergillus sp.* ST-01, a fungal strain is found to degrade PCL into valuable products such as succinic acid and valeric acid.

**Polyethylene succinate:** PES is made by the copolymerization of ethylene oxide and succinic anhydride [23]. It is used in the production of shopping bags, in the paper industry as a coating agent and in agriculture for film production. Microbes that degrade PES are limited in number as compared to microbes that degrade PCL. *Pseudomonas sp.* AKS2, a bacterial strain is found to degrade PES efficiently [24].

**Bio-based biodegradable plastics:** Bio-based biodegradable plastics can be degraded completely biologically so they have wide industrial applications [25]. These polymers are degraded by extracellular enzymes. Starch is commonly used in the production of bio-based biodegradable plastics. The wide use of starch in the production of bio-based biodegradable plastics is due to its availability, inexpensiveness and biodegradability. Starch-based polymers are classified into starch filled polymers and starch-based polymers. Various microorganisms degrading these polymers under both aerobic and anaerobic conditions.

**Polylactic acid:** PLA is obtained from renewable resources like tapioca roots and corn starch. This polymer can be introduced into animal bodies so its use is widespread in medicine [26]. PLA is used widely among bio-based biodegradable plastics due to its mechanical attributes and biodegradability [27]. The hydrolytic products of its degradation can be degraded completely by microorganisms [28]. Lactic-co-glycolic acid is a bio-based polymer which is used in drugs and food delivery in host microbes [29]. *Cryptococcus sp.*, *Amycolatopsis sp.* and *B. licheniformis* degraded PLA efficiently [30].

**Biodegradable polymer blends:** Biodegradable polymers with desirable characteristics can be formed by blending different materials. This method is more efficient than copolymerization. [31]. Polymer blends are considered to be more efficient than fossil-based polymers due to their certain applications [32]. Starch-based biodegradable polymers are considered to be completely biodegradable. The primary process of degradation increase surface area of polymer enhancing

action of the enzyme. Various microorganisms are responsible for complete degradation of starch and blend. Examples of polymer blends are mentioned.

**Starch and Polyvinyl Alcohol blends:** Starch is basically water soluble biodegradable polymer blend. It is blended with polyvinyl alcohol. This blend is used for packaging material and in agriculture due to its film-forming ability [33,34]. Various enzymes degrade this polymer blend with their hydrolytic ability [31,35].

**Starch and polyester blend:** Starch and polyester blends are cost-effective, readily available and accessible [31]. Degradation capacity can be increased by increasing starch concentration. Addition of anhydride polyesters gives popular characteristics to these blends. These polymers are thermoplastics and used in engineering [36]. Lipase enzymes secreted by *R. arrhizus* and *R. delemar* hydrolyze polyester blends and lead to degradation [9]. According to different reports, there is gradual increase in annual production of bioplastics worldwide. Maximum production of bioplastics is estimated as 7848 thousand tonnes in year 2019. The increasing trend of bioplastics production world wide is given in table 1.

#### Occurrence of plastic degrading microorganisms

The diversity of polymer degrading microorganisms vary depending on environmental conditions such as the sea, soil and sludge. In degradation process microbes first adhere to surface of the plastic and then colonize the exposed surface of plastic followed by biodegradation. It is necessary to investigate microbial degradation in ecosystems. Enzymatic degradation of plastics by hydrolysis is divided into two steps. Enzymes first adhere to plastics and then subsequent hydrolysis occur that results in cleavage [31].

To check degradation potential of micro-organisms toward certain polymer, clear zone method employing agar plate is used. Emulsified polymers are applied on agar plate, inoculation of microbes occur, microbes release an extracellular enzyme that diffuse in agar and degrade polymers into water-soluble components. A clear zone is formed by degradation of polymers. Degradation of polymers results into

**Table 1:** Annual production of Bio plastics.

Year	Biodegradable Plastics	Non-biodegradable plastics/ Bio based	Total production in 1000 tonnes	References
2009	226		249	[74]
2010	342	674	1016	[74]
2011	486	675	1161	[74]
2012	921	571	1492	[75]
2013	591	990	1581	[76]
2014	663	1034	1697	[76]
2015	737	1291	2028	[76]
2016	762	1291	2053	[76]
2017	901	2511	3412	[76]
2018	1287	5511	6798	[76]
2019	1287	6561	7848	[76]

oligomers, dimers and monomers and finally to CO<sub>2</sub> and H<sub>2</sub>O. This technique reveals that poly (3-hydroxy butyrate) (PHB), poly (butylene succinate) (PBS), (PP) and PCL degraders are widely distributed. Majority of microbial strains that degrade PHB belong to bacteria, *Streptomyces* and fungi. Majority of bacterial strains can degrade PCL, PHB and PBS but not PLA. A few microorganisms have been detected that degrade PLA [31].

## Factors affecting microbial degradation of plastics

### Environmental factors

**Moisture:** Moisture is an important factor for the growth of microorganisms so it plays a vital role in the degradation of plastics. Sufficient water content is necessary for activation of microbes. Hydrolytic activity of microbes is increased with increased moisture content.

**pH:** The rate of hydrolytic reaction is affected by change in pH. Degradation of various polymers results into such product that changes the pH. Change in pH alters microbial growth rate and so affects the rate of degradation.

**Temperature:** The degradation capacity of enzymes decrease with increase in temperature. Those polyesters which have a high melting point are less prone to degradation. Enzyme efficiently degrades those polyesters which have a low melting point [31].

### Polymer characteristics

**Molecular weight:** Molecular weight plays a key role in defining properties of a polymer. Increase in molecular weight decrease the rate of degradation [31]. Polyesters with low molecular weight are easily degradable by enzymes [37].

**Shape:** Those polymers which have large surface area are easy to degrade by an enzyme. For biodegradation, there is a standard criteria for shape and size for different kinds of polymers.

**Biosurfactants:** Biosurfactants are those amphiphilic compounds that are produced on living surfaces. The process of biodegradation is enhanced by the addition of biosurfactants due to presence of specific functional groups [37].

Process of biodegradation proceeds even in harsh conditions, if biosurfactants are used [6].

### Effective plastic degradation strategies

Degradation term literally implies to the process which involves breaking down of larger molecules into smaller ones [1]. The procedures which involve the activity of microscopic life forms in concert with chemical and physical methods to treat the plastic debris involving the conversion of long-chain polymers into monomeric radicals have been categorized as plastic (polymer) degradation.

**Non-biological degradation:** Non-biological degradation is synonymous to term abiotic degradation. This type of degradation accounts for the physical and/or chemical

procedure that is responsible for revamping the molecular structures of long polymers [2]. Nonbiological degradation of polymers generally includes photo-oxidation and thermooxidation requiring the exposure of plastics to light and heat respectively.

**Thermal degradation:** It is the process requiring heat to bring the complex polymeric forms to simpler forms whereas biodegradation in the presence of oxygen is thermal oxidation. The core objective in this process is the conversion of long chain polymers into small monomers with subsequent production of peroxide radicals after reaction with oxygen [1]. Degradation of polymers by heating is mainly driven when exposed to the visible portion of sunlight falling in the range of 400–760nm wavelength. However, thermal oxidation is observed when polymers are exposed to infrared radiations [7,38].

Thermal degradation is actually the chemical weathering of polymers at elevated temperatures [7]. Bifurcation of CC backbone structure of the polymer (molecular scission) results at elevated temperatures and allow them to change the characteristics of the polymer by reacting with one another. Changes in polymeric structure also tend to alter their changes in properties including alteration in molecular weight of the polymer, reduction in malleability, discoloration, changes in optical property, cracking and other general physical characteristics [7].

**Photodegradation:** The process involving bombardment of high-intensity photon particles for the deterioration of long-chain polymers into monomeric units is named photodegradation. It is considered to be a vital process for degradation of plastics [11] as the physical and chemical properties of polymers enable them to entrap the tropospheric solar radiations which are considered as noxious part of solar radiations [7]. Photodegradation in the presence of oxygen is referred to as photooxidation. Under the influence of free-radical-mediated mechanisms, chain cleavage (scission) of polymeric molecules takes place with the production of small molecules of plastics which are readily broken down by different microbial strains [8,15]. Moreover, for the enhancement of physicochemical procedures for polymeric degradation, oxo-biodegradable synthetic polymers have been introduced. Development of oxo-biodegradable synthetic polymers is a step towards the enhancement of physicochemical processes for polymeric degradation. Oxo-biodegradable polymers are composed of pro-oxidant units [2], which are often metalbased such as Co, Mn, Fe or Ti and leads to radical formation when undergoing photo or thermal degradation [11].

**Biological degradation:** Biological degradation of plastics is relatively new concept referred to the conversion of large polymeric molecules into simpler ones by the action of biologically active enzymes produced by specific microorganisms which utilize them to fulfill their energy requirements [1]. Generally, the biodegradation of organic compounds into either carbon dioxide and water in the presence of oxygen (aerobic biodegradation) or carbon dioxide, water and methane in the absence of oxygen (anaerobic biodegradation) by living organisms [7], includes the catalytic activity of

microbial enzymes. In this context, different organisms are needed some of which are capable of degrading long polymers into their simple form and some are capable of utilizing simple monomers subsequently releasing simple waste products while others have the ability to deteriorate the simple excreta [7].

The research work on microbial degradation of plastics begin since 1970. Although aliphatic polyesters are amenable for degradation by microorganisms available in an ecological system, there are several plastics which strongly opposes the microbial attack. This type of behavior is exhibited by almost all conventional plastics like PE, PP, PS and PVC etc. [39]. Several microorganisms including bacteria, actinomycetes, and fungi have the striking potential of biodegradation of plastics under changing biotic and abiotic factors. Up to this time, several bacterial and fungal strains have been identified. Recently a new fungal species have been identified which feeds on plastics and is ubiquitous in the soil. The fungus named *Aspergillus tubingensis* breaks down large polymers by releasing certain enzymes [40]. A new discovery related to the natural evolution of a bacterial species capable of breaking down the bonds between the polymers of PET (polyester) was reported in 2016 [41]. Later, in 2018, while studying the enzyme structure of *Ideonella sakaiensis* 201-F6, scientists found that they had unintentionally transformed the enzyme having capability of degrading PET plastics in few days rather than taking centuries to break it down [42]. Moreover, mutant enzyme (PETase) also evolved with the ability to break down polyethylene-2,5furandicarboxylate (PEF, an alternative form of PET) [43].

Some fungi including *Fusarium oxysporum* and *F. solani* [44] were studied previously for their ability to eat up PET but bacteria are relatively easier to exploit on large scale level [42]. A study conducted in 2013 showed the isolation of new bacterial species *Roslateles depolymerans* strain TB-87 with the potential of degrading several biodegradable aliphatic polyesters including PBS, PES, PCL with the exception of PLA and poly (3hydroxybutyrate-co-hydroxy-valerate (PHBV) [45]. Another study conducted by Urbanek et al. (2017) isolated 113 bacterial and 8 fungal species from Arctic environment which could degrade poly (butylene succinate-co-adipate) (PBSA), PBS, PCL or PLA. *Pseudomonas sp.* and *Rhodococcus sp.* were found to have the highest degradation ability. The study further reported *Colonostachys roseas* as efficient degrader causing 100% deterioration of starch films within 16 days and 52.91% degradation of PCL film within 30 days at 28°C [5].

The microorganisms involved in biodegradation process differ from each other in their mode of action and their optimal growth conditions in soil depending upon their properties [7]. Heterotrophic microorganisms can effectively colonize plastics as their substrate [7]. Moreover, different factors such as polymer properties, the nature of organisms and pretreatment methods generally act upon the biodegradation of polymers. Properties of polymers like ductility and friability, molecular weight, melting temperature, glass transition temperature, modulus of elasticity, nature of functional groups and substituents attached, and type of additives added affect polymeric biodegradation [7,39]. Some important biodegraders of plastics are given in the (Table 2).

A brief comparison of photo, thermal and biological degradation is mentioned in table 3.

## Mechanism of polymer degradation

The process of polymeric biodegradation involves several

**Table 2:** List of different microorganisms with their enzymatic capability for degradation of polymers.

Microorganisms	Enzymes	Plastics	References
<b>Bacteria</b>			
<i>Pseudomonas sp.</i> E4	Alkane hydroxylase	LMWPE (Polyethylene)	[56]
<i>P. putida</i> AJ	Alkane hydroxylase	Vinyl Chloride (Polystyrene)	[57]
<i>P. chlororaphis</i>	Polyurethanase	Polyester (PUR)	[58]
<i>P. aeruginosa</i>	Esterase	Polyester (PUR)	[59]
<i>P. protegens</i> BC2-12	Lipase	Polyester (PUR)	[60]
<i>P. fluorescen</i>	Protease	Polyester (PUR)	[61]
<i>Pseudomonas sp.</i>	Lipase	PET	[49]
<i>Pseudomonas sp.</i> AKS2	Esterase	PES	[24]
<i>P. stutzeri</i>	PEG dehydrogenase	Polyethylene glycol (PEG)	[47]
<i>P. vesicularis</i> PD	Esterase	Polyvinyl alcohol (PVA)	[48]
<i>R. arrizus</i>	Lipase	PEA, PBS, and PCL	[31]
<i>P. stutzeri</i>	Serine hydrolase	PHA	[62]
<i>Tremetesversicolor</i>	Laccase	Nylon, PE	[63]
<i>Rhodococcusequi</i>	Aryl acylamidase	PUR	[64]
<i>Brevibacillusborstelensis</i>	Unknown	PE	[65]
<i>Thermomonosporafusca</i>	Unknown	PVC	[66]
<i>Schlegelellathermo-depolymerans</i>	Unknown	Poly(3-hydroxybutyrate-co-3-mercaptopropionate)	[67]
<b>Fungi</b>			
<i>Aspergillusniger</i>	Catalase, Protease	PCL	[31]
<i>Fusarium</i>	Cutinase	PCL	[62]
<i>Aspergillusflavus</i>	Glycosidase	PCL	[31]
<i>Amycolaptosis sp.</i>	Manganese peroxidase	PLA,PE	[62]
<i>Penicilliumfuniculosum</i>	Unknown	PHB	[31]
White-rot fungus IZU-154	Manganese peroxidase	Nylon	[68]
<i>Agromyces sp.</i>	Nylon hydrolase	Nylon-6 (oligomers)	[69]
<i>Acremonium sp.</i>	Unknown	PHB, poly[3HB-co-(10 mol%) 3HV]	[70]
<i>Cephalosporium sp.</i>	Unknown	PHB	[71]
<i>F. solani strain 77-2-3</i>	Unknown	PCL, cutin	[72]
<i>P. funiculosum QM301</i>	Unknown	PEA, PPA, PBA	[73]

**Abbreviations:** PE: polyethylene; PVC: Polyvinyl chloride; PUR: Poly urethane; PET: Poly ethylene tetraphthalate; PEA: Polyethylene adipate; PCL: Polycaprolactone; PES: Polyethylene succinate; PLA: Poly lactic acid; PHB: Poly hydroxyl butyrate; PBS: Poly butylenes succinate; PHA: Polyhydroxy alkanooate; PVA: Polyvinyl alcohol; PEG: Polyethylene glycol.

**Table 3:** Comparison of non-biological and biological degradation.

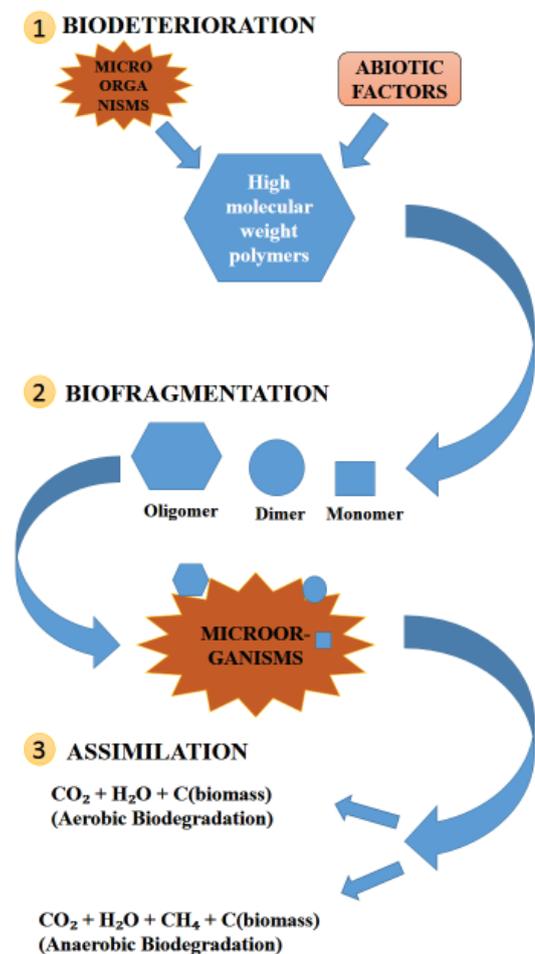
Factors	Non-Biological Degradation		Biological degradation	References
	Thermal degradation	Photo degradation		
Process	Use of high temperature for chemical modification of plastics	Exposure of high energy radiations for breaking chemical bonds in plastics	Cleavage of polymer by microbes	
Major requirement	Heat	High energy photons or UV radiations	Micro-organisms	[7]
Degradation rate	Fast	Process progresses from slow to fast	Moderate	[7]
Temperature requirement	High	Not needed	Not needed	[7]
Advantage	Fast process widely used	and Environmental friendly if high energy radiation is not used, acceptable	Environmental friendly, cheap and acceptable	
Disadvantage	Not acceptable, not environmental friendly	Costly, sun burnt skin, skin cancer, and other problems associated with UV light.	Slow process	

stages and cessation can occur at any stage. The process comprises three major steps which are biodeterioration, biofragmentation and assimilation [46] as shown in figure 2.

**Biodeterioration:** Biodeterioration is the initial stage of biodegradation of plastics. It is the abiotic degradation of the plastic surface resulting in an alteration in its mechanical, physical and chemical properties [46]. Abiotic degradation is considered to be the essential step for initiation of synthetic polymer degradation such as polycarboxylates, PET, PLA and their copolymers, poly( $\alpha$ -glutamic acids) and poly(dimethyl siloxanes) or silicones [7]. Modification of mechanical characteristics of polymers generally occur by physical factors e.g. heating, cooling, freezing, thawing, wetting, drying etc. [7]. Structural modifications of plastics occur when subjected to an external environment. These initial changes are the outcome of environmental factors such as mechanical, chemical, temperature and light [46]. The microbial action in concert with abiotic factors helps in chopping down biodegradable materials into small fragments [47,48]. Little changes like swelling and bursting of polymers can also occur by the growth of fungi on the polymeric surface [7].

**Biofragmentation:** It is the lytic process involving secretion of enzymes and free radicals by microorganisms following molecular bond cleavage of polymers, thereby producing low molecular weight plastics including monomers, dimers and oligomers [48,49]. The process is also termed as depolymerization. Microbial enzymes have potential to depolymerize various synthetic polymers like PCL [7]. Plastic biodegradation involves the use of various enzymes released by microorganisms which include lipase, proteinase K, pronase, hydrogenase etc. However, proteinase K enzyme secreted by *Tritirachium album* was reported as the potent degrader of PLA. PLA was also found to be degraded by many strains of *Amylocolatospsis* and *Saccharothrix* [1].

**Assimilation:** The monomers, dimers, and oligomers produced from the biofragmentation process are absorbed through the cellular membrane into the cells of microorganisms and referred to as assimilation stage [46]. Cell membrane receptors of microbial cells recognize some of the fragmented molecules and make their entry possible through the membrane into the cells. The non-recognizable fragments of plastics by

**Figure 2:** General schematic illustration of polymer biodegradation under aerobic and anaerobic conditions.

cell membrane receptors require further biotransformation reactions to produce the products which can easily be diffused into the cell [50]. The molecules which got entry into the cell further undergoes various metabolic pathways for the production of adenosine triphosphate, new biomass, various primary and secondary metabolites and packaging vesicles [50]. During the process various metabolites of simple and complex nature such as organic acids, aldehydes, terpenes, antibiotics etc. are released into the extracellular surroundings.

In addition, intracellular metabolites including CO<sub>2</sub>, N<sub>2</sub>, CH<sub>2</sub>, H<sub>2</sub>O, and different salts are hydrolyzed completely and reaches at the stage called mineralization following transfer of mineralized products into the environment [50]. Mineralization of monomers, dimers and oligomers by microorganisms occur either aerobically or anaerobically.

**Aerobic biodegradation:** Aerobic microorganisms utilize oxygen (O<sub>2</sub>) as an electron acceptor and breakdown monomer, dimer and oligomer material into a simpler one. The process release CO<sub>2</sub>, H<sub>2</sub>O and biomass as its end products. The process is also named as aerobic respiration [51].



**Anaerobic biodegradation:** In the absence of O<sub>2</sub>, destruction of complex polymers into smaller units by microbes with CH<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O and biomass as its byproducts is termed as anaerobic biodegradation. Anaerobic microorganisms in the absence of oxygen utilize other sources as their electron acceptor such as nitrate, sulphate, iron, manganese and carbon dioxide for biodegradation [51]



It is imperative to note that biodeterioration and biodegradation of polymer substrate cannot be achieved up to 100% as a small percentage of it becomes part of microbial biomass, humus, and other natural products [50].

### Mechanism of enzymatic degradation of plastics

Enzymatic degradation of plastics involves secretion of enzymes by microbes and then enzymes act on plastics and resolve plastics efficiently. Enzymes act on long chain polymers and convert them to monomers. Amorphous region of plastic is attacked first by enzyme and subsequently followed by crystalline region. The rate of enzymatic degradation is affected by polymer characteristics [52]. First step of biodegradation by enzyme is hydrolysis in order to enhance the hydrophobicity by receptive enzyme by giving functional group to polymer. Thus enhancing the susceptibility of polymer to microbes. Exoenzymes secreted by microbes, convert polymers to monomers and these monomers are then taken up by semi-permeable membranes of microbes. However if, in some situations when size of polymer is large even after hydrolysis, then the polymers are depolymerized first in order to pass through the cellular membrane and then subsequently degraded by intracellular enzymes. Various factors affect the rate of degradation of plastics by enzymes. These factors include both physical and physiochemical. Physical factors include temperature and humidity. Physiochemical condition of a microbe e.g. temperature, pH and moisture also effect the mode of degradation. Hydrolase enzymes proceeds the hydrolytic reactions. This class of enzymes include large number of enzymes e.g. phosphatase, lipase, esterase, glycosidase and many others [53]. Cell derived proteins that are responsible for cleavage are the part of this class of enzymes [54].

### Conclusion and Future prospects

This is an era of plastics. The demand for plastics is an

ever increasing trend. The need of the time is to use biobased biodegradable plastics to maintain the health of environment [6]. For the disposal of plastics, biodegradation is an effective method. Various microbial strains have been detected that convert plastic polymers to monomers [6]. Exploitation of microbes for degradation of plastics is eco-friendly method [1]. Various properties of plastics affect its rate of biological degradation. The weak forces (hydrogen bond), the covalent forces, affect the physical and chemical properties of plastics and thus affect the rate of degradation [31]. As, synthetic plastics are most durable, therefore, there is a need to generate bioplastic materials which will reduce impact of plastics on the environment [55]. Moreover, radiolabeling processes are now available that detect assimilation of degradation product in living systems which degrade it [4].

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