

Review

Analytical review on Biodegradation of Plastics

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Abstract— In some areas of the world, people are aware of the impact of plastic on the environment and implementing the strict rule not to use plastic. With the new advancement in Research and Development, a new concept of biodegradable plastics is introduced. It has a wide range of applications in many sectors. In this study, the biodegradation of various types of plastic using different bacteria was studied. Bacteria convert the polymer molecule into small water-soluble molecules like oligomers and dimers and then utilize as carbon and energy source and thus degradation of the polymer takes place.

Keywords— Plastics, Biodegradation, Degradation

I. INTRODUCTION

Plastics are very versatile solid materials that are strong, lightweight, moisture resistant, and durable. Polymers composed of sulfur, carbon, hydrogen, nitrogen, and other organic and inorganic elements, are also called plastics. It is produced from non-renewable resources such as fossil fuels.

Thermoplastics and thermosets are classes of plastics according to their type of chemical reaction. Plastics can be categorized as high-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), polystyrene (PS), polypropylene (PP), polyethylene (PE), and polyurethane (PUR) as they have different chemical structures[1], [2]. Owing to its consistency and price, plastic is used in our everyday lives. Plastic has enormous applications such as infrastructure such as agriculture, telecommunications, consumer goods, building and construction, medicine, and packaging health are all areas of high growth which ensure

the current demand for plastics. Even use in the manufacture of electrical products, plastic furniture, agricultural pipes, containers, sanitary products, pipes and fittings, tiles and floors, artificial leathers, bottles, boxes, shoes, thousands of household items. As it has these many applications and it is difficult to degrade, the environmental pollution and hazards of plastics are increasing day-by-day[3]. Most of the polyethylene is used and found to be non-degradable hazardous waste which has recently been identified as a major hazard to marine life. Polyethylene degradation is a great challenge as it is increasingly used[4]. Worldwide about 300 million tonnes of plastic are manufactured annually. 10% of it is recycled. Every year 7 million tonnes of plastic end up at sea. In 2017, humans produced 8.3 billion metric tonnes of plastic[5]. For effective degradation, plastic can take a thousand years. Recently several microbes are found to produce plastic degrading enzymes. As they produce enzymes that cleave the polymer into oligomers and monomers and then microbes use these water-soluble small molecules as their energy source[6], [7].

II. BIODEGRADATION

The ability of micro-organisms to break down organic substances through physical, chemical, or enzymatic action is biodegradation which involves certain complex processes and conditions that favors the action of the microorganism[8], [9]. Both synthetic and natural polymer needs the involvement of microorganisms in the process of degradation and deterioration[10]. Firstly, most of the biochemical processes took place before microorganism utilizes polymers, they don't use polymers directly. It took many years for the complete degradation of plastic. Some environmental factors are also involved in this such as pH and UV. Bacteria and fungi have some natural power to degrade plastic, they also differ from each other even they required different optimal

growth conditions. Enzyme-catalyzed hydrolysis and non-enzymatic hydrolysis both are there in the process of biodegradation. The exo-enzymes which are present in the microorganism allow the breakdown of complex polymers and form short chains and smaller molecules such as oligomers, dimers, and monomers. All these smaller molecules can pass through the semipermeable membrane present in the bacteria as they are water-soluble. Bacteria required these small molecules to complete their carbon energy source[11]–[14].

A. Polyethylene

Polyethylene is categorized as a synthetic polymer with a high level of hydrophobicity and high molecular weight. As this is a synthetic polymer it is widely used in the manufacturing of disposal or packaging material and it is not biodegradable which causes hazardous problems to the environment. Changing the molecular weight of its crystallinity and the mechanical properties responsible for PE resistance to degradation will enable this biodegradable. Hydro-biodegradation and oxo-biodegradation are the two mechanisms operated with the modification due to starch and pro-oxidant additives used in the synthesis of biodegradable PE and which make biodegradation of Polyethylene feasible[15], [16].

At the beginning of the degradation process for the activation of an inert material polyethylene, UV light is being used as an activator and then also treated with nitric acid. Using *Fusarium sp.* in mineral salt medium providing treated plastic as a source of energy and carbon, this treated polymer was then brought into microbial treatment[17], [18]. A rise in fungal growth and some structural changes revealed the breakage of the polymer chain and the formation of Polyethylene oxidation products. In the mechanism of biodegradation, the enzyme monooxygenase converts the carbonyl group of polyethylene or paraffin molecule to an alcohol-containing -OH group than alcohol gets oxidized to an aldehyde containing -CHO group by alcohol dehydrogenase. After which an enzyme name aldehyde dehydrogenase converts aldehyde to the fatty acid group-containing -COOH group, fatty acid goes through the β -oxidation pathway inside cells[19], [20].

B. Polypropylene

It is a thermoplastic polymer which has a crystallinity level somewhere between High-density polyethylene and Low-density polyethylene, used for packing, textiles such as ropes, carpets thermal underwear, labeling purpose, Reusable

containers, laboratory equipment, loudspeakers, automotive components, polymer banknotes, stationery, plastic parts, etc. It is isotactic and normally tough and flexible because of the copolymerization with ethylene[21], [22].

Polypropylene can be degraded with heat and UV radiation by chain degradation. It has a tertiary carbon atom in every repeat unit where oxidation takes place. To get carboxylic acid and aldehydes, free radical is formed which reacts with oxygen and then chain scission takes place. Some microbes which are isolated from soil can degrade Polypropylene when mixed with starch. *Vibrio*, *Pseudomonas stutzeri*, *Pseudomonas chlororaphis* are some species present in the 3s community which can degrade Polypropylene without any pre-treatment, but when Polypropylene is pre-treated with UV light it is more susceptible to biodegradation. In the soil burial method when Polypropylene was mixed with different additives it showed no changing crystalline region fraction and in melting temperature even after one year. It means that the degradation of Polypropylene starts in the amorphous region, not in the crystalline region[21], [23]–[25].

C. Polyvinyl chloride

This is also known as PVC and used in construction as it is cost-effective over other materials like iron, copper, wood and it is also very strong plastic which has very low moisture absorption and it resists abrasion and also chemical resistance. When plasticizers are mixed with PVC, it becomes flexible then it can be used in electrical wire insulation, synthetic leather products, and floor coverings. Rigid pipes, shoe soles, garden hoses, and textiles are made up of PVC polymer[26].

It can be biodegraded by photodegradation and thermal degradation. A White-rot fungus degrades PVC having low molecular weight. Plasticized PVC can be degraded by the fungus *Aspergillus fumigatus*. It is seen that *Lentinus tigrinus*, *Aspergillus niger*, *Phanerochaete chrysosporium*, and *Aspergillus sydowii* degrade PVC very effectively[27]–[29].

D. Polystyrene

It contains a repeating group. It is highly stable and less susceptible to biodegradation. PS is used in the manufacturing of laboratory ware, packing materials, disposable cups, and also in some electronic materials because it has excellent thermal insulation, it is lightweight and stiff too[28], [30]. Polystyrene can be degraded by both chemical and thermal degradation. When PS is degraded, styrene, benzene, acrolein, and toluene are formed and after

the formation of these styrene oligomers and other copolymers, it is treated with both bacteria and fungi also of mixed culture and enzyme using suitable conditions. Hydroquinone peroxidase enzyme is used in the enzymatic degradation of polystyrene; This enzyme is extracted from lignin decolorizing bacterium *Azotobacter beijerinckii* HM121[31]. The enzyme can be used in both aqueous and solvent (two-phase) system. In the end, polystyrene was degraded in small water-soluble molecules that can be passing through the membrane of microbes. The molecules can be detected by TLC. The enzyme forms radical species from polystyrene which undergoes through the degradation process to release simple compounds[32].

E. Polyurethane

In furniture, fibers, paints, coating, and construction material polyurethane is used as a constituent material. Polyisocyanate and polyol both have intermolecular urethane bonds (carbonate ester bond, -NHCOO-) which make polyurethane as their condensation product. Polyurethane is comparatively more resistant to biodegradation, but it can be degraded by fungi, bacteria, and enzymes[33], [34]. They cleave and hydrolyze ester bonds from the polyester segment of PUR. Enzyme Polyurethanases is used in the process of enzymatic degradation of PUR[35], [36]. *Curvularia senegalensis*, *Fusarium solani*, *Aureobasidium pullulans*, and *Cladosporium sp.* these are four species of fungi that are used in fungal biodegradation of PUR and they are isolated from soil[37]–[39]. Polyurethane having an ester base can be degraded by these four species of fungi. The five bacterial strains which are *Corynebacterium sp.* Aflz, *Arthrobacter sp.* Aflf, *Micrococcus sp.* Aflo, *Pseudomonas sp.* Afg, and *Bacillus sp.* AF8 is obtained from PUR after the soil burial method done for 6 months. Biodegradation of PUR takes place by hydrolysis ester bonds, which can be confirmed by Fourier-transform infrared spectroscopy (FTIR)[40]. Degradation of PUR involves a decrease in the ratio of ester bonds by 50% over ether bonds. Urea units are degraded by realizing ammonia which is the main part of PUR degradation. When polyester PUR is degraded by fungi it produces extracellular esterase, ureases, and proteases. Fungus like *C. senegalensis* is used in fungal degradation of PUR.

III. ROLE OF MICROBES IN BIODEGRADATION

Microorganisms possess some enzymes which allow them to use environmental contaminants as energy and carbon source

because of their too-small size they can contact contaminants very easily, and they are ideal for the destruction of contaminants[41]. Bioremediation systems provide essential chemicals, nutrients, and optimal growth conditions to microbes native to contaminated sites, and thus encourage them to work. Some non-native microorganisms can degrade some specific contaminants. For that many researchers are working and investigating ways to augment contaminated sites with non-native microbes including genetically engineered microbes[42]. When microbes use contaminants for their source of energy, food, and reproduction then the transformation of contaminants takes place. Contaminants provide the carbon source, electrons to obtain energy to microbes. Microbes catalyze chemical reactions in which chemical bonds are broken down and electrons are transferred away from the contaminant which is further taken by microbes only. This is a kind of oxidation-reduction system, where organic compound loses an electron and the chemical that gains the electrons is reduced. It means that the donor is a contaminant and the acceptor is the electron recipient. Then these gained electrons are invested with carbon obtained from contaminants and some electrons which leads to producing more cells. When a microbe degrades contaminants with the presence of O₂ is called aerobic respiration. Where microorganisms use O₂ to oxidize part of the carbon from contaminants to CO₂ and some amount of carbon is used to produce new cell mass. In the reaction, water is produced when O₂ gets reduced[43]. So, the by-products of this reaction are water, carbon dioxide, and an increased number of cells of microbes.

Some microbes can live in the absence of O₂ this process is known as anaerobic respiration. In this type of reaction (Mn⁴⁺) manganese, (NO³⁻) nitrate, (Fe³⁺) iron, (SO₄²⁻) sulfate, and even (CO₂) carbon dioxide plays the role of oxygen which is needed to accept electrons from degraded contaminant. Here inorganic chemicals are electrons acceptors. By-products of this type of reaction are methane (CH₄), nitrogen gas (N₂), reduced forms of metals, hydrogen sulfide (H₂S) depending on the electron acceptor.

The main mechanism for the degradation of plastics is oxidative degradation. It reduces the molecular weight of the plastic material which leads to degradation. The polymer is converted into monomer, oligomer, and dimer by intracellular and extracellular enzymes produced by microorganisms[15]. Then these by-products can enter into the microbial cells and then can be utilized as food and energy source. Microbes can synthesis all the enzymes which are necessary for the degradation of plastics constantly or they

can activate the synthesis of enzymes as necessary to metabolize when needed. They can produce thermodynamically favorable enzymes. To degrade HDPE both physical and chemical environmental factors play an important role and these factors also support microbes to degrade PE (HDPE).

Table 1: List of microorganisms used for a different type of plastic degradation

Type of plastic used	Bacteria	Fungi
LDPE (low-density polyethylene)	<ul style="list-style-type: none"> <i>Pseudomonas stutzeri</i> <i>Brevibacillus borstelensis</i> 707 <i>Rhodococcus ruber</i> C208 <i>Staphylococcus epidermidis</i> <i>B. cereus</i> <i>B. subtilis</i> 	<ul style="list-style-type: none"> <i>Aspergillus niger</i> <i>Penicillium funiculosum</i> <i>Pullularia pullulans</i> <i>Aspergillus spp.</i> <i>Fusarium sp.</i> AF4
Polyethylene bags and plastic cups	<ul style="list-style-type: none"> <i>Streptococcus sp.</i> <i>Staphylococcus sp.</i> <i>Micrococcus sp.</i> <i>Pseudomonas sp.</i> <i>Bacillus sp.</i> <i>Moraxella sp.</i> 	<ul style="list-style-type: none"> <i>Aspergillus niger</i> <i>Aspergillus flavus</i> <i>Aspergillus glaucus</i> <i>Aspergillus cremeus</i> <i>Aspergillus ornatulus</i> <i>Aspergillus nidulans</i>
Polyurethane	<ul style="list-style-type: none"> <i>Pseudomonas sp.</i> <i>Corynebacterium</i> <i>Arthrobacter globiformis</i> <i>Pseudomonas cepacia</i> <i>Bacillus sp.</i> 	<ul style="list-style-type: none"> <i>Aspergillus terreus</i> <i>Fusarium solani</i> <i>Chaetomium</i> <i>Aureobasidium pullulans</i> <i>Cladosporium sp.</i>
PVC powder	<ul style="list-style-type: none"> <i>Pseudomonas aeruginosa</i> 	<ul style="list-style-type: none"> <i>Aureobasidium pullulans</i> <i>Geotrichum candidum</i> <i>Aspergillus sp.</i> <i>Penicillium sp.</i>

Isotactic polypropylene	<ul style="list-style-type: none"> <i>Pseudomonas chlororaphis</i> <i>Vibrio spp.</i> <i>Pseudomonas stutzeri</i> 	
HDPE	<ul style="list-style-type: none"> <i>Bacillus sp.</i> <i>Micrococcus sp.</i> <i>Vibrio sp.</i> <i>Listeria sp.</i> <i>Arthrobacter sp.</i> <i>Pseudomonas sp.</i> 	<ul style="list-style-type: none"> <i>Aspergillus niger</i> <i>Aspergillus oryzae</i> <i>Aspergillus flavus</i> <i>Phanerochaete chrysosporium</i> ME-446

IV. ROLE OF ENZYMES IN BIODEGRADATION

To produce microbial cultures suitable for the degradation of a specific plastic, some time-taking and costly methods may be used. Sometimes the microbial cells can be metabolically inactive because of some environmental factors like toxins, physical and chemical treatments, predator action, high concentration of pollutants, etc. Enzymes are present in each living cell and thus in all microbes.

Different species of microbes or even different strains from the same species may vary in the synthesis of relative amounts of various enzymes. Different enzymes are useful in the degradation of different types of plastics as enzymes are very specific in their action on substrates. The process of oxidation of the hydrocarbon backbone of PE is done by enzyme laccase. It reduces the molecular weight of PE by 20% and the molecular number of PE by 15%. The cell-free laccase incubated with polyethylene can be detected by (GPC) i.e. gels permeation chromatography. The lignin biodegrading fungi possess enzyme laccase which is used to catalyze the oxidation of aromatic compounds. Laccase activity plays the main role to act on nonaromatic substrates. A Ligninolytic system has very important three enzymes which are laccases, manganese-dependent peroxidase, (MnP), and lignin (lip). Some microbial strains like *Bacillus spp.*, *Brevibacillus sp.* Produce enzyme protease which is useful in the degradation of polyethylene (PE)[44].

Medical polyester is degraded by urease and papain. When papain is used in polymer degradation it catalyzes the hydrolysis of urethane and urea linkages producing free amine and hydroxyl groups. PE with high molecular weight is degraded under limited conditions of carbon and nitrogen,

where manganese peroxidase and lignin-degrading fungi are used for degradation which is partially purified from the strain of *Phanerochaete chrysosporium*[45]. Microbial enzymes increase the rate of plastic biodegradation and also do not harm the environment.

V. FACTORS AFFECTING PLASTICS DEGRADATION

Biodegradation is dependent on the type and nature of pre-treatment, characteristics of the polymer, type of organism. Some factors like additives and plasticizers added to the polymer, substituent present in the polymer structure, molecular weight of the polymer mobility, and crystallinity of the polymer play a major role in the degradation of plastics[46], [47]. Characteristic features of polymer and exposure conditions are two main factors which affect the polymer biodegradability. Exposure conditions are then classified as biotic and abiotic factors. Molecular weight is responsible for greater accessibility to the chain of the polymer by microbes and moisture[48], [49]. In the process of chain scission from photodegradation, molecular weight is reduced. Then microbes can use smaller polymer molecules which are easier to hydrolyze too. Photodegradation does both main chain scissions of the polymer and cross-linking in aliphatic-aromatic polyesters. During the process of biodegradation PH, moisture, temperature these abiotic factors affect the rate of the hydrolysis reaction. The rate of hydrolysis reaction and microbial activity also increase with more moisture and high temperature. When the rate of hydrolysis reaction increases, more chain scission takes place which increases the number of available sites for microorganisms to attack the polymer chain and make the degradation process faster.

Some extracellular enzymes produced by microbes have an active site with various shapes and sizes which is useful to degrade some specific polymer. Aliphatic polyester derived from 6-12 carbon di-acid monomers is digested by enzymes that are produced by *aspergillus Niger* and *Aspergillus flavus* effectively[50].

Some factors like composting environment, sewage, fresh water, marine environment, soil, landfill, and humid air, dry air shows the kinetics of polymer degradation. Some important factors in the process of biodegradation vary with a different type of environment for example sunlight, water, oxygen, and microbes present in the environment for biodegradation[51]. Polymer biodegradation is dependent on

conformation flexibility. A polymer is more accessible for microbes if it has more flexibility. Microbes degrade polymers of low molecular weight by taking it into the cell and then they convert it in the form of metabolites. Hence smaller molecules are more accessible for microorganisms compare to larger molecules. Polymer accessibility to microbes increases when co-monomers are added to the structure of polymer which forms irregular polymer chains and thus crystallinity of the polymer decreases. It states that the added co-monomer describes the biodegradability of the copolymer.

VI. CONCLUSION

According to the information, it can be concluded that in our day-to-day life plastic plays a very important role. Because of its good quality, its price and it is water resistance it has huge applications in all sectors. The use of plastics is increasing day-by-day and it is needed to have solutions to its degradation to reduce the rate of pollution. Microbes and other environmental factors play a major role in plastic degradation. There are various steps in this process. Studying the synergism between those microbes will give an insight for future efforts towards the biodegradation of plastic. It takes a lot of time to degrade the plastic material because plastic has a very high-molecular-weight which is difficult to degrade by microbes and as plastic has hydrophobic surfaces it is a difficult task for microbes to be stable and form a biofilm and degrade them into small molecular oligomer, dimmers, and monomers. Biodegradation of plastics using microbes is the eco-friendly and cheapest method.

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VIII. REFERENCE

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