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A Review on the Role of Microbes in Polyethene Degradation

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Abstract

Polyethene is a polyolefin produced from polymerization of the olefin ethylene (C_2H_4). It is one of the most commonly used plastic and one of the most resistant to degradation. Its accumulation in the surrounding has caught the attention of many governments and researchers with attempts to come up with better disposal methods. This review focused on the role played by microorganisms in the degradation of polyethene. The references reviewed were obtained from journals and databases including PubMed, Google Scholar (http: //scholar. google.com) and Science Direct (http://www.science direct.com). We focused on data published from 2010 up to 2021. The findings obtained indicated that 19 genera of bacteria and actinomycetes and 5 fungal genera have the ability to degrade polyethene through secretion of extracellular depolymerases. The enzymes cleave polymer chains into low molecular weight fragments, which are then assimilated through the microbial cell membrane and mineralized. Microbial degradation is a sustainable and promising idea. However, there is need for more research to clearly determine the mechanism of enzymatic degradation, which will be useful in the development of novel biotechnological tools for degradation of a variety of plastic materials by microorganisms.

Key Words: Polyethene, Depolymerases, Degradation, Microorganisms.

Introduction

The manufacture of plastic dates back to the 1950s. Since then, the sector has greatly grown and has become one of the biggest and most important sectors economically (Tudor et al., 2019). In fact, a world without plastics would actually seem unimaginable today (Geyer et al., 2017). Plastic is used in almost all sectors including packaging, car manufacturing, building and construction and agriculture due to its pleasant properties such as flexibility, inertness, durability, malleability, light weight and low costs (Chae & An, 2018). Despite these multiple uses, plastics cause high levels of pollution and leakage to the environment (Emblem, 2012). About 140 million tons of man-made polymers are manufactured yearly (Caruso, 2015). In 2015, the production of plastics globally was 322 million tons out of 6,300 million tons of wastes generated. About 79% of these wastes were disposed on landfills or was leaked to the environment, 9% was recycled and the remaining 12% incinerated (Europe, 2016).

The rapid increase and poor disposal methods of waste plastic is amongst the greatest challenges facing the globe today. This is mainly attributed to plastic resistance to degradation, their outstanding properties and importance in industry (Gewert et al., 2015). Plastics have unusual bonds and high number of aromatic rings in their structure which make them hard to break down in the environment (Pathak, 2017). Disposed plastic remain for many years in the environment without degradation, hence accumulate in the environment, resulting into serious environmental pollution with hazardous effects to both plants, animals and human (Dey et al., 2012). The problem of plastic pollution is a global problem which will continue if the production levels and consumption are not controlled. Proper procedures on plastic waste management and disposal need to be put in place to help curb the menace of plastic pollution (Löhr et al., 2017).

This review discusses the role played by microorganisms in polyethene degradation as well as the limitations of the current methods used in degradation of polyethene.

Methodology

In conducting this review, systematic and comprehensive literature reports on the role played by microorganisms in polyethylene (PE) degradation were used. Empirical online searches were carried out using PubMed, Google Scholar (http:// scholar. google.com) and Science Direct (http://www.science direct.com). About 92.3% of the literature sources were from peer reviewed journals whereas 7.7% were from grey literature. This review focused on the impacts of plastic pollution in the environment, the current methods used for PE degradation and their limitations, role of different microbes in biodegradation, and the mechanism and role of microbial enzymes in PE degradation. Factors affecting plastic degradation, role of intestinal microbiome in PE degradation and the toxicity of polyethene degradation products were also searched. Other articles and publications were obtained by tracking citations from other publications or by directly accessing journal websites. Scientific studies conducted from 2010 up to 2021 were accessed. The keyword combinations for the search were polythene, biodegradation, microplastic, enzymes, microorganisms and degradation.

Findings and Discussion

Polyethene types, properties and uses

Plastics can be categorized either as thermoplastics or thermosets (Lithner, 2011). Those that melt under high temperatures (heated) and harden when temperatures are lowered (cooled) are called thermoplastics. Their strength and thermal properties are determined by the branched or linear molecular structure. Thermoplastics are generally recyclable since they can be re-melted and reformed (Rajendran et al., 2015). They include polystyrene (PS), polypropylene (PP), polyethylene (PE), Polyvinyl Chloride (PVC), polyethylene terephthalate (PET) and polyamide (Rajendran et al., 2015). Thermosets are those plastics that undergo an irreversible chemical change through formation of a 3-dimensional network when subjected to heating. They are unrecyclable since it is impossible to re-melt and reform them. They include unsaturated polyesters, polyurethanes (PUR), melamine, silicone and epoxy, phenolic, and acrylic resins (Ahmad et al., 2017).

Polyethylene is a polyolefin (PO) produced by polymerization of the olefin ethylene (C_2H_4). It is a thermoplastic with the general formula CnH_2n, where n represent the number of carbon atoms in the polymer chain (Sangale et al., 2012). The most commonly used PE grades include high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low density polyethene (LLDPE) (Grover et al., 2015a).

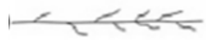
The density and crystallinity of LDPE ranges between 0.915-0.935 g/cm^3 and 50 - 60%, respectively (Favaro et al., 2016). Except by strong oxidizing agents, LDPE is not chemically reactive at room temperature. It can tolerate heat of up to 95^{0}C depending on the length of exposure (Sen & Raut, 2015a). It is tough and flexible but can be broken. LDPE has more branching than HDPE; it has weaker intermolecular forces, low tensile strength and high resilience. These properties make low-density polyethene the most commonly used plastic especially for packaging purposes (Pramila & Ramesh, 2011a).

LDPE has a comparatively low density due to the few branches in the chain (about 2%), (Sen & Raut, 2015b). The most frequent types of LDPE include branched low density polyethylene (BLDPE) and linear low-density polyethylene (LLDPE) which vary in density, surface functional groups and degree of branching (Ghatge et al., 2020a).

LDPE has a broad range of uses which include making of packaging materials and plastic bags. It is also used as a barrier coating on textiles, paper and other plastics (Sen & Raut, 2015b). However, LDPE is not easily broken down after disposal due to presence of a hydrophobic backbone in its structure (Luckachan and Pillai, 2011).

HDPE is a thermoplastic with a density range of 0.941-0.967 g/cm^3 (Favaro et al., 2016). It has few branches hence more tensile strength and stronger intermolecular forces as compared to LDPE. It has excellent insulating properties and is widely used in industrial and daily applications such as making bottles, toys, films , utensils, pipe, wire and cable insulations (Kumar et al., 2011). The properties of different polyethene types vary (Table 1).

Table 1. Summary of Polyethene types and their properties (Favaro et al., 2016)

Property	LDPE	LLDPE	HDPE
Density	0.915-0.935	0.910-0.925	0.941-0.967
Stress (MPA	7-17	14-21	18
Melting (^{0}C)	106-112	121-125	130-133
Elongation (%)	100-700	200-1200	20-100
Elastic modulus (MPa)	102-240	100-200	960-1000
Structure			
Crystallinity (%)	50-60	35-60	>90

Plastics pollution

One of the major challenges that the world faces is the problem of plastic waste management. With the rapid increase and poor disposal methods, plastic wastes have over-accumulated in the environment causing detrimental effects to both flora and fauna.

These detrimental effects have forced many governments through their pollution control boards to develop strategies to minimize the use of plastic materials (Xanthos & Walker, 2017). For example, the Kenya Government through the National Environment Management Authority (NEMA), banned the use of polyethene carrier bags in 2017 (Noor, 2020). In India, the usage and manufacture of polyethene carrier bags with thickness below 50µ was banned by the Government of Maharashtra (Sangale et al., 2019). This has proved to be a good step especially in the Kenyan scenario, in reducing the volume of PE bags going to landfills and those that are carelessly dumped causing visual pollution and clogging the drainage systems. However, it is important to encourage the use of biodegradable plastics or polyethene blends which pose no harm to the environment.

Plastics on land

Plastic pollution on land remains widely unexplored since more attention is on microplastics (MP) in aquatic environments (Machado et al., 2018). Even though plastic pollution is more in the marine ecosystem, more than 80% of these plastics were manufactured, consumed and trashed on land (Bläsing & Amelung, 2018). This implies that plastic disposed on land causes both damage and contamination to the terrestrial environment and the same is transferred to the aquatic ecosystems. Presence of plastics in soil as a result of land filling or careless disposal affect plant root development and also reduce aeration in soil. The toxic chemicals in plastic may also be leached into water bodies (Grover et al., 2015b).

Littering of polyethene and other plastic products cause visual pollution that affect sectors like tourism (Wachira et al., 2014). Plastic litter may clog drainage systems and block sewer systems offering favorable breeding grounds for disease transmitting vectors such as mosquitoes (Bardají et al., 2020).

Plastics in the aquatic environment

Plastic polymers have been found all over the marine ecosystem (Wierckx et al., 2018).

The presence of microplastics has been discovered in marine water, sediment and biota samples (Bour et al., 2018; Mintenig et al., 2017). They catch attention in marine environments due to their small size which is almost equal to the size of prey, or food particles ingested by marine organisms. They can therefore be easily mistaken as food by most marine organisms (Ryan, 2016). Their size make them bioavailable, which facilitate entry into the food chain at various trophic levels and bioaccumulation (Carbery et al., 2018). Analysis of environmental samples has shown presence of both secondary and primary MP (Mintenig et al., 2017; Phuong et al., 2016).

Most marine species face the danger of entanglement and ingestion of plastic objects (Thiel et al., 2018). Juveniles are frequently ensnarled in plastic debris resulting into severe injury during growth of the animal and restricting its movement. This may hinder proper feeding and sometimes even breathing (Sigler, 2014). Many different marine species such as sea turtles, fur seals, filter feeders, marine birds, sharks, cetaceans, bivalves, crustaceans, elasmobranchs, planktons and fishes have been found to be negatively impacted by plastic debris (Gall & Thompson, 2015; Hammer et al., 2012a). Plastic ingestion is most common in marine birds as they mistake the plastic objects for food (Poon et al., 2017). Once ingested, the plastics remain in the alimentary canal and can block the digestive tract, decrease secretion of digestive enzymes, reduce feeding stimuli and also cause reproduction problems due to reduced steroid hormone levels (Webb et al., 2013).

Marine organisms such as zooplanktons, sea birds, cetaceans, marine mammals, turtles and fish get entangled and easily ingest plastic items including bottle caps, cigarette lighters, fishing nets and plastic bags. Marine animals that get entangled in plastic debris may end up dying due to suffocation, drowning, starvation or strangulation (Hammer et al., 2012b). Very often, small whales, birds and seals drown and get entangled in ghost nets, hence losing their ability to escape predators and to catch food. It is not possible to approximate the quantity of plastic litter that end up in the ocean, however, it is worth noting that quantities are quite substantial (da Costa et al., 2016).

In addition, high levels of organic pollutants and other hazardous chemical compounds like polycyclic hydrocarbons (PAHs), organic pesticides and bisphenol A (BPA) among others, have frequently been detected in the marine plastic debris (Bardají et al., 2020; Camacho et al., 2019; Wright & Kelly, 2017; Van et al., 2012). The presence of these compounds greatly exacerbates the threats related to plastic debris ingestion by aquatic species. Biomagnification of these chemical compounds may pose direct risk to human health when they feed on marine food (Gallo et al., 2018).

Plastic disposal methods & their impact

Currently, recycling, incineration and landfills are the most commonly used large scale plastic disposal methods (Deepika & Jaya, 2015; Webb et al., 2013). Each of these methods however, may cause either economic exploitation or damaging effects to the environment.

Incineration

Incineration of solid waste is an efficient method of waste management which reduces the use of landfills. Energy is produced during incineration which could be used as a fuel source to replace fossil fuels. This energy can also be used for electricity generation, heat and power (Al-Salem, 2019; Bardají et al., 2020). Energy recovery through plastic incinerating has many environmental benefits. it reduces the quantity of plastic waste, and destroys harmful chemical additives, foams, blowing agents and granules (Awasthi et al., 2017; Bardají et al., 2020).

However, incineration has disadvantages such as being expensive and production of toxic emissions that may cause health problems to humans and the environment. Burning of plastics produces soot and solid residue ash as by-products (Verma et al., 2016a). Soot is accompanied with smoke, polychlorinated di-benzo furans (PCDFs), volatile organic compounds (VOCs), particulate bound heavy metals, polycyclic aromatic hydrocarbons (PAHs), and dioxins which are carcinogenic and highly mutagenic (Ujowundu et al., 2016). The plasticizers added during manufacture of plastics are carcinogenic and may cause various cancers (Halden, 2010). Furans and dioxins produced during plastic combustion play a role in ozone layer depletion (Zhang et al., 2017; Verma et al., 2016b). Dioxins may also disrupt the activity of the human endocrine hormone hence raising health concerns (Casals-Casas & Desvergne, 2011).

Landfilling

Landfill is an old method of managing solid wastes. The major disadvantages of landfilling are space utilization and leaching of chemicals to soil and ground water (Awasthi et al., 2017). One major problem in landfills is secondary pollution, which results from leaching of pollutants and chemicals such as trimethyl-benzene, xylene and toluene. Additionally, estrogenic compounds including phthalate, bisphenol A (BPA), and polybrominated biphenyls (PBB) may be produced (Grover et al., 2015b). These compounds are associated with health risks including diseases of the reproductive system and cancer of the prostate, ovaries and breasts (Verma et al., 2016b).

Plastics in dumpsites take about 3 centuries to naturally break down. Additionally, photo degradation break down plastics into very tiny toxic parts which eventually pollute water and soil (Grover et al., 2015b).

Landfilling is associated with limitations such as long time occupation of space which could otherwise be used for other activities such as agriculture (Webb et al., 2013). Generally, landfilling is unsustainable due to space requirement and also the release of harmful liquids and gases leading to secondary pollution (Awasthi et al., 2017).

Recycling

The process of plastic recycling involves recovery, reprocessing and refining waste plastic to create new altered products (Vanapalli et al., 2019). It involves different processes that includes chemical, mechanical and thermal depolymerization (Garcia & Robertson, 2017). Plastic recycling can be classified into four types which include primary, secondary, tertiary and quaternary recycling. Secondary and primary recycling are collectively known as mechanical recycling. Tertiary recycling involves de-polymerization of plastic polymer to its chemical constituents (Al-Salem, 2019). Energy recovery occurs during quaternary recycling (Singh et al., 2017). Crates, brush arms, non-food bottles, stationery such as rulers, speed bumps, and truck cargo liners are manufactured from recycled HDPE. Recycled LPDE are used to produce trash cans, non-food plastic bags and garbage can liners among others (Pohjakallio, 2020).

Recycling has been thought to be a better option compared to incineration and landfilling. However, recycling is relatively ineffective and may decrease the quality of the resulting polymer, the process is expensive and also emits toxic compounds resulting from melting waste plastic (Bardají et al., 2020; Webb et al., 2013). The colors, additives and stabilizers added to plastics during recycling make the recycled plastics more dangerous than virgin plastics. The volatile organic compounds have serious health effects due to presence of many hazardous compounds which can either be cancerous or non-cancerous (Hahladakis et al., 2018a). Additionally, plastic recycling cannot be done more than thrice since each recycling decreases the strength of plastics. Some plastics such as multilayer and thermoset plastics are not recyclable hence creating disposal problems (Grover et al., 2015b). Recycling is an attractive method compared to incineration and landfilling. However, it is also considered much costly and inefficient due to presence of additives and other substances (Bardají et al., 2020).

Biodegradation of polyethene

Microorganisms from over 90 genera have been found to have potential of plastic degradation (Ghosh et al., 2013a). Degradation by microbes is mainly caused by extracellular enzymes secreted by microorganisms (Karigar & Rao, 2011). Bioremediation of plastic waste is effective when microbial depolymerases attack and convert contaminants into harmless products (Karigar & Rao, 2011). It results from oxidation/ hydrolysis by enzymes secreted by microorganisms that cleave large polymer chains into shorter chain molecules such as monomers and oligomers, a process known as depolymerization (Das & Kumar, 2015; Pathak, 2017). These small sized molecules can cross the bacterial plasma membrane and can then be utilized as a carbon source (Mohan, 2011).

Polyethene degradation by microbes has been studied by many researchers and has become a great topic of interest. These studies have described PE degradation by bacteria, fungi, insects, algae and actinomycetes from sources such as garbage soil, marine water, compost soil, garden soil amongst others (Abraham et al., 2017; Bano et al., 2017a; Devi et al., 2015). The entire process of biodegradation involves four stages: biodeterioration, biofragmentation, bioassimilation, and mineralization (Montazer et al., 2020). Microorganisms need points of access in the PE structure to initiate the process of fragmentation. Initial oxidation of PE may occur in presence of environmental factors like chemicals, ultraviolet radiation (UV) and or heat without the microbial action. Some microorganisms are however, able to initiate the process of oxidation on their own through hydroperoxidation, a process called biodeterioration (Montazer et al., 2020).

This is followed by enzymatic cleavage where the polymer is broken down into low molecular weight monomers and oligomers through a process called biofragmentation (Urbanek et al., 2018 ; Bhardwaj et al., 2013). Hydrolase enzymes such as esterases and proteases catalyze the process of polymer break-down (Loredo-Treviño et al., 2012). Through bioassimilation the fragmented polymer is taken up by microbes and mineralized into CO_2, H_2O, CH_4 depending on the conditions available (Khan & Majeed, 2019). Different steps are involved in polyethene degradation (Figure 1).

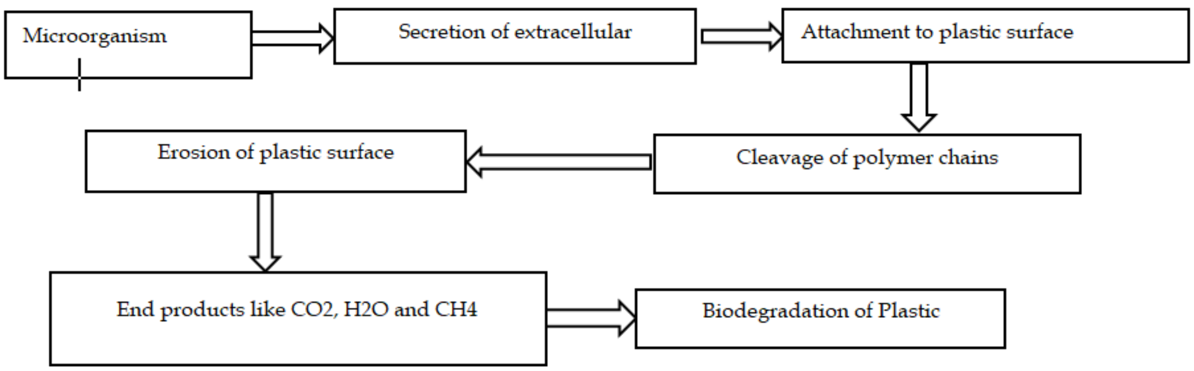


Figure 1. Mechanism of polyethene biodegradation (Bhardwaj et al., 2013)

The speed of biodegradation also called biodegradation rate is dependent on the structure, chemical composition of polymer and abiotic conditions such as pH, temperature, microbial community present and moisture (Geyer, 2020). The main challenge to microbial colonization of plastic polymer as reported in cite literature here is high polymer hydrophobicity, compared to the hydrophilic surfaces of many microorganisms. Therefore, microbes with more hydrophobic surfaces can be more useful in initiating polymer colonization process hence improving the degradation process (Tribedi & Sil, 2013). Microbial degradation can be improved by finding out and improving growth conditions including temperature, moisture, pH, nutrient levels, carbon, nitrogen, oxygen and any other factor that may limit microbial growth and activity. This process is known as biostimulation (Adams et al., 2015; Kalantary et al., 2014). Furthermore, polyethylene (PE) biodegradation can be enhanced through addition of surfactants. Surfactants are surface active amphiphilic compounds that can reduce surface tension and interfacial tension of a solution (Duddu et al., 2015). Reduction of surface tension increases bioavailability of hydrophobic materials (Ahmad et al., 2017; Karlapudi et al., 2018).

Some microbes are able to produce biosurfacants on their own. For example, *Bacillus sp., Bacillus licheniformis, Streptomyces coelicoflavus* among others (Duddu et al., 2015; Kavitha and Bhuvaneswari, 2021; Mukherjee et al., 2018). However, nonionic surfactants such as Tween 80 can be added to a biodegradation system to improve PE degradation (Mukherjee et al., 2018). Surfactants are amphiphilic compounds that can reduce the hydrophobicity of PE hence increasing microbial attachment to the PE surface (Mukherjee et al., 2018).

Pseudomonas species are one of the most commonly cited bacteria that have potential to degrade PE and other polymers (Montazer et al., 2019; Wilkes and Aristilde, 2017; Ghosh et al., 2013b). *Pseudomonas* sp. AKS2 was found to carry out PE degradation through enzymatic activities and also through formation of biofilm (Tribedi & Sil, 2013). Formation of biofilm improves microbial adhesion to polymer surface due to better cell surface hydrophobicity, as compared to planktonic cells. *Pseudomonas* sp. AKS2 was reported to possess biodegrading ability against LDPE without prior oxidation by chemicals, UV radiation or thermal radiation (Tribedi & Sil, 2013). This suggests that *Pseudomonas* sp. AKS2 produces enzyme(s) that catalyse the cleavage of alkene bonds to carbonyl groups and/or carboxylic acids. Alkane hydroxylase enzyme (alkB) from *Pseudomonas* has been found to play a key role in LDPE degradation (Yoon et al., 2012).

Fungi in Polyethene biodegradation

The potential of fungi to degrade PE have been investigated in various studies (Sheik *et al.*, 2015; Ameen *et al.*, 2015; Pramila and Ramesh, 2011b). Their potential to degrade PE is associated with their ability to secrete enzymes and extracellular polymers such as polysaccharides, which are important in colonization of polymer surface (Esmaeili et al., 2013). Fungi are important in polymer degradation because of their robust nature and for the wide variety of enzymes they secrete. Examples of these enzymes include cutinases, xylanases, lipases, esterase among others (Deshmukh et al., 2016).

A number of fungal species have been demonstrated to use PE as the sole carbon source. For example, Raaman et al., (2012) studied the biodegradation of LDPE polyethene carry bags under laboratory conditions. These authors isolated *Aspergillus niger* and *Aspergillus japonicus* from plastic polluted soils at 37^{o}C in 48 hrs. incubation. The effectiveness of these fungi on LDPE degradation was tested after 4 weeks incubation by weight loss analysis and Scanning Electron Microscopy (SEM). *Aspergillus japonicus* showed 12% weight loss while *Aspergillus niger* showed a weight change of 8% after the 4 weeks period. The same authors also reported pores on surface of the fungal degraded polythene from SEM analysis. In another study by Immanuel et al., (2014), LDPE and HDPE degrading *Aspergillus japonicus* and *Aspergillus terreus* from mangrove soils were incubated with pre-treated PE films for 45-60 days. Biodegradation rate was determined by weight loss analysis and by Fourier-Transform Infrared (FTIR). FTIR results indicated new carbonyl group after natural weathering, which decreased after microbial treatment. Decrease in carbonyl index ranged between 11.8-22.4%. This author also reported a reduction in weight of the PE films ranging between 10.70-22.54%. Several other studies that have investigated PE biodegradation using fungal isolates exist (Table 2).

Table 2. Other literature sources of polyethene degrading fungi

Name	PE type	Reference
Aspergillus niger	LDPE	(Alshehrei, 2017; Raaman et al., 2012)
Aspergillus japonicas	LDPE	(Raaman et al., 2012)
Aspergillus nomius	LDPE	(Munir et al., 2018) (Abraham et al., 2017)
Aspergillus tereus, Aspergillus fumigatus	LDPE	(Sangale et al., 2019; Zahra et al., 2010)
Aspergillus sydonii	LDPE	(Sangale et al., 2019)
Aspergillus fumigatus	LDPE	(Muhonja et al., 2018a; Zahra et al., 2010)
Trichoderma viridae	LDPE	(Munir et al., 2018)
Penicillium oxalicum	HDPE/LDPE	(Ojha & Pradhan, 2017)
Fusarium sp, Mucor sp	LDPE	(Jyoti & Gupta, 2014)
Penicillium sp	LDPE	(Alshehrei, 2017)
Aspergillus tubingensis, Aspergillus flavus	HDPE	(Devi et al., 2015)

Bacteria in polyethene degradation

A number of bacterial species from different genera have been shown to have potential of polyethene degradation (Muhonja et al., 2018b; Begum et al., 2015; Sharma et al., 2014). Previous studies have determined PE biodegradation by bacteria isolated from garbage soil, compost soil, marine environment, mangrove soil and recently from guts of insects like the wax moth. Most of these potential candidate bacteria belong to the genera *Bacilli, Pseudomonas, Staphylococcus,*

Rhodococcus, Streptococcus, Streptomyces, Brevibacilli, and *Micrococcus* (Pramila et al., 2012; Harshvardhan & Jha, 2013; Singh & Bhatt, 2016).
In a study conducted by Montazer et al., (2018), *Acinetobacter pitti* isolated from a plastic polluted landfill was found capable of degrading UV-pretreated LDPE. Evaluation of biodegradation extent showed 26.8 ± 3.04% gravimetric weight reduction. More examples of bacterial strains associated with PE degradation exist (Table 3).

Table 3. Polyethene degrading bacteria

Name	**Substrate**	**Reference**
Bacillus sp, Staphylococcus sp, Pseudomonas sp	PE	(Singh et al., 2016)
Staphylococcus aureus	PE	(Archana et al., 2017)
Arthrobacter sp, Pseudomonas sp.	HDPE	(Balasubramanian *et al*., 2010)
Streptomyces sp.	LDPE	(Abraham et al., 2017)
Pseudomonas sp	LDPE	(Tribedi & Sil, 2013)
Pseudomonas citronellolis	LDPE	(Bhatia et al., 2014)
Kocuria palustris, Bacillus pumilus. Bacillus subtilis	LDPE	(Harshvardhan & Jha, 2013)
Brevibacilli parabrevis, Acinetobacter baumannii, Pseudomonas citronellolis	LDPE	(Pramila et al., 2012)

Actinomycetes in polyethene degradation

Actinomycetes are a diverse group of Gram-positive branching bacteria. They possess unique mycelial structures and spore-forming abilities. Their colonies are hard and stick to agar, have soil-like odors and pale colors (Salim et al., 2017). Plastic degrading actinomycetes including *Rhodococcus ruber, Streptomyces* sp, *Microbispora, Actinomadura sp*. among others have been isolated from garbage soils, mangrove soils, plant tissues and marine environment (Duddu & Guntuku, 2015; Usha et al., 2011). Their ability to break down plastic polymers is mainly attributed to their ability to secrete hydrolytic enzymes like laccase, lipase, protease, xylanase, cellulase among others (Hari, 2019). Biofilm formation by actinomycetes also helps in surface colonization and degradation of plastic polymers (Amobonye et al., 2020).

A polyethene and plastic cup degrading *Streptomyces species* isolated from garbage soil by Usha et al., 2011 was found to possess the greater biodegrading ability than other bacteria and fungi after 6 months incubation period (Usha et al., 2011).

In another study, a thermophilic *Streptomyces coelicoflavus* NBRC 15399^T was isolated from oil contaminated soil. A 30% weight loss was reported on the tested LDPE after four weeks incubation indicating the potential of this actinomycete in polyethene degradation (Duddu *et al*., 2015). Polyethene degradation has also been demonstrated in *Nocardiopsis sp*. isolated from *Hibiscus rosasinensis* leaves (Singh & Sedhuraman, 2015).

Biodegradation by intestinal microbiome

Recently, several insect species have been reported to consume or degrade polyethene by the help of microbes isolated from their gut. The larvae of meal moths, darkling beetles and wax moths have been reported to consume and degrade a various plastic polymers (Lear et al., 2021). For example, *Plodia interpunctella* larvae were reported to possess the ability to consume and crush polyethene films in a study carried out by Yang et al., 2014. *Bacillus sp*. YP1 and *Enterobacter asburiae* YT1 were isolated from the gut of this worm and were reported capable of polyethene degradation (Yang et al., 2014). *Galleria mellonella* larvae were reported to consume and metabolize LDPE (Cassone et al., 2020). In addition, this study also showed the ability of a gut bacteria (from the genus

Acinetobacter) to use polyethylene as the sole carbon source (Cassone et al., 2020).

Three bacterial species *Microbacterium oxydans, Lysinibacillus fusiformis* and *Bacillus aryabhattai* were isolated by Montazer et al., 2021 from whole body extracts of *Galleria mellonella* larvae. He evaluated their potential to consume low-density polyethylene (LDPE) and obtain carbon from it Invitro. He reported that these bacteria have potential to degrade LDPE (Montazer et al., 2021).

Aspergillus flavus isolated from the gut *Galleria mellonella* degraded HDPE microplastic particle into low molecular weight microplastic fragment after 28 days of incubation. Further analysis using Fourier Transform - Infrared Spectroscopy (FT-IR) showed presence of ether and carbonyl groups, which further proved PE degradation by the fungus (Zhang et al., 2020).

However, there is need for further studies to determine the enzymatic degradation mechanism in the guts of these insects. This information will be useful in the development of novel biotechnological tools useful in the biodegradation of a variety of plastic materials.

Polyethene degrading enzymes

The type of chemical bonds present in plastic polymer determine the modification of polymers by enzymes (Wei & Zimmermann, 2017). Plastic polymer biodegrability greatly depend on presence or absence of hydrolysable functional groups in the polymer back bones (Restrepo-Flórez et al., 2014; Wei & Zimmermann, 2017). Plastic polymers that have hydrolysable functional groups can easily be depolymerized by microbial hydrolase enzymes including esterase, proteases and lipases (Bano et al., 2017a; Wei & Zimmermann, 2017; Wierckx et al., 2018). Plastic degrading enzymes are grouped into two; the intracellular and extracellular enzymes. The latter are the most studied and are said to be more reactive, and can carry out both oxidative and hydrolytic roles (Glaser, 2019; (Amobonye et al., 2020; Ghatge et al., 2020b; Mohanan et al., 2020). They include the extracellular hydrolases and depolymerases. Extracellular depolymerases produce shorter polymer chains which can pass through the microbial plasma membrane and undergo subsequent chain cleavage and further metabolism (Dey et al., 2012). Hydrolytic cleavage occurs when an enzyme attaches itself to the polymer surface catalyzing its breakdown (Banerjee et al., 2014). This cleavage results into low molecular weight oligomers, dimers and monomers which are then converted to H_2O and CO_2 through the process of mineralization (Ghosh et al., 2013; Mohan, 2011). The monomers, oligomers and dimers are small enough to move across the cytoplasmic membrane where they are further exploited as carbon and energy source (Bano et al., 2017b). It is not yet clear how these molecules are metabolized inside the microbial cell. Some studies have however described that the low molecular weight molecules undergo oxidation in order to be transformed into carboxylic acid that can be metabolized through the tricarboxylic acid (TCA) cycle (Restrepo-Flórez et al., 2014). Enzymes which have been associated with PE biodegradation are laccases also called the blue copper oxidases, manganese peroxidase (MnP) (Bardají et al., 2020; Restrepo-Flórez et al., 2014), hydroxylases and reductases (Amobonye *et al.*, 2020). The blue copper oxidases are so called because they have copper in their structure (Bardají et al., 2020). Addition of copper ions to cultures of *Rhodococcus ruber* C208 containing PE increased by 75%. FTIR analysis of the PE films indicated an increase in carbonyl peak. They reported a reduction of the molecular weight of the PE, indicating enzymatic oxidation by laccase (Santo et al., 2013).

Factors affecting biodegradability of polymers

The main factors affecting polymer biodegradation are exposure/environmental conditions and polymer characteristics. Polymer characteristics are divided into chemical and physical characteristics and include features like shape, size, morphology, molecular weight, additives, hydrophobic and hydrophilic characteristics (Su, 2013). Exposure conditions are classified as biotic and abiotic. Abiotic factors include ionizing radiation, temperature, pH and moisture which affect the rate of hydrolysis reaction (Glaser, 2019). All these are important in influencing polymer surface colonization by microorganisms.

The molecular weight of a polymer can limit microbial colonization since the process is dependent on the surface properties that allow the microorganisms to attach (Restrepo-Flórez et al., 2014). Polymer crystallinity is important for microbial attachment since microorganisms attach only on to the amorphous sections of the polymer surface (Glaser, 2019).

Additives such as pro-oxidants or starch can be used to improve polymer biodegradability. They are low molecular weight organic chemicals that can provide a starting point for microbial colonization. The presence of these additives influence the types of microorganisms colonizing the surfaces of these polymers (Ammala et al., 2011; Corti et al., 2010).

Abiotic factors including ionizing radiation, temperature, pH and moisture affects the rate of hydrolysis reaction. Increased temperature and moisture speeds up the hydrolysis reaction rates and microbial activity (Haider et al., 2019). In high-moisture environments, there is an increase in hydrolysis reaction which increases chain scission leading to an increase in the available sites for microbial attachment hence faster degradation (Chamas et al., 2020). Photo degradation reduces the number of average molecular weight, which provides greater accessibility to the polymer chain by moisture and microorganisms (Rabek, 2012). Among biotic factors, extracellular enzymes produced by microorganisms have active sites with different shapes and hence more able to biodegrade certain polymers. Smaller molecules are more accessible to microbes than larger ones. Low molecular weight portions are taken into the cells and then converted into metabolites (Khan & Majeed, 2019).

Toxicity of polyethene degradation products (PEDP)

The finished plastic is non-toxic but the monomers that are used in the production of the parent polymers can be toxic. Toxicity of plastic products is as a result of additives and plasticizers such as fillers, stabilizers, reinforcements, adipates, phthalates and colorants (Andrady & Rajapakse, 2016). These are usually mixed with the polymers to help in improving both the physical (mechanical, thermal, etc.) and chemical properties of the polymers (Hahladakis et al., 2018b). These chemicals can leak out of the product in traces causing toxic effects. The products of polymer degradation vary depending on the polymer type, degradation mechanism, presence of impurities and exposure conditions such as temperature and oxygen (Lithner, 2011). Various studies have investigated the effect of polyethene biodegradation on both plants and animals. For example, the toxicity of PE degradation products was tested on sorghum and fish in a culture supernatant containing *Bacillus cereus strain* VASB1/TS and *Lysinibacillus fusiformis strain* VASB14/WL. The toxicity test on sorghum revealed a decrease in germination index and inhibited elongation. However, no death of the fishes was recorded (Shahnawaz et al., 2016). In another study by Aswale, 2010, moderate reduction in seed germination was recorded when studying toxicity of PEDP on soybean, sunflower, groundnut and safflower seeds using culture filtrate. Toxicity test was also done using Chironomous larvae and there was no mortality reported (Aswale, 2010).

Studies by Das and Kumar on the toxicity of degration products produced by LDPE degrading microorganisms including *Bacilli sp* , *Aspergillus sp and Fusarium sp* on *Cicer arietinum* and *Vigna radiate* showed a significant germination rate and seedling growth. They concluded that PEDP are do not harm the environment and can be used to promote plant growth (Das & Kumar, 2013).

Based on the above studies, there's no clarity on the toxicity of PEDP since some studies reveal moderate toxicity and others report no toxicity. Therefore, there is need for more research in this area to determine whether PEDP can be safely disposed into the environment or not.

Challenges and opportunities in polyethene biodegradation

Many researchers have studied microbial degradation of PE. Despite all these studies proving the potential of microbes in PE degradation, this has not been made possible in reality such as in dump sites and landfills (Montazer et al., 2020). Furthermore, most commonly used methods to evaluate changes in biodegradation such as change in tensile strength, formation of holes, cracks and biofilms, fragmentation, change in color, and surface roughening do not give conclusive evidence of complete degradation. Instead they indicate microbial activity on PE indicating a stage in biodegradation (Bardají et al., 2020; Gnanavel et al., 2012). There is no standardized protocol and procedure for studying PE degradation. Different researchers use different experimental procedures, conditions and even different kinds of PE when performing degradation assays which makes comparison of results almost impossible *(*Montazer et al., 2020).

Conclusion

Polyethene is one of the most common and frequently used plastic worldwide due to its pleasant properties. Its total elimination is neither feasible nor desirable since it offers many applications in industry and in day to day life. The over-accumulation and detrimental effects of PE and other plastics in the environment have caused some governments to take the step of banning usage of some plastic materials especially the polyethene carrier bags. This to a good percentage has helped in reducing PE pollution in the respective countries. However, PE pollution is still evident because what was already disposed still remains undegraded in the dumpsites and in landfills, not forgetting those that are still being used and disposed. Therefore, it is important to encourage use of biodegradable plastics to replace the non-degradable ones.

Microorganisms have been proven to have potential of PE degradation without causing more harm to the environment. Microbial degradation is very promising. However, the mechanism of biodegradation is not clearly understood. There is need for more research to clearly determine the mechanism of enzymatic degradation which will be useful in the development of novel biotechnological tools useful in degradation of a variety of plastic materials by microorganisms. It's also important that more research be done to determine the mechanism of biodegradation in the guts of insects such as *Galleria mellonella.*

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Author's Contributions

Beryle Atieno Okoth, Huxley Mae Makonde, Carren Moraa Bosire, Jeophita Mwajuma and Cromwell Mwiti Kibiti conceptualized the review and co-authored the manuscript. Cromwell Mwiti Kibiti, Huxley Mae Makonde and Carren Moraa Bosire critically reviewed the manuscript. All authors have read and approved the manuscript.

References

Abraham, J., Ghosh, E., Mukherjee, P. & Gajendiran, A. (2017). Microbial degradation of low density polyethylene. Environmental *Progress & Sustainable Energy* 36: 147–154.

Adams, G. O., Fufeyin, P. T., Okoro, S. E. & Ehinomen, I. (2015). Bioremediation, biostimulation and bioaugmention: a review. *International Journal of Environmental Bioremediation & Biodegradation* 3: 28–39.

Ahmad, A., Razali, A. & Razelan, I. (2017). Utilization of polyethylene terephthalate (PET) in asphalt pavement: A review. Presented at the IOP Conference Series: Materials Science and Engineering, IOP Publishing: 012004

Al-Salem, S. (2019). Energy production from plastic solid waste (PSW), in: *Plastics to Energy*. Elsevier: 45–64

Alshehrei, F., 2017. Biodegradation of low density polyethylene by fungi isolated from Red sea water. *International Journal of Current Microbiology and Applied Sciences* 6: 1703–9

Ameen, F., Moslem, M., Hadi, S., Al-Sabri, A.E. (2015). Biodegradation of Low Density Polyethylene (LDPE) by Mangrove fungi from the red sea coast. *Progress in Rubber Plastics and Recycling Technology* 31: 125–143

Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C. & Leong, K. (2011). An overview of degradable and biodegradable polyolefins. *Progress in Polymer Science* 36: 1015–1049

Amobonye, A., Bhagwat, P., Singh, S. & Pillai, S. (2020). Plastic biodegradation: frontline microbes and their enzymes. *Science of the Total Environment* 759: 143536

Andrady, A. L. & Rajapakse, N. (2016). Additives and chemicals in plastics. *Hazardous Chemicals Associated with Plastics in the Marine Environment* 78: 1–17

Archana, B., Rajesh, M., Samundeeswari, M., (2017). Isolation of polythene degrading bacteria from garbage soil. *International Journal of Recent Advances in Multidiciplinary Research* 04, 2813-2818, September, 2017

Aswale, P. N., (2010). Studies on biodegradation of polythene.

Awasthi, A. K., Shivashankar, M., Majumder, S., (2017). Plastic solid waste utilization technologies: a review. Presented at the IOP Conference Series: Materials Science and Engineering, IOP Publishing, p. 022024.

Azzarello, M. Y., Van Vleet, E. S., (1987). Marine birds and plastic pollution. *Marine Ecology Progress Series* 37, 295–303.

Balasubramanian, V., Natarajan, K., Hemambika, B., Ramesh, N., Sumathi, C., Kottaimuthu, R., Rajesh Kannan, V., (2010). High-density polyethylene (HDPE)-degrading potential bacteria from marine ecosystem of Gulf of Mannar, India. *Letters in applied microbiology* 51, 205–211.

Banerjee, A., Chatterjee, K., Madras, G., (2014). Enzymatic degradation of polymers: a brief review. Materials *Science and Technology* 30, 567–573.https://doi.org/10.1179/1743284713Y.0000000503

Bano, K., Kuddus, M., R Zaheer, M., Zia, Q., F Khan, M., Gupta, A., Aliev, G., (2017a). Microbial enzymatic degradation of biodegradable plastics. *Current pharmaceutical biotechnology 18,* 429–440.

Bardají, D. K. R., Moretto, J. A. S., Furlan, J. P. R., Stehling, E. G., (2020). A mini-review: current advances in polyethylene biodegradation. *World Journal of Microbiology and Biotechnology* 36, 1–10.

Bhardwaj, H., Gupta, R., Tiwari, A., (2013). Communities of microbial enzymes associated with biodegradation of plastics. *Journal of Polymers and the Environment* 21, 575–579.

Bhatia, M., Girdhar, A., Tiwari, A., Nayarisseri, A., (2014). Implications of a novel Pseudomonas species on low density polyethylene biodegradation: an in vitro to in silico approach. *SpringerPlus* 3, 1–10.

Bläsing, M., Amelung, W., (2018). Plastics in soil: Analytical methods and possible sources. *Science of the Total Environment* 612, 422–435.

Bour, A., Avio, C. G., Gorbi, S., Regoli, F., Hylland, K., (2018). Presence of microplastics in benthic and epibenthic organisms: influence of habitat, feeding mode and trophic level. *Environmental Pollution* 243, 1217–1225.

Bowes, P., (1974). Smoke and Toxicity Hazards of Plastics in Fire. *The Annals of occupational hygiene* 17, 143–156.

Camacho, M., Herrera, A., Gómez, M., Acosta-Dacal, A., Martínez, I., Henríquez-Hernández, L.A., Luzardo, O. P., (2019). Organic pollutants in marine plastic debris from Canary Islands beaches. *Science of the total environment* 662, 22–31.

Carbery, M., O'Connor, W., Palanisami, T., (2018). Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environment international* 115, 400–409.

Caruso, G., (2015). Plastic degrading microorganisms as a tool for bioremediation of plastic contamination in aquatic environments. *Journal of Pollution Effects Control* 3, 1–2.

Casals-Casas, C., Desvergne, B., (2011). Endocrine disruptors: from endocrine to metabolic disruption. *Annual review of physiology* 73, 135–162.

Cassone, B. J., Grove, H. C., Elebute, O., Villanueva, S. M., LeMoine, C. M., (2020). Role of the intestinal microbiome in low-density polyethylene degradation by caterpillar larvae of the greater wax moth, Galleria mellonella. *Proceedings of the Royal Society B* 287, 20200112.

Chae, Y., An, Y.-J., (2018). Current research trends on plastic pollution and ecological impacts on the soil ecosystem: *A review. Environmental pollution* 240, 387–395.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., Suh, S., (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering* 8, 3494–3511.

Corti, A., Muniyasamy, S., Vitali, M., Imam, S.H., Chiellini, E., (2010). Oxidation and biodegradation of polyethylene films containing pro-oxidant additives: Synergistic effects of sunlight exposure, thermal aging and fungal biodegradation. *Polymer Degradation and Stability* 95, 1106–1114.

da Costa, J. P., Santos, P. S., Duarte, A. C., Rocha-Santos, T., (2016). (Nano) plastics in the environment–sources, fates and effects. *Science of the Total Environment* 566, 15–26.

Das, M. P., Kumar, S., (2015). An approach to low-density polyethylene biodegradation by Bacillus amyloliquefaciens. *3 Biotech* 5, 81–86.

Das, M. P., Kumar, S., (n.d). Comparative study of germination rate and plant growth by secondary metabolites and in vitro LDPE biodegraded fragments by microbes. *International Journal of Pharmaceutical Sciences Rev Res*, 21(2), 134-136.

de Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., (2018). Microplastics as an emerging threat to terrestrial ecosystems. *Global change biology* 24, 1405–1416.

Deepika, S., Jaya, M., (2015). Biodegradation of low density polyethylene by microorganisms from garbage soil. *Journal of Experimental Biology and Agricultural Sciences* 3, 1–5.

Deshmukh, R., Khardenavis, A. A., Purohit, H.J., (2016). Diverse metabolic capacities of fungi for bioremediation. *Indian journal of microbiology* 56, 247–264.

Devi, R. S., Kannan, V. R., Nivas, D., Kannan, K., Chandru, S., Antony, A. R., (2015). Biodegradation of HDPE by Aspergillus spp. from marine ecosystem of Gulf of Mannar, India. *Marine pollution bulletin* 96, 32–40.

Dey, U., Mondal, N. K., Das, K., Dutta, S., (2012). An approach to polymer degradation through microbes. *IOSR IOSR Journal of Pharmacy* 2, 385–388.

Duddu, M.K., Guntuku, G., (2015). Isolation and screening of actinomycetes for biodegradation of low density polyethylene from mangrove sediment. *International Journal of Pharma Research & Review* 4, 14–22.

Duddu, M. K., Tripura, K. L., Guntuku, G., Divya, D.S., (2015). Biodegradation of low density polyethylene (LDPE) by a new biosurfactant-producing thermophilic Streptomyces coelicoflavus NBRC 15399T. *African Journal of Biotechnology* 14, 327–340.

Emblem, A., (2012). Plastics properties for packaging materials, in: *Packaging Technology*, 287–309.

Esmaeili, A., Pourbabaee, A.A., Alikhani, H.A., Shabani, F., Esmaeili, E., (2013). Biodegradation of low-density polyethylene (LDPE) by mixed culture of Lysinibacillus xylanilyticus and Aspergillus niger in soil. *Plos one* 8, e71720.

Europe, P., (2016). Plastics–the Facts. An analysis of European plastics production, demand and waste data. Retrived from: *http://www. plasticseurope. org.*

Favaro, S. L., Pereira, A. G. B., Fernandes, J.R., Baron, O., da Silva, C.T.P., Moisés, M.P., Radovanovic, E., (2016). Outstanding impact resistance of post-consumer HDPE/Multilayer packaging composites. *Materials Sciences and Applications* 8, 15–25.

Gall, S.C., Thompson, R. C., (2015). The impact of debris on marine life. *Marine pollution bulletin* 92, 170–179.

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A., Romano, D., (2018). Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. *Environmental Sciences Europe* 30, 1–14.

Garcia, J.M., Robertson, M. L., (2017). The future of plastics recycling. *Science* 358, 870–872.

Gewert, B., Plassmann, M. M., MacLeod, M., (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science: Processes & Impacts* 17, 1513–1521.

Geyer, R., (2020). Production, use, and fate of synthetic polymers, in: *Plastic Waste and Recycling,* 13–32.

Geyer, R., Jambeck, J. R., Law, K. L., (2017). Production, use, and fate of all plastics ever made. *Science advances* 3, e1700782.

Ghatge, S., Yang, Y., Ahn, J.-H., Hur, H.-G., (2020a). Biodegradation of polyethylene: a brief review. *Applied Biological Chemistry* 63, 1–14.

Ghosh, S. K., Pal, S., Ray, S., (2013b). Study of microbes having potentiality for biodegradation of plastics. *Environmental Science and Pollution Research* 20, 4339–4355.

Glaser, J. A., (2019). Biological degradation of polymers in the environment, in: *Plastics in the Environment*. 1, 13.

Gnanavel, G., JayaValli, M., Thirumarimurugan, M., Kannadasan, T., (2012). Degradation of plastics using microorganisms. International *Journal of Pharmaceutical Chemistry Sciences* 1, 691–694.

Grover, A., Gupta, A., Chandra, S., Kumar, A., Khurana, S., (2015a). Polythene and Environment. *International Journal of Environmental Sciences*, *5*(6), 1091-1105

Grover, A., Gupta, A., Chandra, S., Kumari, A., Khurana, S., (2015b). Polythene and environment. *International Journal of Environmental Sciences* 5, 1091–1105.

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., Purnell, P., (2018a). An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of hazardous materials* 344, 179–199.

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., Purnell, P., (2018b). An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of hazardous materials* 344, 179–199.

Haider, T.P., Völker, C., Kramm, J., Landfester, K., Wurm, F.R., (2019). Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angewandte Chemie International Edition* 58, 50–62.

Halden, R. U., (2010). Plastics and health risks. *Annual review of public health* 31, 179–194.

Hammer, J., Kraak, M. H., Parsons, J. R., (2012b). Plastics in the marine environment: the dark side of a modern gift. *Reviews of environmental contamination and toxicology* 220 1–44.

Hari, S., (2019). Screening of Enzymes from Actinomycetes and Fungi isolated from Plastic Dumped Soil. Research *Journal of Pharmacy and Technology* 12, 2261–2266.

Harshvardhan, K., Jha, B., (2013). Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India. *Marine Pollution Bulletin* 77, 100–106.

Immanuel, O., Ibiene, A., Stanley, H., (2014). Enhanced biodegradation of polyethylene by fungus isolated from the koluama mangrove swamp in the Niger Delta. Journal of Microbiol *Biotechnology Research* 4, 1–9.

Jyoti, S., Gupta, K., (2014). Screening and identification of low density polyethylene (LDPE) degrading soil fungi isolated from polythene polluted sites around Gwalior city (MP). *International Journal of Current Microbiology and Applied Sciences* 3, 443–448.

Kalantary, R. R., Mohseni-Bandpi, A., Esrafili, A., Nasseri, S., Ashmagh, F. R., Jorfi, S., Ja'fari, M., (2014). Effectiveness of biostimulation through nutrient content on the bioremediation of phenanthrene contaminated soil. *Journal of Environmental Health Science and Engineering* 12, 143.

Karigar, C. S., Rao, S. S., (2011). Role of microbial enzymes in the bioremediation of pollutants: a review. *Enzyme research 2011.*

Karlapudi, A. P., Venkateswarulu, T., Tammineedi, J., Kanumuri, L., Ravuru, B.K., ramu Dirisala, V., Kodali, V. P., (2018). Role of biosurfactants in bioremediation of oil pollution-a review. *Petroleum* 4, 241–249.

Kavitha, R., Bhuvaneswari, V., (2021). Assessment of polyethylene degradation by biosurfactant producing ligninolytic bacterium. Biodegradation. *Biodegradation*, 32(5), 531-549.

Khan, A. K., Majeed, T., (2019). Biodegradation of synthetic and natural plastics by microorganisms: a mini review. *Journal of Natural and Applied Sciences Pakistan* 1, 180–184.

Kinmonth Jr., R. A., (1964). Weathering of plastics. *Polymer Engineering & Science* 4, 229–235.

Kumar, S., Panda, A. K., Singh, R. K., (2011). A review on tertiary recycling of high-density polyethylene to fuel. *Resources, Conservation and Recycling* 55, 893–910.

Lear, G., Kingsbury, J., Franchini, S., Gambarini, V., Maday, S., Wallbank, J., Weaver, L., Pantos, O., (2021). Plastics and the microbiome: impacts and solutions. *Environmental Microbiome* 16, 1–19.

Lithner, D., (2011). Environmental and health hazards of chemicals in plastic polymers and products.

Löhr, A., Savelli, H., Beunen, R., Kalz, M., Ragas, A., Van Belleghem, F., (2017). Solutions for global marine litter pollution. *Current opinion in environmental sustainability* 28, 90–99.

Loredo-Treviño, A., Gutiérrez-Sánchez, G., Rodríguez-Herrera, R., Aguilar, C.N., (2012). Microbial enzymes involved in polyurethane biodegradation: a review. *Journal of Polymers and the Environment* 20, 258–265.

Luckachan, G. E., Pillai, C., (2011). Biodegradable polymers-a review on recent trends and emerging perspectives. *Journal of Polymers and the Environment* 19, 637–676.

Mintenig, S., Int-Veen, I., Löder, M.G., Primpke, S., Gerdts, G., (2017). Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water research* 108, 365–372.

Mohan, K., (2011). Microbial deterioration and degradation of polymeric materials. *Journal of Biochemical Technology* 2, 210–215.

Mohanan, N., Montazer, Z., Sharma, P.K., Levin, D. B., (2020). Microbial and enzymatic degradation of synthetic plastics. *Frontiers in Microbiology* 11, 2837.

Montazer, Z., Habibi, N. M. B., Levin, D. B., (2021). In vitro degradation of low-density polyethylene by new bacteria from larvae of the greater wax moth, Galleria mellonella. *Canadian Journal of Microbiology* 67, 249–258.

Montazer, Z., Habibi N. M.B., Levin, D. B., (2020). Challenges with verifying microbial degradation of polyethylene. *Polymers* 12, 123.

Montazer, Z., Habibi N., M. B., Levin, D. B., (2019). Microbial degradation of low-density polyethylene and synthesis of polyhydroxyalkanoate polymers. *Canadian journal of microbiology* 65, 224–234.

Montazer, Z., Habibi-Najafi, M.B., Mohebbi, M., Oromiehei, A., (2018). Microbial degradation of UV-pretreated low-density polyethylene films by novel polyethylene-degrading bacteria isolated from plastic-dump soil. *Journal of Polymers and the Environment* 26, 3613–3625.

Muhonja, C. N., Makonde, H., Magoma, G., Imbuga, M., (2018a). Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya. *PloS one* 13, e0198446.

Mukherjee, S., RoyChaudhuri, U., Kundu, P. P., (2018). Biodegradation of polyethylene via complete solubilization by the action of Pseudomonas fluorescens, biosurfactant produced by Bacillus licheniformis and anionic surfactant. *Journal of Chemical Technology & Biotechnology* 93, 1300–1311.

Munir, E., Harefa. S. M., Priyani, R., & Suryanto, N. D., (2018). Plastic degrading fungi Trichoderma viride and Aspergillus nomius isolated from local landfill soil in Medan. In *IOP Conference Series: Earth and Environmental Science* 126 (1), 012145. https://doi.org/10.1088/1755-1315/126/1/012145

Noor, K., (2020). Towards the End of Plastic Era. *International Conference of Advance Research & Innovation (ICARI)* 2020. Available at SSRN 3557129.

Ojha, N., Pradhan, N., (2017). Evaluation of HDPE and LDPE degradation by fungus implemented by statistical optimization. *Applied Ecology and Environmental Sciences* 7, 695-703

Orr, I. G., Hadar, Y., Sivan, A., (2004). Colonization, biofilm formation and biodegradation of polyethylene by a strain of Rhodococcus ruber. *Applied microbiology and biotechnology* 65, 97–104.

Pathak, V. M., (2017). Review on the current status of polymer degradation: a microbial approach. *Bioresources and Bioprocessing* 4, 15.

Phuong, N. N., Zalouk-Vergnoux, A., Poirier, L., Kamari, A., Châtel, A., Mouneyrac, C., Lagarde, F., (2016). Is there any consistency between the microplastics found in the field and those used in laboratory experiments? *Environmental Pollution* 211, 111–123.

Pohjakallio, M., (2020). Secondary plastic products—examples and market trends, in: Plastic Waste and Recycling. Environmental Impact, Societal Issues, Prevention, and Solutions, 467–479.

Poon, F. E., Provencher, J. F., Mallory, M.L., Braune, B. M., Smith, P. A., (2017). Levels of ingested debris vary across species in Canadian Arctic seabirds. *Marine pollution bulletin* 116, 517–520.

Pramila, R., Padmavathy, K., Ramesh, K.V., Mahalakshmi, K., (2012). Brevibacillus parabrevis, Acinetobacter baumannii and Pseudomonas citronellolis-Potential candidates for biodegradation of low density polyethylene (LDPE). *African Journal of Bacteriology Research* 4, 9–14.

Pramila, R., Ramesh, K.V., (2011a). Biodegradation of low density polyethylene (LDPE) by fungi isolated from marine water a SEM analysis. *African Journal of Microbiology Research* 5, 5013–5018.

Pramila, R., Ramesh, K. V., (2011b). Biodegradation of low-density polyethylene (LDPE) by fungi isolated from municipal landfill area. *Journal of Microbiology and Biotechnology Research* 1, 131–136.

Raaman, N., Rajitha, N., & Jayshree, A., R., (2012). Biodegradation of plastic by Aspergillus spp. Isolated from polythene polluted sites around Chennai. *Journal Academic Industrial Reseach*, *1*(6), 313-316.

Rabek, J. F., (2012). Photodegradation of polymers: physical characteristics and applications. *Springer Science & Business Media*.

Rajendran, S., Kannan, V., Natarajan, K., Durai, N., Kannan, K., Sekar, C., Arokiaswamy, R. A., (2015). The Role of Microbes in Plastic Degradation. *Environ*. *Waste Manage* 341 (2016): 341-370. pp. 341–370. https://doi.org/10.1201/b19243-13

Restrepo-Flórez, J.-M., Bassi, A., Thompson, M. R., (2014). Microbial degradation and deterioration of polyethylene–A review. *International Biodeterioration & Biodegradation* 88, 83–90.

Ryan, P., (1988). *Effects of ingested plastic on seabird feeding: Evidence from chickens.* https://doi.org/10.1016/0025-326X (88)90708-4

Ryan, P.G., (2016). Ingestion of plastics by marine organisms, in: Hazardous Chemicals Associated with Plastics in the Marine Environment. *The Handbook of Environmental Chemistry* 78, 235–266.

Salim, F. M., Sharmili, S. A., Anbumalarmathi, J., Umamaheswari, K., (2017). Isolation, molecular characterization and identification of antibiotic producing actinomycetes from soil samples. *Journal of Applied Pharmaceutical Sciences 7*, 69–75.

Sangale, M., Shahnawaz, M., Ade, A., (2012). A review on biodegradation of polythene: the microbial approach. Journal of Bioremediation and Biodegragation 3, 1–9.

Sangale, M. K., Shahnawaz, M., Ade, A. B., (2019). Potential of fungi isolated from the dumping sites mangrove rhizosphere soil to degrade polythene. *Scientific reports* 9, 1–11.

Santo, M., Weitsman, R., Sivan, A., (2013). The role of the copper-binding enzyme–laccase–in the biodegradation of polyethylene by the actinomycete Rhodococcus ruber. *International Biodeterioration & Biodegradation* 84, 204–210.

Sen, S.K., Raut, S., (2015a). Microbial degradation of low density polyethylene (LDPE): A review. *Journal of Environmental Chemical Engineering* 3, 462–473.

Shahnawaz, M., Sangale, M. K., Ade, A. B., (2016). Bacteria-based polythene degradation products: GC-MS analysis and toxicity testing. *Environmental Science and Pollution Research* 23, 10733–10741.

Sharma, J., Gurung, T., Upadhyay, A., Nandy, K., Agnihotri, P., Mitra, A., (2014). Isolation and characterization of plastic degrading bacteria from soil collected from the dumping grounds of an industrial area. *International journal of advanced and innovative research* 3, 225–232.

Sheik, S., Chandrashekar, K., Swaroop, K., Somashekarappa, H., (2015). Biodegradation of gamma irradiated low density polyethylene and polypropylene by endophytic fungi. *International Biodeterioration & Biodegradation* 105, 21–29.

Shimao, M., (2001). Biodegradation of plastics. *Current opinion in biotechnology* 12, 242–247.

Sigler, M., (2014). The effects of plastic pollution on aquatic wildlife: current situations and future solutions. *Water, Air, & Soil Pollution* 225, 2184.

Singh, G., Singh, A. K., Bhatt, K., (2016). Biodegradation of polythenes by bacteria isolated from soil. I*nternational Journal of Research and Development in Pharmacy & Life Sciences* 5, 2056–2062.

Singh, M. J., Sedhuraman, P., (2015). Biosurfactant, polythene, plastic, and diesel biodegradation activity of endophytic Nocardiopsis sp. mrinalini9 isolated from Hibiscus rosasinensis leaves. *Bioresources and Bioprocessing* 2, 1–7.

Singh, N., Hui, D., Singh, R., Ahuja, I., Feo, L., Fraternali, F., (2017). Recycling of plastic solid waste: A state of art review and future applications. Composites Part B: *Engineering* 115, 409–422.

Su, W.-F., (2013). Chemical and physical properties of polymers, in: *Principles of Polymer Design and Synthesis* 82, 61–88.

Thiel, M., Luna-Jorquera, G., Álvarez-Varas, R., Gallardo, C., Hinojosa, I. A., Luna, N., Miranda-Urbina, D., Morales, N., Ory, N., Pacheco, A. S., (2018). Impacts of marine plastic pollution from continental coasts to subtropical gyres—fish, seabirds, and other vertebrates in the SE Pacific. *Frontiers in Marine Science* 5.

Tribedi, P., Sil, A. K., (2013). Low-density polyethylene degradation by Pseudomonas sp. AKS2 biofilm. *Environmental Science and Pollution Research* 20, 4146–4153.

Tseng, M., Hoang, K.-C., Yang, M.-K., Yang, S.-F., Chu, W. S., (2007). Polyester-degrading thermophilic actinomycetes isolated from different environment in Taiwan. *Biodegradation* 18, 579.

Tudor, V. C., Mocuta, D. N., Teodorescu, R. F., Smedescu, D. I., (2019). The issue of plastic and microplastic pollution in soil. *Materiale Plastice* 56, 484.

Ujowundu, C., Ogbede, J., Igwe, K., Nwaoguikpe, R., (2016). Modulation of biochemical stress initiated by toxicants in diet prepared with fish smoked with polyethylene (plastic) materials as fuel source. *African Journal of Biotechnology* 15, 1628–1640.

Urbanek, A. K., Rymowicz, W., Mirończuk, A. M., (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied microbiology and biotechnology* 102, 7669–7678.

Usha, R., Sangeetha, T., Palaniswamy, M., (2011). Screening of polyethylene degrading microorganisms from garbage soil. *Libyan Agriculture Research Center Journal International* 2, 200–4.

Van, A., Rochman, C. M., Flores, E. M., Hill, K. L., Vargas, E., Vargas, S. A., Hoh, E., (2012). Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California. *Chemosphere* 86, 258–263.

Vanapalli, K. R., Samal, B., Dubey, B. K., Bhattacharya, J., (2019). Emissions and environmental burdens associated with plastic solid waste management, in: Plastics to Energy. *Fuel, Chemicals, and Sustainability Implications*, 313–342.

Verma, R., Vinoda, K., Papireddy, M., Gowda, A., (2016a). Toxic pollutants from plastic waste-a review. *Procedia Environmental Sciences* 35, 701–708.

Wachira, T.D., Wairire, G., Mwangi, S., (2014). Socio-economic hazards of plastic paper bags litter in periurban centres of Kenya; a case study conducted at Ongata rongai township of Kajiado County. *International journal of scientific research and innovative technology* 1, 24.

Webb, K. H., Arnott, J., Crawford, J.R., Ivanova, P. E., (2013). Plastic Degradation and Its Environmental Implications with Special

Reference to Poly(ethylene terephthalate). *Polymers 5,* 1-18. https://doi.org/10.3390/polym5010001

Wei, R., Zimmermann, W., (2017). Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? *Microbial biotechnology* 10, 1308–1322.

Wierckx, N., Narancic, T., Eberlein, C., Wei, R., Drzyzga, O., Magnin, A., Ballerstedt, H., Kenny, S. T., Pollet, E., Averous, L., (2018). Plastic biodegradation: Challenges and opportunities. Consequences of microbial interactions with hydrocarbons, oils, and lipids: *Biodegradation and bioremediation* 1–29.

Wright, S. L., Kelly, F. J., (2017). Plastic and human health: a micro issue? *Environmental science & technology* 51, 6634–6647.

Xanthos, D., Walker, T. R., (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. *Marine pollution bulletin* 118, 17–26.

Yang, J., Yang, Y., Wu, W.-M., Zhao, J., Jiang, L., (2014). Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. *Environmental science & technology* 48, 13776–13784.

Yoon, M. G., Jeon, H. J., Kim, M. N., (2012). Biodegradation of polyethylene by a soil bacterium and AlkB cloned recombinant cell. *Journal of Bioremediation and Biodegradation* 3, 1–8.

Zahra, S., Abbas, S. S., Mahsa, M.-T., Mohsen, N., (2010). Biodegradation of low-density polyethylene (LDPE) by isolated fungi in solid waste medium. *Waste management* 30, 396–401.

Zhang, J., Gao, D., Li, Q., Zhao, Yixuan, Li, L., Lin, H., Bi, Q., Zhao, Yucheng, (2020). Biodegradation of polyethylene microplastic particles by the fungus Aspergillus flavus from the guts of wax moth Galleria mellonella. *Science of The Total Environment* 704, 135931.

Zhang, M., Buekens, A., Li, X., (2017). Open burning as a source of dioxins. *Critical Reviews in Environmental Science and Technology* 47, 543–620. https://doi.org/10.1080/10643389.2017.1320154