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Impact of the non-biodegradable plastics and role of microbes in biotic degradation

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ABSTRACT

Plastic is a group of elastic organic compounds whose definition has radically changed from being a large family of useful polymers to an indispensable part of life. We might say we are residing in the “era of plasticene”. If we simply pause and look around, we would realize that a majority of things in our daily life comprise plastic polymers. Currently, the international production of these polymers has spiked to around 300 million metric tons annually. Surprisingly about 50 percent of the products are discarded within a year of fabrication. Once discarded ‘outside’ they end up ‘somewhere’ and start exerting their disruptive consequences. Despite its enormous utility, it is now being increasingly known that these polymers are surely not without their downsides. Several steps are taken and even more, are being investigated so the mayhem of plastic doesn't prove for a “no pilot in cockpit” situation. Here we have conducted a review work of the available literature on various biological entities that can utilize plastic while at the same time focusing our attempts to assemble information regarding the probable enzymes that do it. We have also provided a report on the effect of different plastics on the ecosystem and the various management alternatives out there.

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1 Introduction

The plastic sector, among the quickest expanding industry, has begun its mass-scale production since the 1950s nevertheless its program in day to day life dates back a hundred years ago (Geyer et al. 2017). The property of elasticity of plastic has led to a marked increase in its usage in various daily life activities. As a result, its manufacturing volume right now has far exceeded 300 million tons per year. A major portion of the global plastic create comprises polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PU), and nylon.

The marine ecosystem is one of the worst-hit environments by these polymers where they are gathered most. Especially in the five suburban gyres typically at their zone of convergence (Cózar et al. 2014). One of the most visible effects of marine plastic pollution is the formation of plastic islands in oceans and rivers, such as the Great Pacific Garbage Patch, frequently called a "gyre within a gyre" (Howell et al. 2012).

Due to oxidation, the surface of plastics develops micro-cracks and pits, which are broadly prone to fracturing due to humidity and temperature stress or scraping against sand particles generating a lot of microparticles. This phenomenon is often observed in UV introduced plastics particles such as high-density polyethylene, low-density polyethylene, or polypropylene (Andrady 2011).

A major drawback in petrochemical-derived plastic waste control is that it requires a long time to be degraded by abiotic variables such as UV or temperature and is very immune to absolute degradation by microbes due to its properties such as large molecular mass, absence of specific functional moieties for the enzymes to act upon, degree of crystalline nature and high hydrophobic nature (Urbanek et al. 2018).

Even though plastic polymers are difficult to degrade but certainly, their degradation is not impossible. Certain enzymes can make this possible. In general, molecules of large molecular mass cannot be hauled as such across the cell wall. They are divided up into smaller subunits that are more hydrophilic and then be degraded by intracellular metabolism (Shah et al. 2008). Therefore, many microbes secrete certain extracellular enzymes that can carry out this chopping activity which breaks down large hydrophobic polymers into smaller monomeric units. Consecutively, easy biotic degradation and mineralization followed by microbial assimilation (Gewert et al. 2015).

If somehow, we could enhance the potential of these enzymes (many of which are already isolated) and cost-effectively harness their activity, then we can come up with an instrument to degrade plastic efficiently. It is now increasingly realized that

microorganisms can colonize almost all plastics that enter the marine earth. These colonizations are guided by the material properties and ecological variables like oxygen accessibility, levels of temperature, salinity level, and light exposure (De Tender et al. 2015).

As per a study conducted across the coastal Baltic stations, households of *Hyphomonadaceae* (largely the *Hyphomonas*) and *Erythrobacteraceae* (largely the *Erythrobacter*) which were known to metabolize Polycyclic Aromatic Hydrocarbons (PAH) were found in abundance colonizing the microplastics (Oberbeckmann et al. 2017).

2 Impact of microplastic

The microplastic travels far and wide along the ocean surface layer circulation driven by wind thereby, and its impacting places many kilometers away from the source of contamination (Thevenon et al. 2014). Various studies have shown the microplastics are amassing in a huge variety of marine organisms which range from zooplanktons and mussels (Caruso 2015), decapod lobsters such as *Nephrops norvegicus* (Murray and Cowie 2011), sea turtles such as *Chelonia Mydas* (Caron et al. 2018) to the large blossom Fin whale (Fossi et al. 2012) and various types of fishes where it may cause esophageal toxicity and pathology as detected with the experiment on adult medaka (Rochman et al. 2013). In 2013, in a study on short-tailed shearwaters, it was found that frequently Persistent Organic Pollutants (POP) are leached from ingested plastics to the cells of the bird ingesting it (Tanaka et al. 2013). This is of major concern because those organisms that have their daily diet exposed to a good deal of plastics are possibly under threat. Wilcox et al. (2018) attempted to establish a connection between the mortality of turtles and their ingestion of these kinds of plastics. They found that as low as 14 pieces of plastic in the gut of an animal could activate a 50 percent likelihood of its mortality.

In a nutshell, the disposed of compound fragments are usually hazardous as these xenobiotic compounds, once ingested by birds mistakenly may result in their death by interfering with the normal physiological processes like digestion. The reason can be due to blockage of the gastrointestinal tract (Ryan 1987). The disposed of plastic products can not only degrade to form smaller microplastics but also can break down further to even smaller nanoplastics of size ranging from 1nm to 1000nm based on a recent opinion. These nanoplastics because of their small size have a large surface area thereby having high absorption and adsorption properties (Gallo et al. 2018). Due to this, the nanoplastics could be expected to harbor more heavy metals contaminants and toxic organic chemicals compared to microplastics. In humans, both micro and nano variants of plastic debris can cause DNA damage, osteolysis, inflammation, apoptosis, necrosis of tissues, oxidative stress, and variations in gene expression and consequently in protein

expression (Lusher et al. 2017). A recent publication even reported the possible ingestion of microplastic clutter by jellyfish (Macali et al. 2018). Exploration of the effects of microplastic from the terrestrial background has resulted in the observation that it reduces the sorption capability of certain organic pollutants from the soil, thereby speeding up groundwater contamination (Metzelder et al. 2019).

3 Non-Biodegradable plastics, their effects and microbial arsenals for degradation

3.1 Nylon

Nylon, the multiple varieties of which are already available in the current market, are synthetic polyamides made from different reactions. There is the inherent polymerization of ω -amino acids, copolymerization of diacid and diamine, or the polymerization involving the ring-opening of the lactam that forms the nylon polymer. Nylon-6 and nylon-66 are the major members of the family sharing about 90% of its production worldwide. These are predominantly used in making fishing nets, ship hulls, disposable plastics, textile fibers, bristles for toothbrushes, and several other items. So clearly they would likewise be the major polluting variants of nylon. However, in the open environment, many rogue microbes have been discovered to exhibit some quantity of degradation of the polyamides or their replicating units say, for example, there are microbes like *Pseudomonas aeruginosa* that was discovered to degrade ϵ -caprolactam that is practically absolutely needed for the synthesis of nylon-6 and was found to grow on the surface of the 6-Amino hexanoate cyclic dimer, a common by-product from nylon factories or *Flavobacterium* sp. K172 (IFO14590) was found to use up at least one percent of the same (Negoro 2000) or another microbe *Geobacillus thermocatenulatus* that has been discovered to degrade nylon 66 and nylon 12 (Tomita et al. 2003).

The breakdown of a cyclic dimer of 6-amino-hexanoate requires the assistance of three enzymes. All of these three might be very instrumental in degrading the polymer. The first is the 6-aminohexanoate-cyclic-dimer hydrolase (nylA), an amidase signature hydrolase having a catalytic triad of Ser¹⁷⁴-cis-Ser¹⁵⁰-Lys⁷² that was found to degrade the dimer into its monomeric units. It achieves this function by carrying out a nucleophilic attack of the serine in its catalytic site on the carbonyl moiety of the amide bond followed by the formation of an acyl-enzyme complex and finally, a two-step deacetylation process with the help of a water molecule, ultimately regenerating the functional enzyme for another round of catalysis (Yasuhira et al. 2010). The second enzyme is 6-aminohexanoate-dimer hydrolase, two-domain penicillin recognizing serine reactive hydrolase of 392 amino acid residues and has been reported to act via a nucleophilic attack of a serine residue at 112th place of the enzyme and ultimately

deacetylating the substrate through the formation of an acyl-enzyme complex (Negoro et al. 2007). The next enzyme is Endo-Type 6-Amino-hexanoate-Oligomer Hydrolase of 355 amino acid residues transcribed from the nylC gene and utilizes the linearized trimer, tetramer, or pentamer of 6-amino-hexanoate through an endo-type response (Kakudo et al. 1993). According to an article printed in 2018, two enzymes, nylD1 and nylE1 have been discovered to play a substantial role in the metabolism of their 6-amino-hexanoate oligomer after it has been converted to the individual monomers. The nylD1 transcribes a molecule known as amino-hexanoate aminotransferase that converts the 6-amino-hexanoate to adipate semialdehyde through a pyridoxal phosphate (PLP) dependant pathway while utilizing α -ketoglutarate, pyruvate, and glyoxylate as acceptors. Further, the adipate semialdehyde dehydrogenase, another enzyme transcribed by the nylE1 receptor uses an NADP⁺ cofactor and converts the adipate semialdehyde to adipate (Takehara et al. 2018).

An interesting study claims that alkalophilic bacteria *Agromyces* sp. KY5R strain and *Kocuria* sp. strain KY2 produces 6-Amino-hexanoate oligomer hydrolases that have much better thermal stability, affinity, and catalytic function under alkaline pH (Yasuhira et al. 2007). In 2009, researchers discovered another type of enzyme, aryl acylamidase that could cleave off amide bonds in adipic acid bis-hexyl amide and aggravate the surface degradation of nylon-6 (Nagai et al. 2014). According to a Sudhakar et al. (2007), several marine bacterial species identified as *Bacillus cereus*, *Bacillus sphericus*, *Vibrio furnisii*, and *Brevundimonas vesicularis* have been reported to act upon both Nylon 6 and nylon 66 (Sudhakar et al. 2007). In the same study, the authors have hypothesized that as a substrate for bacterial degradation nylon 66 is much more favored than nylon 6. This behavior may be explained in terms of the basic structure of the 2 polyamides. Nylon 66 has about twice the amount of carbon-nitrogen bonds compared to nylon 6 which is a favorable target for the bacterial enzyme because less energy is required to break this bond in comparison to the carbon-carbon bonds of nylon 6. Because of this reason, nylon 66 falls a simple prey to bacterial degradation. Lignin-degrading fungus like the white-rot fungi IZU-154 is also reported to attack nylon-66 by oxidative metabolism (Deguchi et al. 1997).

3.2 PVC

Polyvinyl chloride (PVC) is a thermoplastic polymer of vinyl chloride monomeric units which was serendipitously discovered by Baumann in 1872. Originally hard and brittle, this polymer is made soft by the inclusion of a plasticizer such as di-n-butyl phthalate. It is utilized for making garden hoses, raincoats, pipes, insulation cables, shower curtains, simulated leather, water tank, or electrical insulator. Besides its elastic usage, it's also potentially toxic. The inhalation of PVC dust was reported to induce lung cancer

(Wagoner 1983). Also, its vinyl chloride repeating units are extremely dangerous and are known to cause hepatic angiosarcoma, brain tumor, and other severe problems such as pneumoconiosis, lymphatic and hematopoietic cancer, and emphysema (Kielhorn et al. 2000). Vinyl chloride has an anesthetic effect and its inhalation leads to irregular heartbeats in dogs (Oster and Carr 1947). Other indicators of chronic exposure include dizziness, headache, lack of breath and respiratory disease (Fralish and Downs 2021), and acroosteolysis that's a medical condition characterized by the presence of osteolysis and Raynaud phenomenon in the palms precisely in the terminal phalanges (Lopez et al. 2013). Also, there are pieces of evidence that indicate the cause of asthma and allergies as a result of the use of phthalate plasticized PVCs (Jaakkola and Knight 2008). A way out must be investigated to handle the PVC-related wastes and by-products that accumulate in the environment.

At the research level, several microbes have been detected to biodegrade these polymers and entities related to them. Sumathi et al. (2016) have discovered a low molecular weight PVC that could be biodegraded by *Cochliobolus* sp. by using an enzyme typically of 60-80kD known as laccase (Sumathi et al. 2016). This enzyme was obtained from the Japanese lacquer tree *Rhus vernicifera* in 1883 by Yoshida and later on isolated from fungus by Bertrand and Laborde (Viswanath et al. 2014). Hence, it has the possibility to be present in a variety of host organisms and is truly a green enzyme as would be discussed in the upcoming text.

The enzyme comes under the class of oxidoreductase and is a blue oxidase (due to the T1 copper) that is dependent upon oxygen as an electron acceptor for its purpose (Vishwanath et al. 2014). This cupredoxin could be monomeric, homodimeric, heterodimeric, or multimeric (Jaiswal et al. 2015). It could act upon a broad spectrum of substrates due to its low specificity especially a wide range of aromatic and non-aromatic compounds such as inorganic ions, phenolic and non-phenolics compounds (Nguyen et al. 2016).

This enzyme, laccases have been isolated from *Pycnoporus sanguineus* and *Trametes versicolor* which could break down bisphenol A (Barrios-Estrada et al. 2018). The laccase obtained from *Anthracophyllum discolor* could biodegrade polycyclic aromatic hydrocarbons (PAH) (Acevedo et al. 2011). Additionally, in a study, it was discovered that a laccase from an ascomycete *Stachybotrys chartarum* could act upon 2,2'-azino-di-(3-ethylbenzthiazolinsulfonate) (ABTS). It is now known that *Aspergillus nidulans* can produce as many as six different laccases with different substrate specificities (Mander et al. 2006). Therefore, it's highly evident that such a resourceful enzyme could degrade a variety of xenobiotic entities and not just PVC.

The catalytic site of laccase consists of four copper atoms in different oxidation states of which one is in type 1 and

paramagnetic 'blue copper', another type-2, and the remaining two in type-3 oxidation states and exist as a diamagnetic copper-copper set. There is a characteristic cupredoxin fold which is two β -sheets organized like a Greek-key barrel with approximately seven antiparallel β -strands with varying sequences interconnected by hairpin loops. This enzyme contains three homologous domains and the third domain harbors type 1 copper. The trinuclear cluster (TNC) made of one type 2 and the rest two are type 3 dimer, exists between the first and third domains with the second domain exclusively functioning to orient the other two domains so that the TNC is properly formed. An electron transfer chain has also been reported between the type 1 copper ion and the trinuclear cluster (Arregui et al. 2019).

This enzyme works by either directly oxidizing the substrate to its respective radical or by an indirect oxidation process for those substrates that have their ionization potential higher than the redox potential of the type 1 copper center (Agrawal et al. 2018). The whole cascade is initiated once the substrate associates with the binding site where it's stabilized by numerous hydrophobic residues. For example, in the instance of the laccase of *T. versicolor*, the substrates are stabilized by Phe162, Leu164, Phe265, Phe332, and Pro391 and also by an Asp206 which influences its orientation by interacting with His 458. For each enzymatic cycle, four substrate molecules are required. Following the proper binding, the substrates are modulated by the removal of one electron from each of its four molecules by the type 1 copper ion. This copper ion transfers the electrons to the TNC with assistance from a highly conserved cysteine-histidine electron transfer bridge. Next, the oxygen enters the TNC site and gets reduced to water. At first two of the four migrating electrons are contributed to it resulting in the formation of a laccase-peroxide intermediate. At length, two more electrons are provided to crack the peroxide linkage. Parallel to this hydrogen ions are provided from the 424th glutamic acid residue to produce water molecules with the help of a semi-conserved aspartate at the 77th position present at the trinuclear cluster interface (Arregui et al. 2019).

Laccase (isolated from *Cochliobolus* sp.) can hamper PVC due to its structural relatedness to chlorophenolic compounds which are known to be degraded by the enzyme (Sumathi et al. 2016). Similarly, xylophilic basidiomycetes such as *Phanerochaete chrysosporium* and *Trametes (Coriolus) versicolor* also have been reported to degrade polychlorinated phenols though it might not play any pivotal part in its mineralization (Ricotta et al. 1996). *Trametes pubescens* were found to act against chlorophenol mix at a pH of 6 and a temperature of 40 degrees (Gaitan et al. 2011). *Panus tigrinus*, basidiomycete was found to hamper chlorophenol (Rabinovich et al. 2004). A phytopathogenic fungus, *Rhizoctonia praticola* was detected to degrade chloroanilines. However, the question of whether they could degrade PVC similar to

Cochliobolus sp. has to be investigated. The answer could be yes or it could be no.

Aside from that, plasticized PVC has also been reported to be colonized by *Aureobasidium pullulans*. In the same study *Alternaria alternata*, *Alternaria infectoria*, and *Purpureocillium lilacinum* are reported to nicely degrade plasticized PVC (Webb et al. 2000). Members of the genera *Pseudomonas*, *Bacillus*, and *Chelatococcus* have been found to hamper PVC, *P. citronellolis* partially degrading the PVC materials without sterilization (Giacomucci et al. 2019). Further, PVC was also found to be degraded by white-rot fungi like *Pleurotus* sp. and *Poliporus versicolor* (Kirbas et al. 1999). There might be many other enzyme systems to hamper the PVC; therefore, further extensive investigation is necessary. But what turns out is that the main difficulty is the time required for complete degradation of PVCs deposited in the open environment due to different anthropogenic activities is very long. Hence, the biggest challenge of the hour is to bioengineer the enzymes to improve their efficiency.

3.3 Polyurethane (PU)

Polyurethane (PU) is a class of condensation plastic polymer that was innovated as a rubber substitute during the second world war. This elastic polymer manufactured chiefly by the reaction of a diisocyanate with a diol could also incorporate a wide range of modifications due to the presence of different aromatic compounds, ester, urea, or ether. Due to this, it finds its usage in a wide array of fields such as building, textile, automobile parts production and recently in a high number of biomedical implementations like artificial skin, adhesive for soft tissues, tissue engineering scaffolds, vascular prostheses, devices for drug delivery, pericardial patches, artificial nerve graft and dressing of wounds (Krasowska et al. 2015).

Despite being so malleable in usefulness this polymer also has significant disadvantages once it's disposed of in the environment. Due to this, it has been enlisted among the top polluting plastic polymers on the planet. For example, spraying of PU foam for thermal insulation in homes and offices emits tiny particles of urethane indoors which have been reported to irritate lungs and cause dyspnea and asthma. Studies also have shown that objects made up of PU could emit volatile organic compounds (VOCs), which can cause acute respiratory harm (Huang and Tsuang 2014). In 2016 multiple cases of allergies, irritation of the throat, bleeding of the nose, burning sensation in the eyes, and tightening of the chest have been reported in children who practiced routinely in running tracks made from PU (Wu et al. 2019). The observation had incited lots of societal perturbation especially, among the parents and their kids. In light of the circumstance, research was conducted by a group of specialists. The results showed that there is the emission of xylene, toluene diisocyanate, and unpredictably

very low concentrations of sulfur dioxide which can have a profound effect on long-term exposure, especially in the shape of impairments like chronic obstructive pulmonary disease (COPD) (Wu et al. 2019).

The polyurethanes comprise so-called "sections", which are actually alternating blocks. Every one of these blocks could be either the hard sections or the soft sections depending on their chemical nature. Polymers of different natures could be produced by varying the proportion of soft and hard sections (Krasowska et al. 2015). This family of polymers encompasses both non-biodegradable and biodegradable polymers. But it's fascinating to say that the recalcitrant non-biodegradable ones have been reported to be biodegraded by certain microbes.

The biodegradation of polyurethane by the fungus was first confirmed by Derby and Kaplan (1968). They also suggested that compared to polyether polyurethane, the polyester version is a better choice of substrate for fungal biodegradation. They further reasoned that for significant enzymatic degradation to occur, the presence of long unbranched carbon string separating the urethane linkages along with the presence of three neighboring methylene groups is very essential (Darby et al. 1968). Similarly, Hedrick and Crum (1968) reported the growth of *Pseudomonas aeruginosa* and *Cladosporium resinae* on the polyester polyurethane baffles of aircraft gas tanks (baffles are utilized to decrease the sloshing and projectile impact). Later on, Crabbe et al. (1994) reported four species of fungi i.e. *Curvularia senegalensis*, *Fusarium solani*, *Aureobasidium pullulans*, and *Cladosporium* sp. from garden soil could use up the polymer. Additionally, they found out that *C. senegalensis* used an esterase-based enzyme for its actions (Crabbe et al. 1994).

Subsequently, Nakajima-Kambe et al. (1995) reported the active degradation of polyester PU by *Comamonas acidovorans*. The microbe behaves so with the assistance of a 522 amino acids long esterase transcribed by a gene named Pud A. In its catalytic site, it exhibits a high degree of homology with the serine hydrolase and was discovered to possess the Ser-His-Glu catalytic triad. Three-dimensionally this catalytic site is close to the surface binding domain (Nomura et al. 1998). The surface binding domain was pointed out to be hydrophobic and is considered to entail the hydrophobic PU substrate followed by catalytic degradation (Akutsu et al. 1998).

Fungal isolates from sand infected with PU had deteriorogenic activity on the polymer and was found primarily to be due to urease activity (Loredo-Treviño et al. 2011). Numerous researches in the literature show a vast array of microbes that could degrade polyester polyurethane such as the five strains of *Nectria gliocladioides*, seven strains of *Geomyces pannorum* and one strain of *Penicillium ochrochloron* (Barratt et al. 2003) endophytic

fungus *Pestalotiopsis microspora* isolated from *Taxus wallachiana* from Ecuadorian Amazonian region is found to act on PUR via serine hydrolase activity under both aerobic and anaerobic conditions (Russell et al. 2011) and various other organisms such as *Candida rugosa* (Gautam et al. 2007), *Pseudomonas chlorophis*, *Phoma* sp., *Geomyces pannorum*, *Alicyciphilus* sp., *Pseudomonas fluorescens*, *Acinetobacter gomeri*, *Bacillus subtilis*, *Enterobacter agglomerans* and *Serratia rubidaea* (Mahajan and Gupta 2015), and *Acinetobacter gomeri* (Howard et al. 2012). From *P.chlorophis* three PUase enzymes, one of 65KDa and another of 31KDa, and a third of 60KDa have been identified (Howard 2002).

Lately, studies exhibited the chance of biodegrading the highly recalcitrant polyether polyurethane that was previously regarded as highly resistant to microbial degradation. A study demonstrated that *Cladosporium cladosporioides*, *Aspergillus fumigatus*, and *Penicillium chrysogenum* could attack the polyether polyurethane by considerable esterase activity and low urease activity (Álvarez-Barragán et al. 2016). Again, another study demonstrated that *Alternaria* sp. can do the same by a coalition of physical and chemical procedures. Physically it disrupts the structural arrangement of its substrate by its innumerable hyphae while using enzymes like urethanase and urease to carry out the degradative activity (Matsumiya et al. 2010). Reports suggest that cholesterol esterase can hamper Polyether based PUs liberating free amines (Christenson et al. 2006). However, the activity might be too low.

3.4 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) is a condensation polymer in which the monomeric units of ethylene glycol and terephthalic acid are combined by ester linkages (Sinha et al. 2010). This polyester is a fine illustration of a thermoplastic polymer and can be glass-like amorphous in its purest form. This polymer is commonly utilized in fabrics and food packaging industries and the production of microwavable packaging and drinking bottles. Besides its tremendous advantages, it has certain disadvantages which can no more be ignored. In its microplastic type, it's reported to damage *Parvocalanus crassirostris*, a copepod. The outcomes are a decline in its population density along with a radical effect on its survivability and reproductivity (Heindler et al. 2017). A recent study reports that terrestrial organisms such as *Achatina fulica* (snail) are adversely affected by the microplastic fibres of the polymer. The various effects include substantial damage to the intestinal villi and enhancement of oxidative stress within the body by upregulating the malondialdehyde level and lowering the level of glutathione peroxidase (Song et al. 2019). Recent data reports some pieces of evidence about the leaching of certain amounts of phthalate which could act as endocrine disruptors and other genotoxic and carcinogenic compounds in

bottles used to store various items (Rastkari et al. 2017). This might occur under conditions of long term storage. The PET polymers are indeed very lasting. This makes the substances to be utilized in various programs in day to day life but once such substances are eventually worn out, they are finally disposed of. This then turns the boon of durability into the bane of ecological burden.

Many enzymes have been reported to degrade PET polymers such as lipase (*Thermomyces lanuginosus*, *Rhizopus chinensis*, *Candida antarctica*, *Burkholderia* sp.), cutinase (*Fusarium solani*, *Humicola insolens*, *Penicillium citrinum* & some members of *Thermobifida* genera) (Kawai et al. 2019).

A breakthrough in the quest for a bio-based enzyme to degrade synthetic PET polymers came in 2016 with the discovery of *Ideonella sakaiensis* 201-F6, a gram-negative aerobic bacterium in Japan (Tanasupawat et al. 2016). Since then, much work was done to understand the degradation of the polymer by the bacterium. The deterioration of the PET polymers is carried out by two different enzymes- one is the PETase that could breakdown PET into mono-(2-hydroxyethyl) terephthalate (MHET) and another is MHETase that degraded the end product of PETase to ethylene glycol and terephthalic acid (Palm et al. 2019).

PETase is a α/β -hydrolase fold enzyme protein comprising of three polypeptide chains and a serine based catalytic triad of Ser-Glu-Asp (precisely, S133-H210-D179). The nucleophilic serine is polarized by the histidine residue which in turn is stabilized by the aspartic acid residue in the catalytic site whose flexibility is maintained by the disulphide bonds (Fecker et al. 2018). The catalytic cleavage occurs after the proper binding of the substrate. For this purpose, the wobbling kind of conformation of the tryptophan at the 156th position is very important. Once the substrate binds to the enzyme, there is a conformational change in the enzyme which displaces the carbonyl moiety of the leading hydrophobic ring into the middle of the substrate-binding section where the catalytic nucleophilic attack is carried out by the triad. During this process, the oxyanion hole acts as a substrate polarizer, thereby polarizing the ester linkages and stabilizing the intermediate. Subsequently, there is the nucleophilic attack of water just after the formation of the acyl-enzyme complex (Chen et al. 2018).

The MHETase comprises a typical lid domain (that confers substrate specificity) and a catalytic α/β -hydrolase fold domain. It is a type of feruloyl esterase with a molecular weight of 65KDa. Its lid domain is lodged in between the β strand and the fifteenth α helix. The enzyme has a calcium-binding website and five disulfide bonds. It possesses a typical catalytic triad of serine, histidine, and aspartic acid (S225, H528, D492) along with the oxyanion hole like the PETase (Palm et al. 2019).

Experts are already giving a lot of effort to make the PETase industrially available. In reality, according to recent work, the researchers have improved the expression of the enzyme by using the secretion system of *Escherichia coli*. They had used a Sec-dependant and SRP-dependant signal peptide from *E. coli* to generate an extracellular enzyme capable of degrading PET. However, the activity of this extracellular PETase was discovered to be lower than the cytosolic version expressed in *E. coli* RossettaGami-B which could generate a degraded product of 4.8 mg/L post 36 hours of incubation (Seo et al. 2019). The MHETase has been successfully propagated in *E. coli* BL21 by using the pUCIDT plasmid vector (Janatunaim and Fibriani 2020).

In 2019, there was a successful demonstration of PETase production by a diatom called *Phaedactylum tricornutuma* though its main problem was poor growth (Moog et al. 2019). After green algae, *Chlamydomonas reinhardtii* (industrially GRAS organism) was shown to produce PETase (Kim et al. 2020). Using the metagenomic approach a different group of researchers had identified a novel cutinase homolog out of leaf-branch compost effective at degrading PET (Sulaiman et al. 2012). Lately by using a similar strategy about 504 possible PETase generating genes have been identified mainly in organisms of the genera *Proteobacteria*, *Bacteroidetes*, and *Actinobacteria* (Danso et al. 2018).

3.5 Polypropylene (PP)

Polypropylene is a thermoplastic polymer made up of repeating units of propylene monomers. Stereochemically, it appears in three distinct conformations: isotactic where the methyl substituents are oriented on the same side, syndiotactic where methyl groups frequently alternate on the other hand, and atactic where methyl groups are randomly oriented. This polymeric compound is widely used in the production of strappings, movies, sheets, injection mouldings, auto parts, fibres, and fabrics (Maddah 2016). This versatile polymer was found by Rehn and Natta in 1954 and commercialized in 1957 (Andrady and Neal 2009).

It is quite similar to polyethylene but is conducive with tougher mechanical characteristics along with higher heat resistance but consecutively low resistance to chemicals such as non-polar solvents or oxidizing agents (Scalenghe 2018). As a result of its high susceptibility to oxidation by dint of its chemical structure, it is capable of creating a lot of free radicals (Sternschuss et al. 2012). If such a reaction occurs in the human body due to the consumption of a microplastic contaminated diet then it is likely to induce oxidative stress. On the other hand, the intensity of damage caused due to the consumption of microplastics from the human body requires additional investigation. Already there's evidence that exposure to polypropylene flock can cause the onset of

interstitial lung disease along with peribronchial thickening in some cases (Atis et al. 2005).

Polypropylene is one of the most frequently discovered plastics in oceans worldwide and is known to accumulate polychlorinated biphenyls (Teuten et al. 2007). In an experiment conducted by using *Daphnia magna*, it was discovered that leachates from this polymer were relatively not as toxic as plasticized PVC (Lithner et al. 2011). Further, explorations on this subject would be very helpful because its influence on the environment is certainly not unmanifested if not overtly extensive.

Degradation of the polymer may be carried out by chemical means but the use of microbes in this pursuit could be a green strategy. Fortunately, some data support the possibility of the development of this strategy. For example, some researchers claim the possibility of PP degradation by reactive oxygen species (ROS) created by sulfate-reducing bacteria (Cacciari et al. 1993). Inside the body polypropylene implants are reported to be assaulted by the myeloperoxidase enzyme of macrophages (Iakovlev et al. 2015). The myeloperoxidase is a porphyrin ring containing an enzyme that takes up hydrogen peroxide to produce hypochlorous acid which is a powerful oxidant. All these studies suggest that reactive oxygen species may play a main part in the degradation of the polymer.

3.6 Polystyrene (PS)

Polystyrene is a versatile thermoplastic xenobiotic polymer that is a byproduct of free radical addition polymerization of styrene and is highly recalcitrant. The benzene derivative styrene was found in 1831 from the exudates of *Liquidambar orientalis* and *L. styraciflua* (Miller et al. 1994). It is widely used in the production of toys, radio, TV cabinets, and thermal insulators such as Styrofoam. It might be strong or foamed and is mostly made in four distinct varieties, i.e., general-purpose polystyrene (GPPS), high impact polystyrene (HIPS), polystyrene foams, and expanded polystyrene (EPS) foam.

Certain environmental problems arise when various products of those polymers are unprecedentedly discharged as wastes. One of the clearest problems is the contamination brought on by microplastic formation. A noteworthy effect of such microplastic has been observed from the *Crassostrea gigas*, an economically important oyster (served as seafood), where there is a lowering of their sperm motility and the oocyte diameter and number thereby decreasing their reproductivity and inhabitants (Sussarellu et al. 2016). The effects were investigated from the medaka (*Oryzias melastigma*) and were found to induce oxidative stress, negative regulation of the hypothalamus-pituitary gonadal axis, retardation of offspring development, and hampering of gonadal maturation (Wang et al. 2019). A team of scientists has discovered that

polystyrene nanoparticles that have positively charged amino alterations and are of sizes of about 52nm are toxic to *Daphnia magna*. The group has reported the possibility of such things crossing the blood-brain barrier of fish and accumulating inside thereby bringing about alterations in the brain and behavioral changes (Mattsson et al. 2017). According to a current analysis, the PS nanoparticles might negatively impact the microbial population from the soil by exerting some sort of antimicrobial properties where dehydrogenase activity and other enzymatic activities related to N-(leucine-aminopeptidase), P-(alkaline-phosphatase), and C-(β -glucosidase and Cellobiohydrolase) cycles in the soil are detrimentally lowered (Awet et al. 2018). Styrofoam has been proven to accumulate heavy metal mercury after being disposed of. This may indicate the possibility of mercury bioaccumulation and biomagnifications (Graca et al. 2014). Again, styrene is known to cause lymphohematopoietic cancers and hence is a possible carcinogen (Huff and Infante 2011). Therefore, the toxicological evaluation of polystyrene has to be further examined. A group of researchers while expressing their concerns regarding the effects of polyester microparticles within the human body discovered that such entities might cause mitochondrial depolarization, thereby interrupting energy productions from the individual Caco-2 epithelial cell lines (Liu et al. 2019). However, based on a current experiment (based on exposure concentrations) with environmentally realistic conditions to examine the exposure patterns, another group reported that micro-sized particles on accidental ingestion impose a negligible impact on mammals (Stock et al. 2019). Such type of contradictory observations indicates that there is a need for extensive investigations because the issue of absorption of toxic contaminants of hydrophobic nature is a well-proven truth and cannot be ignored. Hence all these polymeric wastes influence the environment but to what extent, is a matter that has to be further explored.

Several works focused on this field are already done. There are reports of *Pseudomonas aeruginosa* degrading modified polystyrene (PS) polymeric materials. Also, PS scents and powder are degraded by *Rhodococcus ruber*. A fungal species, *Curvularia* sp. has been found to show some degradative action towards pre-oxidized atactic polystyrene (Ho et al. 2017). Also, it has been found that *Bacillus* sp. and *Pseudomonas* sp. could degrade brominated HIPS by an enzymatic depolymerase action (Mohan et al. 2016). Such action has also been reported in *Enterobacter* sp., *Citrobacter sedlakii*, *Alcaligenes* sp., and *Brevundimonas diminuta*, all of which can hamper HIPS to some extent (Sekhar et al. 2016). Esterase activity of *Lantinus tigrinus* was found to biodegrade polystyrene (Tahir et al. 2013). A few years ago an interesting discovery was made that the larvae of *Tenebrio molitor* (commonly referred to as mealworms) could use Styrofoam as a supply of food. The gut of the organism was found to possess a firmicutes *Exiguobacterium* sp. that can biodegrade the polymer

(Ho et al. 2017). Further investigations have resulted in the discovery of a super worm, the larvae of *Zophobas atratus* which may digest and mineralize styrofoam with the potential credit moving to its gut microbiota (Yang et al. 2020). Two species of an extremophilic gram-positive bacterium, *Exiguobacterium sibiricum* strain DR11 and *Exiguobacterium undae* strain DR14 were reported to exhibit reassuring degradation of polystyrene (Chauhan et al. 2018). Other microorganisms like *Microbacterium* sp., *Paenibacillus urinalis* were also found to degrade the polymer. As per a study conducted in Mumbai, *Bacillus subtilis* was found to have maximum degradative action within this context concerning different microbes which were isolated out there. A smart strategy to degrade this highly recalcitrant polymer once its utility expires is by integrating biodegradable molecules in its backbone during the manufacturing of the polymer as exemplified by the degradation of the starch-polystyrene copolymer by *Bacillus coagulans* (Ho et al. 2017).

To the best of our knowledge, there is absolutely no thorough mechanism of microbial degradation of polystyrene deciphered till now. However, the degradation of styrene has been well analyzed. It is well known that the microbial degradation of styrene is dependent upon two different trajectories. One manner is by targeting the aromatic ring to get direct cleavage. As detected in *Rhodococcus rhodochrous* NCIMB 13259, there's lead ring hydroxylation bringing about the formation of styrene cis-glycol via enzymatic catalysis of a dioxygenase. The product of the reaction is then dehydrogenated to 3-vinyl catechol. The reaction then divides into a meta cleavage pathway, wherein, one sub-chain precisely the 3-vinyl catechol degrades to acetaldehyde and pyruvate with the help of many enzymes such as catechol 2,3-dioxygenase, semialdehyde hydrolase, hydratase, and aldolase involving many intermediates. At another part, 2-vinyl muconate is formed as the end product. The second pathway is the oxidation of the vinyl side chain that finally contributes to the formation of phenylacetic acid through certain intermediates. The phenylacetic acid is then converted into phenyl-acetyl-CoA which enters the tricarboxylic acid cycle via the formation of different intermediates (Mooney et al. 2006). The existence of a well-organized styrene biodegradation mechanism in microbes is a clear sign of the prospect of not only discovering more efficient polystyrene degrading microbes but also engineering the present ones to boost the rate of doing so.

3.7 Polyethylene (PE)

Polyethylene is a polyolefinic chain growth thermoplastic polymer that is made from unsaturated ethylene units. This homopolymer is stable at high temperatures (precisely as much as 290°C in the absence of oxygen). Even after such elevated temperatures, it does not completely degrade to its most straightforward monomeric units; instead breaks down into forms that are smaller units with

comparatively fewer degrees of polymerization (Aggarwal and Sweeting 1957). It is economical, adaptable, and extremely resistant to chemicals and may act as a marvellous electrical insulator (Bhakta 2017).

Depending on the method of manufacture it may assume more or less branched construction. There are various sorts of polyethylene depending upon the molecular arrangement and texture with slightly varying properties. The most frequently used ones are low-density polyethylene (LDPE), high-density polyethylene (HDPE), and linear low-density polyethylene (LLDPE) (Gulmine et al. 2002).

3.7.1 LDPE

The low-density polyethylene is a branched-chain polyolefin with a high degree of branching and with a low density and melting point of 110 degrees (Bhakta 2017). However, it is highly vulnerable to stress cracking, has UV resistance, and is highly flammable. Largely used for fabricating plastic bags, dispensable bottles, and tubing.

3.7.2 HDPE

A cheap, thermoplastic polymer that is made by coordination polymerization while utilizing the Ziegler-Natta catalyst. This linear polymer has a high density and a high melting point of about 130 degrees Celsius (Bhakta, 2017). It has higher resistance and strength in comparison to the LDPE. Consecutively, it is employed in the production of pipes, containers, and moulded hardware. However, it has low UV and heat resistance.

3.7.3 LLDPE

The linear low-density polyethylene is a polyolefinic copolymer with a linear backbone with short-chain branches. It is manufactured by utilizing α -olefin and ethylene monomeric units in the existence of a catalyst, precisely the metallocene or the Ziegler-Natta catalyst (Krupa and Luyt, 2001).

Apart from these three, there are different variations of polyethylene that are available in the form of Ultra-high-molecular-weight polyethylene (UHMWPE) (Kurtz et al., 1999), cross-linked polyethylene (PEX) (Xiong et al. 2017), medium-density polyethylene (MDPE) (Bashford 1997) and very-low-density polyethylene (VLDPE) (Mathot et al. 1989).

It is now that we've started to realize that these versatile commodities with such a wide assortment of skills are not without their disadvantages. Usually, the fact that it might form microplastic has resulted in plenty of concerns. As such kinds of entities not only can act as vectors for toxic chemicals but also are damaging themselves. They contribute to bioaccumulation and

biomagnification with plenty of side effects. Starting from lower-order organisms such as *Mytilus galloprovincialis* also known as the Mediterranean mussel, these microparticles may cause tumultuous altered developments of the digestive tract by lowering the intestinal content and thinning of epithelial cells from the tubules. Also, it boosts the necrotic development of various body cells like those of their mantle and gonads due to haemocytic aggregation (Thomas et al. 2018). Disruptive effects were studied in sediment-dwellers such as *Chironomus tepperi* (the non-biting midge) and was discovered that particles of 10-27 μm caused retarded development, congestion of the digestive tract, and increased mortality among the inhabitants (Ziajahromi et al. 2018). Evaluation of microplastic ingestion in zebrafish revealed considerable accumulation from the larval digestive tract and also disproportionate transcriptional agitation typically in the genes involved in processes such as glycolysis, purine metabolism, and lysine metabolism to name a few which were strangely sorted out in 14 days post-exposure (LeMoine et al. 2018). Earthworms (*Eisenia fetida*) which play an important role in soil fertility on exposure to 100-200 μm low-density polyethylene incurred substantial damages to their skin while experiencing an increased activity of the catalase enzyme and enhanced concentration of malondialdehyde, signalling the occurrence of oxidative stress (Chen et al. 2020). These particles are cytotoxic to microalgae and have been found to interfere with the anaerobic sludge management by reacting with traces of oxygen via its electron donor sites (generated by the action of UV) resulting in the formation of $\text{O}_2^{\bullet-}$ and H_2O_2 which could cause oxidative stress to the microbes (Wei et al. 2019). Recently some conflicting results have also come up that state that microplastics probably have no significant impact on zooplanktons. It might however in the fishes cause a lowered rate of egg hatching with often the conditions being premature (Beiras et al. 2018). But such problems could not be neglected concerning the increasing signs of toxic effects in organisms of varying sophistication levels. In mice, it might activate inflammation and intestinal dysbacteriosis (Li et al. 2019). It is now increasingly suspected that nano and microplastic exposure may be neurotoxic to human beings just like in different organisms where it might change the neurotransmitter activity (Prüst et al. 2020). Already, there is a lot of evidence that we are frequently subjected to such particles. Not only that we are also exposed to many different natural products as leachates of plastic products such as PEX (cross-linked polyethylene) pipes (Lund et al. 2011). Very recent research focused on the feeding behavior of goldfish has found out that the ingestion of microplastics occurs while food intake with the green and black particles eaten more than the red, blue, or white ones. It also discovered that particles of more than 2mm were automatically discarded even if ingested (Xiong et al. 2019). This type of monitoring indicates that there's a varying proclivity level for different microplastics. Some are more damaging than others. Genetic insights into the chemoreception of

Daphnia pulex have been conducted. The analysis has identified 58 gustatory receptors (Grs) which were included in their unique tasting and smelling process, in a nutshell, the chemosensing of the environment (Peñalva-Arana et al. 2009). In light of these works, it is now thought that the surface eco-corona of nano plastic particles plays a significant part in promoting ingestion by organisms such as *Daphnia magna* (Balakrishnan et al. 2019).

In the last few years, a great deal of focus is given to the exploration of different microbes which could act as possible degraders of plastic polyethylene. Efforts were given to solve the enzymatic mechanisms that enter interplay. It is now being increasingly recognized that such endeavours would be very difficult due to the lack of functional groups capable of hydrolysis. However, pre-treating such waste issues with heat, UV, or oxidizing agents could enhance the degradation process. This can be attributed to the fact that such treatments produce functional groups (such as carbonyl groups) which are easily acted upon by microbial enzymes such as laccase, manganese peroxidase, and lignin peroxidase aiding in the process of degradation.

The manganese peroxidase, a heme-based enzyme, requires a hydrogen peroxide as an acceptor of two electrons producing a specific intermediate (compound I) which oxidizes the substrate to make free radicals along with the other intermediate (compound II) that oxidizes Mn^{2+} into Mn^{3+} . The generated cation chelated by the fungal malonate and oxalate results in the development of reactive radicals which may act upon non-phenolic chemicals (Chowdhary et al. 2019). In this context, an innovative strategy was adopted by Ehara et al. (2000) where they successfully degraded the polyethylene with this enzyme by using tween 80 in place of hydrogen peroxide.

The lignin peroxidase, a ferric ion-based enzyme, works similarly by utilizing hydrogen peroxide and a distinctive oxo-ferryl intermediate (Falade et al. 2017). However, these enzymes work mostly upon lignin whose redox potential is way lower than polyethylene chains, hence appreciable degradation is not achieved (Zimmermann and Wei 2017). Therefore, the quest for an efficient PE degrading enzyme continues.

Many microbes discovered so far are predicted to degrade the polymer by the above-mentioned enzymatic processes. Typical examples within this context are *Trichoderma harzianum* (laccase & manganese peroxidase) (Sowmya et al. 2014), *Phanerochaete chrysosporium* (manganese peroxidase) (Iiyoshi et al. 1998), *Trametes versicolor* (laccase) (Fujisawa et al. 2001), *Penicillium simplicissimum* (laccase, manganese peroxidase) (Ramalingappa et al. 2014), *Rhodococcus ruber* (laccase) (Santo et al. 2013), *Bacillus cereus* (laccase, manganese peroxidase) (Rajeswari et al. 2015) and *Klebsiella pneumonia* (laccase, peroxidase, lipase, tyrosinase) (Srivastava et al. 2017).

According to Sangale et al. (2019) *Aspergillus terreus* and *Aspergillus sydowii* have been discovered to be the most efficient one of the consortium of 109 fungal members. However, not many enzymatic accounts were referred to in the same. Microbes of genera *Fusarium*, *Aspergillus*, *Pseudomonas*, *Brevibacillus*, *Lysinibacillus* (Muhonja et al. 2018), *Streptomyces* (Anthony et al. 1992) are expected to have some degradation activity. Furthermore, microbes such as *Mucor rouxii* NRRL 1835, *Rhizopus oryzae* NS5 (Awasthi et al. 2017), *Micrococcus luteus*, *Proteus vulgaris*, *Staphylococcus aureus* (Priyanka and Tiwari 2011), *Rhodococcus ruber*, and combined cultures of *Aspergillus niger* and *Lysinibacillus xylanilyticus* (Esmaeili et al. 2013) are discovered to have some degradative action. Recently, it's been indicated that the marine fungus *Zalerion maritimum* could use PE microplastics hence may have a tremendous future program in bioremediation (Paco et al. 2017). Apart from all this, a new study claims that the gut of *Galleria monella*, commonly called the greater wax moth harbours a microbe, *Enterobacter* sp. D1, that could degrade polyethylene by an extracellular oxido-reductase enzyme (Ren et al. 2019). Similar results are reported by *Plodia interpunctella* (Indian mealworm) and *Achroia grisella* (lesser waxworm). While in the former two PE degrading strains of *Enterobacter asburiae* Y1 and *Bacillus* sp. YP1 was identified from the gut, from the latter, it is not clear whether the effect is due to the gut microbes or due to an exceptional enzyme produced inside its own body (Kundungal et al. 2019). The action of *Pseudomonas* sp. E4 requires appreciation as researchers found out that it might act upon entirely untreated polymer with the assistance of its alkaline hydroxylase (alkB) gene product (Yoon et al. 2012). Presently a thorough investigation has resulted in the discovery of two cyanobacterial species *Phormidium lucidum* and *Oscillatoria subbrevis* that can degrade low-density polyethylene via laccase and relatively less manganese peroxidase activity (Sarmah and Rout 2018). Different species of algae such as Bacillariophyceae, Chlorophyceae, and Cyanophyceae were found to colonize the surface of polyethylene but how far they could degrade the polymer in the near future is a matter that has to be explored (Sharma et al. 2014). Some important microorganisms, their synthesized enzymes and impact of these on plastic degradation have been represented in table 1.

4 Present Management

Despite the exclusive attempts to find the one perfect solution to fight against plastic pandemic, the war continues while every day the environmental conditions due to plastic pollution get more and more desperate. Presently, in this COVID era, some serious pollution is occurring due to the worldwide disposal of these one-time use PPE kits much of which are plastic based products. While there are groups of researchers or bioengineers that are struggling

to locate the best degrading enzyme or to find others who are analyzing the threat factors and designing a proper management strategy from the existing amenities. Plastic management is a way to lower the burden of xenobiotic plastics in the environment, sustainably. It widely involves the recovery of plastic waste, recycling, and reusing them.

The first step in this process is the grouping of plastic wastes deposited in the environment followed by shredding to reduce the sizes, then washing with detergent to remove contaminants and sorting based on their substance build-up (Goodship 2007). The sorting could be done manually based on certain identification codes or it might be automated. But the manual process is labour-intensive with significant chances of human error. The newer automated methods are very powerful in sorting out the polymers using high precision technology. These methods are classified under three heads:

- (i) The dry sorting techniques (such as detection utilizing near-infrared radiation and X rays, atmosphere sorting, electrostatic sorting, mechanical sorting, and sorting by melting)
- (ii) The wet sorting techniques (such as sink float sorting procedure, hydrocyclones, and selective dissolution), and
- (iii) The chemical sorting techniques (such as hydrolysis, glycolysis, and hydroglycolysis) (Ruj et al. 2015)

Often the combination of automated and manual techniques is included. After this, the particles are melted followed by compression to produce the pellets which may be reused to make several materials like water packing bottles. Contrary to thermoplastics, the thermosetting polymers cannot be remoulded or staged rather they're used as reinforcing fillers in thermoplastic polymers that lower their production price. Often the plastic materials are exposed to thermal degradative processes such as pyrolysis, hydrogenation, or gasification for energy recovery and also to reduce the quantities (Goodship 2007). These processes are much better in comparison to simple combustion in the open air. Energy recovery processes are greatly used in countries such as Japan. Plastics may be a replacement for coal due to their high calorific values. The proper combustion of plastic particles is potentially carried out in blast furnace and cement kilns during co-incineration with zero risks of toxic emissions. The residual slag by-product might be utilized in construction (Singh and Sharma 2016).

Rather than discarding carelessly in the open environment, disposing of plastic wastes in landfills is an old option but it may cause problems particularly the leaching of toxicants. However, in addition to all scientific strategies, we feel there is a good need to

create more public awareness through several programs. No great feat in this subject could be achieved as long as the general public languishes in innominate darkness.

In the past few years, many campaigns have been launched to propagate the ill effects of plastic. Alternatives to polyethylene carry bags such as bags made of paper, fabric, or jute should be promoted among the general public. Amidst all these developments, a few controversies have arisen. One of them is the incineration of plastics. As the growing amounts of waste incinerated, several intellectuals have started questioning whether such huge public investment in this industry as it is turning out to be may hinder the advancement of waste recycling processes. Plastic waste management has a behavioural part that often sparks consumer uncertainties regarding the sorting out of wastes. For example, individuals might easily distinguish between plastic and paper but, often they fail to classify whether it is packing or non-packaging plastic (Henriksson et al. 2010). Perhaps more awareness and providing means for effortless access to simplified information might appreciate better recycling rates. Another way of decreasing plastic contamination might be to decrease the production of petroleum-based plastics and increase the use of bio-based plastics as they're easily degradable in the environment. But within this context care should be taken that the sale price of such biodegradable plastic should be just like that of the petrol-based counterparts or else the customers may be discouraged from buying them.

Conclusion and Future prospects

In the present situation, about 99 percent of the plastic generated is based on fossil fuels. While the bio-based ones claim to be a suitable replacement we have got a bigger issue to deal with. The issue is how to deal with those that are already accumulated after their specific utility expired. We just cannot wait for a few thousand years to let them all go away naturally. We do not even know to what extent they are impairing our ecosystem. The microbes, typically the ones that go rogue and develop in a variety of challenging environments might help in the process. However, much more conclusive works regarding their proteomics have to be carried out. We should attempt to reduce our everyday life usage of Petro-based plastics and every time we do we say a big no to the query raised by the first Brandt Commission- "Are we to leave our successors a scorched planet of advancing deserts, impoverished landscapes, and ailing environment?". Driven by our ambitious vision to have the most durable commodities in our daily life we have unknowingly opened Pandora's box of silent pollution. Therefore, we must find an absolute solution for this plastic mayhem before it could prove to be the hideous "Mr Hyde" for our beloved ecosystem.

Table 1 Various microbes and their enzymatic effect on the plastics degradation

Type of Plastic	Usage examples	Potential degraders	Enzymes	References
Nylon	fishing nets, plumbing pipes, sewage pipes	Bacteria of family <i>Bacillaceae</i> , <i>Nocardiaceae</i> , <i>Vibrionaceae</i> , <i>Caulobacteriaceae</i> , <i>Microbacteriaceae</i> , <i>Micrococcaceae</i> and fungus of <i>Phanerochaetaceae</i>	6-aminohexanoate-cyclic-dimer hydrolase, 6-Aminohexanoate-dimer hydrolase and endotype 6-Aminohexanoate oligomer hydrolase, Amino-hexanoate aminotransferase & Adipate semialdehyde dehydrogenase, Aryl acylamidase	Negoro 2000; Takehara et al. 2018; Nagai et al. 2014
Polyvinyl chloride	garden hose, raincoat, pipes, insulation wires	Bacteria of family <i>Chelatococcaceae</i> , <i>Bacillaceae</i> , <i>Pseudomonadaceae</i> and fungus of family <i>Pleosporaceae</i> , <i>Polysporaceae</i> , <i>Aspergillaceae</i> , <i>Ceratobasidiaceae</i>	Laccase	Arregui et al. 2019
Polyurethane	construction, textile, automobile production, artificial skin	Fungi of the family <i>Pleosporaceae</i> , <i>Bionectriaceae</i> , <i>Aspergillaceae</i> , <i>Sporocadaceae</i> and bacteria of the family <i>Moraxellaceae</i> , <i>Bionectriaceae</i> , <i>Comamonadaceae</i> , <i>Pseudomonadaceae</i>	Polyurethanase, Serine hydrolase, cholesterol esterase, urease	Russell et al. 2011; Christenson et al. 2006
Polyethylene Terephthalate	textiles, and food packaging	Fungi of the family <i>Trichocomaceae</i> , <i>Rhizopodaceae</i> , <i>Ustilaginaceae</i> and bacteria of the family <i>Nocardiosporaceae</i> , a proteobacteria <i>Ideonella sakiensis</i>	cutinase & lipase, MHETase, PETase	Kawai et al. 2019; Palm et al. 2019; Fecker et al. 2018
Polypropylene	automobile parts, fibres and fabrics	Certain Sulphate reducing bacteria, macrophages (inside body)	Myeloperoxidase	Iakovlev et al. 2015
Polystyrene	Toys, thermal insulator, television cabinet	Bacteria of the family <i>Pseudomonadaceae</i> , <i>Nocardiaceae</i> , <i>Enterobacteriaceae</i> , <i>Caulobacteriaceae</i> fungus of the family <i>Polyporaceae</i> , <i>Pleoporaceae</i> , larvae of <i>Zophobas atratus</i> , <i>Zophobas morio</i>	Esterase	Tahir et al. 2013
Polyethylene	Packaging, disposable bottles	Fungi of the family <i>Hypocreaceae</i> , <i>Polyporaceae</i> , <i>Aspergillaceae</i> , <i>Phanerochaetaceae</i> Bacteria of <i>Bacillaceae</i> , <i>Morganellaceae</i> and Cyanobacteria of the family <i>Oscillatoriaceae</i> , larvae of <i>Galleria monella</i> , <i>Plodia interpunctella</i>	Manganese peroxidase lignin peroxidase & laccase, alkaline hydroxylase	Wei et al. 2019; Yoon et al. 2012

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Conflict of interest

We declare that there is no conflict of interest.

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