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A Review on Biodegradation of Post-Production and Post-Consumer Polyurethane Wastes

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Abstract

In terms of synthetic polymer material abundance, polyurethanes (PU) are ranked sixth in the world. The majority of PUR materials have been specially designed to ensure excellent levels of environmental resistance and long-term durability. A lot of polyurethane waste is being produced, which needs to be properly disposed of, as the demand for various polyurethane materials rises each year in many industrial sectors. Polyurethanes have xenobiotic qualities compared to other polymeric waste like PET, PE, PP, etc. Under ambient and laboratory conditions, it has been discovered that PU is sensitive to biodegradation by several microbes, although at a very low rate. The biological breakdown of polyurethanes in post-consumer and post-production waste is very promising. It is crucial for a circular plastic economy that highly effective PU-degrading microorganisms and enzymes are discovered and characterised because they can break down PU polymer chains into oligo- and monomeric chemicals. In this review, the primary approaches for identifying PU-degrading microorganisms and enzymes are outlined and discussed in terms of their catalytic processes. This critical analysis focuses on the potential for using renewable resources to produce polyurethane and provides a detailed understanding of the development, application, and most recent improvements in the area of various bio-based polyurethane polymers that have emerged over the past ten years.

Keywords

Polyurethane, biodegradation, bacterial degradation, isocyanate, polyol

Introduction

The demands of the newest technologies for recycling of waste synthetic polymers are increasing for three reasons: less availability of land for waste landfilling, which leads to water and soil pollution and prohibition of landfilling in many countries, lack of or non-biodegradability of polymeric waste; and shortage of raw materials such as crude oil (Gary T. Howard, 2002*)*. The global production of polyurethane was about 24.7 million metric tonnes in 2021 and it is expected to reach about 29.2 million metric tonnes by 2030 (Lucía Fernández, 2022). Globally, 368 million tonnes of plastic are produced in 2019, a slight decrease from 367 million tonnes in 2020 due to the COVID-19 pandemic (Plastic Europe, 2021), with polyurethane accounting for 7.8% of total plastic produced due to its versatile applications in the form of flexible and rigid foam, coating, adhesive, sealant, and elastomers (Deng, Y et al., 2020).

Only 9% of plastic is recycled worldwide, and 22% of total plastic waste goes to mismanaged sectors, where it is burned in open pits or thrown out in terrestrial or aquatic environments. The incinerated portion of plastic waste is about 19%, while 50% of plastic waste ends up in landfills.

Due to the large and continual production of plastic, over a few decades, plastic has become a major contaminant of terrestrial and aquatic ecosystems and a major environmental pollutant (Mueller 2006). Plastics with the backbone of a carbon-carbon homopolymer, such as polystyrenes, polyethylenes, and polyvinyl chloride, are more resistant to degradation than those with a heteropolymer backbone, such as polyurethane, which is biodegradable and mineralizable (Zheng, et al., 2005). In the modern world, polyurethanes play a crucial role in how people live. Sadly, this also implies that a substantial amount of PU produced is eventually disposed away through multiple streams (Ravindra V. Gadhave, et al., 2019).

The building, automotive, and electrical industries all benefit greatly from the use of polyurethanes, a broad family of polymers that may be adapted to a variety of purposes (https://matmatch.com). Figure 1 shows various end user applications of polyurethane. Although applications for polyurethane can range from soft, flexible foams to rigid insulation, liquid coatings and paints are the more prevalent uses. There are both thermoplastic and thermosetting polyurethanes, making a wide range of applications feasible. During World War II, polyurethane was first created synthetically as a replacement for natural rubber. The adaptability of this novel polymer and its capacity to substitute scarce resources soon led to the development of a wide range of applications. Currently, this group of polymers makes for 7.7% of the demand for plastic in Europe, trailing just the commodity polymers polyethylene, polypropylene, and PVC (Plastic Europe, 2018).

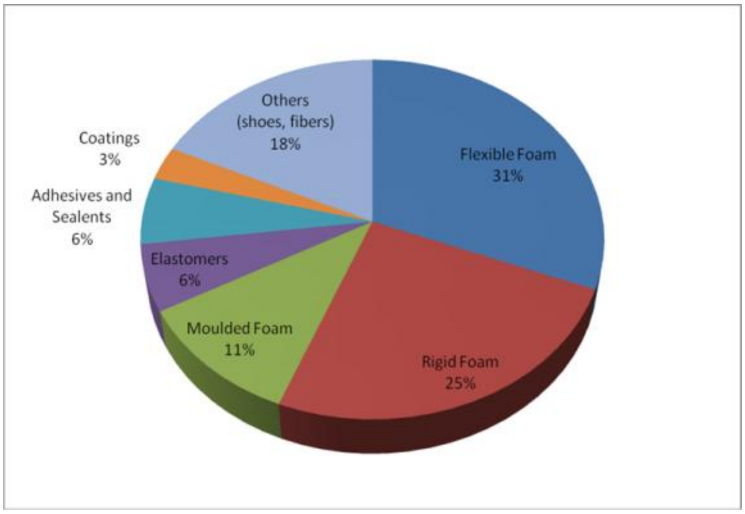

Figure 1. End user applications of Polyurethane (https://www.essentialchemicalindustry.org)

Rigid and flexible foams account for 32 and 36 percent, respectively, of global PU production. For the cushioning of furniture, bedding, and car seats, flexible foams are employed because of the comfort they offer. Rigid foams are favoured for thermal insulation in the construction industry, and their use is rising in line with a rising demand for energy-efficient structures. PU are also frequently utilised as elastomers, varnishes, adhesives, and sealants (CASE). PU coatings offer a protective layer against corrosion, abrasion, and the climate. Elastomers can take on any desired shape and are both elastic and flexible, like the wheels of rollerblades. Certain forms of polyurethanes are biocompatible, making them the preferred polymers for medical applications such orthopaedic prostheses and cardiovascular devices (Gunatillake et al., 2011; Zhou et al., 2012). These PU materials all have the characteristic of being primarily designed for long-term applications. They are primarily made to withstand environmental elements like UV deterioration, abrasion, hydrolytic (moisture) degradation, and microbiological degradation.

1. Polyurethanes

German chemist Otto Bayer created polyurethane in the 1930s while working on polymer fibres. Contrary to other thermoplasts like polyethylene, polyurethanes lack polymerization products and are instead categorised as condensation polymers made by the reaction of polyhydroxyl compounds (polyether or polyester polyol; polymeric alcohol with more than two reactive -OH groups per molecule), which include polyols like propylene glycol and polytetramethylethylene glycol (commonly known as polyols), and polyisocyanates such as toluene diisicyanate (TDI) or 4,4-diphenylmethane diisocyanate (MDI) in the presence of suitable catalysts, additive sand chain extenders (Debuissy, T et al., 2017a, Debuissy, T. et al., 2017b, Simón, D. et al., 2018). Figure 2 illustrates the condensation reaction, which binds the polyol and isocyanate molecules together via urethane linkage.

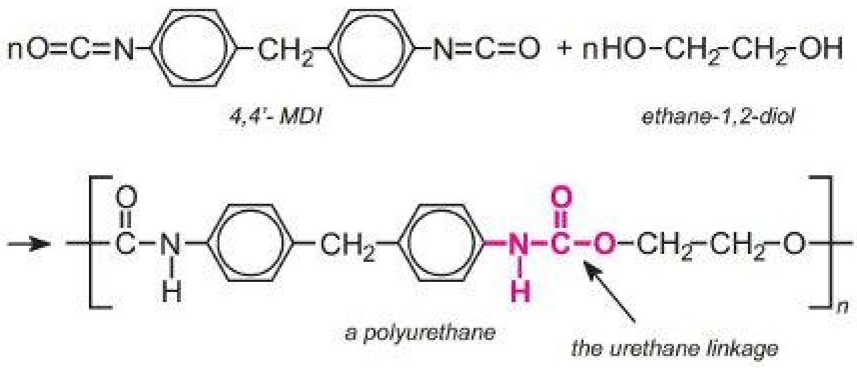

Figure 2. Formation of Polyurethane (https://www.essentialchemicalindustry.org)

Various combinations of alcohol molecules and corresponding isocyanate molecules can be made, and each one results in a distinct polyurethane composition with unique characteristics. The structure of this polymer backbone influences the properties of polyurethanes, which can be designed to have either high stiffness and rigidity or great flexibility and durability.

The characteristics and degree of crosslinking in the final polyurethane product are significantly influenced by the polyol molecule chosen. To modify the mechanical properties of the final polyurethane material, one can specifically choose the polyol according to number of hydroxyl groups per molecule for producing the desired size and flexibility of the hydrocarbon backbone. When a diol interacts with a diisocyanate, a thermoplastic, linear polymer is produced. If there are more than two hydroxyl groups in the alcohol, the molecule will become stiff, cross-linked, and thermosetting. Table 1 provides the common physio-mechanical properties of thermoplastic polyurethane (https://matmatch.com).

Since there are so many polyisocyanate and polyol compounds that can be used to make polyurethane, a wide range of materials can be generated to meet the specifications of different applications.

It is a versatile material that is suitable for use in construction, automotive, maritime, and even textile applications considering its relative light weight.

Lightweight, strong, supportive, and comfortable are all attributes of flexible polyurethane foam. In bedding, furniture, car interiors, carpet underlay, and packaging, it is frequently utilised as cushioning. Due to its use as a commodity, this makes for 31% of the market for polyurethane.

The most economical and energy-efficient insulations, rigid polyurethane foams considerably reduce energy expenditures. It contributes in maintaining a constant temperature and lowering noise levels when used in roof and wall insulation, as well as insulated windows and doors. In freezers and refrigerators, rigid polyurethane foam is frequently utilised as thermal insulation.

Due to polyurethane's wide range of applications and economic success, there are enormous amounts of post-consumer and post-production polyurethane waste produced every year. Up to 10% of the PU produced is post-production PU waste, which results from processing procedure flaws (Simón, D. et al., 2015). However, because they are heavily polluted and less likely to be reused, post-consumer PU trash poses a significant obstacle to their disposal and recycling (Cregut, M et al., 2013).

An overview of the mechanical and chemical recycling of polyurethane waste was provided in the preceding article (Lokesh Kumar, 2022). Both of these techniques are types of downcycling as compared to the direct recycling of polyurethane waste into goods with comparable value.

This article provided a review of the existing research on the biological processing and recycling of polyurethane waste and it also include an analysis of possible applications of those methods.

Table 1. Common Physio-mechanical Properties of Thermoplastic Polyurethane

Properties	**Value**
Density	0.05-107 g/cm^3
Elastic Modulus	0.03-1.88 GPa
Flexural Modulus	0.029-18 GPa
Elongation at Break	2-950%
Hardness	45-98 Shore A 51-85 Shore D
Coefficient of thermal expansion	100-200X10^{-6} /°C
Thermal Conductivity	0.14-0.5 W/m.K
Max. Service temperature	80-90 ºC
Min. Service temperature	~-60 ºC
Dielectric strength	17-25 V/mm

2. Biodegeradation

Generally speaking, biodegradation is the process of breaking down or degrading things using biological agents like enzymes or microbes. This method is employed in a variety of industrial applications, including the treatment of waste water (Watanabe, 2001) and the decontamination of contaminated sites caused, for instance, by polycyclic aromatic hydrocarbons (Shuttleworth and Cerniglia, 1995). The complex organic materials can be broken down into its constituents or simpler molecules under aerobic and anaerobic environment (Aleksandra Kemon, et al., 2020). Landfill and compost degradation can be conducted by naturally occurring microorganisms or with the addition of a specially selected consortium of microorganisms or enzymatic mixture.

The biodegradation of polymers is primarily influenced by chemical composition and macromolecular structures (Kim and Kim, 1998). Key factors affecting the polymer resilience to biological attacks include the type of chemical bonding, crystallinity, and molar mass (Zeng et al., 2016). The biodegradation of polyurethane completes in several steps. The first step in the process is the fragmentation of materials due to biotic and abiotic forces like UV, hydrolysis, abrasion, or pressure from filamentous bacteria. Cracks are brought on by filament growth in polymer pores. The generation of low molar mass molecules like oligomers and monomers occurs as a result of the cleavage of macromolecules by enzymatic hydrolysis and/or oxidation. Microorganisms eventually take up and mineralize these compounds to support microbial development (Lucas et al., 2008, Shah et al., 2008b). In vitro replication or mimicry of the enzymatic depolymerization or degradation phase is possible without involving microbial degradation. It's interesting to note that the liberated molecules from enzymatic depolymerization of polymers could be used to make high-quality products and building blocks for the chemistry market (Wierckx et al., 2015).

High molar mass polymers are formed by first forming a linear prepolymer having isocyanate end groups, and then adding a chain extender, typically a short diol. Molar mass is a factor that affects how susceptible polymers are to biological breakdown. It has been demonstrated that for polymers with identical chemical structures but differing molar masses, the sensitivity to biological degradation decreases with increasing molar mass (Philip et al., 2007; Zheng et al., 2005). Because the procedure does not require high temperatures or complex ingredients, in general, biodegradation is better for the environment than chemical degradation. Both post-consumer and post-production polyurethane waste can be recycled using this technique. Three different types of alterations to polyurethane exist: enzymatic degradation, fungal degradation, and bacterial degradation. Compared to polyether polyurethanes, polyester polyurethanes are substantially more sensitive to biological breakdown. Research using fungus strains produces more encouraging outcomes for polyether ones. This disparity can be explained by the mechanical cracking of more resistant polyether urethanes, which are typically used in foams, by mycelium penetrating material pores. However, the majority of PU coating degrading research employs bacteria. However, the majority of PU coating degrading research employs bacteria. The bacterial ability to build biofilm on the smooth coated surface may be the reason of that.

However, despite encouraging results, polyurethane biodegradation investigations are still in the early stages. However, despite encouraging results, polyurethane biodegradation investigations are still in the early stages. The prolonged period it takes to get results could be the primary cause of this situation (Howard, G.T., et al., 1999).

2.1. Fungal Degradation

Recent literature includes a number of publications that discuss the polyurethane's susceptibility to fungus attack. A variety of fungal species that are capable of degrading PU have been isolated and identified (Darby RT, et al., 1968, Barratt SR, et al., 2003, Cosgrove L, et al., 2010, Cosgrove L, et al., 2007, Mathur G, et al., 2012, Russell JR, et al., 2011 and Pathirana RA, et al., 1984), and it has been demonstrated that fungi are the predominant microorganisms engaged in the biodegradation of polyester PU when buried in soil (Barratt SR, et al., 2003, Cosgrove L, et al., 2010 and Cosgrove L, et al., 2007). The majority of studies focus on soil microorganisms related to polyurethane degradation.

The biodegradation of polyurethane is facilitated by fungal hydrolases like lipase, esterases, ureases, and proteases. All of these enzymes can break down ester bonds, but only proteases can hydrolyze amide and urethane bonds, and only ureases can attack urea (Temporiti, M.E.E., et al., 2022). By releasing phenolic compounds into culture media, urease activity can be monitored. The activity is then used to calculate the rate of biodegradation (Loredo-Treviño, A., et ai., 2011). The distance between urethane linkages, however, can negatively impact biodegradation by interfering with the action of degradative enzymes (Loredo-Treviño, A., et ai., 2012). Additionally, there are particular enzymes known as polyurethanases (PUase) that may break down polyurethane (Wei, R., et al., 2017, Howard, G.T., 2012).

All varieties of polyurethanes, including polyester, polyether, thermoplastic PU, foams, and coatings, were found to degrade by the action of fungi strains and communities (Magnin, A., et al., 2018). In contrast to the control sample, an *Aspergillus tubingensis* strain that was isolated from polyurethane film that had been buried in soil for a month was found to be able to disappear the urethane carbonyl group and manifest the -NH group (Khan, S., et al., 2017).

Six fungi species were isolated from various environments based on their capacity to break down polyester (Impranil) and polyether (Poly-Lack) polyurethane varnish as the only carbon and energy source. These species included *Aspergillus niger*, *Penicillium chrysogenum*, and four strains of the *Cladosporium cladosporoides* complex (Álvarez-Barragán, J., et al., 2016). The chemical changes caused by those microorganisms were analysed using FTIR, and the results revealed a decrease in the carbonyl signal, which can be attributed to the attack of ester bonds from the polyol fraction as well as the attack of urethane groups. An additional indication of the presence of polyurethane groups is provided by the decline in the CONH bond signals. After being incubated on mineral medium containing Impranil, the fungus *Cladosporium pseudocladosporoides* displayed high esterase, low urease, and no protease activity. This suggests that the ester and urethane groups in the PU are being attacked by the enzyme esterase. In addition, Impranil-degrading fungi might develop on polyether polyurethane varnish, which served as their sole carbon source, and could destroy polyether polyurethane foams.

2.2. Bacterial Degradation

Many of the encouraging findings can be attributed to fungi, however some studies suggest that bacteria may also be possible microorganisms that degrade polyurethane. Since the 1990s, Howard and his colleagues have investigated how bacteria break down polyurethanes. They discovered in their research that certain strains of *Pseudomonas chlororaphis*, *Bacillus subtilis*, *Comamonas acidovorans*, and *Acinetobacter gerneri* are capable of degrading polyester polyurethane Impranil DLN. They also demonstrated that lipases and esterases are the causes behind this polyurethane hydrolysis (Allen, A.B., et al., 1999, Howard, G.T., et al., 2001 and Ruiz, C., et al., 1999). Esterases are assumed to be primarily responsible for the microbial breakdown of polyester polyurethane rigid foam. A hydrophobic PUR-surface-binding domain and a catalytic domain are present in a solid-polyester PUR-degrading enzyme (PUR esterase) derived from *Comamonas acidovorans* TB-35. The surface-binding domain was thought to be important for polyurethane rigid foam degradation (T Nakajima-Kambe , et al., 1999). The three polyester hydrolases TfCut2, LCC, Tcur0390, and Tcur1278 are able to hydrolyze thermoplastics as well as polyester polyurethane dispersions (Juliane Schmidt, et al., 2017). *P. capeferrum* TDA1 efficiently breaks down PU monomers. As a result, TDA1 may be used preferentially in a two-step degradation process where the macromolecular polymer was first enzymatically catalysed to produce plastic monomers (Òscar Puiggené, et el., 2022). Furthermore, according to a recent study, *P. capeferrum* TDA1 might utilise these monomers to create brand-new, value-added products in a new circular plastic economy

(Ren Wei,. Et al., 2020). The polyurethane sheets can be broken down by *Bacillus licheniformis* SY2 at a rate that is much faster than that of other organisms (V. Shree Yazhini, et al., 2021).

2.3. Enzymatic Degradation

The primary benefit of enzymatic degradation over microbial degradation is the potential for controlled bond cleavage, which results in the synthesis of building blocks that may either be added back into the production process or used as a substrate to produce various materials. The key challenge with this method is that each type of polyurethane must be treated separately due to the wide variety of raw ingredients involved in polyurethane synthesis. Furthermore, there are very few enzymes that can degrade polyurethanes because they do not exist in nature. The enzymes that used for degradation of Polyurethane include oxidoreductases and hydrolases like esterases, ureases, proteases, and elastase, depending on the compounds involved in production together with isocyanate (Gamerith, C., et al., 2016, Biffinger, J.C., et al., 2015, Magnin et al., 2020). Enzymes are typically employed to depolymerize thermoplastic polyurethanes or coatings, whilst foams are degraded using a microbiological approach as shown in table 2 **(**Aleksandra Kemon and Małgorzata Piotrowska, 2020). Wales and Sagar first proposed the theory for how esterases break down polyester-polyurethane rigid foam in 1988 (Crabbe, J.R., et al., 1994). The hydrolysis of the polyester component of polyester-based polyurethanes by esterases, which produces carboxylic acid and alcohol, can be attributed with the majority of the favourable biodegradation results (figure 3).

According to certain research, esterases are also capable of hydrolyzing urethane linkages, releasing carbamic acid and alcohol chain-ends in the process (Mahajan, N. and Gupta, P., 2015). However, because acid is unstable and breaks down quickly, amine and carbon dioxide are more frequently released as a result (Ionescu, M. (2005).

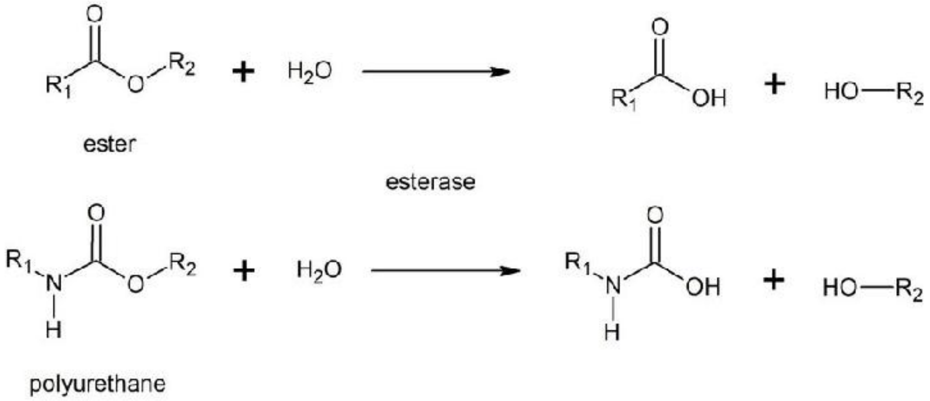

Figure 3. Schematic representation of hydrolysis reaction of polyurethane and ester (Aleksandra Kemon and Małgorzata Piotrowska, 2020)

However, because the majority of polyurethane degradation tests used polyester types, particularly Impranil® (Covestro, Leverkusen, Germany) as a model, they cannot differentiate between the hydrolysis of urethane and ester linkages(Biffinger, J.C., et al., 2015). This has the limitation that evaluation of urethane bond hydrolysis by esterase would only be possible if the substrate did not contain ester bonds. There aren't many studies that deal with this idea (Smith, R., et al., 1987, Santerre, J.P., et al., 1994).

Research studies examining polyurethane breakdown by ureases encounter the same issue (Figure 8), and the majority of them produce encouraging outcomes so long as polyurethane retains urea linkages (Fang, J., et al., 2014, Labow, R.S., et al., 1994, Phua, S.K., et al., 1987). The Schematic representation of hydrolysis reaction of polyurethane by urease is given in figure 4 **(**Aleksandra Kemon and Małgorzata Piotrowska, 2020).

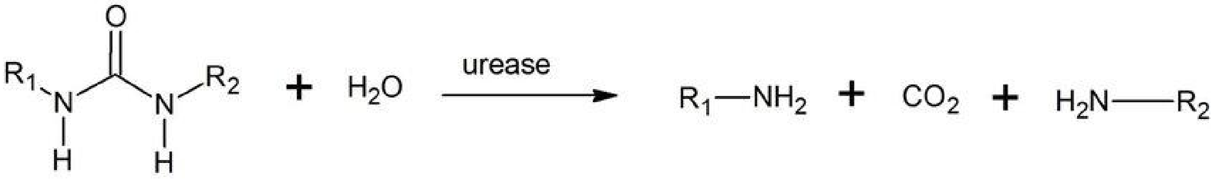

Figure 4. Schematic representation of hydrolysis reaction of polyurethane by urease

Two more kinds of enzymes that contribute to polyurethane (PUR) breakdown are proteases and amidases. They have been shown to hydrolyze urethane bonds in PUR and are capable of hydrolyzing peptide or amide bonds intrinsically (Phua et al., 1987; Magnin et al., 2019).

Table 2. Different types of polyurethane are degraded by enzymes

Type of Polyurethane	**Enzyme**
Polyester PU (Impranil)	Esterase, Lipase, Protease, cutinase
Thermoplastic polyester PU	Lipases, Esterases, Pancreatin, Polyamidase Proteases
Thermoplastic polyether PU	Esterase, Chymotrypsin, Proteases
Thermoplastic Polycarbonate PU	Cholesterol esterase
Thermoplastic poly (ester ether) PU	Chymotrypsin
Thermoplastic poly (ester urea) PU	Lipase, Cholesterol esterase
Thermoplastic poly (ether urea) PU	Cholesterol esterase, Elastase, Papain
Polyester PU coating Lipase	Lipase
Polyacryl PU coating	Pancreatin

The hydrolysis of urethane bonds by amidases and peptidases also seems to be extremely effective, producing an amine, an alcohol, and the release of carbon dioxide (Gamerith, C., et al., 2016, Ferris, C., et al., 2010, Ciardelli, G.,et al., 2004). Figure 5 shows the Schematic representation of hydrolysis reaction of polyurethane and peptide by protease/ amidase **(**Aleksandra Kemon and Małgorzata Piotrowska, 2020).

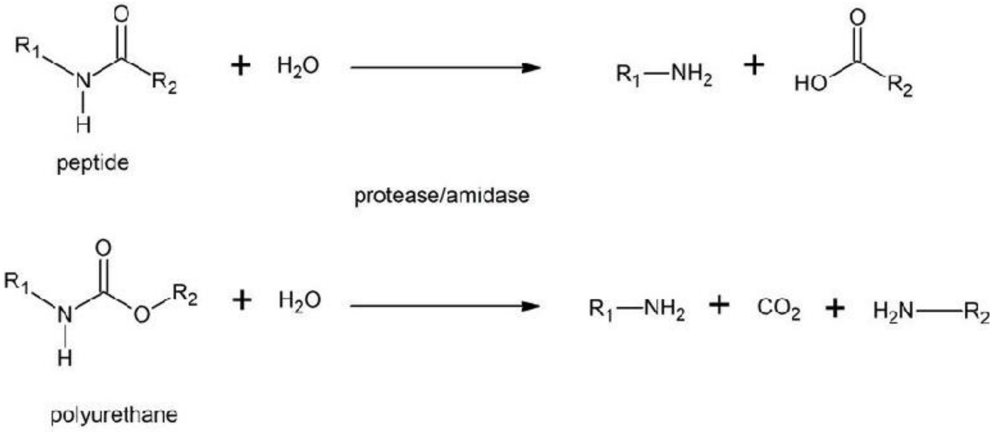

Figure 5. Hydrolysis reaction of polyurethane and peptide by protease/ amidase.

In the cleavage of urethane linkages in PUR and segmented polyurethane urea plastics (SPUUs) generated from lysine diisocyanate (LD), the proteases bromelain (EC 3.4.4.24) and ficin (EC 3.4.22.3) were found to be more efficient than other proteases (Yamamoto et al., 2007). Esterase E3576 and amidase E4143, two commercial enzymes, worked better together than they did separately to improve the breakdown of polyester-PUR (Magnin et al., 2019). The esterase E3576 (EC 3.1) hydrolyzes the ester bonds first during this process to break down the macromolecules into Lower molecular weight intermediates that are easier for the amidase E4143 (EC 3.5.1.4) to hydrolyze the urethane bonds.

In particular poly(urea-urethane) polymers, urea linkages are hydrolyzed by urease, releasing two amines as well as carbon dioxide. As urea bonds are more difficult to break down than ester bonds, there aren't many reports on PUR breakdown by ureases. Ureases (EC 3.5.1.5) were active on poly(ether urea) PUR, and it was discovered that the hydrolysis of urea bonds was mostly accountable for the degradation (Phua et al., 1987).

In recent years, two bottlenecks that prevent the enzymatic breakdown of polyurethane have been identified (Jiawei Liu, et al., 2021). First off, the majority of the polyurethane hydrolases discovered so far are polyester hydrolases, which are limited to hydrolyzing ester bonds in soft PUR segments made of polyester. A real urethanase, on the other hand, has not yet been identified that can directly breakdown the urethane linkages in PUR polymers (Wei et al., 2020). In the future, more research should concentrate on the screening of enzymes having "polyurethanase" activity, which will significantly lower the barriers for the biocatalytic degradation of PU in coordination with the known polyester hydrolases. Second, the insoluble hydrophobic structure of PU polymers prevents enzymes from readily accessing the hydrolysable chemical bonds. By including particular polymer-binding domains in PUR, this might possibly be assisted (Van et al., 1986; Fukui et al., 1988; Hansen, 1992). To increase the accessibility of insoluble polymers, functional polymer binding peptides (anchor peptides) can enable the precise attachment of entire cells to polymer surfaces (Dedisch et al., 2019).

It would appear that only polymers with a degradable flexible chain might be disposed of in this way as the majority of findings indicate that the availability of urethane bonds for enzymes is limited. However, the necessity for energy-intensive, high-tech processing methods for the synthesis of polyurethanes comprising petroleum-based polyols and the growing environmental problem led to a need for materials made from renewable and biodegradable resources. The great potential of polyols and isocyanates derived from vegetable oils, such as soybean oil (Mizera, K. and Ryszkowska, J.2016), rapeseed oil

(Kura´ nska, M.,,et al., 2015), castor oil (Das, B., et al., 2013, Spontón, M., et al., 2013), jatropha oil, cardanol oil, and palm oil (Ng, W.S., et al., 2017) has been reported in a number of studies. Bio-polyols, which are produced by liquefying lignocellulosic biomass in polyhydric alcohols, are another option for petroleum-based polyol replacement (Huang, G. and Wang, P.2017). Additionally, adding particular chain extenders and biodegradable aliphatic polyesters, such as poly (lactic acid) (Jašo, V., Glenn, et al., 2015), poly (caprolactone), and poly (butylene succinate), increases the biodegradability of polyurethanes (Yamamoto, N., et al., 2007).

The impact of the added molecule on the qualities of the finished product is the key barrier to applying this method. For instance, the density of polyurethane foam increases as lignin is added, and its thermal stability decreases as the lignin level rises. The density and compressive strength of foam also increased as castor oil concentrations increased (Carriço, C.S., et al., 2016). Due to the reduction of resistive waste and potential use of milder reaction conditions, biodegradable additives or alternatives in polyurethane synthesis make such polymers far more environmentally friendly (Ng, W.S., et al., 2017). However, due to the effect of additions and substitutions on a wide range of properties, extensive testing is required for any novel biodegradable material.

Polyurethane monomer is used as a high-value feedstock

The goal of biotechnological plastic recycling is to get raw materials that can be used to create virgin polymers in order to complete the recycling cycle (Wei et al., 2020). Biotechnological recycling is expected to have a high yield of small-molecule products from polymer breakdown compared to mechanical and some chemical techniques (such as dissolution/precipitation) focusing on the reuse of polymers with minimum chain scissions (Vollmer et al., 2020). The ultimate goal of a low-carbon circular bio-economy is the transformation of plastic waste into sustainable and high-value products.

It was also intended to valorize polyurethane waste by producing value-added products using biotechnology. Comparing polyurethane polymers to other polymeric waste, the backbone of these materials is frequently more complicated. As a result, PUR produces a wider range of degradation products, which presents difficulties for downstream processing. Amines, alcohols, acids, aromatics, and other residues like ethylene glycol, adipic acid, 1,4-butanediol, 4,4′ -methylenedianiline or 2,4′ -toluene diamine can be degradation products obtained from PUR (Magnin et al., 2019; Shah et al., 2013a, b). PHA and glyoxylic acid, which have numerous uses in the chemical industry, can be made using EG as a substrate (Mückschel et al., 2012). Utilizing carboxylic acids and alcohols produced during the biodegradation of polyurethane waste, virgin PUR and other polyesters such as poly(butylene succinate), poly(1,3-propylene succinate-ran-1,4-butylene succinate), and poly(1,3-propylene adipate-ran-1,4-butylene adipate) (PPBA) can be produced (Tiso et al., 2020; Debuissy et al., 2017). Similar to this, various by products from biodegradation can be used as feed stocks to produce significant new chemical compounds.

Conclusion

The most common method for disposing of polyurethane trash right now is to put it in a landfill, however this method has many negative environmental, land-use, and economic consequences. Mechanical recycling is a further popular technique. Even though it is reasonably priced, it has many limitations. High temperatures and vigorous reagents are required for chemical and feedstock recycling, although only one of those procedures is now used on a wider scale. In conclusion, additional research into the biological degradation of polyurethane will help to reduce the world's plastic pollution problem. While a biotechnological approach for the recycling of polyurethane waste, as opposed to other polymeric waste like PET, is currently lacking and will require additional scientific research, it is still a viable option. The combination of highly effective bio-catalytic degradation modules, synthetic biology-based valorization approaches geared toward the synthesis of value-added products, and advanced physicochemical treatment processes under mild reaction conditions that do not generate secondary pollution will undoubtedly be advantageous in an ideal solution, especially for the polyurethane waste, in order to finally achieve the sustainable use of polyurethane plastic waste.

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