

Bioremediation - A Progressive Approach toward Reducing Plastic Wastes

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ABSTRACT

Plastic has become an indispensable part of every sphere of human life due to its high quality, durability and inexpensiveness, etc. Hence, an innovative method of bioremediation should be adopted, that utilizes the potential of microbes in degrading such non-biodegradable plastics. Various chemical and biological approaches are involved in degradation of plastic, but from ecofriendly way biological approaches are in more common trend today, which involves use of microbes for hydro-biodegradation and oxo-biodegradation of the polymers following photo degradation and chemical degradation of the plastic. It has been found by previous researches that different groups of microbes including bacteria, fungi, actinomycetes etc have versatile property of degrading both natural and synthetic plastics by converting non-biodegradable plastics into low molecular weight polymers, CO₂, water, biogases like methane and other less harmful components by modifying their crystalline level, molecular weight and mechanical properties that are responsible for their resistance towards easy degradation. This review mainly focused on new innovative ways to utilize microbial activity in reducing environmental pollution to a vast extent making this planet a safe home to live, and directly preventing the humans, animals, plants and soil from harmful consequences of plastic pollution.

Keywords

Bioremediation,
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Introduction

Environmental pollution is the most challenging problem in the today's world that is increasing day by day leading to devastatingly and irreparable damage to our mother earth. With the constant rise in the global population and progression in modern technology, the plastic has become an imperative choice in every aspect of life and we have left with no other option. But the most serious concern is that most of the conventional plastics viz., polyethylene,

polypropylene, polystyrene, poly (ethylene terephthalate), poly (vinyl chloride) etc., are non-biodegradable and their augmentation in the nature has been constant threat for the environment. A significant amount of research has been done by the researchers all over the world on synthetic plastic waste and to overcome the consequences associated with their non-biodegradability. Accumulation of plastic in environment is hazardous for food chain, causing overall ecological imbalance

leading to health impairment in humans as well. Although plastic is beneficial from technological point of view, but the problems associated with its usage and disposal have outweighed its beneficence. Hence, the concept of microbial degradation of plastics has been put forward by the scientists enabling the high throughput analysis of microorganisms responsible for biodegradation, thus providing various methodological breakthroughs for bioremediation and biotransformation of polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), heterocyclic compounds (such as pyridine or quinolone), metals, pharmaceuticals and radionuclides, and hence, getting a deeper knowledge of the biodegradative pathways involving microbes to harness their natural capacity of xenobiotic metabolism.

Biological processes contribute a significant role in the removal of pollutants utilizing the catabolic versatility of microbes in degradation or conversion of these contaminants. In environmental biology, genome based studies of micro-organisms have widened our information about their metabolic and regulatory pathways, thus providing new insights of degradative networks and molecular adaptability to constantly changing environment. Keeping in mind the above concerns, this study has been carried out to explore the different types of plastic and the micro-organisms that can degrade them.

Plastics and their types

Plastics are defined as the synthetic long chain polymeric units (Scott, 1999). They are nonmetallic moldable compounds, a property responsible for their widespread utility. They have become irreplaceable and an integral part of every sector of economy due to their easy availability, durability and stability.

Owing to their better chemical and physical properties like lightness, strength and resistance to water, they have replaced paper and other cellulose based compounds for packaging and other utilities. There are various different types of plastics, classified on the basis of their chemical structure and physical properties.

Classification on the basis of thermal properties

Thermoplastics

These are the polymers which when heated does not change its chemical composition and hence can be molded any number of times without any negative effect on it. Thermoplastics are the most commonly used plastics having different number of polymeric units. Examples include polyethylene (PE), polypropylene (PP), polystyrene (PS), polytetrafluoroethylene (PTFE), polyvinylchloride (PVC) etc.

Thermosetting polymers

Thermosetting plastics are non-recyclable polymers due to their highly cross linked structures, hence, cannot be melted and modified and remains in solid form. The chemical change in these type of plastics is irreversible while in thermoplastics it is reversible due to their linear chains. Examples of thermosetting polymers are phenol-formaldehyde, polyurethanes, etc.

Classification on the basis of degradability

Plastics can be classified into non-degradable and degradable polymers (Ghosh *et al.*, 2013).

Non-biodegradable plastics

Non-biodegradable plastics also known as synthetic plastics are derived from

petrochemicals and are very high molecular weight polymers. They do not degrade naturally and hence accumulate in environment.

Biodegradable plastics

Biodegradable plastics are synthesized from natural sources such as components of algae, plants and animals which act as the source of cellulose, starch and protein for their synthesis. They get easily degraded on interaction with UV rays, water, enzymes, gradual changes in pH etc. They are further classified into four classes (Arikan *et al.*, 2014).

Bio-based bio plastics

Plastics in which whole proportion of carbon is derived from agricultural and forestry resources such as corn starch, soybean protein etc.

Biodegradable bio plastics

These plastics get degraded completely by microorganisms into biogases and biomass (mainly carbon dioxide and water) without leaving behind any toxic byproducts (Jain *et al.*, 2010).

Compostable bio plastics

These bio plastics get decomposed biologically on composting that occurs at a similar rate as that of other compostable materials without producing any toxic remainders.

Photodegradable bio plastics

These plastics have light sensitive groups attached into their backbone, hence, on getting exposure of UV light for a long period of time disintegrate their polymeric structure

making them vulnerable to further microbial degradation.

Classification on the basis of chemical composition

Addition polymers

Polymers having all monomeric atoms integrated into to form a complete polymer, majority of which are derived from olefins.

Condensation polymers

These types of polymers are derived from monomers having two different group of atoms such as amide or ester groups linked together. Examples include polyethylene, polyethylene terephthalate, polypropylene, polystyrene, polyurethane, polyvinyl chloride etc.

Applications of plastic

Plastics are nonmetallic moldable compounds which is responsible for their wide utilization and popularity. Synthetic polymers has substituted natural materials in almost every area for more than half a century ago and nowadays have become an indispensable part of our life because of their easy availability and comfort in use. Plastic is the mother industry to hundreds of components and products that are manufactured and used in our daily life and hence became an integral part of all sectors of economy. For example, in sectors such as agriculture, telecommunication, building and construction, consumer goods, packaging, health and medical are all high growth areas that ensure present demand for plastics.

Limitations of plastic

As human civilization is moving towards modern technology, the production of plastic

has increased manifolds, but due to its non-biodegradable nature, an alarming situation of environmental pollution has created that could persist for centuries (Albertssons *et al.*, 1987). Their permanent accumulation in the environment has caused deleterious effects not only on humans and animals but has also deteriorated the aesthetic quality of cities and forests. Moreover, the burning of plastics produce persistent organic pollutants (POPs) such as dioxins and furans leads to environmental pollution (Jayasekara *et al.*, 2005).

Pure plastics themselves have low toxicity due to their chemical inertness and insolubility in water but their persistent nature leads to the production of toxicants. Plastics when disposed of in soil produce chlorides, heavy metals, phthalates etc. which migrates to the surrounding soil causing soil pollution. Some plastic additives are not bound chemically to the polymers and are in freely movable and leachable state causing ecological imbalance by deteriorating the water and soil quality that affects plant growth leading to negative consequences on human causing improper hormone functions and the release of carcinogenic substances. They are also a great threat to animals and other living beings as it causes blockage in intestine of birds, animals, fish and marine mammals as they feed upon them (Spear *et al.*, 1995; Secchi and Zarzur, 1999).

Low density polyethylene is one of the main cause of environmental pollution. Owing to the wide aspect utility of polyethylene, its production is increasing with the rate of 12% per annum producing approximately 140 million tons of synthetic plastic annually all over the world (Shimao, 2001). With a large number, their degradation has become a major concern leading to the synthesis of biodegradable polymers that can be easily degraded naturally.

Bioremediation

Bioremediation has evolved as an effective technique to counteract the negative impacts of environmental pollution in various ways. According to EPA, bioremediation is a waste management technique that relies upon the microorganisms and uses their biological activity to interact with the environmental factors and causes change in the physical chemical conditions of hazardous waste and finally convert it into comparably less toxic or even nontoxic products.

Microbial degradation or biodegradation is the result of the enzymatic activities accompanied by the formation of biofilm.

Factors affecting degradability

Following factors affect the biodegradability of any polymer (Alshehrei, 2017)

Functional groups that increases the hydrophobicity as hydrophobic degradation is slower than hydrophilic one.

Molecular weight and density of the polymer.

Morphology of polymer as determined by the proportion of crystalline and amorphous regions; amorphous degrades faster than crystalline.

Structural complexity such as linearity or the presence of cross linked chains in the polymer.

Presence of easily breakable bonds in the chemical structure of polymer (ester > ether > amide > urethane).

Molecular composition (blend).

The nature and physical form of the polymer *viz.*, fibrous, films, pellets or powdered form.

Hardness of the polymers as soft polymers degrades faster than the hard ones.

Mechanism of plastic degradation by microorganisms

Bacteria and fungi both are involved in the degradation of natural as well as synthetic plastics (Gu *et al.*, 2000a). Plastics are the potent substrates for heterotrophic microbes. Environmental conditions prevailing in a particular area are responsible for the dominating bacteria and the degradative pathway utilized by that microbe. Biodegradation of plastics or any other complex material proceeds variably under different environmental conditions in accordance with their properties as different microorganisms have different optimum growth conditions (Glass and Swift, 1989). When there is abundant oxygen, aerobic microorganisms are responsible for the conversion of complex compounds into simpler ones yielding microbial biomass, carbon dioxide and water as the final products. Extracellular and intracellular depolymerase enzymes are the two main categories which are involved actively in natural degradation of polymers (Doi, 1990; Gu *et al.*, 2000b). Exoenzymes process by converting complex compounds into simple molecules that are small enough to pass through the semi permeable bacterial plasma membrane and then utilized them as carbon and energy resources while endoenzymes work by hydrolyzing the different bonds that hold the polymers. Major steps involved in the biodegradation of plastics are given as under.

Bio-deterioration

It is a natural process in which plastic gets modified chemically, physically and mechanically by the superficial degradation caused by microbes and decomposer

organisms. Abiotic parameters are the main factors that helps in weakening the polymeric structure of the plastics (Helbling *et al.*, 2006; Ipekoglu *et al.*, 2007) and also behave as a synergistic factor by initiating the bio-deterioration process (Jakubowicz *et al.*, 2006). This process is triggered by the formation of biofilm over the surface of plastic. The formation of biofilm depends upon the chemical composition and physical structure of the plastic as well as on the prevailing environmental conditions (Lugauskas *et al.*, 2003). The microbial film leads to the growth of the highly diverse microbial community on the plastic that causes its chemical and physical deterioration (Zettler *et al.*, 2013). The development of biofilm is associated with the secretion of extracellular polymeric substances (EPS) which reinforces the cohesion of the microbial film and its adhesion over the surface of plastic. These secretory EPS enter the pores of the plastic thus increasing the pore size which in turn promotes the formation of cracks that weakens the physical structure of the plastic, hence contributing to physical deterioration (Bonhomme *et al.*, 2003). Biofilm formation also causes the release of acidic compounds such as nitrous acid (*Nitrosomonas* sp.), nitric acid (*Nitrobacter* sp.) or sulphuric acid (*Thiobacillus* sp.) by chemolithotrophic bacteria. Organic acids such as citric, fumaric, gluconic, glutaric, glyoxalic, oxalic and oxaloacetic acids are also released by chemoorganotrophic bacteria. The formation of acid leads to the change in the pH inside the pores that result in progressive degradation of plastic causing changes in their microstructure contributing to the chemical deterioration of plastic.

Bio-fragmentation

This term refers to the catalytic action of the ecto enzymes or the free radicals secreted by

the microbial community that cleaves the polymeric plastics into oligomers, dimers or monomers. Due to their high molecular weight plastics could not cross the cell wall of microorganisms, hence, microbes secrete the extracellular enzymes that catalyzes the reaction mainly at the surface of the plastic. Bacteria generally require the imbalance electric potential to perform lysis and causing further chemical reactions. But the highly stabilized structure of plastics owing to the long chains of carbon and hydrogen resulted in its balanced charge. Therefore, to destabilize this local electric charge, bacteria generally secrete oxygenases that adds up oxygen to the long carbon chain of plastic. For instance, mono-oxygenases and di-oxygenases incorporate one and two oxygen atoms respectively forming alcohol or peroxy groups that are less resilient for biodegradation. Further transformations are then catalyzed by esterases and lipases after the formation of carboxylic groups and by endopeptidases after amide group formation (Lugauskas *et al.*, 2003).

Assimilation and mineralization

Assimilation refers to the integration of molecules transported in the cytoplasm with the microbial metabolism while the term mineralization characterizes the complete degradation of molecules resulted in the excretion of completely oxidized molecules (CO₂, N₂, CH₄, and H₂O).

Assimilation is the integration of molecules inside the microbial cells with or without getting degraded completely. Formation of monomers does not ensure their assimilation by microbes. Some monomers remain in the surrounding environment of microbial cells without getting assimilated. Monomers require specific carriers to cross the cell wall and/or cytoplasmic membrane of microorganisms. The plastic monomers get

oxidized inside the microbial cells through the catabolic pathways resulted in the production of energy and biomass. Microorganisms that do not have the pathways to catabolize the secondary metabolites produced as a result of assimilation transport them outside the cell where they further used by other cell for degradation or may stay outside the cell.

Biodegradation of natural products

Natural products are the biomaterials that are synthesized and catabolized by different microbes. A number of different species are responsible for their assimilation without having any toxic effect on them. Bioplastics are the natural polymers produced by different microbial species and cultured under different environmental and nutrient conditions (Madison *et al.*, 1999). These polymers are generally lipid in nature, get accumulated inside microorganisms as storage materials and helps in their survival under stress conditions. The number and size of granules, monomer composition, chemical structure and physicochemical properties of the bioplastics vary greatly in accordance with the microorganism responsible for its production.

Biodegradation of Polyhydroxyalkanoates (PHB and PHBV)

Microorganism utilizes poly(3-hydroxybutyrate) (PHB) and poly(3-hydroxybutyrate-co-valerate) (PHBV) as possible energy sources, thus causing their degradation in microbial active environment. Microorganisms secrete enzymes on the surface of the polymer resulting in the degradation of PHB into HB (hydroxybutyrate) and PHBV into HB and HV (hydroxyvalerate) which will further be used as a carbon source by the microbial cells, for their growth. The biodegradation rate of polymer varies with a number of factors, *viz.*,

surface area of polymer, pH, temperature and moisture content of the surrounding environment, presence of other nutrients and microbial activity.

PHB degradation by fungi was observed by Lee *et al.*, (2005). He inoculated the different isolates of fungi collected from different environments into the vials filled with PHB containing medium. A clear zone was observed around the fungal colony which is the sign of PHB depolymerization. The fungi was isolated mainly from compost, hay, lichens and soil and belongs to the genus *Penicillium* and *Aspergillus*. Protozoa also act as PHB degraders and were found from the samples collected from horse dung, hay, lichen, pond and soil. Distribution and phylogenetic association of actinomycetes involved in polymer degradation was investigated by Tokiwa and Jarerat (2003). They were found to be distributed among the different families, viz., Micromonosporaceae, Pseudonocardiaceae, Streptomycetaceae, Streptosporangiaceae and Thermonosporaceae. Bacteria were also found to be observed as PHB degraders by Tansengco and Tokiwa (1997). They observed the biodegradability of *Bacillus* and *Streptomyces* against PHAs.

Biodegradation of aliphatic polyesters

Poly(Ethylene Adipate) (PEA)

PEA is a pre-polymer of polyurethane and often mixed with different polyesters for desirable properties like soft segments. *Penicillium sp.* exhibits strongest PEA biodegrading activity among all the isolated PEA biodegraders with degradation in 120 hrs at high cellular concentration. It is also responsible for degradation of PBS, poly(butylene adipate) (PBA) and poly(ethylene succinate) (PES)(Tokiwa and Suzuki,1974). The enzyme involved in PEA

degradation has a molecular weight of 25 kDa and is similar to lipase in having broad substrate specificity. This enzyme could also degrade poly(ϵ -caprolactone) (PCL) and poly(β -propiolactone) (PPL) and is responsible for the hydrolysis of methyl esters of fatty acids, plant oils and triglycerides.

Poly(ϵ -Caprolactone) (PCL)

PCL is a biodegradable synthetic partially crystalline polyester with low melting point of 60°C. It gets degraded by both aerobic and anaerobic microbes widely distributed in environment. Tokiwa *et al.*, 1976 investigated the PCL degradative ability of *Penicillium sp.* isolated from soil. It takes 12 days by *Penicillium* to degrade it completely.

It can also assimilate alicyclic polyesters besides aliphatic polyesters but not aromatic polyesters. *Aspergillus* was also observed to be PCL degrading microorganism as it degraded the PCL in 6 days at incubation of 50°C (Sanchez *et al.*, 2000). PCL was also degraded by *Clostridium* under anaerobic conditions (Abou Zeid *et al.*, 2001). Lipases and esterases are the enzymes involved in PCL biodegradation (Tokiwa and Suzuki, 1977).

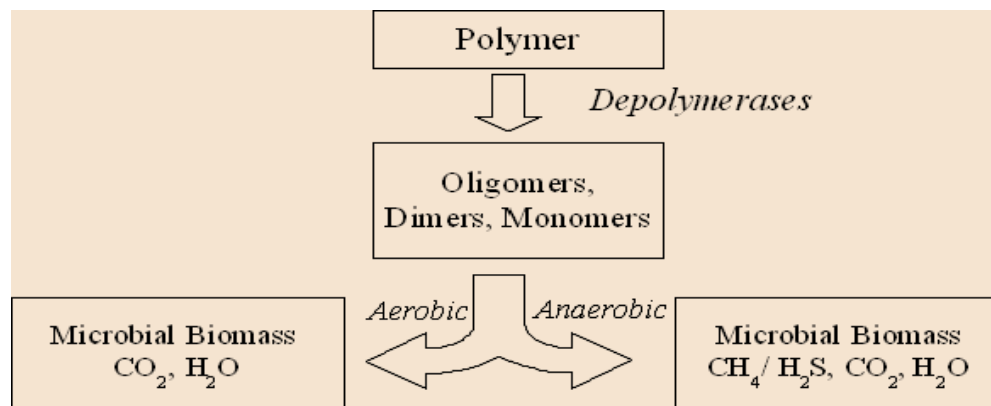
Poly (β -Propiolactone) PPL

It is a chemosynthetic biodegradable aliphatic polymer having good mechanical properties. Its monomeric units are same as that of PHB and PCL, hence can be depolymerized by both PHB depolymerase and lipase (Tokiwa and Suzuki, 1977b, Tanio *et al.*, 1982, Mukai *et al.*, 1993). PPL is mainly degraded by *Bacillus sp.* (Nishida *et al.*, 1998) but other microorganisms are also involved in its degradation, e.g. *Rhizopus delemar* (Tokiwa and Suzuki, 1977b), *Acidovorax sp.*, *Sphingomonas paucimobilis* and *Variovorax paradoxus* (Kobayashi *et al.*, 1999).

Table.1 Different types of microbes degrading plastics

Type of Plastic	Organism degrading Plastics	References
Poly Ethylene Adipate	<i>Penicillium sp.</i>	Tokiwa <i>et al.</i> , 1974
Poly E Caprolactone	<i>Penicillium sp.</i> <i>Aspergillus sp.</i> <i>P. finiculosin</i>	Tokiwa <i>et al.</i> , 1976 Sanchez <i>et al.</i> , 2000 Cook <i>et al.</i> , 1981
Polypiolacone(PPL)	<i>Bacillus sp.</i> <i>Accidovorax sp.</i> <i>Varivorarax paradoxus</i>	Nishida <i>et al.</i> , 1998
PBS and PES	<i>Amycolactopism sp.</i> <i>M. rosea</i> <i>Thermophilus bacillus sp.</i> <i>A. clavatus</i>	Paranamuda <i>et al.</i> , 1995 Jarerat <i>et al.</i> , 2001 Ishii <i>et al.</i> , 2007
Aliphatic Aromatic	<i>R. delemar</i> <i>T. fusca</i>	Tokiwa and Suzuki, 1981 Kleeberg <i>et al.</i> , 1998
Polyurethane	<i>R. delemar</i> <i>C. acidovorans</i>	Darby and Kaplan, 1968 Nakajima-Kambe <i>et al.</i> , 1995
Nylon	<i>A. niger</i> <i>B. pallidium</i> <i>Flavobacterium sp.</i>	 Kinoshita <i>et al.</i> , 1975
Co-Polyamide ester	<i>R. arehizum</i>	Komatsu <i>et al.</i> , 1993
Polystyrene	<i>Actinomycetes strain</i>	Mor, 2008
Poly vinyl chloride	<i>White rot fungi</i>	Kirbas <i>et al.</i> , 1999
Polyethylene	<i>Brevibacillus borstelensis</i> <i>Rhodococcus rubber</i> <i>P. simplicissimum</i>	Hadad <i>et al.</i> , 2005 Sivan <i>et al.</i> , 2006 Yamada-Onodera <i>et al.</i> , 2001
Polyurethane	<i>C. acidovorans</i> <i>Curvularia senegalensis</i> <i>Pseudomonas chlororaphis</i>	Akutsu <i>et al.</i> , 1998 Howard, 2002 Zheng <i>et al.</i> , 2005
Polyvinyl chloride	<i>P. putida</i> <i>P. fluorescens</i>	Danko <i>et al.</i> , 2004 Mogil`nitskii <i>et al.</i> , 1987
Poly(3-hydroxybutyrate)	<i>P. lemoignei</i> <i>Schlegelellathermodepolymerans</i>	Jendrossek <i>et al.</i> , 1995 Romen <i>et al.</i> , 2004
Poly(3-hydroxybutyrate-co-3-hydroxypropionate)	<i>Acidovorax sp.</i>	Wang <i>et al.</i> , 2002
Poly(3-hydroxybutyrate) Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	<i>Streptomyces sp.</i>	Mabrouk and Sabry, 2001
Polycaprolactone	<i>Clostridium botulinum</i> <i>Fusarium solani</i>	Abou-Zeid <i>et al.</i> , 2001 Benedict <i>et al.</i> , 1983
Polylactic acid	<i>F. moniliforme</i>	Torres <i>et al.</i> , 1996
Starch/polyethylene	<i>A. niger</i>	Lee <i>et al.</i> , 1991
Starch/polyester	<i>Streptomyces</i>	Lee <i>et al.</i> , 1991

Fig.1 Mechanism of biodegradation of polymers (Alshehrei, 2017)



Poly (Butylene Succinate) (PBS)

PBS is a synthetic aliphatic polyester possessing high melting point (112-114°C). It is polymerized from dicarboxylic acids (adipic and succinic acid) and glycols (1,4-butanediol and ethylene glycol) (Takiyama *et al.*, 1994). PBS degrading microbes are widely spread all over the environment but proportionately lower in number as compared to PCL degraders. It can be degraded by *Amycolatopsis* sp. which is also involved in the degradation of PHB and PCL (Pranamuda *et al.*, 1995). Jarerat and Tokiwa, 2001 investigated the PBS degrading ability of several thermophilic actinomycetes obtained from Japan Culture of Microorganisms (JCM). He observed a clear zone on agar plates containing emulsified PBS when inoculated with *Excelllospora japonica*, *E. viridilutea* and *Microbispora rosea*. It took eight days by *M. rosea* to degrade 50% (w/v) of PBS film.

Poly (Ethylene Succinate) (PES)

PES is similar to PBS in having high melting point (103– 106°C) and synthesizing monomeric units. It is synthesized either by polycondensation of ethylene glycol and succinic acid or by ring opening polymerization of succinic anhydride with ethylene oxide (Maeda *et al.*, 1993). Its

degradability varies with the change in the environmental factors (Kasuya *et al.*, 1998). Moreover, the distribution of PES degrading microbes is limited when compared with PHB and PC degrading microorganisms. A thermophilic *Bacillus* sp. TT96 isolated from soil was found to be PES degrader. A number of mesophilic microorganisms isolated from soil and water were also observed to be PES degrader and were found to be belonging to the *Bacillus* and *Paenibacillus* genus on analyzing phylogenetically. KT102 isolate of *B. pumilus* degraded PES much faster than the other isolates. It can also degrade PCL and olive oil but not PBS, PHB and PLA (Tezuka *et al.*, 2004). *Aspergillus clavatus* NKCM1003 strain was found to degrade PES film at a rate of 21µg/cm²/h. (Ishii *et al.*, 2007).

Aliphatic-Aromatic Copolyesters (AAC)

AAC are synthesized from PCL and aromatic polyesters like poly(butylene terephthalate) (PBT), poly(ethylene terephthalate) (PET) and poly(ethylene isophthalate) (PEIP). They are mainly hydrolysed by *R. delemar* lipase (Tokiwa and Suzuki, 1981). The susceptibility of hydrolysis of AAC's is inversely proportional to the aromatic polyester content as the rigidity of aromatic ring influence the biodegradability of AAC. *Thermobifidafusca* isolated from compost degraded 20 fold faster

than usually observed uncommon compost test (Kleeberg *et al.*, 1998).

Polycarbonates

These are the aliphatic compounds possessing greater resistance to hydrolysis in comparison to aliphatic polyesters. PEC degrading microbes are limited in number with only 0.2-5.7% of total microbial colonies (Nishida *et al.*, 1994) while PPC is almost non-biodegradable. Poly(hexamethylene carbonate) (PHC) degrading microbes which were isolated by Suyama *et al.*, 1998 and were found to be phylogenetically diverse. *Roseateles depolymerans* 61A hydrolyzed PHC into di(6-hydroxyhexyl) carbonate and adipic acid and poly(butylene carbonate) (PBC) into di(4-hydroxybutyl) carbonate and succinic acid. *Amycolatopsis* sp. HT-6 was also found to degrade PBC by Pranamuda *et al.*, (1995) PBC was also degraded by cholesterol esterase from *Candida cylindracea*, lipase from *C. cylindracea*, *Chromobacterium viscosus* and lipoprotein lipase from *Pseudomonas* sp. (Suyama and Tokiwa, 1997). 1,4-butanediol, di(4-hydroxybutyl) carbonate and CO₂ were formed from PBC by lipoprotein lipase from *Pseudomonas* sp (Suyama and Tokiwa, 1997).

Polyurethanes (PU)

PU are used to manufacture a number of products like adhesives, cushions, plastic foams, fibers, synthetic leathers, paints, rubber goods etc. Chemically, they are of two types- ester type (ES-PU) and ether type (ET-PU). The soft component of PU are derived mainly from the polymer-diol, *e.g.*, PCL-diol, polyethylene glycol, poly-tetramethylene glycol etc., and hard one from diisocyanate, *e.g.*, 1,6-hexamethylene-diisocyanate (HDI), diphenylmethane-4,4'-diisocyanate (MDI), tolylene-2,4-diisocyanate (TDI) and diols such as butanediol and ethylene glycol.

According to Darby and Kaplan, 1968, ES-PU were more susceptible to fungus than ET-PU. ES-PU made up of HDI hydrolyzed fast in comparison to ES-PU made up of either MDI or TDI. It explains the fact that the biodegradability of ES-PU molecules by *R. delemar* lipase depends upon their aromatic rings rather than the hydrogen bonding between them. Esterase enzyme of *Comamonas acidovorans* strain TB-35 degraded ES-PU made up of poly(diethylene adipate) and TDI and released adipic acid and diethylene glycol (Nakajima-Kambe *et al.*, 1995). But PUs is unable to degrade completely as no microorganism is reported till date to degrade them in whole.

Polyamide (Nylon)

Polyamide-6 (PA-6) is widely used for engineering purposes. It gets degraded when a decrease in its average molecular mass is observed (50% after 3 months) or when its fibres get physically damaged (visible under scanning electron microscope). Lignin degrading white rot fungi could degrade high molecular weight PA-66 when grown under ligninolytic conditions with limited supplement of ammonium tartrate and glucose (Deguchi *et al.*, 1998). Thermophilic *B. pallidus* has been reported to degrade PA-6 and PA-12 but not PA-66. Strong hydrogen bonding in between the chains of nylon polymer is responsible for its poor biodegradability. *Flavobacterium* sp. (Kinoshita *et al.*, 1975) and *Pseudomonas* sp. (NK87) (Kanagawa *et al.*, 1989) have been identified to degrade nylon 6 oligomers, but not nylon 6 polymers.

PA-4 has been reported to get degraded in soil (Hashimoto *et al.*, 1994) as well as in the activated sludge (Kawasaki *et al.*, 2005). Hashimoto *et al.*, 2002 identified that nylon 4 in the blend get completely degraded in 4 months but nylon 6 was unable to degrade.

Pseudomonas sp. strain ND-11 degrade the emulsified PA-4 in 24 hrs with the release of γ -aminobutyric acid (GABA) as degradation product (Yamano *et al.*, 2008).

Copolyamide-Esters (CPAE)

CPAE is synthesized by the amide-ester interchange reaction between PCL and different nylons. Simple blend of PCL and nylon retains the high biodegradable property of PCL. They are mostly degraded by lipase enzymes.

CPAE was synthesized by Komatsu and Tokiwa in 1993 from ϵ -caprolactam with ϵ -caprolactone and δ -valerolactone by using sodium as a catalyst under reduced pressure by ring opening copolymerization and used *R. arrhizus* lipase for its degradation.

As the content of amide bonds (nylon) is increased in CPAE, it causes an increase in its T_m (melting temperature) and hence its biodegradability decreases.

Polyethylene (PE)

PE is a stable polymer, hence, cannot be degraded easily by microbes. Tsuchii *et al.*, 1980 investigated the biodegradability of PE oligomers. He observed that low Mw PE oligomers get degraded partially but there was no effect on high Mw oligomers of PE. PE degrades in environment by interaction of photo and thermo oxidative degradation with biological activity of microorganisms. Photo and thermo oxidation of PE causes the release of alcohols, aldehydes, alkanes, alkenes, carboxylic acids, esters, keto-acids and lactones as the by-product. PE when mixed with additives leads to an increase in the rate of its auto oxidation, which in turn reduces its molecular weight, and hence makes it easier for microorganisms to degrade it.

Polypropylene (PP)

PP is a thermoplastic widely used in diapers, packaging materials, plastic moldings, plastic tubs, stationary folders, non-absorbable sutures etc. it can be degraded easily once it gets exposed to the UV rays. Moreover, it is also oxidized at high temperatures.

Polystyrene (PS)

PS is a high molecular weight hydrophobic synthetic polymer. It is used in the manufacturing of disposable cups and cutleries, insulating material, packing material etc. owing to its transparent hard plastic nature. PS exists in solid state at room temperature but get liquefies upon heating above its glass transition temperature and turns back into solid again on cooling. It is not biodegradable but recyclable. Mor *et al.*, (2008) reported the biodegradation of PS film by *Actinomyces* strain but the degree of biodegradation was very low.

Polyvinyl chloride (PVC)

PVC is a strong plastic with low moisture absorption and resists abrasion and chemicals. It is mainly used in buildings for electric wire insulation, floor coverings, pipes and fittings. It is also used to prepare synthetic leather products, shoe soles, textiles and garden hoses. It is reported to be degraded generally by exposure to light and high temperature (Braun and Bazdadea, 1986; Owen, 1984) but only a few reports are available on its degradation by microorganisms. Low molecular weight PVC can be biodegraded by the white-rot fungi (Kirbas *et al.*, 1999).

Biodiversity of polymer degrading microorganism

Biodiversity and prevalence of polymer degrading microbes depends upon the

surrounding environment like sea, soil, activated sludge, compost etc. It is important to determine their distribution and population in different ecosystems to avail their beneficial property of degrading the synthetic polymers. The main mechanism behind the microbial degradation of synthetic polymers is the adherence of microbes over the surface of plastic followed by their colonization.

The population of aliphatic polymer-degrading microorganisms in different ecosystems was found to be in this order- PHB = PCL > PBS > PLA (Nishida *et al.*, 1993).

Future perceptive

This review mainly focused on the natural and synthetic polymers, their types, uses, problems associated with their accumulation and their biodegradability by microorganisms. The major and foremost concern about the synthetic polymers is their low degradability, hence efforts are going on to promote their degradability either by chemically modifying them or by developing new alternatives for their degradation by any of the following mechanisms; biodegradation, environmental erosion, photo degradation and thermal degradation. Biodegradable plastic or bioplastic is the best alternative of synthetic polymers from degradation point of view. Development of bioplastics provides new insight of the waste management strategies owing to their easy degradation ability under natural environmental conditions.

Biodegradability tests of polymers should have been made compulsory to avoid the negative impact of synthetic plastic onto our environment and to find alternative methods to combat this problem of accumulation of plastic materials. Hence, it is a necessity to have complete knowledge about the steps involved in biodegradation of synthetic polymers (i.e. bio-deterioration, bio-

fragmentation, assimilation and mineralization). A sound knowledge about the whole process of biodegradation may also help in finding better options for improving biodegradation. Different factors could be explored in this respect like (i) use of surfactants or inducing the microbes to produce surface active agents for their improved adherence over the polymer surface, (ii) by blending the non-degradable synthetic polymers either with the natural polymers or with the biodegradable synthetic polymers like polylactic acid or polycaprolactum, (iii) by pretreating the plastics with high temperature, chemicals, UV and other high energy radiations, (iv) by culturing the plastic degrading microorganisms (bio addition) and (v) by addition of nutrients present in limited amount in the environment (bio-stimulation).

Cost effective, high efficient and eco-friendly technology capable of reducing and eliminating synthetic plastics are of great environmental interest. Microbial agents are the most effective tools among all the biological agents for the biodegradation of polymers. There is an increasing demand to explore these microorganisms that can easily grow in different environmental conditions under specific stress conditions and can use carbon from the plastic polymers as an energy source.

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