JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

ROLE OF BIOLOGICAL AGENTS IN PLASTIC REMEDIATION- A REVIEW

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Abstract : Plastic is widely used and present in most of the materials we use every day, but the degradation rate of plastic is very slow. Due to this slow degradation, deposition of plastic waste became a huge problem resulting in the pollution of our environment. Among different types of plastics, Polyethylene is most widely used plastic in the world which is toxic to human health & aquatic organisms. In this article we discussed the biological methods i.e. microorganisms to increase degradation rate of plastic. Biodegradation is an eco-friendly method where microorganisms or the enzymes produced by microbes act on the plastic materials and degrade into simpler compounds by utilizing plastic as the sole carbon source for their growth. Different microbial strains act on different types of plastics which results in variation of degradation rates. The mechanism of biodegradation can occur in aerobic and anaerobic conditions and seems to be simple but it involves complex 3 step processes like depolymerization, random chain scission and side group elimination. Different factors are involved in the biodegradation process. Among these temperature, inoculums, pH and initial concentration are considered in this review. When optimal temperature and pH are considered for a particular microorganism, then the rate of degradation can be identified as maximum. In this review we briefly discussed the types of plastics, complications involved in using plastics, types of treatment methods for degradation, different microorganisms used for biodegradation, and factors affecting the process of biodegradation.

Keywords **- Plastic Pollution, Biodegradation, Microorganisms, Environmental threat, Temperature.**

I. PLASTIC POLLUTION

Plastics are defined as synthetic or semi-synthetic polymers, which are made of different materials like coal, natural gas, and oil. Worldwide the annual production of non-degradable plastic ranges from 350-400 million tons. Out of that 5-13 million tons of plastic waste is released into the ocean which adversely affects the aquatic environment (Jambeck JR et al, 2015) (Plastics Europe 2018). The total amount of plastics manufactured in the world from 1950-2019 is 8100 Mt. The production of plastics increased from 2 million tons in 1950 to 450 million tons in 2019 (R. Geyer et al, 2017). Bio-based or biodegradable plastics currently have a global production capacity of only 4 million tons. Most of the monomers used to make plastic are ethylene and propylene derived from fossil hydrocarbons which are non-renewable sources (R. Geyer et al, 2017). None of the commonly used plastics are biodegradable resulting in accumulation of plastics in landfills and water, which do not decompose and thus threatening the environment. Plastic pollution in the sea is a global concern and found everywhere throughout the ocean with a concentration of about 580,000 plastic pieces per square kilometer (K. Willis et al, 2018). A recent review for the United Nation convention on biological diversity documented over 600 species ranging from microorganism to whales, affected by marine plastic waste largely through ingestion (C. Wilcox et al, 2015).

Fragmentation of plastics into smaller particles is known as microplastics. Microplastics are regarded as the global concern due to their persistence in the environment and their potential to act as vectors for various harmful substances or pathogenic microorganisms. One possible solution to overcome this problem is biodegradation of plastics by microorganisms. Plastic is the most used synthetic material because it is durable, lightweight, and cost effective (Yooeun Chae and Youn-Joo An, 2018). However, only 21% of plastic has been recycled or incinerated (Geyer, Jambeck, and Law, 2017), while the rest is broken down into "microplastics" (b5 mm in diameter). Microplastics (MPs) contribute to 92.4% of plastic waste and primarily consist of polystyrene (PS), polyethylene (PE), and polypropylene (PP) (Carr et al, 2016; Santana et al, 2016). MPs are globally distributed and polluted rivers, lakes, cultivated land, etc. (Duis et al, 2016; Eerkes-Medrano et al, 2015; Van Cauwenberghe et al, 2015). Studies have shown that MPs are consumed by a wide range of organisms causing reduced growth rate and reproductive complications (Batel et al, 2016).

The plastic waste is increasing every year due to population growth, developmental activities and changes in lifestyle. And on average it takes up to 1000 years for natural degradation in the environment. The countries China, Thailand, Indonesia, Vietnam and Philippines have major contributions in dumping of plastic in the sea as compared to 54 other countries (Mrowiec, 2017). Recent studies have revealed marine plastic pollution in 36% of seals, 40% of seabird species, 59% of whales, and 100% of marine turtles. Additionally, deaths of 1 million seabirds are reported by plastic pollution annually (Kedzierski et al, 2018). Microplastics make 92.4% of plastic waste (Santana et al, 2016) and consist mainly of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride, nylons, polylactic acid, polyamide, and polyethylene terephthalate (PET) (Carr et al, 2016). Microplastics originate from different sources; Primary microplastics are produced in microscopic scale and used in cosmetics, toothpaste, exfoliating scrubs, hand cleaners, clothing, and drilling fluids (Duis and Coors, 2016). Secondary microplastics originate from the breaking down of macroplastic debris (Anika Ballent et al, 2016). Microbeads in toothpaste and cosmetic products can enter the aquatic environment through wastewater treatment plants and drainage systems (McCormick et al, 2016; Murphy et al, 2016). The degradation of large plastic from waste dumps or landfills can also serve as a source of microplastics to oceans (Alomar et al, 2016).

With developments of science and technology and the increase in global population, the demand for plastics is ever increasing. Plastic materials have been widely used in every aspect of human life and industries such as packaging, building, furniture, house wares, electrical, electronic, transport, and agriculture. As a result of such wide use, plastics have accumulated in the environment, causing environmental pollution, human health problems, and ecosystem changes due to their toxicity and recalcitrant compounds. Many animals die due to waste plastics either by being caught in the waste plastic traps or by swallowing the plastic debris (Usha R et al, 2011). Some plastic products cause human health related problems because they mimic the human hormone. PVC, which is carcinogenic is used in adhesives, detergents, lubricating oils, solvents, plastic clothing, personal care products, toys and building materials (IARC, 2011). Prolonged exposure to BPA shows a significant effect on the sex hormones in females (Hao J et al, 2011). Dioxins cause soil pollution, Phthalates and Bisphenol A are causing thyroid dysfunction in humans.

In a research conducted on reducing plastic waste, It was found that 710 million metric tons of plastic waste entered aquatic and terrestrial ecosystems. To avoid a massive build-up of plastic in the environment global action is needed to reduce plastic & increase reuse, and recycling (Lau et al, 2020). 6% of the current global oil production is used to manufacture plastic commodities and it is predicted to rise by 20% in 2050 (Christopher J. Rhodes, 2018). Preventing accumulation of plastic pollutants, awareness & producer/manufacturer responsibility are practical approaches towards addressing the issue of plastic pollution. Development of solutions on research gaps can open a novel pathway to address this environmental issue (G.G.N. Thushari et al, 2020). In 2016, 20 million metric tons of plastic waste approximately entered into the aquatic ecosystems (Borrelle et al, 2020). To reduce emissions, extraordinary efforts are needed to transform this global plastics. Technology can be used to target marine plastic pollution hotspots. Technology alone cannot solve this plastic pollution issue. An approach that combines technology and policy makers should be collaborative to prevent further plastic pollution to safeguard aquatic ecosystems and human health (Schmaltz et al, 2020).

II. CLASSIFICATION OF PLASTICS ON THE BASIS OF THERMAL PROPERTIES:

Based on the thermal properties, plastic can be divided into: Thermoplastics, Thermosetting plastics.
Thermoplastics are easily molded in desired shapes by heating and subsequent cooling at room temperature. They are soft in heating and hard on cooling without undergoing any chemical change. Hence they can be reused. They can be linear or branched chain polymers.
Examples: Polyethylene, Polyvinyl Chloride, Polystyrene, Polypropylene, Nylon, Terylene Etc.
Thermosetting plastics cannot be softened by heating so they cannot be reused. These are cross linked polymers.
Examples: Polyurethane, Melamine, Bakelite Etc.

Based on the structure of covalent network, polymeric materials are categorized into thermoplastics and thermosets (J. Am. Chem. Soc, 2019). The life expectancy of thermoplastics varies from about 10-50 years and even 100 years in certain cases (Alexander Chudnovsky et al, 2012).

Polyethylene (PE):

Polyethylene (PE) has the simplest basic structure of any polymer and is the largest produced plastic material. All commercial PE was produced by high-pressure processes until the mid-1950's. The discovery that some metal compounds make it able to catalyze the polymerization of ethylene in less extreme conditions allowed the controlled synthesis of a large variety of PE (Ronca and Sara, 2017). By utilizing different manufacturing processes, varying catalyst and co-monomer types, a broad range of ethylene homo polymers and copolymers can be produced. The ability to manufacture many variations allowed producers to use in different applications such as packaging films, rigid containers, drums, and pipes. There are a broad range of polymers like high density or low density or linear low density or polar ethylene copolymer (Patel and Rajen M, 2016). Polyethylene has been used as a biomaterial for surgical implants. High-density polyethylene is used for implants in facial and cranial reconstruction

(Paxton et al, 2019). Polyethylene is used as a carbon source by many microorganisms. This has shown significance from an environmental point of view, due to the accumulation of millions of tons of waste plastics every year and also regarding the infrastructures incorporating this plastic. A number of microorganisms that have the ability to grow on polyethylene have been isolated (Restrepo-Flórez et al, 2014).

PVC:

PVC is a versatile material used in the construction industry. There is always a controversy about whether there are health risks associated with its use or not, because a number of toxic additives are involved (G. Akovali, 2012). Understanding microplastics on soil microbiomes and nutrients is important for estimating the ecological consequences of microplastic in terrestrial ecosystems (Ali et al, 2014). In a study conducted to investigate whether PVC can affect soil bacterial communities. The results showed that a number of bacterial genera were significantly reduced by the presence of microplastics (Yan et al, 2020).

Polystyrene (PS):

Exposure to ultraviolet (UV) radiation may cause the degradation of many materials. UV radiation causes degradation which results in breaking of the polymer chains. Polystyrene (PS) has been used all over the world, due to its excellent physical properties and low cost (Yousif and Haddad, 2013). Degradation of plastic results in the nano-sized plastic particles to the environment. Polystyrene degrades into nanoplastics (Lambert et al, 2016). Plastic debris accumulates in the marine environment in the form of microplastics (MP), causing toxic effects to marine organisms. Micro plastics were accumulated in crustaceans, without affecting their mortality but Swimming activity was altered when exposed to high MP concentrations (Chiara Gambardellaa et al, 2017). Expanded polystyrene (EPS) is used due to sustainability and enhancement in energy & durability of the building materials (Ramli Sulong et al, 2019).

Polyurethane:

Polyurethane foams (PUFs) have low density and thermal conductivity. PUFs is highly petroleum-dependent, so this industry must adapt to more strict regulations (Gama et al, 2108). Modification of the raw materials can produce PUs that are suitable for varied applications (Akindoyo et al, 2016) (28). Polyurethanes (PUs) are formed by isocyanates and diols in their main chain (Cherng et al, 2013). Polyurethane elastomers sometimes may undergo degradation resulting in modification of the properties or may even undergo complete failure. The degradation will not only affect instruments but may also cause catastrophic outcomes risking people's safety and health (Xie et al, 2019). Polyurethane has various applications. Using this polymer has spread to military applications even. Polyurethane is a product of Isocyanate and ploy; Iso + poly = polyurethane (Amir Samimi et al, 2012).

III. TYPES OF DEGRADABLE PLASTICS:

There are four types of degradable plastics: Photodegradable Bioplastics, Compostable Bioplastics, Bio-Based Bioplastics, Biodegradable Bioplastics (Figure-1).

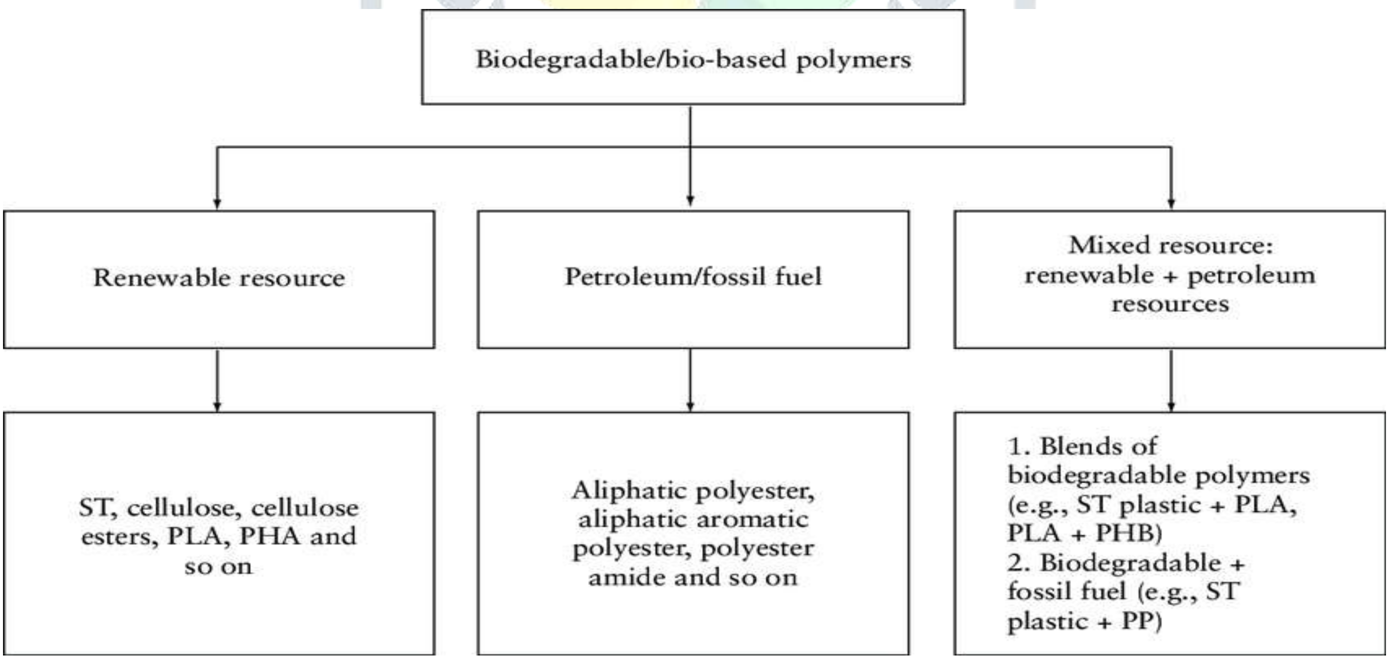

Figure 1: Classification of biodegradable and bio-based-polymers (Siddharth Bhasney et al, 2017)

Photodegradable Bioplastics:

Photodegradable plastics are designed in order to degrade when exposed to sunlight from the environment. Photo-degradable plastics made of plastics like Polyethylene, PP or PET etc with some catalytic materials. These catalytic materials are transition metals like cobalt (Co), magnesium (Mg), manganese (Mn), zinc (Zn), iron (Fe), or nickel (Ni). These metal ions weaken the tensile strength of the polymer chain when exposed to light, heat and moisture. Photodegradable plastics take so long to decay and may also contribute to the solid waste volume.

Compostable Bioplastics:

A compostable plastic is defined as a plastic that undergoes biological degradation during composting to yield Co_2, water, inorganic compounds, and with other known compostable materials and leaves no toxic residues (Bhagwat et al, 2020). The compostable bioplastics need industrial facilities to break down (Niaounakis, 2019). Therefore a lot of compostable bioplastics fail to meet the composting facility and go to landfill. PLA consists of 13% of the bioplastic market in 2019 (M.H. Rahman and P.R. Bhoi 2021).

Examples: Polylactic acid (PLA) derived from renewable sources such as corn, sugar beets, and potato starch (Bhagwat et al, 2020).

Bio-Based Bioplastics:

Bioplastic is made from renewable raw natural materials. Some bioplastics are biodegradable while many of them are not. Bio-based polymers are obtained from renewable resources like microorganisms, plants, etc. Bio-based polymers are mostly used in packaging (Koncar and Vladan, 2019). Bio-based plastics are a key component of the growing global bio-economy. They can reduce the harmful effects to the environment (Mendes et al, 2021). The limitation of fossil resources & environmental issues have led to the development of bio-based plastics (Spierling et al, 2018). The chemical industry is continuing to produce conventional plastics in parallel they are also developing bio-based plastics (Prieto and Auxiliadora, 2016).

Examples: Bio-based PET, polyhydroxyalkanoates (PHAs), polyamide, polypropylene (PP).

Biodegradable Bioplastics:

Biodegradable plastics can degrade by microorganisms, regardless of the material from which they are made. Biodegradable bioplastics are degraded completely by microorganisms without producing any toxic products. When exposed to a microbial environment biodegradable bioplastics can degrade and break down naturally into biogases and biomass (mostly carbon dioxide and water) (Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015). Biodegradable Bioplastics are more environmentally friendly compared to petrochemical plastics (Folino et al, 2020). Utilizing renewable sources make them acceptable mostly, than the conventional plastics (Emadian et al, 2016).

Polymer biodegradation is affected by many factors:

1) The properties of polymers: chemical composition, type of functional groups, molecular mass, etc.

2) The environment in which the process takes place: like temperature, light, humidity, mechanical and chemical factors (pH, Oxygen, etc.) (Dana Adamcová and Magdalena Vaverková, 2014).

Bioplastics that are degradable(or partly bio-based) are one of the fastest growing markets. The average growth rates over the past years have constantly been doubling. Bioplastics currently represent less than 1% of plastics produced annually; around 2.11 million tonnes of bioplastic materials were produced in 2018; 43% biodegradable and 57% biobased nonbiodegradable plastics. As of now, disposal platforms for synthetic polymers have not been developed much. Consequently, their wastes remain as a source of pollution (Kabir et al, 2020). Biodegradable plastics are broken down easily and can be absorbed by the soil. Even if complete breakdown does not occur, they are still a good choice to dispose of the global plastic waste. The use of biodegradable products is not the only solution to landfill problems or environmental issues, but measures such as reducing consumption, reusing products and recycling should also be implemented.

IV. COMPLICATIONS CAUSED BY PLASTICS:

Annually over 300 million metric tons of plastics are produced in the world. Although there are multiple uses, plastic waste often clogs up rivers, oceans, lands and adversely affects biodiversity (Singh et al, 2016). 79% of the plastics has ended up in the environment, 9% has been recycled & 12% is incinerated (Zaman et al, 2021). Plastics are used mostly in packaging of beverages, fresh meats, fruits and vegetables. Single-use packages result in several billion tons of garbage which pollutes the environment. It has come to light that micro plastics are consumed by marine organisms which disturbs marine life extensively (Dey et al, 2020). The excessive amounts of plastics pose a threat to both humans and the environment. Immediate approaches towards reducing plastic consumption and increasing its recyclability are much needed (Paletta et al, 2019).

In a review conducted in 2018 about the impact of chemical additives which are present in plastic it was clearly found that despite how useful these additives are in prolonging the polymer shelf life, they are potential to contaminate soil, air, water and food and is widely documented in this literature. These additives can also come in contact with human exposure via food contact materials such as packaging. They can also be released from plastics during the various recycling and recovery processes and from the recycled products. This suggests good recycling has to be ensured to avoid recycled products that harm the environment and human health (Hahladakis et al, 2017).

Micro plastics and Nanoplastics are pollutants in the human environment. Different studies have proven the dangerous effects of these polymers in the ecosystem and on the health of animals and plants. In a literature conducted by Lithuanian University of Health Sciences it was found few studies that relate Micro plastics and nano plastics with human health are limited, however the results shows a clear correlation between these pollutants and their chemical additives (BPA and PHT), with the harmful effects in human immunological, endocrinological, reproductive, respiratory and gastrointestinal systems (Navarro et al, 2020). However in a latest literature found in 2020, it is clearly stated the adverse use of plastics has led to endocrine-disrupting compounds (EDCs) such as bisphenols (BPA, BPS, BPF), bis(2-ethylhexyl) phthalate, and dibutyl phthalate (DBP). Exposure to these compounds in utero lead to the diseases of testis, prostate, kidney and abnormalities in the immune system, and cause tumours, uterine haemorrhage during pregnancy and polycystic ovary. Data are emerging on how these plastic-derived compounds affect pregnant women and foetuses during preconception and throughout gestation. With regards to plastic entering the marine environment especially microplastics, various effects from the entanglement or ingestion of these plastic particles cause suffocation including death, have been reported (Basak et al, 2020).

Plastic waste management is also complicated due to poor recovery rates through recycling, and causing contamination in composting operations (Thyberg et al, 2014). A literature review from Bangladesh showed that people used the plastics without knowing their toxic effects. Hazardous substances such as phthalates, Bisphenol A (BPA), poly- fluorinated chemicals, antiminitroxide, etc. found in plastics are hazardous to human health and environment. Different health problems like vision failure, breathing difficulties, respiratory problems, liver dysfunction, cancers, lung problems, reproductive, cardiovascular, genotoxic, and gastrointestinal problems arise due to the toxic use of plastics. Implementing proper regulations for the production and use of plastics can reduce toxic effects of plastics on human health and environment (Proshad et al, 2017).

Plastics are not biodegradable and pathogens that cause diseases to humans grow on the plastic film surfaces. The majority of consumer products we use today consist of some form of plastic. While plastics are lightweight, inexpensive, and durable, the same qualities can make them very harmful to aquatic life, especially once they become waterborne. Several cutting edge technologies have been piloted to gather the plastics present in our environments and convert them back into some useful products to reduce the impact on ecosystems (Sigler and Michelle, 2014).

Compared to plastic pollution in the marine and freshwater ecosystems, soil ecosystem has been relatively neglected & there is relatively less research on this (Chae et al, 2018). Soil in agricultural and urban areas are expected to represent major environmental reservoirs of micro(nano)plastics, comparatively larger than the marine pollution (Hurley et al, 2018). In a research conducted on wheat plants regarding micro plastics effect on soil, it was found that macro and micro- plastic residues affected both above-ground and below-ground parts of the plant during both vegetative and reproductive growth (Qi et al, 2018). In a research conducted in China on residual plastic film waste on soil for more than ten years, it was found that residual plastic film pollution significantly decreases soil fertility and alters the structure of the microbial community (Qian et al, 2018).

In a review conducted by Korean scientists on the distribution of micro- and nanoplastics in marine and freshwater ecosystems, it was found that micro-sized plastics and plastic debris were distributed in aquatic ecosystems around the world at various concentrations. They had various toxic effects on the growth, development, behavior, reproduction and mortality of aquatic animals(Chae et al, 2017). More than 260 species of marine organisms such as turtles, invertebrates, seabirds, fish and mammals ingested are entangled with plastic debris leading to reduced movement, feeding, reproductive output, ulcers, lacerations and eventual death (Alabi et al, 2019).

V. TYPES OF TREATMENT METHODS FOR DEGRADATION:

There are a total of 3 treatment methods that we are using in the present day that are used in degradation (Figure-2).

1. Physical treatment 2. Chemical treatment 3. Biological treatment

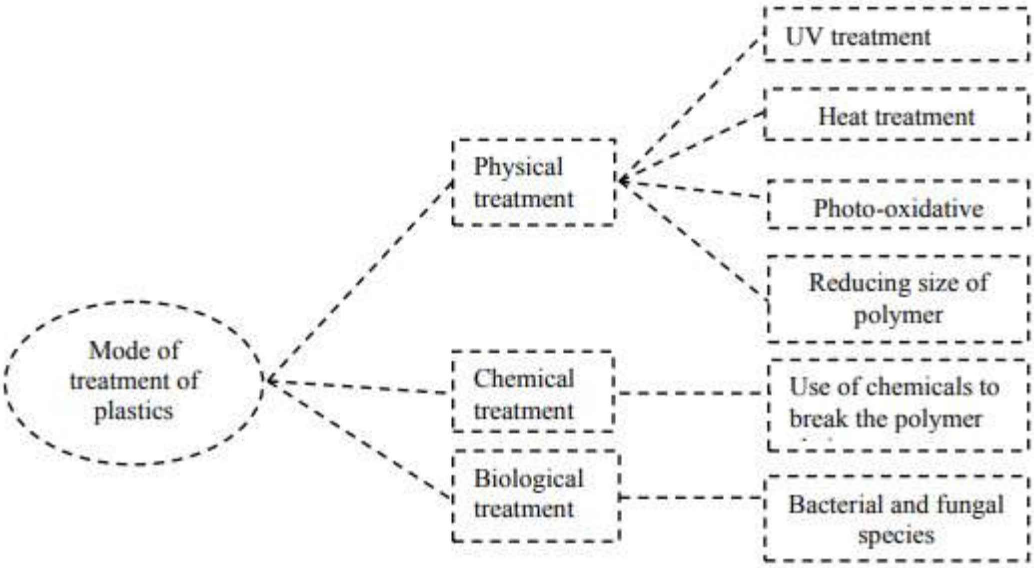

Figure 2: Total types of degradation methods present for degradation of plastics. (Rucha V. et al. 2018)

Physical treatment method:

Physical treatment as the name suggests that the size of the plastic is reduced by using physical modes like grinding, pulverizing and incineration (Rucha V et al, 2018). Biodegradation process occurs in four stages: bio-deterioration, bio-fragmentation, bio-assimilation, and mineralization. Before initiation of microorganisms begin to attack Plastic, they need access points in the plastic structure for starting the fragmentation. Thus, initially, oxidation of plastics occurs through abiotic process commonly known as physical process, such as exposure to ultraviolet (UV) irradiation (Ranjan et al, 2020) in combination with heat and oxidation process (Celina et al, 2019) where complete disposal of plastics.

Chemical treatment method:

In this method the degradation of plastics depends on the chemicals but is not considered for production on a large scale due to cost and disposal problems with the chemicals (Rucha V et al, 2018).

Biological treatment method:

Microorganisms can catalyze the oxidation-reduction for breakdown of chemical bonds in the plastic polymers (Tokiwa et al, 2009). This process of biological deterioration of plastic depends on numerous factors like surface area, functional groups, molecular weight, hydrophilic, and hydrophobicity, melting temperature, chemical structure, crystallinity, etc. (Okada, 2002). There are many ways in the degradation of plastics; one of them is enzymatic degradation of plastics by which hydrolysis occurs in which enzymes attack the polymer substrate resulting in hydrolytic cleavage. During hydrolysis, extracellular enzymes secreted by the microorganism for biodegradation degrade the polymer to simpler molecules e.g. oligomers, dimmers and to monomers. Enzymes secreted by microorganisms for biodegradation of plastics are mostly lipase, proteinase k, dehydrogenase (R. Mohee et al, 2007). Esterases, lipases, and cutinases are hydrolases considered as main instrumentals that help in plastic degradation (Sangale *et al*, 2012; Novotný *et al*, 2015; Mohan *et al*, 2016). Another way of degradation is clear zone formation, which a polymer penetrates as fine particles within the synthetic agar medium. The microorganism secrets extracellular enzymes; these enzymes diffuse through agar plastic degrade into water soluble (A.A. Shah et al, 2008). Figure 3 given below briefly explains the biodegradation activity of microorganisms on the plastics.

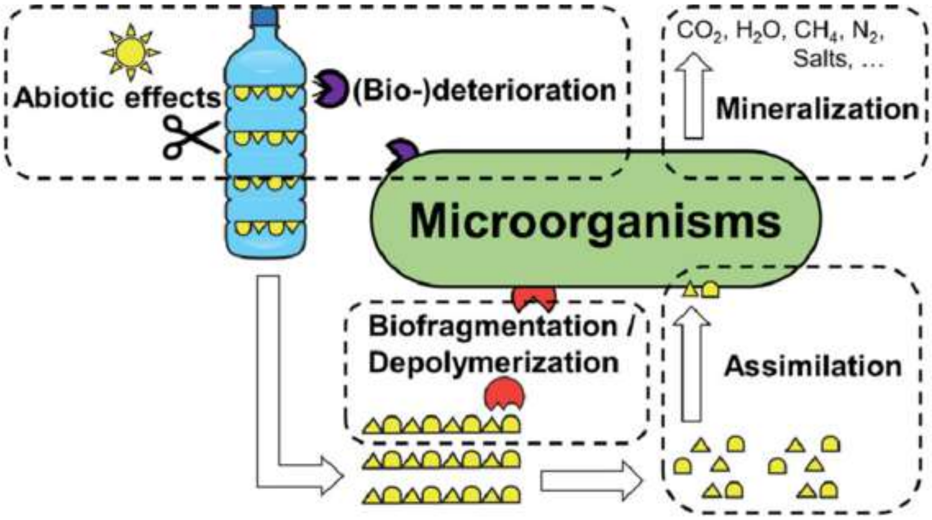

Figure 3: Biodegradation of plastics by microbial action (Lucas et al. 2008)

VI. WHY DO WE PREFER BIODEGRADATION?

In a certain material or a polymer any physical and chemical change which is caused by the action of microorganisms is known as biodegradation. Natural plastics as well as the synthetic plastics are degraded by the action of microorganisms (Alshehrei et al, 2017). Even if these plastics are re-used, they will surely become waste at some point of time (Plastics Europe, 2018). Unfortunately, a huge quantity of plastic waste leaks into the environment which is causing significant economic and ecological damage. For example, some 5–13 million tons of plastic end up in the ocean every year (Geyer et al, 2017).

As of now the products that we use in our daily life are mostly that of the plastics in one way or the other. But disposal or degradation of the plastic has become a major problem that has bothered many of the scientists for over many years. So this caused a huge effect on the environment and many of the side effects. Degradation of plastic by natural processes is very slow and takes a long time to fully degrade even a small amount of plastic. The common physical processes we naturally use are UV light and heat and later we even used some of the chemical processes for our own purposes. To get rid of plastic waste, people usually put them in landfills or burn it, but both of these practices cause a very serious threat to the environment and the ecosystem.

Later on the discovery of the action of microorganisms on the plastics brought to new and great understanding of the degradation of the plastics. Microorganisms play a very important role in the degradation of plastics. There are different types of microorganisms that degrade different types of plastics. This type of biodegradation requires less energy supply externally, reduces the emission of carbon release, saves nonrenewable sources and they are eco friendly. Some plastics are designed to be biodegradable and can be used to break them in a controlled environment such as landfills. Biodegradation of waste plastic is an innovative area of research which is solving many of the environmental problems (Raziya Fathima et al, 2016).

Even though we prefer biodegradation it is complex and not fully understood. Research to clarify the biodegradability of plastic material has different strategies. One of them uses degradation studies carried out using pure microbial strains which are able to degrade plastic materials (Navinchandra Shimpi et al, 2012). The other approach is that plastics were placed in different environmental conditions such as marine, soil, water, sludge or compost. The main reason for this approach is to find the capacity of plastic biodegradation and to find microbes that can digest plastic materials. (Nikolic et al, 2014).
There are two types of biodegradation methods we use:
Aerobic biodegradation is the breakdown of large organic compounds into simpler compounds by using oxygen as an electron acceptor by the action of the microorganisms (Priyanka and Archana, 2011).
Carbon plastic + $O_2 \rightarrow CO_2 + H_2O$+ other Carbon residues
Whereas for the Anaerobic biodegradation oxygen is not necessary for the breaking down of compounds when action of microorganisms occurs. Anaerobic bacteria use nitrate, iron, sulphate, manganese and Co_2 as an electron acceptor in place of oxygen to break down large organic compounds into smaller compounds.
Carbon plastic $\rightarrow CH_3 + CO_2 + H_2O$+ other Carbon residues

The clear understanding of microorganisms which colonize the plastic surfaces using modern technology like DNA sequencing (Zettler et al, 2013) has also been brought into existence. The role which was played by the microbes on degradation of plastic in the ocean is considered as the secondary subject as a concern. Latter on the comprehension it is concluded that present international standards and test methods are not effective in their ability to completely estimate the biodegradation of plastic materials in marine environment, this is due to several obstacles in experimental procedures that are conducted and insufficient of information in the scientific literature (Harrison et al, 2018). The adaptability of microorganisms for biodegradation of plastic was reported for many bacterial strains (Krueger et al, 2015). Due to convenience of using, low cost, maintenance and action on the degradation of the plastics we prefer to use microorganisms as the main component for biodegradation.

Microorganisms are abundant in the environment and we have many options so selecting the strains required for a wide variety of plastic material for their degradation with much effectiveness either in soil or in water without causing any massive changes to nature became a best option in recent years.

VII. Mechanism of biodegradation

The complexity of the biodegradation mechanism of the plastics is not even fully understood now. Various abiotic and biotic factors play a vital role in the biodegradation of plastic materials in the environment (Sivan A, 2011). Studies on biodegradation are accomplished by using pure cultures that are helpful in degrading plastic materials (Tribedi P and Sil AK, 2013; Wilkes RA and Aristilde L, 2017) or we can also use complex microbial communities from various terrestrial sources like landfill sites, Composting and also from the marine habitats (Lobelle D and Cunliffe M, 2011).

The mechanism of biodegradation is mainly divided into three stages. In the first stage the bacteria get attached to the surface of the plastic materials. Temperature on the surface of the taken material along with the structure will influence the process of biodegradation. In the second stage the polymer chain gets broken down by the enzymes that are secreted by bacteria by the hydrolysis and oxidation reactions. Later at the end of the second stage the fragments which are with low molecular weight will get absorbed and are then digested by bacteria. This final process goes through a series of metabolizing processes and then eventually gets rid of these in the form of carbon dioxide, water along with other carbon residues (A Moses et al, 2012). This detailed mechanism process is shown in the below figure 4.

The first stage can also be known as depolymerization because the breaking of the polymer occurs. Second stage can also be known as random chain scission as disproportion termination and intermolecular chain transfer take place which results in formation of new free radicals with a high reactivity. And the third stage can be described as side group elimination because the random removal of the side groups from the backbone occurs on any further breakage of the plastic materials. The Illustration of mechanism induced chain scission and the design of enhanced mechanical degradation are represented diagrammatically in the figure 5.

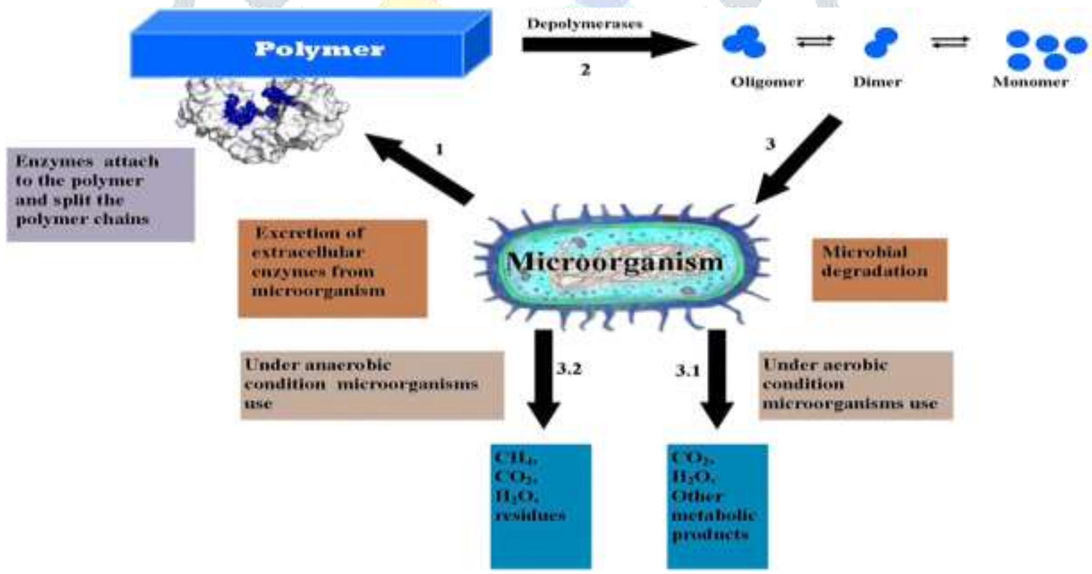

Figure 4: Plastic biodegradation mechanism under aerobic and anaerobic conditions (Tokiwa et al. 2009).

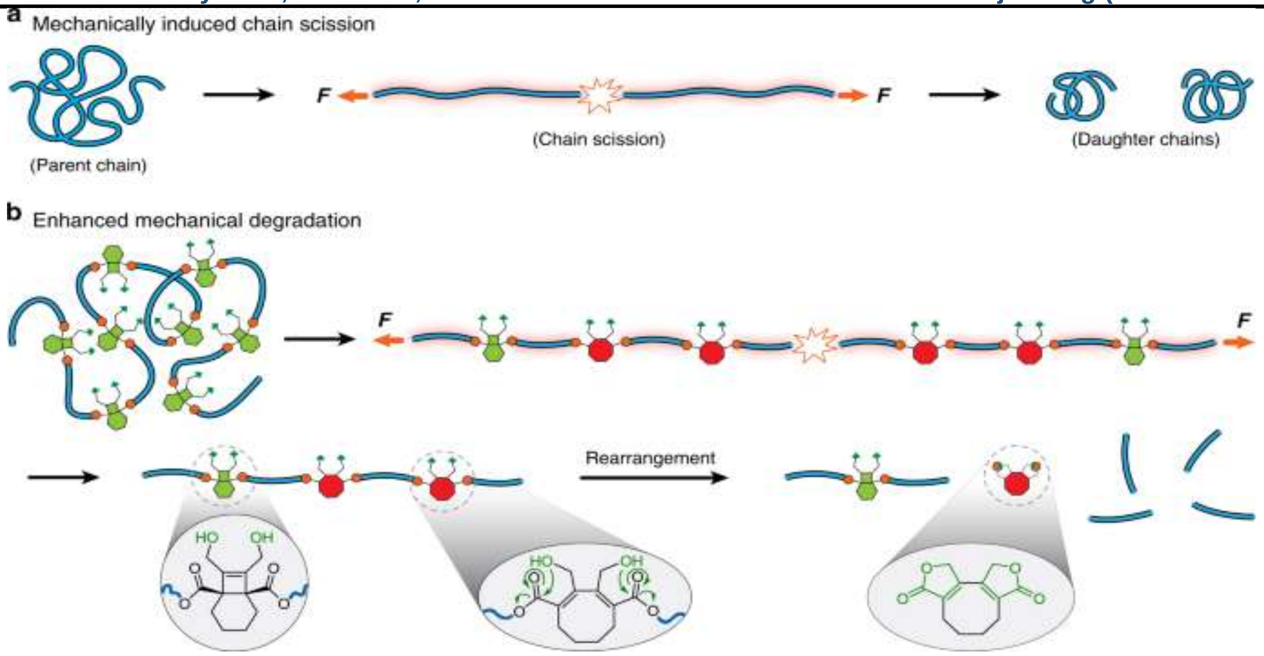

Figure 5: Illustration of mechanically induced chain scission & enhanced mechanical degradation design. (Lin et al. 2020)

VIII. PLASTIC DEGRADATION BY MICROORGANISMS

Microorganisms are mostly used in the present day world for most of the processes that are included in the production of the products or for the degradation of the product. Now-a-days we are facing a huge problem with deposition and degradation of plastics which are mostly unique in their properties and result in long lasting changes to the environment (Sivan A, 2011). Microorganisms contain different characteristics which result in degradation that differ from one microorganism to another.

Based on the different types of environment, biodegradation of plastic materials is an integrated process along with physicochemical and microbial degradation factors (Ammala et al, 2011). This microbial or bacterial degradation has greatly affected the transformation of plastic materials. Even though the plastics are less susceptible for the bacterial attacks when compared to the other degradable materials (Rujnic-Sokele and Pilipovic, 2017).

Bacteria are more abundant and easily available and are the main group of microorganisms of all organisms; bacteria that are present primarily live in soil, water, as well as the atmosphere. There are many species that are well known for their ability for degradation of pollutants like plastics (Bakir et al, 2014). In recent years, a large group and number of bacterial isolates that can degrade plastics have been identified. This resulted in the detailed understanding and up to date knowledge on their degradation properties and also the effects on plastics which received an increasing attention (Table 1).

Table 1: Some of the bacterial strains that are capable of degrading plastics under laboratory conditions and in the environment

Genus	Source	Plastic type	Duration of degradation (d)	Gravimetric weight loss (%)	References
Bacillus	Digester sludge	PLA	40	–	(Kim et al, 2017)
Bacillus	Plastic contaminated sites	PE	28	–	(Mukherjee et al, 2017; Shao et al, 2019)
Bacillus	Plastic-eating Waxworms	PE	28	10.7 ± 0.2	(Yang et al, 2014)
Bacillus	Mangrove sediment	PP	40	4.0	(Auta et al, 2018)
Bacillus gottheilii	Mangrove ecosystems	PE, PET, PP, PS	40	6.2,3.0, 3.6, 5.8	(Auta et al, 2017)
Bacillus subtilis	Soil samples	Polyurethane (PUR)	28	–	(Shah et al, 2013)
Chelatococcus	Compost	PE	80	–	(Jeon et al, 2013)
Enterobacter asburiae	Plastic-eating Wax worms	PE	28	6.1 ± 0.3	(Yang et al, 2014)
Lysinibacillus fusiformis	PE Contaminated site	PE	28	–	(Puglisi et al, 2019)
Paenibacillus amylolyticus Ideonella sakaiensis	Contaminated samples	PE, PET	60	–	(Yoshida et al, 2016)

Pseudomonas	Digester sludge	PLA	40	–	(Kim et al, 2017)
Rhodococcus	Mangrove sediment	PP	40	6.4	(Auta et al, 2018)

Note: this symbol "–" represents unknown

IX. WHAT ARE THE FACTORS AFFECTING BIODEGRADATION?

There are many factors that affect biodegradation and they are mainly divided into 2 types as exposure conditions and polymer characteristics. Based on exposure conditions they are divided into 2 types: abiotic and biotic. Temperature, moisture, pH, UV radiation comes under abiotic factors and extracellular enzymes, hydrophobicity and bio-surfactants belong to biotic factors. Flexibility, crystallinity, morphology, functional groups, copolymers, molecular weight, inoculums come under polymer characteristics (Thitisilp Kijchavengkul and Rafael Auras; 2008). Because of all factors we are unable to determine the exact definition of the biodegradation. Factors affecting are given as an illustration in the below figure 6.

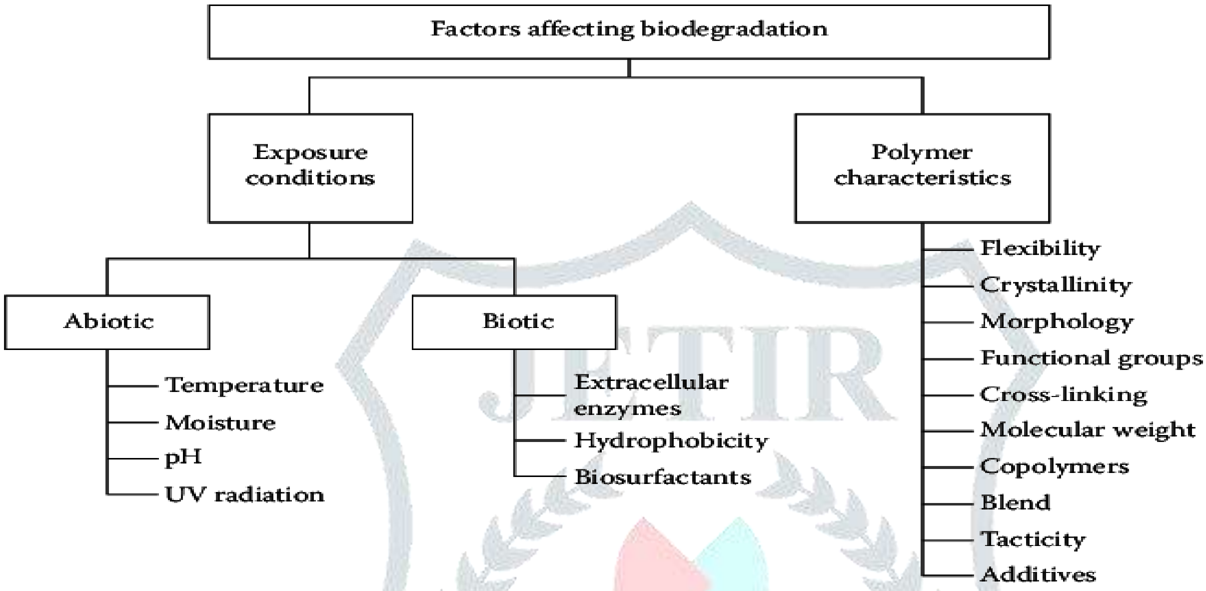

Figure 6: Illustration of the factors that affect biodegradation. (Kijchavengkul T et al. 2008)

Here we are having a detailed understanding of the major factors that affect biodegradation

- **Temperature:**

Temperature has a direct impact and effect on biodegradable plastic by increasing the rate of biodegradation rates (M. Matthies et al. 2017). Until now researches were only focused on determination of biodegradability, which has become one of the essential information when we classify the environmental properties of plastic materials. When the interest has shifted from the characteristics properties of the plastic materials to the behavior of products when they are introduced into the environment, it is necessary that we have to understand the influence of the fundamental environmental parameters on the degradation rates. Effect of temperature can be described perfectly by the Arrhenius equation in the tested temperature range.

- **pH:**

At a neutral pH which ranges from 5 to 9 there will not be much effect on the biodegradation but on increasing or decreasing of this pH will affect the processes. The optimal pH value varies from organism to the other organism. At this optimal pH the rate of biodegradation will be at the top (Sui et al, 2016).

- **Inoculum:**

Inoculum is the initial starter culture that we add for the initiation of the biodegradation processes. Based on the amount of the inoculum we add for the culture the reaction rate will be directly proportional to the degradation rate.

- **Initial concentration:**

It is the concentration or the total material of plastic that has to be biodegradable. When we take the initial concentration of the plastic is low when the inoculums is added then the process of biodegradation increases. Whereas the initial concentration is much higher than that of the inoculums that we are adding then the degradation rate will be very low (Sui et al, 2015).

- **Functional groups, cross-linking, molecular weight:**

If functional groups or cross-linkages or molecular weight of the taken plastic are high, the rate of biodegradation will decrease to the minimum level. This is because the microorganisms take more time to break these complicated bonds for this it takes more time which is directly affecting the biodegradation rate.

- **Enzymes:**

Enzymes are the substances that are secreted by the microorganisms during the processes of their growth. These enzymes mainly of two types: one is extracellular enzymes which are released out of the bacteria and are free to act on plastic materials other is intracellular enzymes that are secreted within the body of the bacteria and external methods like cell disruptions should be used for their release and to act on the plastic materials. So for this purpose most of the time we prefer extracellular enzymes producing bacteria that boosts up the process of biodegradation.

X. Reviews

Kartikey Kumar Gupta and Deepa devi, 2019 explored the degradation of LDPE by three strains of Bacillus sp. i.e ISJ51, ISJ55 and ISJ57. Percentage of degradation was evaluated by weight loss of the polyethylene, reduction in bacterial hydrophobicity and estimation of biomass attached to the polyethylene film. 1.5% is biodegraded as bacterial biofilm is adhered on LDPE in Bacillus sp. strain ISJ55 after 60 days. ISJ55 strain has more hydrophobicity than ISJ51 and ISJ57. Since a 20.3% reduction in culture turbidity was observed towards hydrophobic substances.

Anthoni Agustien et al, 2016 screened polyethylene synthetic plastic degrading bacteria from soil samples. Results showed that there are 24 different bacterial strains isolated. From 24 bacterial strains isolated, 11 isolates indicate the degrading bacteria of polyethylene synthetic plastic. 11.7% w/w polyethylene plastic waste was degraded by Pseudomonas sp and bacteria with code BTS-9, BTS-12 has lowest potential (0,9% w/w).

H.S. Auta et al, 2017 studied eight bacterial strains from mangrove sediment in Peninsular Malaysia. The weight loss of microplastic by Bacillus. cereus after 40 days of biodegradation is 1.6%, 6.6%, and 7.4% for PE, PET, and PS respectively. Bacillus gottheilii recorded weight loss of 6.2% for PE, 3.0% for PET, 3.6% for PP and 5.8% for PS.

Ch. Tahir Mehmood et al, 2016 analyzed biodegradation of photodegraded and non-photodegraded LDPE films, modified by dye titania (TiO2) of food grade. Strains of Pseudomonas aeruginosa, Burkholderia seminalis and Stenotrophomonas pavanii were isolated. Stenotrophomonas pavanii showed highest biofilm, hydrophobicity and growth rate compared to other strains.

Janczak et al, 2018 examined differences in degradation of biodegradable plastics (polylactide, PLA) and conventional plastics(polyethylene terephthalate, PET). Polymer biodegradation is evaluated in compost soil with three plant species. Biodegradation in the plastics are calculated based on changes in their surface structure and chemical properties after a 6-month incubation in the soil. Biodegradation of the analysed sheets is rapid in the presence of the S. plymuthica and L. laccata strains.

Zhongyu Li et al, 2020 investigated the growth of Microbulbifer hydrolyticus IRE-31 and its biological degradation on low-density PE. Upon 30 days of degradation, IRE-31 strain on linear low-density PE by morphological changes on the polymer surface is clearly observed.

Sekhar et al, 2016 used high impact polystyrene (HIPS) to isolate microbial cultures. Enterobacter spp Citrobacter sedlakii, Alcaligenes sp. and Brevundimonas diminuta are identified. Biodegradation experiments showed the degradation rate to a maximum of 12.4% (w/w) within 30 days. All isolates displayed depolymerase activity to degrade e-plastic.

Li Jiaojie et al, 2020 isolated Pseudomonas sp. from soil. This study demonstrates the efficient biodegradation of Polyphenylene sulfide (PPS) by Pseudomonas sp. , which exists in the superworms. Bead form plastic showed significant biodegradation compared to conventional plastic in a 10 day period.

Shrikant D. Khandare et al, 2021considered four bacterial strains capable of from the marine environment. These four bacterial isolates resemble Cobetia sp., Halomonas sp., Exiguobacterium sp. and Alcanivorax sp., respectively. These Bacterial isolates formed the biofilm on the LDPE. At the end of study, a maximum weight loss of 1.72% of LDPE film was observed in Halomonas sp strain.

Ya-Nan Han et al, 2020 isolated two novel strains of Arthrobacter sp. and Streptomyces sp. from agricultural soils. The strains were able to degrade PE film in a 90-day inoculation up to some extent.
Azeko et al, 2015 presented the biodegradation of low density polyethylene (LLDPE) by Serratia marcescens subsp. marcescens bacteria without exposing LLDPE to thermo oxidative aging. The results show that the cell-free extracts degrade LLDPE quicker than the S. marcescens marcescens.

Bhone Myint Kyaw et al, 2012 aims to investigate biodegradability of LDPE by four different strains of Pseudomonas bacteria—Pseudomonas aeruginosa PAO1, Pseudomonas aeruginosa, Pseudomonas putida and Pseudomonas syringae. After 120 days of incubation period, the percentage of weight reduction was 20% in Pseudomonas aeruginosa, 11% in Pseudomonas aeruginosa, 9% in Pseudomonas putida, and 11.3% in Pseudomonas syringae strain. Maximum weight loss is seen in polythene incubated with Pseudomonas aeruginosa.

Sinosh Skariyachan et al, 2015 identified plastic-degrading bacteria from plastic-contaminated soil and water samples in six hot spots of urban and rural areas of Bangalore. The percentage of polymer degradation was monitored by weight loss. The bacteria utilized the plastic polymer upto 20–50% weight reduction over 120 days. The two bacteria responsible for the degradation are Pseudomonas spp. The bacteria showed degradation of 35-40 % over 120 days. Microbial consortia formulated by combining Pseudomonas spp. showed 40% weight reduction in 90 days. Lipase enzyme is responsible for polymer degradation.

Ponniah Saminathan et al, 2014 made an attempt to isolate Pseudomonas putida from garden soil. They examined garden soil microbes are capable of degrading. P. putida 75.3% within a month. The plastics tested in this study were polythene bags, plastic cups and milk cover. Milk cover is found to be (75.3%) degradative.

Prosun Tribedi et al, 2011 targeted isolating mesophilic organism(s) capable of efficient degradation of Purpose Polyethylene succinate (PES). Results showed a new strain of Pseudomonas, AKS2 isolated from soil, has survived on a selection plate. AKS2 degrades PES maximally at a rate of 1.65 mg/day. Pseudomonas new strain from soil is able to degrade PES.
Vimala P et al, 2015 tested Bacterial species Bacillus subtilis, for its potential in utilizing polyethylene as their sole carbon source. Pretreated polyethylene films with Bacillus subtilis by the addition of its biosurfactant proved to be most efficient with a weight loss of 9.26% in 30 days.

Sonil nanda et al, 2010 analysed the comparison between biodegradation of natural polyethylene and synthetic polyethylene from three species of Pseudomonas. Pseudomonas sp. isolated from sewage sludge dump degraded 46.2% natural polyethylene and 29.1% of synthetic polyethylene. Pseudomonas sp. from household garbage dumps has 31.4% for natural polyethylene and 16.3% for synthetic polyethylene. However, Pseudomonas sp. isolated from textile effluents gave 39.7% for natural polyethylene degradation and 19.6% for synthetic polyethylene degradation.

Hyun Jeong Jeon et al, 2013 examined degradation of PLA with a mesophilic bacterium, Stenotrophomonas maltophilia LB 2-3. PLA lost molecular weight and tensile properties when exposed to UV irradiation. The same behavior was also observed when PLA degradation was carried out in compost waste.

XI. CONCLUSION

Plastics are petroleum-derived polymers that are used for various purposes. PE bags are used at large levels all over the world. The presence of micro and nanoplastics in aquatic environment has been increased many folds due to biodegradation, thermo-oxidative degradation, photodegradation, thermal and hydrolysis processes in the ecosystem and poses serious threat to the aquatic (both fresh and marine) and human life by entering into food chain. So, there is a need to use biodegradable methods to eradicate these polymers from the ecosystem. Due to hydrophobicity and inert nature, it is difficult to degrade polymers. Besides physical and chemical methods, biological methods i.e., using of microbes have shown promising potential to degrade these polymers. As described above, there are a number of plastic-degrading microorganisms and enzymes that have been sourced from the environment. However, an understanding of depolymerases that contribute to the breakdown of plastics remains scarce. Many living organisms but specially microorganisms have evolved strategies to survive and degrade plastics. Plastic degradation and bioremediation potential make these microorganisms favourable for green chemistry to eliminate harmful plastics from the ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGMENT

The authors extend their appreciation to the Department of Chemical Engineering, A U College of Engineering (A), Andhra University, Visakhapatnam).

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