AMERICAN JOURNAL OF
ENVIRONMENT AND CLIMATE (AJEC)

ISSN: 2832-403X (ONLINE)

VOLUME 2 ISSUE 3 (2023)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Environment and Climate (AJEC)

Volume 2 Issue 3, Year 2023
ISSN: 2832-403X (Online)
DOI: https://doi.org/10.54536/ajec.v2i3.1937
https://journals.e-palli.com/home/index.php/ajec

Enzymatic Degradation of Polyethylene and Polyethylene Terephthalate: A Mini Review

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Article Information

Received: August 12, 2023

Accepted: September 06, 2023

Published: September 16, 2023

Keywords

Polyethylene, Polyethylene Terephthalate, Biodegradation, Microbes, and Enzymatic Degradation

ABSTRACT

Polyethylene (PE) and Polyethylene Terephthalate (PET) are the most widely used plastics for many purposes, including packaging, textiles, medicine, engineering, the electronic industry, etc. Among existing approaches to manage and recycle plastic waste, the enzymatic method is promising due to its quality in the environment, low energy consumption, lack of hazardous chemical elements, and expansive machinery. Several enzymes produced by a group of microorganisms, such as bacteria, fungi, and algae, play a significant role in this method. These enzymes can depolymerize plastic's polymer when they are released by the microbes on the plastic surface under suitable conditions. This study was conducted by surveying the published articles on PubMed and Elsevier. We searched the TS (topic search) in the webs and applied some criteria and filters, such as text availability ("The free full text") and publication date ("5 years"). Based on the TS "PE", "PET" and "enzymatic degradation", the articles were selected. Among hundreds of articles, we chose only 26 to review. Several enzymes (e.g., cutinase, lipase, laccase, PETase, and esterase) that can degrade PE and PET have been reported in the literature, and they are isolated from microorganisms that are categorized into fungi, bacteria, and algae.

INTRODUCTION

Plastics are artificial materials made from synthetic organic polymers, namely fossil hydrocarbon derivatives (Khairul Anuar *et al*., 2022). Today, most plastic production is manufactured from non-renewable petrochemicals derived from fossil fuels, natural gas, and coal. Plastics have an important role in all modern societies due to attributes such as durability, resistance, transparency, lightweight, low price, high stability, and compact structural characteristics (Ahmaditabatabaei *et al*., 2021; Siracusa *et al*., 2020). Plastics are a vital entity for many domestic and industrial sectors, including electronics, construction, transportation, health care, agriculture, and packaging materials (food and other industries), and moreover, they account for 70% of the market for consumer products (Benyathiar *et al*., 2022; Bobori *et al*., 2022; Siracusa *et al*., 2020). Because of increasing demand and use in many sectors and their commercial importance, the annual production of plastics is increasing, and it is expected to double by 2035 (about 800 Mt) and reach around 1600 Mt by 2050.

However, plastics are one of the most vital materials in the modern world (Zhang *et al*., 2022), but plastic waste is one of the most serious problems in modern society (Zichittella *et al*., 2022). The increased and strong demand for plastic production has a negative impact on the environment because of the degradation problems in the environment. Only 9% of the generated plastic waste from the 6300 million tons produced between 1950 and 2015 was recycled (Kawai *et al*., 2022). Annually, global plastic waste was generated at approximately 141 million tons in 2015 (Benyathiar *et al*., 2022), about 300 million tons in 2020 (Ahmaditabatabaei *et al*., 2021), and it is expected to triple by 2060 (Kim *et al*., 2021). Daily plastic waste generation per person is different according to the countries (e.g., Germany with 0.48, the United States with 0.34, the United Kingdom with 0.21, France with 0.19, Italy with 0.13, China with 0.12, Belgium with 0.08, and India with 0.01 Kg/person/day in 2010) (Montanari, 2020). Despite the advantages of plastic use, plastic pollution is one of the most important environmental issues in the world (Kim *et al*., 2020). Annually, between 4.8 and 12.7 million tons of plastic waste are dispersed in the ocean (Lionetto *et al*., 2021).

Polyethylene (PE) and Polyethylene Terephthalate (PETE/PET) are petroleum-based polymers that are widely used in many applications (films, packaging bottles, manufacture, medicine, textiles, engineering, etc.). These wastes do not degrade easily when they are released into the earth's environment. Although there are several degradation strategies, such as mechanical, chemical, and biological strategies, to reduce the accumulation of plastic waste, Because of the low energy consumption, no need for hazardous chemical materials and expensive machinery, and mild process, biological degradation is a more viable environmental degradation strategy than mechanical and chemical methods (Budhiraja *et al*., 2022). In this method, microorganisms are the main agents, and they are able to produce some enzymes that degrade plastics and plastic waste in normal conditions.

Several enzymes have been isolated from the group of microorganisms, including Bacteria, fungi, and Algae, that break down the plastic polymers into monomers. These microorganisms are able to degrade plastic in the various ecosystems (soil, sea water, compost, and activated sludge) through the production of enzymes

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(Mohanan *et al.*, 2020). These enzymes (e.g., laccase, manganase, peroxidase, alkane hydroxylase, lipase, and cutinase) are able to degrade PE, while cutinase, lipase, carboxylesterase, esterase, PETase, IsPETase, and polyesterases are capable of degrading PET. The production of enzymes by microorganisms has been reported in many studies; this study categorized enzymes and microorganisms. This study was conducted as a review of the literature. We used the scientific web, such as PubMed and another source, and focused on enzymatic degradation topic searches.

LITERATURE REVIEW

Plastics (PE, PET) are polymers used widely in many applications, so their wastes in the ecosystems do not degrade easily when they are released into the environment. Many investigates were conducted to find some safe strategies to degrade the plastic's waste like biodegradation or enzymatic degradation. Many enzymes isolated from the group of microorganisms, including bacteria, fungi and algae are able to degrade PE and PET (Mohanan *et al.*, 2020).

Lipase, Cutinase, Esterase are generated by bacteria and fungi, and they hydrolyze PE and PET (Mohanan *et al.*, 2020; Bollinger *et al.*, 2020; Maurya *et al.*, 2020; Zeenat *et al.*, 2021; Temporiti *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022; Dhaka *et al.* 2022; Blaasgues-Sanches *et al.*, 2022). PE is degraded by Laccases, Peroxidase, Manganase, Alkane, Dioxygenase, Polyurethanase, Monooxygenase and Carboxylesterase that are produced by bacteria and fungi (Maurya *et al.*, 2020; Zeenat *et al.*, 2021; Jeon *et al.*, 2021; Dhaka *et al.*, 2022; Mohanan *et al.*, 2020; Temporiti *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022).

MATERIALS AND METHODS

We conducted a literature survey by using the keywords "Polyethylene or PE" and " Polyethylene Terephthalate or PET " "enzymatic degradation of plastics or PE or PET", and "biodegradation of PE or PET" in the web of PubMed and Elsevier. The data were collected from published literature in which the biofragmentation or biodegradation of PE and PET is indicated. The following topics were searched to select and find the literature:

Topic search = (Polyethylene or PE" and "Polyethylene Terephthalate or PET " "enzymatic degradation of plastics" or "PE", or "PET", and "biodegradation of plastics" or "PE" or "PET". This search was last updated on August 4, 2023, and returned hundreds of records. Then, we applied the filtering option based on text availability and publication date. The free full text and five years were selected in the filtering phase. Based on the topic search, more than 175 articles were found. These articles were sent to EndNote for more processing. Moreover, TS were done on another web site as well.

The following criteria were used for the selection of literature:

At least one of the TS should be discussed;

The characteristics of enzymes that can degrade polymers in plastics should be reported;

The microorganisms that can release enzymes to degrade PE and PET should be reported;

The Production of the specific enzyme by the microbes should be identified;

Enzymatic degradation should be reported under biological degradation.

We applied the above strategies and selected only 26 articles for full review; the summary of our procedure is shown in Figure 1.

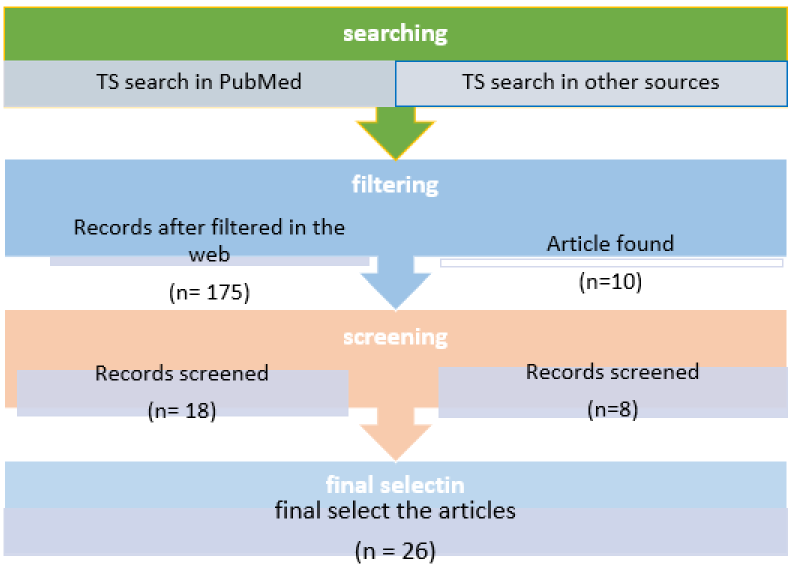

Figure 1: Procedure of the review of the article

RESULTS AND DISCUSSION

Types of Plastics Frequently Used (PE and PET)

Some of the most commonly used plastics for varied purposes are described below, along with their main uses in different industries. Table 1 shows the types and amounts of commonly used plastics.

Polyethylene (PE)

Polyethylene (PE) is one of the most common types of plastics and one of the commercial materials that is widely used in applications like films and bottles for packaging applications (Czarnecka-Komorowska *et al.*, 2021). PE is the main polymer of the Polyolefins group, with more than 100 million tons of production per year, which is 34% of the total plastics market (Table 2). This is extensively used due to its good mechanical and chemical resistance, low density, cost-effectiveness, easy of processing, low toxicity, and good electric insulation (Rezvani *et al.*, 2020). It can also be transformed into different shapes (Kaushal *et al.*, 2021). It is a polymer of ethylene monomers and belongs to the class of thermoplastics. Every year, these plastics are produced in millions of tons and are used in many different areas and industries (Kaushal *et al.*, 2021). Polyethylene is classified mainly into three types: low-density PE (LDPE), with a density ranging between 0.910 and 0.940 g/cm3, linear low-density PE (LLDPE), with a density ranging between 0.910 and 0.920 g/cm^3, and high-density PE, with a density ranging between 0.941 and 0.967 g/cm^3 (Table 2) (Ugbolue, 2017).

Polyethylene Terephthalate (PETE/PET)

Polyethylene Terephthalate is one of the major synthetic petro- and thermoplastics that is used worldwide in many applications. It is produced in large amounts globally, amounting to 82 million tons per year (Kawai *et al.*, 2022) (Table 2). It is most commonly used in the manufacturing of single-use disposable drink bottles and in many different applications (Kaushal *et al.*, 2021; Montanari, 2020). Due to PET's excellent mechanical properties and biocompatibility, the demand for PET-based products (textile, food, packaging, medicine, and engineering) is very high in very large amounts globally (Damayanti *et al.*, 2021; Flores-Rojas *et al.*, 2022; Panowicz *et al.*, 2021). In 2015, the total production of PET packaging was estimated at 18.8 million tons (Damayanti *et al.*, 2021). It is the most common thermoplastic polymer belonging to the polyester family and containing the alternating ethylene glycolate and terephthalate subunits, linked via the ester functional group in their main chain (Kaushal *et al.*, 2021; Montanari, 2020; Shamas *et al.*, 2020). PET is widely used in the production of fibers for clothing, the textile industry, the production of single-use bottles for liquids and food packaging products, the packaging industry, the manufacturing of thermoforming methods, and in combination with glass fibers for engineering resins (Kaushal *et al.*, 2021; Montanari, 2020). More than 60% of the PET production is used for synthetic fibers and 30% for bottle production (Montanari, 2020). It is one of the main reasons for the pollution of plastics caused by the one-time use of plastic products (Kaushal *et al.*, 2021).

Table 1: Total plastic use and waste by sector in 2015 (Montanari, 2020)

Used	Primary plastic production (million tons)	Plastic waste generation (million tons)
Packaging	146	141
Building and construction	65	13
Textiles	59	42
Other sectors	47	38
Consumer products	42	37
Transportation	27	17
Electrical/ electronic	18	13
Industrial Machinery	3	1

Table 2: The characteristics of plastics (PE, PETE)

Plastic types	Chemical formula	Density (g/cm^3)	Melting Point (C)	Life span (years)	Amount production/ year (million tons)	Ref.
Polyethylene (PE)	$(C_2H_4)n$	0.88 – 0.96 (g/cm^3)	115 - 135		>100	(Ahmaditabatabaei *et al.*, 2021; Rezvani *et al.*, 2020)
Low density of PE (LDPE)		0.915-0.932	105-115	10-600		(Rezvani *et al.*, 2020; Mohanan*et al.* 2020)
High density of PE (HDPE)		0.940-0.970	128-136	>600		(Rezvani *et al.*, 2020; Mohanan*et al.* 2020)
Polyethylene Terephthalate (PET)	$(C_{10}H_8O_4)n$	1.370 * – 1.455 **	>250	450	82	(Ahmaditabatabaei *et al.*, 2021; Kawai *et al.*, 2020)

** amorphous, ** single crystal*

Enzymatic Degradation of PE and PET

Enzymes are biocatalysts that accelerate the process of chemical reaction to change substrate into a valuable product (Kaushal *et al.*, 2021). Several enzymes have an important role in the plastic degradation produced by a group of microorganisms that are both prokaryotic and eukaryotic. According to the release of enzymes by the microbial cells, there are two kinds of enzymes, extracellular and intracellular, which breakdown polymer chains and release new products like CO_2, H_2O, CH_4, and N_2 (Kaushal *et al.*, 2021). Due to low energy consumption, no need for hazardous chemical materials and expensive machinery, and mild process conditions, the biodegradation method is a good option for plastic degradation compared with mechanical and chemical degradation methods (Soong *et al.*, 2022). The degradation processes of PE and PET are done by Bacteria, Fungi, algae, and other microorganisms under biological processes in various ecosystems, including oceans, soil, farmland, animal manure, compost, landfills, sewage, etc. (Rezvani *et al.*, 2020; Zhang *et al.*, 2023). Biodegradation occurs in two types: oxido-biodegradation and Hydro-biodegradation. The first one consists of two stages: abiotic oxidation and biotic degradation. In abiotic oxidation, the carbon backbone of Plastics is oxidized into small parts by thermal and UV radiation. In biotic degradation, microbes colonize the surface of polymers and cause change by releasing some enzymes (Zeenat *et al.*, 2021).

The degradation process can be done while microorganisms exist according to the following conditions: enzymes should be released, the released enzyme should adhere to the surface of the polymers, enzymes can cleave polymer chains, and polymers should be changed into end products such as CO_2, H_2O, CH_4, and N_2 (Figure 2).

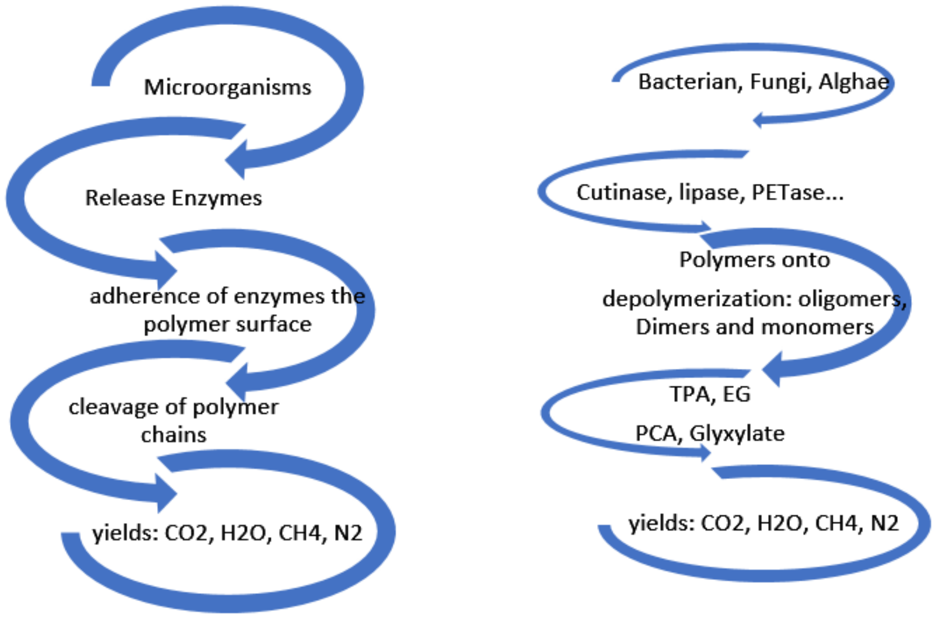

Figure 2: Mechanism of enzymatic biodegradation of polymers by Alshehrei (2017) (Shamas *et al.*, 2020; Zeenat *et al.*, 2021; Soong *et al.*, 2022).

Enzymatic Degradation of PE

The enzymes secreted by microorganisms can reduce the number of carbonyl groups, break them into carboxylic acids, and hydrolyze the polymer carbon chains into fragments, or bio-fragmentation, including long-chain aliphatic compounds such as alkanes and alkenes (Zhang *et al.*, 2022). Alkane compounds such as petroleum derivations are hydrolyzed by a key enzyme, namely Alkane hydroxylase (AHs) enzymes (Zhang *et al.*, 2023). Several enzymes (e.g., laccase, manganese peroxidase, and alkane hydroxylase) are released by microorganisms and act on the linear chain of carbons, which are joined together by hydrogen bonds and compound PE structures. This structure is usually semi-crystalline and resistant to biodegradation. PE polymers have different densities and physical structures due to different manufacturing processes and the arrangement of the linear chains (Monahan *et al.* 2020). Cutinase, lipase, PETase, and esterase are the most common enzymes for plastic degradation. These enzymes are generated by several microorganisms that can degrade PE and PET polymers in a similar manner (Kaushal *et al.*, 2021) in the soil, sea water, compost, and activated sludge (Monahan *et al.*, 2020).

Several enzymes capable of degrading PE are oxidoreductases. These are the main enzymes that degrade plastic materials in the environment (Kaushal *et al.*, 2021). Some well-known enzymes, such as Laccase, manganese peroxidase, alkane hydroxylase, and soybean peroxidase, oxidize polyethylene (PE) (Kaushal *et al.*, 2021; Zhang *et al.*, 2022). The terminal carbon in PE can be oxidized by most PE-degrading enzymes. For example, Laccase and manganese peroxidase, by hydroxylation reaction through either terminal or subterminal, can do terminal oxidation in the main component of polyethylene, and Alk B can degrade n-alkanes (Zhang *et al*., 2022).

Laccases

Laccases, a group of enzymes belonging to the blue copper oxidases, are monomeric glycoproteins, and they use oxygen as an electron acceptor to oxidize compounds, phenolic and non-phenolic (Temporiti *et al*., 2022). These enzymes were first identified in the plant species *Rhus vernicifera* in 1883, after many species of fungi belonging to *Ascomycetes, Basidiomycetes,* and *Deuteromycetes* were discovered. Laccases have the ability to oxidize a wide range of phenols, and they are produced by fungi and bacteria. in the higher plants have been reported as glycoproteins (Zhang *et al*., 2022). The LDPE was degraded by laccase isolated from R. ruber C208 strains in experimental conditions for 30 days of incubation at 30 °C with 1.5–2.5% weight loss (Zhang *et al*., 2022). The bacteria, like Klebsiella pneumoniae, are gram-negative and release lipase, peroxidase, and laccase that play important roles in PE degradation (Zeenat *et al*., 2021). Because these enzymes have roles in lignin degradation, the synthesis of dihydroxy naphthalene melanin, and the removal of toxic phenols produced, some writers appreciated their properties as protection against environmental stress. Temporiti *et al.* (2022) wrote "Thanks to their characteristics, laccases are used in a number of industrial applications such as delignification, pulp bleaching, and bioremediation processes removing toxic compounds through oxidative enzymatic coupling".

Alkane

Alkane hydroxylases (AHs) are key enzymes in the degradation of alkane compounds such as petroleum derivations (Zhang *et al*., 2023). The number and types of Alkane hydroxylases vary greatly in different microorganisms, like bacteria (Rezvani *et al*., 2020). Alkane has a similar structure to that of PE. These are mono-oxygenase enzymes that are candidates for PE degradation. AlkB is one alkane hydroxylase for PE degradation, and it was first isolated in alkane-consuming *Pseudomonas species* (Zhang *et al*., 2022).

Manganase

Manganase was identified as a lignin-degrading enzyme in the fungus *Phanerochaete chrysosporium*, and it enhanced the degradation of PE (Zhang *et al*., 2022). In experimental conditions for 12 days of incubation at 37 °C, it decreased the Mw (Zhang *et al*., 2022).

Peroxidases

Peroxidases are a class of enzymes that catalyze the oxidation of organic and inorganic compounds and the reduction of hydrogen peroxide (Temporiti *et al*., 2022). Manganese peroxidases, lignin peroxidases, versatile peroxidases, and dye decolorizing peroxidases are the main extracellular fungal peroxidases (Temporiti *et al*., 2022). A group of microorganisms, including *Phanerochaete chrysosporium*, *Trametes versicolor*, *Pleurotus spp.*, *Phlebia radiata*, *Bjerkandera adusta*, *Ceriporiopsis subvermispora*, *Dichomitus squalens*, and gram-negative bacteria like *Klebsiella pneumoniae*, produce peroxidases (Temporiti *et al*., 2022; Zeenat *et al*., 2021). They have a high redox potential to oxidize substrates, so they are used in a large number of applications. There are some other enzymes that degrade both PE and PET, including cutinases, lipases, and esterases, discussed in the next section under enzymatic degradation of PET.

Enzymatic Degradation of PET

PET is degraded by many microorganisms, including fungi and bacteria. PET consists of aromatic polyesters with a high glass transition temperature (Tg) of around 75–80 °C in air. This polymer becomes more accessible and flexible to enzymatic (microbial) degradation above the Tg (Mohanan *et al*., 2020). PET polymers are used for metabolism and growth by several microorganisms (e.g., bacterium I*deonella sakainsis*, *Pseudomonas spp.*, *Saccharomonos poraviridis*, *Humicola insolens*, *Necardia species*, *Thermobifida halotolerans*, *Bacilus flexus*) (Table 3) and depolymerized by *bacterium sakaiensis* as carbon and energy sources (Mohanan *et al*., 2020).

Many fungal hydrolytic enzymes can hydrolyze the monomeric structural units of PET that act on ester bonds as well. These enzymes include esterases, lipases, cutinases, and carboxylesterases (Ahmaditabatabaei *et al*., 2021; Temporiti *et al*., 2022). The microorganisms adhere to the surface of PET films and then secrete extracellular PET hydrolases, which bind to the PET films and initiate the biodegradation process. Ester bonds of PET were affected by PET hydrolases, generating incomplete hydrolysis products (Qi *et al*., 2021; Soong *et al*., 2022).

Several enzymes have been biochemically characterized for PET hydrolysis. These enzymes belong to the α/β hydrolase group, including carboxylic ester hydrolyses (Soong *et al*., 2022). Due to their solubility, they have the ability to hydrolyze PET (Khairul Anuar *et al*., 2022). Hydrolytic enzymes act on ester bonds on PET polymers and break them down into simpler monomers (Khairul Anuar *et al*., 2022). There are many types of hydrolase enzymes included in the general class of carboxylic ester hydrolases, including Cutinases, Lipases, Carboxylesterases, PETase, MHETase, and esterase (Table 3) (Khairul Anuar *et al*., 2022; Temporiti *et al*., 2022; Soong *et al*., 2022). The polyester hydrolases have originated from bacteria (e.g., *Thermobifida fusca, Thermomonospora curvata,* and *Ideonella sakaiensis*) and fungi (e.g., *Fusarium solani, Humicola insolens,* and *Aspergillusoryzae*) (Soong *et al*., 2022).

Cutinases

Cutinases are extracellular enzymes that are able to degrade plastics and catalyze the breaking of ester bonds (Khairul Anuar *et al*., 2022). These enzymes are produced by groups of microorganisms like fungi and bacteria. These microorganisms are either saprophytic or phytopathogenic (Maurya *et al*., 2020). Cutin, an insoluble aliphatic polyester excreted from the plant cuticle, is hydrolyzed by cutinases (Soong *et al*., 2022). Unnatural substrates that are synthetic polyesters, such as PET, are degraded by cutinases as well (Khairul Anuar *et al*., 2022). Various polyesters are hydrolyzed by cutinases at temperatures between 40 and 70 °C and pH 7-9 (Soong *et al*., 2022). Cutinases belong to the hydrolase superfamily, and they have an α/β fold and a central sheet composed of five parallel strands covered by two or three helices on either side of the sheet (Maurya *et al*., 2020; Temporiti *et al*., 2022). High-molecular-weight compounds such as cutin and other related synthetic compounds are accommodated by the active site of cutinase (Maurya *et al*., 2020). Cutinases are multifunctional enzymes that are used in the textile, detergent, and food industries as industrial biocatalysts due to their ability to catalyze hydrolysis reactions with many industrial applications for polymer and fiber degradation (Khairul Anuar *et al*., 2022; Temporiti *et al*., 2022). Cutinase enzyme that can degrade PET structure was generated by thermophilic actinomycetes bacteria (e.g., *Thermobifida fusca, T. alba, T. cellulosilytica, T. curvata, and Sacchromonspora viridis*) and fungi (e.g., *Humicola insolens, Fusarium solani pisi, Fusarium oxysporum, Penicillium citrinium citrinium, Saccharospora viridis, Aspergillus fumigatus,* and *Aspergillus nidulans*) (Khairul Anuar *et al*., 2022; Temporiti *et al*., 2022; Soong *et al*., 2022).

Lipases

Lipases are extracellular triacylglycerol acyl hydrolases, and they can hydrolyze ester bonds from insoluble substrates of tri-, di-, and mono-glycerides into free fatty acids and glycerol. These enzymes hydrolyze long-chains that are greater than C_{10} and water-insoluble triglycerides (Khairul Anuar *et al*., 2022; Temporiti *et al*., 2022). The physiochemical properties of these enzymes, like wettability, dyeability, and absorbency, cause good degradation of PET textiles (Khairul Anuar *et al*., 2022). The lipases are produced by fungi and bacteria such as *Aspergillus, Acremonium, Alternaria, Beauveria, Candida, Eremothecium, Fusarium, Geotrichum, Humicola, Mucor, Ophiostoma, Penicillium, Rhizomucor, Rhizopus, and Trichoderma (Temporiti et al., 2022), Triticum aestivum, Burkholderia spp., and Thermomyces lanuginosus, Cryptococcus sp., Pseudomonas spp., Bacillus spp.,* and *Klebsiella pneumoniae* (Zeenat *et al*., 2021; Kaushal *et al*., 2021; Khairul Anuar *et al*., 2022). Most of these are produced by *Aspergillus oryzae, Candida antarctica,* and *Pichia pastoris*. A lipase that can "catalyze PET hydrolysis using 0.1g/L bis (2-hydroxyethyl) terephthalate (BHT)" is produced by *Aspergillus oryzae* (Temporiti *et al*., 2022). The yeast *Pichia pastoris generates* lipase triacylglycerol hydrolase, which is able to modify the surface morphology of polyester fibers at 60 °C and pH 7.5–8 (Temporiti *et al*., 2022).

Carboxylesterase

In both prokaryotic and eukaryotic microorganisms, Carboxylesterase has been reported. Because of its open active site and distinctive binding pocket, this enzyme has broad substrate specificity (Khairul Anuar *et al*., 2022). Carboxylesterase is released by thermophilic T. *fusca* belonging to the actinomycete, and it is able to hydrolyze PET fibers at 50 °C and pH 8.0. This enzyme was identified from *Pseudomonas aestusnigri's genome*, a mesophilic marine bacterium (Khairul Anuar *et al*., 2022).

Esterase

Esterase is present in nearly all living organisms, and it can cleave ester bonds in PET monomers that are linked by ester bonds (Maurya *et al*., 2020; Khairul Anuar *et al*., 2022). Bacillus and Nocardia were the first microorganisms to discover PET esterase. P-nitrobenzylesterase hydrolyzes PET into ATP and mono(2-hydroxyethyl) (MHET) TPA using bis (benzoyloxyethyl) terephthalate in optimum conditions at 37 ◦C and pH 7.0 (Khairul Anuar *et al*., 2022). Kawai *et al*. (2014) reported polyesterase capable of hydrolyzing PET in the presence of Ca ions from *Saccharomonospora viridis*. Esterase from *Thermobifida halotolerans* was reported by Ribitsch *et al*. (2012) to degrade PET into TA and MHET as well (Maurya *et al*., 2020).

IsPETase

IsPETase belongs to the α/β hydrolase superfamily and was isolated from a plastic bottle recycling factory in Japan. This enzyme is isolated from a mesophilic bacterium, *Ideonella sakaiensis*, and is active at low temperatures (20 °C–40 °C). This is a unique characteristic of this enzyme for PET degradation. This is because this enzyme has a broader open active site that increases the enzyme's specificity for bulkier substrates like PET (Khairul Anuar *et al*., 2022; Blázquez-Sánchez *et al*., 2022).

PETase

PETase is secreted by a bacterium, *Ideonella sakaiensis*, and it breaks down PET into simple monomers that are harmless. This enzyme hydrolyzes the polymer of PET into mono(2-hydroxyethyl) terephthalic acid (MHET), and MHETase produces Terephthalic acid (TPA) and Ethylene glycol (EG) (Maurya *et al*., 2022; Khairul Anuar *et al*., 2022). *Chlamydomonas reinhardtii* is a unicellular microorganism, photosynthetic microalgae, and it produces PETase for plastics degradation (Kim *et al*. 2021).

MHETase

The bacterium *Ideonella sakaiensis* releases another enzyme, namely MHETase. This enzyme acts synergistically with PETase to complete PET degradation. PET is hydrolyzed by PETase or cutinase to generate bis (2-hydroxylethyl) terephthalate (BHET) and mono (2-hydroxyethyl) terephthalate (MHET). Then, BHET and MHET are hydrolyzed by MHETase to produce TPA and EG (Khairul Anuar *et al*., 2022).

Polyesterases

Beauveria brongniartii and *Penicillium citrinum* produce the extracellular polyesterases that can degrade PET. During

Table 3: Enzymes produced microbes and involved in the enzymatic degradation of PE and PET

Enzyme	Microorganisms	Activity	Plastics	References
Lipases	**Bacteria** *Pseudomonas fluorescens, Pseudomonas putida, Pseudomonas chlororaphis, Bacillus cereus, Bacillus thuringiensis, Bacillus albus Bacillus aerius Maraxellas sp., Klebsiella pneumoniae, Acanthopleuribacter pedis* **Fungi (genera)** *Aspergillus, Acremonium, Alternaria, Beauveria, Candida, Eremothecium, Fusarium, Geotrichum, Humicola, Mucor, Ophiostoma, Penicillium, Rhizomucor, Rhizopus, Trichoderma , Triticum aestivum*	Hydrolases	PET, PE	(Mohanan *et al.*, 2020; Bollinger *et al.*, 2020; Maurya *et al.*, 2020; Zeenat *et al.*, 2021; Temporiti *et al.*, 2022; Dhaka *et al.* 2022; Blaasgues-Sanches *et al.*, 2022)
Cutinase	**Bacteria** *Thermobifida spp., Pseudomonas spp., Saccharomonospora spp., Saccharomonos poraviridis, Humicola insolens* **Fungi** *Cryptococcus sp., Thermomonospora spp., Fusarium solani pisi, Fusarium oxysporum, Humicola insolens Aspergillus fumigatus*	Hydrolases	PE, PET	(Mohanan *et al.*, 2020; Bollinger *et al.*, 2020; Maurya *et al.*, 2020; Zeenat *et al.*, 2021; Temporiti *et al.*, 2022; Dhaka *et al.* 2022; Blaasgues-Sanches *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022)
Laccases	**Bacteria** *Klebsiella pneumoniae* **Fungi** *Aspergillus flavus, Pleurotus ostreatus Trichoderma harzianum, Trametes versicolor, Agrocybe aegerita*	Oxidoreductases	PE	(Zeenat *et al.*, 2021; Temporiti *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022)
Peroxidases	*Klebsiella pneumoniae, Phanerochaete chrysosporium, Trametes versicolor, Pleurotus spp., Phlebia radiata, Bjerkandera adusta, Ceriporiopsis subvermispora, Trichoderma harzianum, Dichomitus squalens*	Oxidoreductases	PE	(Zeenat *et al.*, 2021; Temporiti *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022)
Manganase	**Fungi** *Phanerochaete chrysosporium Pleurotus ostreatus, Trametes cervine*	Oxidoreductases	PE	(Temporiti *et al.*, 2022)
Polyesterase	**Fungi** *Beauveria brongniartii Penicillium citrinum*	Hydrolyses	PET	(Temporiti *et al.*, 2022)
Esterase	**Bacteria** *Bacillus spp., Clostridium spp., Thermobifida spp., Pseudomonas Putida, Necardia sp., Comanonas testoterone Thermobifida halotolerans Bacilus flexus*	Hydrolyses	PE, PET	(Mohanan *et al.*, 2020; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022; Dhaka *et al.*, 2022)
IsPETase	**Bacteria** *Oleispira antractica Ideonella sakaiensis*		PET	(Blaasgues-Sanches *et al.*, 2022)
PETase, MHETase	**Bacteria** *Escherichia coli Bacillus subtilis Ideonella sakaiensis Pseudomonas aestusnigri*	Hydrolyses	PET	(Palm *et al.*, 2019; Mohanan *et al.*, 2020; Maurya *et al.*, 2020; Kim *et al.*, 2021; Qi *et al.*, 2021;

	Fungi *Yarrowialipolytica Pichia pastoris* **Algae** *Phaeodactylum tricornutum Chlamydomonas reinhardtii*			Liu *et al.*, 2022; Khairul Anuar *et al.*, 2022; Soong *et al.*, 2022; Dhaka *et al.*, 2022)
Alkane	*Lysinibacillus spp*	Oxid	PE	(Jeon *et al.*, 2021)
Dioxygenase and PCA dioxygenase	*Ideonella sakaiensis*		PE	(Dhaka *et al.*, 2022)
Polyurethanase	*Serratia marcescens*			(Mohanan *et al.*, 2020)
Monooxygenase	*Bacillus cereus*		PE	(Mohanan *et al.*, 2020)
Carboxylesterases	*Thermobifida fusca*		PE	(Maurya *et al.*, 2020)

treatment of PET, polyesterase was secreted by *Beauveria brongniartii* (Temporiti *et al.*, 2022). PET depolymerization occurs through the synergic action of cutinase and lipase as well.

CONCLUSIONS

PE and PET are the most important plastics used around the globe. Production and use of these synthetic materials are increasing, as is waste generation. The accumulation of plastic waste in landfills, seas, and oceans is an extremely challenging environment, as some reports indicate that 400 metric tons of plastic waste are generated and 174 metric tons enter natural systems. Many studies have been conducted to present waste management and recycling methods, but traditional methods of recycling PE and PET waste are still hazardous and unfriendly to the environment due to their effects on ecosystems. Currently, biodegradation is a good strategy that has some advantages, such as decreasing the use of chemically hazardous elements, reducing the use of expansive machinery, supporting environmental principles, etc. The enzymes that are able to degrade PE and PET are produced by a group of microorganisms like bacteria, fungi, algae, and even insects. This method could be an effective strategy toward a green recycling scheme for plastic waste. Under a biological process, enzymes such as cutinase, lipase, PETase, IsPETase, esterase, and other enzymes can break down polymers of PE and PET wastes into valuable products like CO2, H2O, and CH4. Therefore, the scientific society's attention has increased on the subject.

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