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Biodegradation of plastic and potential impact of microorganism on Biodegradation

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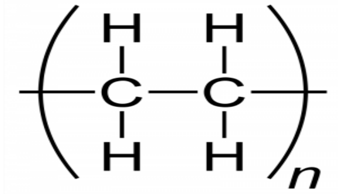
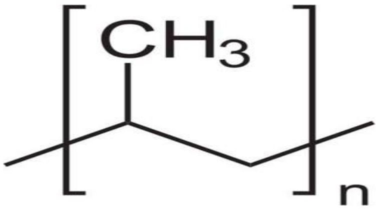
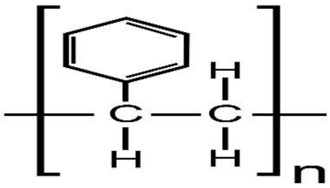
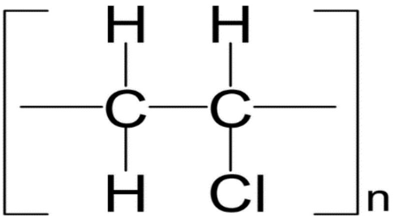
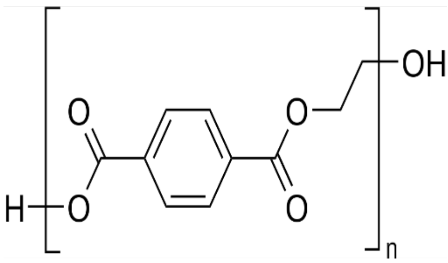
Contents

1. Introduction

Synthetic plastic production is fast growing industry of the modern world. The word Plastic is basically derived from the Greek language 'Plastikos' which means the thing which can be molded to any desirable shape (Ghosh, Pal et al. 2013). Plastic is used in daily life from 100 of years but the beginning of large-scale production back to 1950 when plastic polymers replaced natural materials (Geyer et al 2016). Plastic are basically derived from petrochemical which are further arranged synthetically to long chains polymers with higher molecular weight. Some of the unique properties that make plastic more superior to other materials multiplied their production since 1950 exceeding 300 million tons per year (plastics Europe 2015). Furthermore, it is predicted that plastic production will double over next 20 years (Ellen MacArthur Foundation 2016). Almost 80% of plastic are made of (PVC) poly vinyl chloride (PE) polyethylene, (PP) polypropylene, (PS) polystyrene, and (PET) polyethylene terephthalate (Table 1). Although plastic products are integral part of world economy, but issues associated with wide use of plastic cannot be overlooked.

Plastic pollution arises as the second obvious threat to the world environment after global warming. Plastic debris find its way from terrestrial environment to the marine environment, it is hard to find any area that is not affected by human activity. According to UN environment (www.unenvironment.org) only 9% of plastic waste is recycled, 12% is incinerated while the remaining 79 % is dumped accumulated in the landfills or enter to natural environment. It is estimated that 60 % of plastic produced since 1950 has ended in landfill or natural ecosystem (Gourmelon and org 2015). Since after industrialization era the production of plastic has grown faster than any other material. A shift has also been noticed from production of durable plastic toward the plastic that meant to be thrown away after single use. The properties that make plastic so useful such as durability, persistence and resistance to degradation also make them nearly impossible to completely degrade in nature (Haider, Völker et al. 2019).

Table .1. Generally used plastic structure and its symbols

Plastic	Structure	Symbol
Polyethylene		
Polypropylene		
Polystyrene		
Polyvinyl Chloride		
Polypropylene Terephthalate		

Mostly plastic substance never disappears completely but convert to smaller particles and these tiny particles are consume by animals or fishes mistakenly as food materials creating many problems. These tiny particles or microplastic also found everywhere in the drinking water. Plastic wastes especially plastic bags provide breeding ground for many organism-like mosquitoes and pests. Which can increase transmission of many waters borne diseases.

Different methods which are used for treating plastic wastes are land fill, incineration and recycling. All these methods are commonly used but have their own side effects. The plastic waste in the land fill last for longer time without been broke down make the land soft and use less for construction and any other use. The plastic in the landfills subjected to photooxidation convert large sheets to small fragment called microplastic leads to aquatic ecosystem. The incineration of plastic releases very toxic gases like greenhouse gases which remain in the environment for long time. And recycling of plastic is very expensive method depend on the behavior of common public (Al-Salem, Lettieri et al. 2009). Although recycling is still the most preferred method. Except of all these methods degradation of plastic by microorganism is the most acceptable and environment friendly method and significant research also has been made in related areas. The production of newly developed innovative biodegradable or bio compostable plastic considered to be the potential strategies for future mitigation with the plastic pollution. However, petroleum based synthetic plastic have been produced and accumulating in the environment from the last few decades but there is still complete knowledge gap between degradation of long chain polymer and rate of biodegradation. It is still considered that synthetic plastic is non-compostable. The main limitation of synthetic plastic degradation is that they fragmented in long time under abiotic factor such as temperature, UV, and physical pressure and they cannot be completely decomposed and breakdown by microorganism in biodegradation process. The main hurdles in the way of biodegradation of plastic are long chain polymers matrix a higher molecular weight and lack of functional groups which are favorable for degradation such as crystallinity and hydrophobicity (Wilkes and Aristilde 2017). The higher molecular weight compound cannot pass through the cell membrane of microbes, thus it has to be first converted to smaller monomers to pass through the cell membrane (Shah, Hasan et al. 2008). The molecular weight of the polymer must be (<500 Mw) to pass through cell membrane of microorganism to oxidize them intercellularly (Yoon, Jeon et al. 2012). Next step after passing of monomers through cell membrane is enzymatic reaction to hydrolyze the polymer into oligomer and ultimately to monomers and assimilate it to final product. Some of the polymer like polyethylene, polypropylene and polystyrene have very stable chain and difficult to degrade whereas polyethylene terephthalate are easy to catalyze with enzyme (Yoshida, Hiraga et al. 2016).

For the last three-decade scientists trying to isolate potential microorganism which can enhance the biodegradation of plastic with much faster rate than the natural distraction. Recently some researches have been suggested that there have been several microbes which have the capacity to degrade plastic polymer with much faster rate. All these microorganisms could have some special types of enzymes which can break C-C chain of polymer under stress condition. Some enzymes from the *Rhizopus arrhizus*, *Rhizopus delemar*, *Candida cylindracea*, thermophilic *Streptomyces sp* and *Achromobacter sp* showed activities on polyethylene adipate (PEA) poly(ε-caprolactone) (PCL) and poly(β-propiolactone) (PPL) (Tokiwa and Suzuki 1977, Calabia and Tokiwa 2006).

In this review we have summarized the basic of biodegradation, mechanism involved and colonization of microbes on the surface of synthetic plastic debris and development of new microbial community on plastisphere. The role of microorganism in decomposition of plastic and to what extent it would participates in degradation of plastic. Then, we reviewed the current technique used in laboratories for detection of microbes which have the capacity to degrade plastic polymer. We conclude with several questions regarding the knowledge gap between the laboratories and actual biodegradation of plastic debris and the fate of plastic in the open environment.

2 Objectives

- To sum up relevant information on microbial degradation of plastic in the literatures and establish a resource to display latest data about microbial degradation of plastic.
- To summarize the microbial life on plastic surface and possible development of new microbial community on plastisphere.
- To review the current techniques used in the laboratories for biodegradation of plastic and their limitation.
- To conclude with the questions regarding knowledge gap between laboratory and actual biodegradation in the nature.

3 Material and methods

3.1 Data collection

To collect information about biodegradation of plastic using several keywords such as: “Biodegradation” depolarization”, decomposition”, potentiality of microbes” combined with name plastic were used as input for search in research gate, google scholar. To collect more relevant paper, title or other options were chosen as search filter. Techniques used in the laboratory for microbial activity were also chosen as a search filter. Collect literature papers were read thoroughly to find out plastic degrading microbes and the ways they were find out. Some of the basic information about plastic, microbial colonization and mechanisms involved in the degradation were also described in the study to construct the background for easy understanding.

3.2 Data management

The data consist of microorganism and technique used for degradation of microbes were manually extracted from literature.

For clarity, these data were organized into two categories:

3.2.1 First category

Information about microbial degradation, plastic they degrade and mechanism for some organism, that how biodegradation of plastic occur were obtained if they were available. All these microbes involved in the degradation were used to construct a table consisting of their names, plastic they degrade and the researchers who identified it were put in the table. For some microbes the processes, enzyme involved in the degradation were also enlisted if it was available in the literatures.

3.2.2 Second category

Consist of detection technique use for microbial activity on plastic and possible degradation of polymer. This section also consists of different technique which are commonly used for detection of microbes especially on plastisphere.

4 Degradation of plastic

Plastic polymers are considered one of the major solid waste pollutants. Disposal of plastic waste is also a big problem. Land filling is widely used method for disposing of solid waste pollutant. Plastic industries invest billions of dollars in recycling of waste product and because of public awareness the interest of plastic biodegradation also increase. There are two factor which can break the long chain of polymer. Environmental factor such as light, heat, chemical condition and biological activity. And structural changes like addition of new functional group.

Plastic degradation can be classified based on causing agents such as photooxidative degradation, thermal degradation, mechanical degradation, catalytical degradation and biodegradation (Figure.1). Degradation of plastic starts with the process of rupturing in the bond of long chain molecules creating amorphus sites.

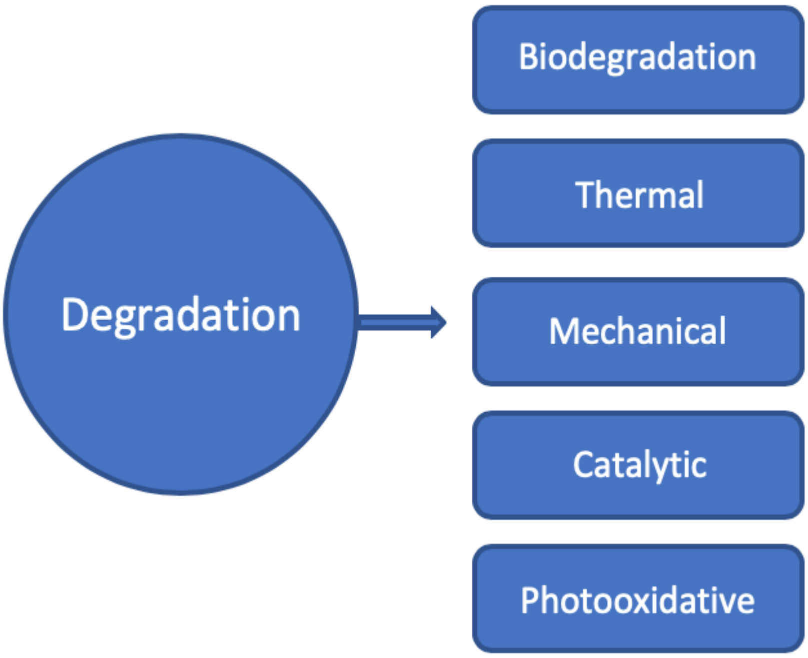


Figure. 1. Degradation and its types.

Photooxidative degradation initiated with the insertion of light especially ultraviolet rays into the appropriate position of polymer chain cut it into small fragments. Photo oxidation occur with the additives molecule present in the polymer or some of responsive group to light inserted in the chain (Sivan 2011). Ultraviolet rays play key role in in decomposition of plastic into its final product and heat which is produced with light is used in the process of oxidation to degrade it. Mechanical and thermal degradation breakdown longer polymer to smaller fragment. It facilitates degradation by reducing molecular weight to allow degradation.

4.1 Biodegradation

Biodegradation is the chemical break down of materials by the action of microorganism such as bacteria, fungi, and algae. Degradation is natural process in which organic compounds are break down in the environment to simpler one mineralized and redistributed in the elemental cycle such as carbon nitrogen and Sulphur. This process occurs only with the involvement of natural organism. It considers to be the only mechanism which is responsible for most of chemicals released to the environment. It is the process where bacteria fungi and algae release their enzyme into surroundings substances consume it as a source of food so that its original form disappear under an appropriate condition leaving behind no toxic or environmental harmful substance._Natural long chain polymers such as protein polysaccharides and nucleic acid are breakdown in natural system by hydrolysis and oxidation (Chandra and Rustgi 1998).

4.2 Biodegradation of plastic

The breakdown of plastic polymer by the action of microorganism which is facilitated by abiotic degradation through physical, chemical and enzymatic process. Biodegradation is very slow process. Microorganism cannot degrade plastic directly. It involves many biochemical processes which make the plastic available for microbial degradation. First the abiotic factor such as temperature, light moisture and pH initiated the process. Microorganism develop different behavior to use the polymer material as a source of energy. Different microorganism has different optimal growth condition to degrade plastic. Biodegradation is the complex process of both enzymatic and non-enzymatic hydrolysis (ADETITUN 2017). During degradation microbes' releases exoenzyme which breakdown polymer to smaller molecules called dimers, oligomers or monomers. These smaller molecules can pass through semi permeable membranes of microbes which use it as a carbon source and energy (Ronen and Abeliovich 2000). Cutting of these larger polymers to smaller with help of enzyme called depolymerization. The degradation of polymers often determined by the environmental factor such as light, temperature and pH. Biological degradation of plastic is complex process where polymers pass through different pathways to convert to final product with the action of enzymes. Linkage between carbon atoms such as peptide, ester or glycoside are hydrolyzed by the attack of enzyme. In short biodegradation of polymers is the combine effect of both biotic and abiotic factor

4.3 Microbial colonization and development of plastisphere

Synthetic plastic is new to environment and considered not readily biodegradable. But the microorganism is readily attached to the surface of the plastic form biofilm a stable microbial community which form a new environmental niche called plastisphere. The term plastisphere is new to science until using the first work of massive DNA sequencing provided the detail picture of microbial communities on plastic (Zettler, Mincer et al. 2013). Several studies on marine and incubated plastic sample detected the presence of bacteria, archaea, fungi and other microbial eukaryotes. Photographs from the scanning electron microscope on plastic debris show diversity within microbial communities in the plastisphere (Debroas, Mone et al. 2017). Plastic sample studied mainly composed of polyethylene, polypropylene and polystyrene. Whatever plastic sampled there was difference in the microbial community living on plastic and the microbes living in free living or on organic matter in surrounding water (Debroas, Mone et al. 2017). Biofilm is the aggregate of cells which grows in matrix of polymeric substance. Biofilm formation considerably change the lifestyle of microorganism from planktonic to motile state. Specific genes involved in the chemotaxis, communication, adhesion to a particular substrate in order to transport the nutrients between the cells (Costerton 1999). The studies focused on the samples collected from the open environment have more chances of successive colonization of microbes than the study on the new plastic debris incubated in the laboratories condition. In open environment the plastic rapidly covered by "conditioning film" made of organic and organic substance which is then colonized rapidly by bacteria (Oberbeckmann, Löder et al. 2015). Microbial colonies selection on a particular substrate depends on many factors like hydrophobicity, crystallinity, toughness, temperature, melting point and available carbon sources in the initial stage of colonization but probably up to less extant when the biofilm become mature (Dussud, Hudec et al. 2018).

The different phases of colonization or biofilm formation well describe by (Dang and Lovell 2000) on natural and artificial surface with marine water. First phase the primo-colonization describes the reversable attachment of the innovator bacteria to the surface where they interact with the conditioning film and form the first layer of initial biofilm. Growth phase is the second phase where bacteria attachment irreversibly and form pili, adhesion protein and extracellular polymeric substance (EPS) produce by the secondary bacterial species which modify the surface of substratum. The third is the maturation phase where the highly competitive, diverse and synergetic interaction between the cells occur with either further selection or loss of the species from the biofilm.

4.4 Potential biodegradation of plastic

The global demand of synthetic plastic is increased day by day, but considering their widespread abundance, potential environmental hazards, and a great concern about the methods of degrading these plastics. Recently there have been worldwide debates about the procedure of degradation of plastic polymers. Biological degradation emerged one of the best potential way for plastic degradation. Alternatively, many researchers reported adverse effect of plastic polymers on human health and these problems of plastic increased day by day, so it is need of the day to develop the methods and to screen and isolate potential microbes for degradation of these plastic polymers. Parallel, to natural deterioration of these long chain polymers which is very slow process, scientists and researcher from many years trying to develop some other way to degrade plastic. The process of dumping plastic in the natural environment is far faster than the process of natural degradation. Recently several microbial species especially bacteria and fungi were identified by many researches. All these researches suggested that they have the capacity to degrade the synthetic polymers with much faster rate as compare to natural degradation process.

There are a wide range of microbes present in the nature which have the capacity to degrade plastic polymers. The occurrence and diversity of these plastic degrading microorganism varies depend upon environment such as soil, sea water, sledges etc. To investigate and identify the microbial population and distribution of potential plastic degrading microorganism in different ecosystem it is general rule to find its adherence on the surface of plastic. The main mechanism involved in finding of plastic degrading microorganism is colonization (Tokiwa, Calabia et al. 2009). A special type of exoenzyme were extracted from these species which is released during stress condition can break down long polymer chain to smaller monomers and simple hydrocarbons. The degradation of plastic by enzyme is two steps process: first the plastic material is attack by the enzyme catalyze the scission site, hydrolyze it to lower molecular weight oligomer, dimer and monomer and second step is absorb it inside and assimilate it to final product CO_2,H_2O,CH_4 and organic acid (Priyanka and Archana 2011).

4.5 Factor affecting biodegradation

Plastic are biodegradable up to some extant because of its organic nature and constituent elements. The process of biodegradation is affected by number of factors such as characteristics of plastic, exposure conditions to environmental condition and types of organisms. Complexity, crystallinity structure and composition of polymeric material is the important aspect of plastic biodegradation. Other properties like mobility, additive such as plasticizer, molecular weight, types of constitute present and functional group added to plastic play vital role in degradation of polymers. Plastic polymer with branch chain is less biodegraded than the straight chain.

Crystallinity of plastic polymers is an important factor which control biodegradation because exoenzyme attack on the amorphous region of the polymer. In the amorphous region the molecules are loosely packed which make it more susceptible for degradation. The rate of degradation decreases with crystallinity of plastic polymer. Crystalline part of polymer is resistant to degradation with respect to amorphous part which promote degradation. More ever the molecular weight also affects the biodegradability of polymer because molecular weight determines many physical properties of plastic polymers. Higher the molecular weight lower will be the biodegradability (Artham and Doble 2008). The factors which affect the biodegradation of polymers are the characteristic of polymer and exposure to environmental condition. Environmental condition is further divided into biotic and abiotic factors (Figure .2)

Abiotic factors such as temperature, pH and moisture indirectly effect biodegradation. All these factors provide medium for hydrolysis reaction which indirectly manage the rate of biodegradation. Increased temperature lead to increase hydrolysis reaction in the presence of water. Presence of water in the shape of moisture is important for hydrolysis. So higher moisture content and higher temperature affect positively the biodegradation reaction and microbial activity (Husárová, Pekařová et al. 2014). In the presence of higher moisture content condition, the hydrolysis reaction increases, more chain exposure site became available for microbial attack in the polymer ultimately, increases biodegradation. On the other hand, melting temperature of the polymer has strong effect on the biological degradation. Higher melting temperature provide more strength and resistance to polymer degradation. Higher melting temperature lower will be the biodegradation of polymer in general (Tokiwa, Suzuki et al. 1978).

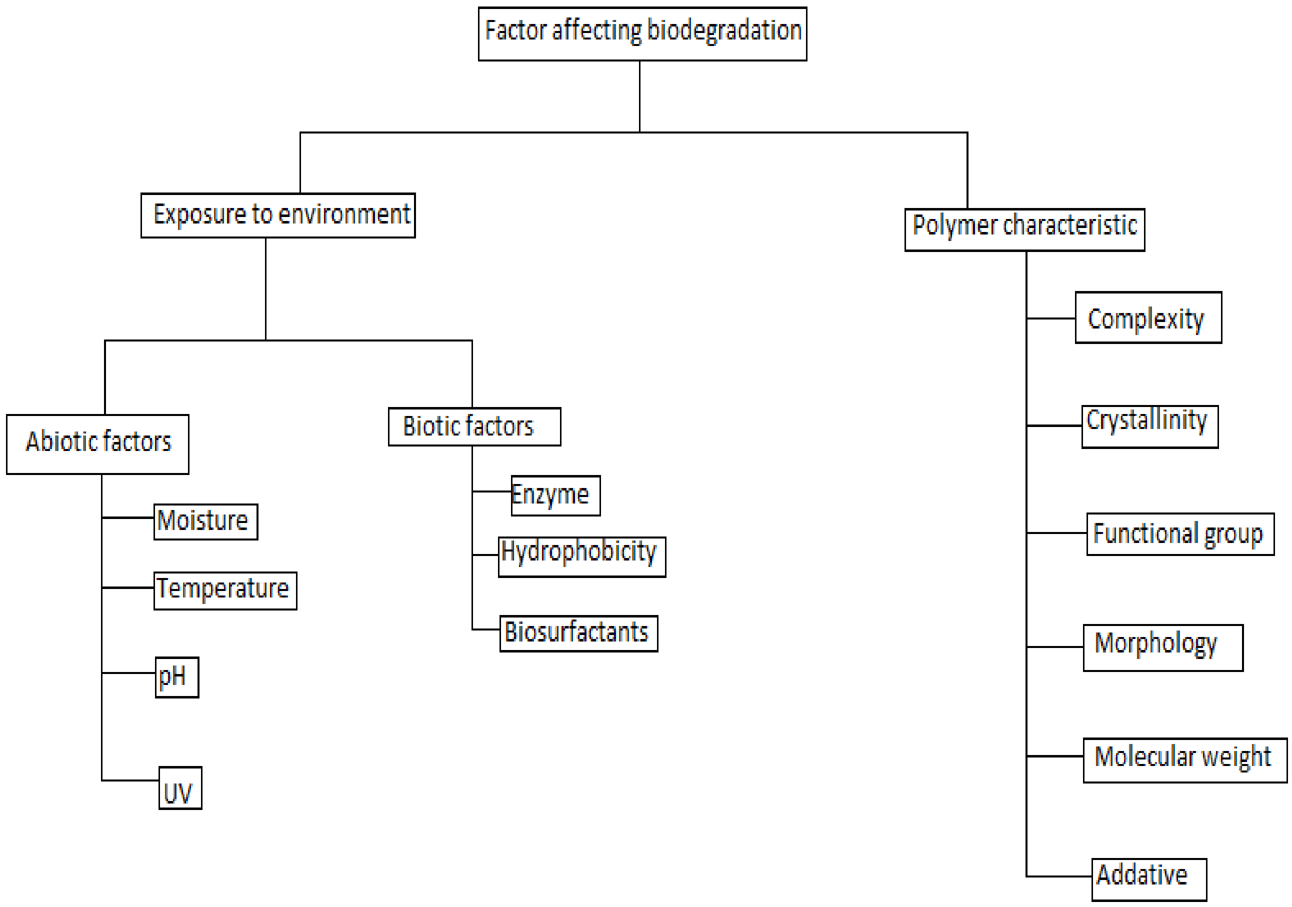


Figure. 2 Factors affecting biodegradation.

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