



Homeland Defense & Security
Information Analysis Center



HDIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

Role of Esterase and Cutinase Activity on Biodegradation of Waste Plastic Materials

Report Number:

HDIAC-BCO-2025-651

Completed March 2025

HDIAC is a U.S. Department of Defense
Information Analysis Center

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 01-03-2025		2. REPORT TYPE Technical Research Report		3. DATES COVERED (From – To)	
4. TITLE AND SUBTITLE Role of Esterase and Cutinase Activity on Biodegradation of Waste Plastic Materials				5a. CONTRACT NUMBER FA8075-21-D-0001	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Moshan Kahandawala				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Homeland Defense & Security Information Analysis Center (HDIAC) SURVICE Engineering Company 4695 Millennium Drive Belcamp, MD 21017-1505				8. PERFORMING ORGANIZATION REPORT NUMBER HDIAC-BCO-2025-651	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Technical Information Center (DTIC) 8725 John J. Kingman Road Fort Belvoir, VA 22060-6218				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Statement A. Approved for public release: distribution is unlimited.					
13. SUPPLEMENTARY NOTES DoDIAC Technical Focus Areas: Advanced Materials DoD Modernization Priorities					
14. ABSTRACT The biodegradation of synthetic polymers is a key element for achieving a circular economy with high material reuse and environmentally friendly waste products. Laccase enzymes, which play a key role in lignin degradation, have been shown to degrade high-molecular-weight polyethylene (PE) and nylon-66 membranes using a laccase-mediator system. Additionally, esterases and cutinases are known to depolymerize polyester-based plastics such as polyethylene terephthalate (known as PET) and polyurethane. However, the mechanisms of enzymatic degradation remain poorly understood. This report highlights the potential for microorganisms and enzymes to contribute to the biodegradation of plastic waste, with a focus on the depolymerization of PE and other nonpolyester plastics. Identifying key enzymes associated with depolymerization activity (e.g., laccase, esterases, and cutinases) facilitates development of novel biotechnological processes for regenerative plastic circularity.					
15. SUBJECT TERMS esterase, cutinase, enzymes, enzymatic activity, microplastics, biodegradation, microorganisms, plastic waste					
16. SECURITY CLASSIFICATION OF: U			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 30	19a. NAME OF RESPONSIBLE PERSON Ted Welsh, HDIAC Director
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-360-4600

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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TI Research

A chief service of the DoDIAC is free technical inquiry (TI) research limited to four research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. Given the limited duration of the research effort, this report is not intended to be a deep, comprehensive analysis but rather a curated compilation of relevant information to give the reader/inquirer a "head start" or direction for continued research.

Abstract

The biodegradation of synthetic polymers is a key element for achieving a circular economy with high material reuse and environmentally friendly waste products. Laccase enzymes, which play a key role in lignin degradation, have been shown to degrade high-molecular-weight polyethylene (PE) and nylon-66 membranes using a laccase-mediator system. Additionally, esterases and cutinases are known to depolymerize polyester-based plastics such as polyethylene terephthalate (known as PET) and polyurethane. However, the mechanisms of enzymatic degradation remain poorly understood. This report highlights the potential for microorganisms and enzymes to contribute to the biodegradation of plastic waste, with a focus on the depolymerization of PE and other nonpolyester plastics. Identifying key enzymes associated with depolymerization activity (e.g., laccase, esterases, and cutinases) facilitates development of novel biotechnological processes for regenerative plastic circularity.

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1.0 TI Request

1.1 Inquiry

What is the role of cutinase or esterase activity on biodegradation of man-made structures?

1.2 Description

The inquirer is interested in obtaining information regarding the action of cutinases (proteins that degrade cutin) on the biodegradation of man-made materials. The inquirer is specifically seeking information on the relationship between cutinase (or, more generally, esterase activity) and the degradation of polymeric coatings of any given material and/or other materials that could impact the environment, such as plastic.

2.0 TI Response

This TI response introduction section has been generated with assistance from the U.S. Department of Defense Air Force Research Laboratory (AFRL) large language model, the Nonclassified Internet Protocol Router Generative Pretrained Transformer (NIPRGPT). It is an alpha version (for first phase formal testing) of a generative artificial intelligence (AI) capability created by AFRL. AFRL based the tool on the Meta AI Llama version 2 (Llama 2). NIPRGPT is not a specific version of Llama 2 but rather a separate model that was trained on a large dataset from various sources with a cutoff date of December 2023. It was prompted with several questions similar in form to “what are the scientific and technical applications of cast glass” and “what is the role of cutinases and esterases in breaking down microplastics.” NIPRGPT was not used for the research done to generate the findings or conclusion of the report [1].

Esterases are a broad class of enzymes that break down ester bonds between a carboxylic acid and an alcohol. These enzymes are found in a wide range of organisms, including animals, plants, and microorganisms and can act on a wide range of ester-containing compounds, including triglycerides, phospholipids, and other esters. Esterases play important roles in various biological processes to include metabolism, detoxification, and biosynthesis where they can help with processes such as breaking down ester-containing compounds like triglycerides and phospholipids, breaking down toxic ester-containing compounds like insecticides and pharmaceuticals, or being used in the synthesis of ester-containing compounds such as waxes and cutin [1].

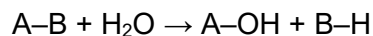
Cutinases, on the other hand, are a specific type of esterase specialized to break down the ester bonds in cutin. Cutin is a complex lipid polymer found in plant cuticles that can be produced by fungi, bacteria, and other microorganisms that infect plants. These enzymes can hydrolyze ester bonds that hold the cutin polymer together and can be used in biotechnology, agriculture, food industry, and other applications for such processes as production of biofuels and bioplastics, production of biopesticides to control plant pathogens and pests, or improvement of the texture and shelf life of fruits and vegetables.

The study of enzyme-substrate interactions is essential in understanding how cutinases and esterases can degrade polymeric coatings like plastics. This is crucial to the study of how the degradation of man-made materials impacts industrial and commercial processes and products, as well as the environment. It is key to the creation of novel solutions to environmental damage caused by microplastics, the development of environmentally friendly materials and better waste management practices such as biobased recycling methods, the development of enzyme-resistant packaging materials and coatings for industrial and commercial products that are more durable and resistant to biodegradation, the development of coatings to extend the shelf life of foodstuffs, and a host of other areas.

This report focuses on the use of esterase and cutinase enzymes for the controlled biodegradation of waste plastic materials.

2.1 Cutinases

Cutinases are serine esterases that belong to the α/β hydrolase family. Hydrolase is a class of enzyme that commonly performs as a biochemical catalyst that uses water to break a chemical bond, which typically results in dividing a larger molecule into smaller molecules:



A hydrolase enzyme splits esters (polymers) into an acid and an alcohol with water in a chemical reaction called hydrolysis.

Cutinases and esterases are found in both fungi and bacteria.

- Cutinases are a subclass of esterase enzyme, which is identified by its ability to hydrolyze polyesters with high molar mass.
- Cutinases are α/β hydrolases or carboxylic ester hydrolases, which were originally extracted from plant fungi (i.e., *Fusarium solani* [FsC] pisi).

- Cutinases are produced by various fungi such as *FsC*, *Penicillium citrinum*, *Pichia pastoris*, *Aspergillus oryzae*, and *Humicola insolens* [2–4].
- “Cutinases hydrolyze soluble esters, insoluble triglycerides, and various polyesters. In addition to the hydrolysis reaction, cutinases also show synthetic activity and transester activity” [5].
- “In recent years, it has been found that cutinases can biodegrade plastic and biomodified synthetic fibers” [5].
- Cutinases are the most important enzymes in solving plastic pollution.

2.2 Enzymatic Degradation of Polymers Mechanism

Microorganisms first excrete extracellular enzymes, which depolymerize the polymers outside the cells. If the molar mass of the polymers is sufficiently reduced to generate water-soluble intermediates, those will be transported into the microorganisms and introduced there into the metabolic pathways, producing microbial metabolic end products such as water, carbon dioxide, and new biomass. Figures 1 and 2 show the general mechanism of enzymatic polymer degradation.

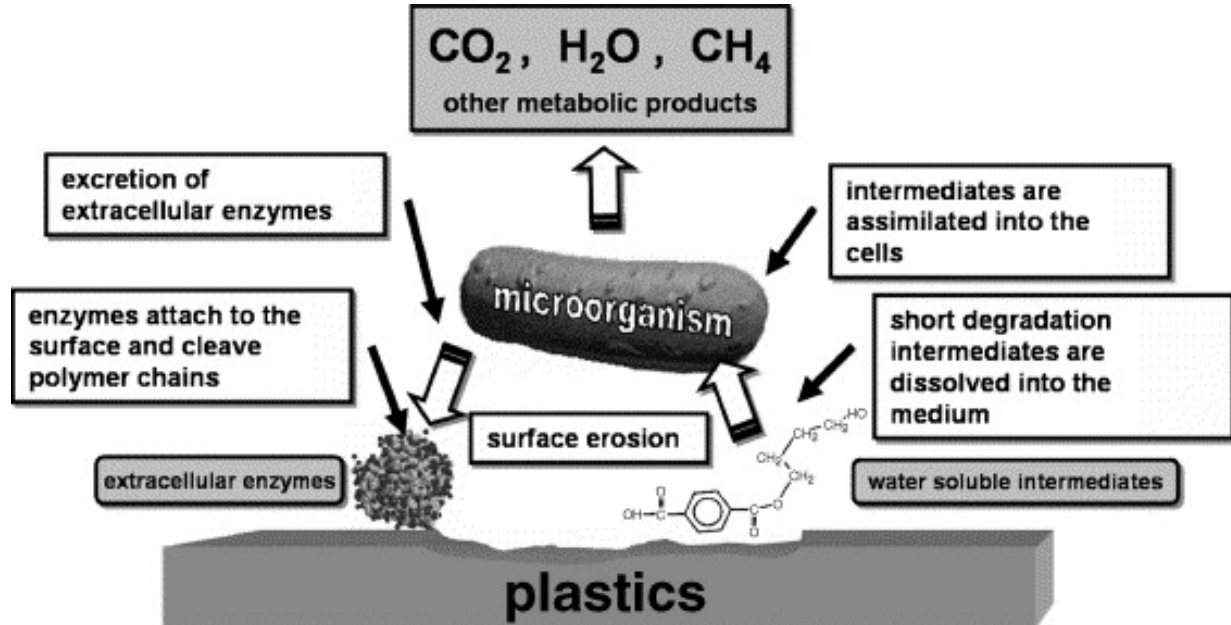
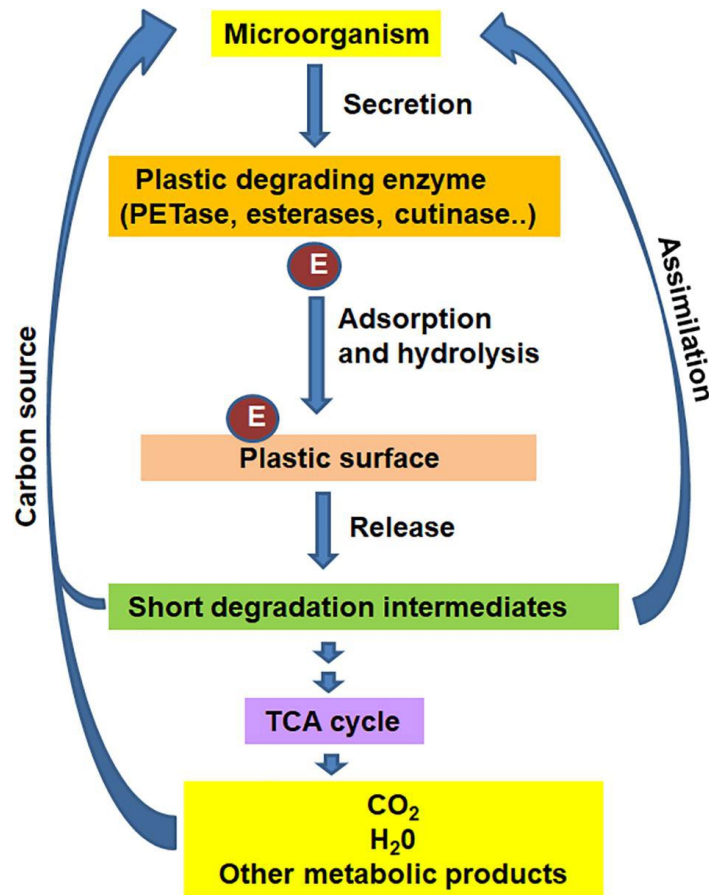


Figure 1. General Mechanism of Enzymatic Catalyzed Hydrolytic Polymer Degradation [6].



Note: TCA = tricarboxylic acid.

Figure 2. General Mechanism for Biological Degradation of Plastics Under Aerobic Conditions [7].

2.3 Polyethylene Terephthalate (PET)

PET, or sometimes poly (ethylene terephthalate), is the most common thermoplastic polymer resin of the polyester family and is used in fibers for clothing, containers for liquids, and foods [8].

Most of the produced plastic material has a fossil origin. Thermoplastic materials such as polyethylene (PE), polyurethane (PUR), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and PET represent 80% of total global plastic usage [9].

The enzymatic degradation of PET is typically conducted by cutinases, which can hydrolyze cutin and various polyesters such as PET at temperatures of 40–70 °C and pH 7–9, without the need for cofactors [10–13]. The enzymatic hydrolysis of PET gives the monomers terephthalic acid (TPA) and ethylene glycol (EG), which aid efficient recovery.

“Cutinase-Catalyzed Hydrolysis of Poly(Ethylene Terephthalate)” [12] is one available article discussing PET. “Catalytic activities of cutinases from *Humilica insolens* (HiC), *Pseudomonas mendocina* (PmC), and *FsC* were studied using low-crystallinity (lc) and biaxially oriented (bo) PET films as model substrates.” A bo-polypropylene film is film stretched in both machine and transverse directions, producing molecular-chain orientation in two directions. Due to its advantages, this film has become very popular and is highly regarded across the globe.

The crystallinity of a polymer refers to the degree to which there are regions where the polymer chains are aligned with one another. Crystallinity defines the degree of long-range order in a material and strongly affects its properties. The more crystalline a polymer is, the more regularly aligned its chains are. Increasing the degree of crystallinity increases hardness and density. An assay of cutinase activity for PET hydrolysis found that HiC maximal initial activity occurred from 70 to 80 °C and at 50 °C for PmC and FsC [12].

Additionally, [12]:

...cutinases had about 10-fold higher activity for the lcPET (7% crystallinity) than for the boPET (35% crystallinity).

The hydrolysis rate constant...was 7-fold higher for HiC at 70 °C (0.62 $\mu\text{mol}/\text{cm}^2/\text{hr}$) relative to PmC and FsC at 50 and 40 °C, respectively.

In a 96-hr degradation study using lcPET films, incubation with PmC and FsC both resulted in a 5% film weight loss at 50 and 40 °C, respectively.

HiC-catalyzed lcPET film hydrolysis at 70 °C, resulting in a $97 \pm 3\%$ weight loss in 96 hr...

For all three cutinases, analysis of aqueous soluble degradation products showed that they consist exclusively of TPA and EG.

To date, numerous polyethylene terephthalate hydrolytic enzymes (PHEs) have been identified. Table 1 summarizes the biochemically characterized PHEs. The majority of this type of enzyme comprises cutinases, which are able to hydrolyze cutin, an insoluble aliphatic polyester excreted from the plant cuticle. Notably, the substrate specificity of cutinases is broad. These enzymes exhibit hydrolytic activities for both insoluble triglycerides (typical substrates for lipases) and soluble esters (substrates for esterases) [14].

Table 1. Biochemically Characterized PHEs With Known Amino Acid Sequence [14]

Enzyme	Organism	Optimal Temperature Range/Substrate*	Reference
PETase	Ideonella Sakaiensis 201-F6	20–45 (40)/PET; 30/pNPB	[15]
TfH	Thermobifida Fusca DSM43793	30–60 (60)/PET; 20–70 (60)/pNPB	[16–18]
LCC	Uncultured Bacterium	30–80 (70)/PET; 30–80/pNPB	[19, 20]
Thc_Cut1	Thermobifida Cellulosilytica DSM44535	50/PET; 25/pNPB	[21]
Thc_Cut2	Thermobifida Cellulosilytica DSM44535	50/PET; 25/pNPB	[21]
Thf42_Cut1	Thermobifida Fusca DSM44342	50/PET; 25/pNPB	[21]
Tha_Cut1	Thermobifida Alba DSM43185	50/PET; 25/pNPB	[22]
Thh_Est	Thermobifida Halotolerans DSM44931	50/PET; 25/pNPB	[23]
Cut190 S226P/R228S	Saccharomonospora Viridis AHK190	60–65/PET; 25–75 (65)/pNPB	[11]
PET2	Uncultured Bacterium	50/agar plate containing PET nanoparticles; 17–90 (60–70)/pNPO	[24]
PET5	Oleispira Antarctica RB-8	50/agar plate containing PET nanoparticles	[24]
PET6	Vibrio Gazogenes	50/agar plate containing PET nanoparticles; 17–90 (55)/pNPO	[24]
PET12	Polyangium Brachysporum	50/agar plate containing PET nanoparticles	[24]
Tcur0390	Thermomonospora Curvata DSM 43183	50/PET nanoparticles; 25–70 (55)/pNPB	[25]
Tcur1278	Thermomonospora Curvata DSM 43183	50–60 (60)/PET nanoparticles; 25–70 (60)/pNPB	[25]

*Reported temperature range in which the enzymatic activity was detected against the indicated substrate.

Note: pNPB = p-nitrophenol butyrate, TfH = from Thermobifida fusca hydrolase, LCC = leaf-branch compost cutinase, pNPO = p-nitrophenol octanoate.

2.4 Polyester PUR

According to Schmidt et al. [26]:

[PURs] are widely used synthetic polymers present in many aspects of daily life.

PUR is used in many industrial applications to produce foams, elastomers, coatings, adhesives, and sealants applied in automotive, furniture, bedding, textiles, and other industrial areas [27].

The large amounts of synthetic polymers produced has resulted in a massive increase of plastic waste requiring novel recycling strategies.

Sections 2.4.1–2.4.4 provide brief summaries of relevant research articles available for PUR.

2.4.1 “Cutinase-Catalyzed Polyester-Polyurethane Degradation: Elucidation of the Hydrolysis Mechanism”

This article discusses enzymatic hydrolysis of a PUR-polyester copolymer using HiC that was investigated at 50 °C for 168 hr. “HiC effectively hydrolysed the polymer, reducing the number-average molecular weight (Mn) and the weight-average molecular weight (Mw) by 84% and 42%, respectively” [28].

2.4.2 “Degradation of Polyester Polyurethane by Bacterial Polyester Hydrolases”

This article discusses the degradation of the thermoplastic polyester polyurethane (TPU) Elastollan B85A-10 and C85A-10 that was performed by the polyester hydrolases LCC, TfCut2 (from *Thermobifida fusca* KW3), Tcur0390, and Tcur1278. Table 2 shows the “weight loss of TPU Elastollan B85A-10 and C85A-10 cubes with an initial weight of approximately 80 mg after hydrolysis by LCC, TfCut2, Tcur0390, and Tcur1278 for 100 hr at 60–70 °C. All values were determined at least in triplicate” [26].

Table 2. Weight Loss of TPU Elastollan B85A-10 and C85A-10 Cubes [26]

Enzyme	Temperature (°C)	Weight Loss (%)	
		B85A-10	C85A-10
LCC	60	1.2 ± 0.2	1.2 ± 0.2
	70	3.2 ± 0.5	2.5 ± 0.4
TfCut2	60	1 ± 0.1	1.1 ± 0.2
	70	1.9 ± 0.3	1.5 ± 0.2
Tcur0390	60	0.3 ± 0.1	0.4 ± 0.0
Tcur1278	60	0.6 ± 0.1	0.8 ± 0.1

2.4.3 “Purification and Properties of a Polyester Polyurethane-Degrading Enzyme From *Comamonas Acidovorans* TB-35”

This article discusses “...a polyester PUR-degrading enzyme, PUR esterase, derived from *Comamonas acidovorans* TB-35, a bacterium that utilizes polyester PUR as the sole carbon source.” PUR esterase degraded solid polyester PUR at 45 °C, with diethylene glycol and adipic acid released as the degradation products. PUR esterase degrades PUR in a two-step reaction: (1) hydrophobic adsorption to the PUR surface and (2) hydrolysis of the ester bond of PUR [29].

This article indicates that [29]:

The PUR degradation activity was detected at the pH range from 4.0 to 8.0, and the highest activity was observed at pH 6.5. The optimum temperature for PUR esterase was 45 °C. The thermostability was also determined: PUR esterase was stable within 30 min of incubation at 55 °C but almost inactivated (85%) at 60 °C. The purified PUR esterase degraded poly(diethylene glycol adipate) [and other different substrates].

Table 3 lists the percent of degradation of PUR esterase on different substrates.

Table 3. Substrate Specificity of PUR Esterase [29]

Substrate	Activity (% Degradation)
Poly(Diethylene Glycol Adipate)	36.4
Tributylin	100
Triolein	0
Poly(3-Hydroxybutyrate)	0
Poly(3-Hydroxybutyrate-Co-3-Hydroxyvalerate)	0
Poly(L-Lactic Acid)	0
Mw, 5,000	7.7
Mw, 20,000	0

2.4.4 “Enzymatic Degradation of Aromatic and Aliphatic Polyesters by *P. pastoris* Expressed Cutinase 1 From *Thermobifida Cellulosilytica*”

This article reports [30]:

Cutinase 1 from Thc_Cut1 expressed in *P. pastoris* was used for hydrolysis of aromatic and aliphatic polyesters.

Both [of the] tested aliphatic polyesters, poly (butylene succinate) (PBS) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), were hydrolyzed by Thc_Cut1 at 65 °C for 96 hr.

The mass of PBS thin films decreased by 93% upon enzymatic hydrolysis with Thc_Cut1, whereas only a small mass change of 3% was observed for PHBV.

2.5 PBS and Copolymers

An article by Nikolaivits et al. states that [31]:

PBS and its copolymers are a family of biodegradable polymers with excellent biodegradability, thermoplastic processability, and balanced mechanical properties.

PBS and its copolymers are degraded by various microorganisms in different environments. It has been found that bacteria [32], fungi [33], and yeasts [34] possess all the necessary mechanisms for PBS degradation, which are mainly based on the secretion of extracellular enzymes [35].

The enzymatic hydrolysis of PBS can be catalyzed by lipases, esterases, cholesterol esterases, and cutinases. Although lipases degrade a wide variety of PBS based-polymers, cutinases derived from the fungus *Fusarium* sp. can achieve higher degradation rates than lipases. For example, a cutinase from *FsC* completely degraded pure PBS films after 26 hr [36]. Additionally, another cutinase from a *Fusarium* sp. completely degraded PBS films with average molecular weight of $1.5\text{--}3.7 \times 10^4$ in less than 10 hr [37]. In contrast to lipases, cutinases probably cause endotype scission of PBS polymer, producing succinic acid monomer and oligomers such as di(hydroxy-butyl) succinate and hydroxybutyl disuccinate, which are subsequently hydrolyzed into monomers and dimers [36].

2.6 Polylactic Acid (PLA)

PLA is different than most thermoplastic polymers in that it is derived from renewable resources like corn starch or sugar cane. It is classified as an aliphatic polyester because of the ester bonds that connect the monomer units and has gained a key role in the biomedical field for a wide range of applications [38]. PLA naturally degrades in situ through a hydrolysis mechanism, as water molecules break the ester bonds that constitute the polymer backbone. The key enzymes that can depolymerize PLA are carboxylesterases, cutinases, and lipases [32, 39, 40].

Nikolaivits et al. further note that [31]:

These enzymes were able to hydrolyze synthetic polyesters, including PLA, producing water-soluble degradation products such as lactic acid monomers, dimers, and higher oligomers [41]. [A study that compared alcalase, esterase, and lipase degradation on PLA showed that] alcalase was the most effective in degrading PLA nonwoven fibers. The reduction of PLA weight in the case of alcalase was 25% after 21 days of treatment, yielding more than 15× higher compared to that of the other enzymes [32].

2.7 Poly(ϵ -caprolactone) (PCL)

PCL is a slow-degrading aliphatic polyester and a widely utilized polymer for biomaterial and sustainable packaging applications. The in vivo degradation of PCL may require 2–3 years [42], which is a remarkably slower rate than the values reported for similar materials, such as PLA or polyglycolic acid, because of its higher hydrophobicity [43, 44].

Nikolaivits et al. also note that [31]:

The most well-studied enzymes for the degradation of PCL are lipases, esterases, and cutinases [45, 46]. A cutinase-like enzyme named PaE from the yeast *Pseudozyma antarctica* JCM 10317 was used to treat PCL films, resulting in 61.5% biodegradation [47]. Another study also examined the activity of cutinases derived from the fungi *FsC* and *Aspergillus fumigatus*. The weight of PCL films treated with the cutinase of *FsC* reduced by 44.3% at 40 °C after 6 hr, while the *A. fumigatus* cutinase completely degraded the PCL films under the same conditions [48].

2.8 PE, PP, PVC, Nylon-66, and Other Plastics

PE and nylon-66 can be degraded using laccase enzyme. Laccase is a copper-containing oxidase enzyme present in many microorganisms, plants, and fungi that plays an important role in the biodegradation of lignin and is known as a lignin-modifying enzyme. According to the study conducted by Fujisawa et. al [49]:

...the laccase-mediator system (LMS) with 1-hydroxybenzotriazole (HBT) as a mediator could degrade high-molecular-weight PE and nylon-66

membranes. The LMS markedly reduced the elongation and tensile strength of these membranes. After 3 days of treatment with the LMS, the [molecular weight] of PE decreased from 242,000 to 28,300, and that of nylon-66 from 79,300 to 14,700.

Laccase enzymes (phenol oxidases), expressed by *Rhodococcus ruber*, have also been shown to play an important role in PE biodegradation [50].

Buchholz et al. note [51]:

Notably today, only for PET, PUR ester-based, and polyamide (PA) (oligomers), a rather small number of degrading enzymes are known, but none for other major fossil-fuel based polymers such as PVC, PE, PP, and PS, and most of the ether-based PUR polymers. The known fossil-fuel-based plastics-degrading enzymes are hydrolases, often annotated as lipases, esterases, cutinases, amidases, or proteases (E.C. 3.1.x). However, we have still a limited understanding of the mechanism of enzymatic degradation. It is not clear to which extent bacteria have evolved specific enzymes that bind to the polymers and cleave the bonds similar to the processes that occur when cellulose or other biopolymers are degraded.

2.9 Type of Enzymes Associated With Depolymerization

Nikolaivits et al. note [31]:

There are a vast number of publications describing the synthetic polyester degradation of PET or [PUR], as well as biodegradable polymers such as PLA, PCL, PBS, or [polyhydroxyalkanoates] PHA mediated by carbohydrate esterases, cutinases or cutinase-like enzymes, and lipases, underpinning the significance of these enzymes long known to the industrial biotechnology in the field of polyester degradation.

Tables 4 and 5 list the type of microorganisms and enzymes associated with the depolymerization activity of plastic material.

Table 4. Type of Enzymes Associated With the Depolymerization Activity of Plastic Materials [31]

Plastics	Type of Enzyme
PE	Laccase (EC1.10.3.0)
PET	Cutinase (EC 3.1.1.74)
PS	Hydroquinone Peroxidase
PUR	Cutinase (EC 3.1.1.74), Esterase (EC 3.1.1.1)
PLA	Cutinase (EC 3.1.1.74)

Table 5. List of Microorganisms and Associated Enzymes for Plastic Degradation

Plastic	Microorganism	Enzyme	Reference
PS	Pseudomonas Sp.	Esterase	[52]
PUR	P. Aeruginosa	Esterase	[53]
PES	Pseudomonas Sp. AKS2	Esterase	[54]
PVA	P.Vesicularis PD	Esterase	[55]
PET	Thermobifida Alba Est119	Esterase	[56]
PES, PCL, PBS, PBSA	R.Depolymerans Strain TB-87	Esterase	[57]
PBS, PBSA, PCL, PLA	P.Antarctica JCM10317	Cutinase	[47]
PAN	FsC	Cutinase	[58]
PA	FsC Pisi	Cutinase	[59]

Note: PES = polyethersulfone, PVA = polyvinyl alcohol, PBSA = poly(butylene succinate-co-hexane succinate), PAN = polyacrylonitrile.

2.10 Conclusions

According to Nikolaivits et al. [31]:

Wild-type microorganisms and communities from the natural habitats are immensely diverse, and their formidable potential for development and harnessing for the controlled biodegradation of waste plastic materials is clearly evident. Microplastics that have been in the environment over long durations already exhibit enrichment of specific bacterial communities. The exploration of enzymatic activities and enzymatic synergies for biotechnological processes is rapidly gaining recognition.

[The] systematic application of selected combinations [of] microbial and enzymatic approaches presents a gateway to regenerative plastic circularity. The progression to deal with more complex plastics such as mixed multilayers is feasible through dedicated exploitation of microbiological diversity and novel enzymatic activities to catalyze the bioconversion of nonpolyester plastics such as PE and PP.

The best-performing enzymes associated with depolymerization activity of plastic substrates are highlighted in Table 6.

Table 6. Best-Performing Enzymes Associated With Depolymerization Activity of Plastic Substrates [31]

Plastics	The Best-Performing Enzyme	Material	Experimental Conditions	Results	Reference
PE	Alkane Hydroxylase From <i>Pseudomonas Aeruginosa</i> E7	Low Molecular Weight Polyethylene (LMWPE) Powder, Mw 1.700	Compost, 37 °C, 80 days, 3.5 g LMWPE blended with 200 g (wet weight) sterilized compost; the mixture was inoculated with <i>Pseudomonas aeruginosa</i> E7	40.8% mineralization	[60]
PET	TfCut2 From <i>Thermobifida. Fusca</i> Expressed in <i>Bacillus Megaterium</i>	PET-Crystalline Packaging (CP), Postconsumer Carton Pack (Carton Pack S.R.L., Rutigliano, Italy), Crystallinity 4–6%	70 °C, 1.8 mL phosphate pH 8, 7 d (17-mg film/mL reaction), 0.05-nmol enzyme/mg film or 1-nmol enzyme/cm ² film	23.9–6.6% weight loss	[61]
	Cut190 From <i>Saccharomonospora</i>	PET-S (Semi-Crystalline Thermoplastic) From Package, 600 µm thick	63 °C, 1 mL 0.1 M Tris pH 8.2, 50 mM calcium chloride, 24% glycerol, 3 d (20–25-mg film/mL reaction) 11-nmol enzyme/mg film	27% weight loss	[11]
PS	Hydroquinone Peroxidase From <i>Azotobacter Beijerinckii</i> HM121	Dissolved PS (Aldrich Chemical Company), Mn 930,000	0.4 mL water, 10 mM hydrogen peroxide, 10 mM tetramethylhydroquinone, 100 mM potassium phosphate buffer pH 7.0, 30 °C, 10 min, 0.4 mL dichloromethane containing 2 g/L polystyrene, 2.4 units (U)/mL hydroquinone peroxide (1.0 mg/mL protein)	Mn reduced to 350 and 1,000	[62]
PUR	Lipase <i>Cryptococcus Microbial</i> Type Culture Collection (MTCC) 5455	Polyester PUR (Based on Poly(Diethylene Glycol Adipate) and 2,4 Toluene Diisocyanate [TDI])	PUR cubes in buffer pH 6, concentrated lipase (1,500 U), 96 hr at 30 °C	96% weight loss with the production of diethylene glycol and adipic acid	[63]
PLA	ABO2449 Esterase From <i>Alcanivorax Borkumensis</i>	Solid PLA (Sigma-Aldrich), Mw 1.0–1.8 × 10 ⁴	35 °C, 1.0 mL 0.4 M Tris–hydrochloride pH 8.0, 0.1% Plysurf A210G (detergent), 36 hr, 10–12-mg PLA powder/mL-reaction ,0.005 g enzyme/g PLA	Up to 90% conversion of PLA into lactic acid monomers and oligomers	[64]
PHB/PHA	PHB Depolymerase From <i>Paucimonas (Pseudomonas) Lemoignei</i>	P(HB-Co-10 mol%HV) Bacterial Origin (Marlborough Biopolymers Ltd., England), Mn 96,000	37 °C, 1.5 mL 50 mM Tris–hydrochloride pH 8, 1 mM calcium chloride, 4 × 20 hr, 25-pmol enzyme/cm ² film/20 hr	85% weight loss	[65]
		Chloroform-Casted Film Melting Temperature (T _m) 145 °C, X _c 61%, 25 × 8x (0.2–0.3) mm			
PBS	Cutinase From <i>FsC</i>	PBS Films Mn 15.0–21.0 × 10 ⁴ , 30 mm × 10 mm, 0.1 mm thick	40 °C, 10 mL 20 mM Tris–hydrochloride pH 8.0, 10 hr, 20 -µg enzyme/mL reaction, 0.33-µg enzyme/mm ² PBS or 0.014-nmol enzyme/mm ² PCL	100% weight loss	[66]
PCL	Cutinase From <i>Aspergillus Fumigatus</i>	PCL Film (Mixing Dichloromethane [20%]) and ω-Caprolactone Monomer), 250 µm thick, 1 cm ²	40 °C, 2,6 mL Tris pH 8.0, 6 hr, 0.011-g PCL/mL reaction, 0.012-g enzyme/g, PCL 0.002-mg enzyme/mm ² PCL	100% weight loss	[48]

Note: mM = millimolar, mol%HV = molar percentage of the compound's hardness.

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Biography

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