Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Biodegradable Polymers Converting Environmental Challenges into Eco-Friendly Solutions

Dina Aboelela[1], M. Bassyouni[2*]

[1]*Faculty of Energy and Environmental Engineering, The British University in Egypt (BUE), El-Sherouk City, 11837, Egypt*
[2]*Department of Chemical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, 42351, Saudi Arabia*

Abstract

1.1.1. Polymers play a crucial role in various industries due to their versatility, affordability, and lightweight characteristics. However, their extensive production and limited biodegradability have become significant environmental challenges. Traditional plastics, often destined for landfills, persist for centuries or contribute to pollution through incineration. The growing environmental concerns surrounding plastic waste have driven the development of biodegradable polymers. These polymers, derived from renewable resources such as starch, cellulose, and vegetable oils, or synthetic bio-based monomers like lactic acid, are designed to degrade naturally through microbial action or photodegradation. The degradation process of these polymers results in harmless byproduct, such as water which supports environmental sustainability. This study provides a detailed examination of the degradation mechanisms of both synthetic and bio-based polymers, identifying key factors that influence polymer degradation in various applications. The study highlighted the significant role of bacteria and fungi in the biodegradation of polymers in freshwater environments, with optimal pH values for landfill degradation ranging between 5.8 and 8.5. The impact of blending biodegradable and non-biodegradable polymers on the overall biodegradation process was thoroughly explored. The findings contributed to a deeper understanding of polymer degradation, offering valuable insights into enhancing the biodegradability of polymers for a more sustainable future.

Keywords: Biodegradable; Sustainability; Renewable resources; Carbon footprint; Microplastics.

Introduction

Polymers are now incorporated into practically all items, including clothing, vehicles, computer equipment, and medical and technological devices that we encounter daily. Polymers are necessary materials in modern society as they are found in a vast array of applications ranging from packaging and textiles to medical devices and electronics. Their versatility, durability, and cost-effectiveness have made them a cornerstone of contemporary technology and everyday life. However, the widespread use of polymers particularly those derived from petrochemicals has led to significant environmental challenges, primarily due to their continuity in the environment and poor biodegradability.

The environmental impact of traditional plastics has spurred research into more sustainable alternatives such as biodegradable and biobased polymers. These materials offer the potential to reduce the environmental footprint of plastics by facilitating natural degradation processes. The adoption of biodegradable polymers presents challenges related to their mechanical properties, degradation behavior, and environmental performance in various conditions [1]. With the 140 million metric tonnes of plastic that are produced each year, more than 99% of the ingredients in plastics come from hydrocarbon sources [2].

Currently, plastics serve as the primary ingredient in a wide range of products due to their ease of production, excellent chemical and physical properties, broad resistance to temperature and light, low cost, strong mechanics, and high durability. The favourable attributes of plastic have increasingly been incorporated into many of the relevant industries, such as automobiles, textiles, packaging, agriculture, building, and consumer goods. These fibers are frequently used in food, pharmaceuticals, cosmetics, detergents, and chemical packing materials as they assist in increasing the shelf life of those commodities [3]. Biodegradable and non-biodegradable polymers differ fundamentally in their environmental impact and degradation processes. Biodegradable polymers are designed to break down into natural byproducts like water, carbon dioxide, and biomass through microbial action or photodegradation. These polymers can be derived from both renewable resources (e.g., starch, cellulose, and vegetable oils) and synthetic bio-based monomers like lactic acid. The key advantage of biodegradable polymers lies in their ability to decompose within a relatively short period, thereby reducing long-term environmental pollution. In contrast, non-biodegradable polymers are resistant to

_____

natural degradation processes, persisting in the environment for extended periods. These materials are primarily derived from petrochemical sources, such as polyethylene and polypropylene, and contribute significantly to landfill accumulation and environmental pollution when improperly disposed of. It is also crucial to distinguish between biobased and biodegradable polymers. Biobased polymers are derived from renewable biological sources, but this does not inherently make them biodegradable. For instance, some biobased polymers, like polyethylene produced from bioethanol, have the same molecular structure as conventional polyethylene and, therefore, do not readily degrade in natural environments. On the other hand, not all biodegradable polymers are biobased; some are synthesized from petrochemical sources but designed to degrade through specific mechanisms.

Synthesis and disposal of biodegradable and non-biodegradable polymers are shown in Figure 1.
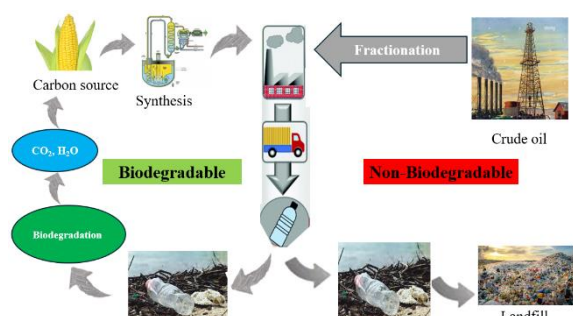

Figure 1 An overview of biodegradable versus non-biodegradable polymers

About 30% of plastics are for packaging, and 90% of them are required for food packaging materials only. Plastics have surprisingly become the leading commodity since the 1950s, as more than 9 billion metric tonnes of polymeric products were produced worldwide, with most of them processed in the last decade [3]. Unfortunately, more than 50% of all those polymers were thrown away and finally became waste. The waste is dealt with using different approaches by being either incinerated, landfilled, or recycled. Environmental pollution is caused by improperly disposing of plastics because many polymeric substances could take up to hundreds of years to break down and degrade. That's why they remain a persistent form of pollution in the environment. In addition to these plastic products being incorrectly disposed of, other pollutants may also appear, like furans and dioxins [4]. Because of their long-term durability, the manufacturing of these materials is inexpensive, and they possess excellent mechanical characteristics as well as physical

properties; therefore, their disposal and biodegradation represent a high priority environmental issue. Thus, large numbers of biobased and biodegradable polymers have been under experimentation over the last few years to minimise environmental and marine pollution originating from this source. Nevertheless, biobased as well as biodegradable polymers are known for their potential to decrease waste; however, despite their seeming ability to solve the problem, the production of these types of polymers remains too expensive. Thus far, the bio-based polymers have not been able to reach the level of the non-biodegradable polymers' applications since they have lower physical properties, mechanical strength, and pricing. These problems may just be overcome by using biodegradable blends or biobased polymers with the right properties. Most polymers or plastics decay somehow, regardless of whether it is in a biological, chemical, or physical way. This outcome is influenced by the causes and environment, as shown in Figure 2. While most polymers degrade at some level, they do not fully degrade; nevertheless, they produce either massive or micro sized plastics. The greatest sources of microplastics are the wear and tear of vehicle parts, the loss of plastic particles from industrial transport, and the plastic in synthetic clothing that is washed [5].
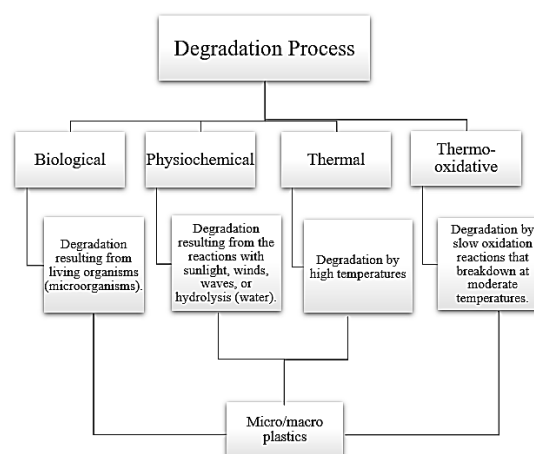

Figure 2 Different environmental degradation processes of polymers.

Polymers and plastics have been designed to facilitate degradation by methods other than conventional. For instance, hydro- and oxo-degradable polymers are made to decay via hydrolysis or oxidation processes. Another type of plastic is not biodegradable in nature and requires multiple steps to degrade as it is frequently made from fossil carbon compounds combined with solutions or natural polymers like starch. This kind of polymer produces microplastics via its end-of-life process since it does not

decompose completely in the environment. However, the public often misinterprets biobased and biodegradable plastics as being the same. There are two types of polymers: biobased and biodegradable, which have different environmental particularities. Biobased polymers are obtained from renewable feedstocks (for example, plants), and biodegradable polymers decompose with the help of microbial digestion or sunlight exposure. Specific examples of biobased polymers are polylactic acid (PLA), which can be derived from corn starch or sugarcane, and polyhydroxyalkanoates (PHA), which are made by microorganisms. These materials may have an advantage over traditional petroleum-based polymers because they come from renewable resources, which can contribute to the reduction of the carbon footprint of the products made from them [6].

However, biodegradable polymers can be derived from many types of materials, including both biobased and non-biobased sources. These compounds can be decomposed by the action of natural processes and offer environmental benefits in comparison to the non-degradable traditional polymers. It should be highlighted that not all biobased polymers are biodegradable, and not all biodegradable polymers are made from renewable resources [7]. For instance, some petroleum-based polymers, such as po. lycaprolactone (PCL) and polylactic acid (PLA), are biodegradable. A shortcoming of biodegradable polymers is that they often require special conditions, like high temperatures and humidity, to degrade effectively. On the other hand, during the process of biodegradation, some biodegradable polymers can release greenhouse gases as byproducts. In general, material dependence on biobased or biodegradable polymers is determined by the material's application and end-of-life management. It's crucial to thoroughly assess the environmental impact of various polymer alternatives and pick sustainable materials that are in line with sustainability goals.

Biodegradable polymers offer a more sustainable alternative to traditional plastics due to their ability to decompose naturally. Table 1 outlines some of their key applications. This study aimed to explore the degradation processes of polymers, with a focus on understanding the factors that influence their biodegradability in different environments. Investigating the effects of molecular weight, crystallinity, and chemical modifications and comparing degradation rates in freshwater and seawater were discussed in detial. The study was conducted to provide insights that can guide the development of more sustainable polymeric materials. The goal was to contribute to a clearer understanding of how polymer design can be optimized to address the pressing issue of plastic waste and its long-term environmental impact.

Biological degradation

Biodegradation of polymers as biological procedures involves the breaking down of polymeric materials by microorganisms, like bacteria and fungi, in the presence of oxygen and other materials that serve as nutrients. This process is part of the natural exchange in the environment and facilitates organic matter recycling. In freshwater environments, polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and starch-based materials generally exhibit relatively faster degradation rates. This is largely due to the higher levels of microbial activity and the presence of enzymes that can break down polymer chains. For instance, PLA was degraded within months in freshwater environments, especially under warm, aerobic conditions. Similarly, PHAs, which are naturally produced by microorganisms [13]. Apart from the above-mentioned biodegradable polymers, polyhydroxyalkanoates (PHAs) are other biodegradable polymers that are manufactured by microorganisms and later degraded in water and soil by bacteria.

Table 1 Biodegradable Polymer Application

Application	Biodegradable Polymer Examples	Notes	References
Packaging	PLA, PHAs, Starch-based blends	Food packaging, disposable tableware, composting bags.	[8]
Agriculture	Mulch films, seed coatings	Improve soil moisture retention, promote seed germination, reduce reliance on chemical herbicides.	[9]
Biomedical Devices	PLA, PCL, PHA copolymers	Sutures, drug delivery systems, implants, tissue engineering scaffolds.	[10]
Waste Management	Compostable bags, liners	Reduce plastic waste going to landfills, promote composting practices.	[11]
Textiles	PLA fibers, cellulose derivatives	Apparel, sportswear, disposable wipes.	[12]

_____

Nevertheless, the degradation rate of biopolymers depends on the combination of various factors, such as types of associations, size and shape of material, and the type of environmental conditions [14]. Furthermore, not all biodegradable polymers are environmentally friendly, as some of them may release harmful substances during degradation. In order to develop the utilization of biodegradable polymers along with proper disposal, many standards and regulations have been enacted. For instance, the European Union has determined compostable packaging materials standards, and the United States has published rules and regulations for packaging labelling and disposal [13]. In the end, biodegradation of polymers shows a reliable approach for minimizing the negative influence of polymers on nature. While biodegradable polymers are an excellent alternative to conventional waste management practices, it is essential to undertake an environmental impact assessment and ensure that all conditions for proper disposal are met.

Factors influencing synthetic polymer disintegration in a biological environment

Biodegradation of solid wastes resulting from synthetic materials is a complex process that is dependent on various factors. Knowing about this is an important step in designing and selecting materials suitable for environmentally friendly degradation [15].

The chemical composition of a polymer is the most influential factor that not only defines its degradation properties by microorganisms but also its rate of degradation. For example, polymers composed of ester or amide bonds are more biodegradable than those having a carbon-carbon bond [16]. Microorganisms are more likely to degrade polymers with groups of water, such as carboxyl and hydroxyl groups.

The polymer's molecular weight also influences biodegradability. The molecular weight of a polymer significantly affects its degradation process. Generally, polymers with lower molecular weights degrade faster due to their shorter polymer chains, which are more susceptible to hydrolysis and microbial attack. For example, studies have shown that poly(lactic acid) (PLA) with a molecular weight below 100,000 g/mol can degrade in as little as a few months under composting conditions, while PLA with higher molecular weights may take several years to fully degrade. This correlation is attributed to the increased mobility and accessibility of the polymer chains to degrading agents in lower molecular weight polymers. However, the specific degradation rate also depends on other factors, such as environmental conditions and the presence of catalysts. Polymers having higher tensile strength and a high molecular weight undergo biodegradation at a slower rate in comparison to low-molecular-weight polymers [15]. Additionally, the use of large polymer chains inhibits microbes from degrading them more easily compared to smaller polymer chains.

The degree of crystallinity of a polymer remains an important factor that may affect its biodegradability. Crystallinity refers to the degree of structural order in a polymer. Polymers with high crystallinity have tightly packed molecular chains, which create more stable and less accessible regions for degradation. For instance, in polyhydroxyalkanoates (PHAs), highly crystalline regions resist microbial attack, leading to slower degradation rates. On the other hand, amorphous regions, which lack ordered structure, are more prone to degradation. Reported data indicated that the degradation rate of PHA decreased significantly as crystallinity increased, with degradation times varying from a few months for low-crystallinity samples to several years for highly crystalline ones [16]. This is the reason why the crystalline areas of a polymer are less available to a microbe, so it is difficult for the microorganisms to breakdown the polymer.

Environmental conditions in the place where the polymer is found can also influence the rate of its biodegradation. Such factors as temperature, moisture, pH, salinity, sunlight, oxygen, the presence or absence of microorganisms, and microorganism growth conditions are the variables that impact the rate of biodegradation and enzyme activity, as well as the microbial population. Therefore, they can either arrest or accelerate the organic matter degradation process [15, 17].

The presence of additives and stabilizers, such as plasticizers and stabilizers, also affects a polymer's biodegradability. Some additives may hinder or facilitate the breakdown process, depending on their chemical composition and concentration [18]. They may also hold the process of breaking down as well as be a poison to microbes.

The biodegradability pathway of a polymer also governs the rate and extent of degradation along with it. On the other hand, some polymers may suffer surface erosion, where the polymer surface is degraded first, while other polymers undergo bulk erosion, where the material degrades uniformly over its whole cross-section [15].

Since they are inversely proportional, the service temperature of polymers will alter the enzymatic degradation process. As the melting temperature of

_____

polymers increases, the rate of biodegradation of polymers is accordingly reduced [19].

Radiation, as well as chemical treatments, cause polymer degradation by providing photolysis and chain confining X-ray radiation. This procedure may be harmful because oxidation may occur, which may, in turn, change the degradability of the polymer [19].

Microbes respond to the existence and activity of polymeric substances. Bacteria perform critical biodegradation. Microorganisms can exhibit the properties of an enzymatic activity that breaks these polymers into smaller molecules, which can be harmlessly digested by the soil microbes. [15] The diversity of microorganisms can vary depending on environmental conditions, and other specific microorganisms may be more effective in degrading specific polymers, as shown in Table 2.

The morphology of polymers, which are found in different shapes or as surface areas, leads to differences in biodegradability. Cells may be absorbed more quickly than integrated structures such as blocks or particles because the former have a greater surface area for microbial activity [27]. In general, the decomposition of polymeric materials in the biological environment is a complex process that is affected by various factors. The debate over such aspects would be critical for the design of biodegradable materials as well as their environmental performance.

Biodegradation of synthetic polymers
4.1 Polyesters

Polyesters are a group of synthetic polymers that are being utilised in different sectors, such as textiles, films, coatings, and packaging. These polymers are synthesised through the esterification reaction between the diacids and diols. These can be modified to have a great variety of physical and chemical properties. Biodegradation of the polyesters is of great interest because they have long-term exposure to the environment when not disposed of properly.

Table 2 Conditions, degradation factors corresponding to degrading bacteria.

Plastics	Conditions	Mechanism of degradation	Enzyme	Reference
PET	Temperature 70–75 ºC	Hydrolysis	PETase, MHETase	[20]
PLA	Temperature 50 ºC	Hydrolysis	-	[21]
PBS	Temperature 50 ºC	Hydrolysis	-	[22]
PHB	Temperature 50 ºC	Hydrolysis	-	[22]
PVC, PP, PE, PS (PAEs)	Temperature 30-70 ºC	Hydrolysis and oxidation	PME hydrolases	[23]
PC (BPA)	Adding electron donors and co-substrates	The expression of different functional genes	A spore-laccase	[24]
PCL	Temperature 50 ºC	Genes colonization	Catalase, Protease	[25]
Various plastic	Salt, low, or high pH, temperatures	Hydrolysis	Bacteriophilic enzyme	[26]

In a nutshell, polyesters can sometimes be biodegraded if exposed to the moisture of microorganisms that cause the enzymes. The three polyesters (i.e., the enzymes) underwent tests and observations. The results showed that they were all degradable by the hydrolysis reaction enzymes. Nevertheless, all the polymerases would show damage, to one extent or another, because of the different enzyme categories that they contain in their reaction with the polyester [28].

PLA is the abbreviation of biodegradable polyester, which is obtained from renewable materials like cornflour and sugarcane. Microorganisms can break down PLA into lactic acid in a short time under both aerobic and anaerobic conditions [29]. Nevertheless, the depletion rate is strongly determined by a wide spectrum of factors, such as the molecular weight of the polymer itself, the possible presence of additional additives, and the hostile outdoor environment [13]. Poly (butylene succinate) (PBS) is another biodegradable polyester nowadays derived from fossil fuels, but since it is a semicrystalline material, it can be entirely made from renewable resources like plant oils. PBS can be biodegraded by a diversity of microorganisms like bacteria and fungi, thereby generating carbon dioxide, water, and other naturally occurring chemicals [30]. The chemical composition of these microorganisms is environment-friendly and easily biodegradable.

4.2 Polyether
Since 1962, polyether degradation by bacteria has been the subject of many biological studies, in particular polyethylene glycol, or PEG metabolism. There have been experiments conducted that show that the ability of a variety of microbes to break down PEG and the degree of their degradable capacity are influenced by the peg molecular mass. Polymers that are showing a drastic deviation in relative molecular mass (almost close to 20,000) have been recorded in the breakdown stage. In the background of the molecular data were the findings of PEG researchers, who said that bacteria with an average molecular weight below 1000 Dalton could break down different molecules on their own, but molecules with a molecular weight above 6000 Dalton would only work in mixed cultures with symbiosis [28]. Many enzymatic processes, which were under PEG biological degradation, have been reported in this case. Besides having hydroxyl end groups, PEG hydroxyl end groups initially involve the enzymatic dehydrogenation of a primary alcohol to its aldehyde. In the second reaction, the terminal carboxylic acid is formed as the product of dissociation. Here is the fourth step, in which the enzymatic oxidation at the a-

position is believed to form the hemiacetal linked to glyoxalic acid and weight reduction by losing one unit of mass once the PEG molecules are hydrolysed. Finally, the huddling together involves the hydrolysis of the methylene groups within the PEG group, which is further oxidised as the last enzymatic step. The result is a phase when ester groups come together [28].

4.3 Polyethylene

Polyethylene is a commonly synthesised plastic material known as one of the polymers that are resistant to degradation. Nevertheless, the last decade or so has brought advances in the biodegradation of polyethylene. It is noted that some microorganisms can breakdown polyethylene, and this process can be enhanced by means that facilitate it. The study, which was published in the journal Environmental Pollution, revealed that a blend of mixed-cultured microorganisms could degrade LDPE under low oxygen conditions in a soil or non-soil environment. The research found that after 6 months of organism exposure, microorganisms had caused the weight of the LDPE samples to lose 6.7%. A different report in PLoS One revealed the isolation of a bacterial strain that could degrade polyethylene plastics. The data showed that the species could degrade up to 5% of a thin film of polyethylene for only 10 weeks, which was higher than the previously reported rates of polyethylene degradation. Furthermore, this study performed in the Marine Pollution Bulletin focused on the ability of marine bacteria to degrade polyethylene. The research showed that marine bacteria were able to degrade polyethylene bags and films under both aerobic and anaerobic conditions. Based on these investigations, some microorganisms can decompose polyethylene, which can take longer under other conditions. Nonetheless, the whole process needs to be investigated to fully understand the mechanisms of polyethylene degradation biologically and to also establish strategies that are applicable for utilising this process [31].

4.4 Polyvinyl alcohols

Polyvinyl alcohol is a polymer with multifunctionality and is widely used in many industries. The biodegradable carbon-carbon bonds that make up the backbone of its molecules are what stand out the most. Water-soluble composites and their copolymers with high vinyl alcohol contents that are useful for coatings and adhesives are achievable. This polymer that is easily soluble in water is degraded in a randomised chain cleavage process, the catalysts of which are two types of enzyme-catalysed oxidation reactions. In its primary form, the process involves the dehydrogenation activity of extracellular enzymes that target the hydroxyl groups sequentially. The 1,3-glycol structure in the two repetitions of the two progressively larger units is converted to a 1,3-diketone. Following the carbon bond breaking process, the subsequent reaction will involve one of the ketone groups, which will convert to the carboxylic group, resulting in chain rupture. The product of the concluding reaction mimics a Claisen condensation shown in organic chemistry, and as a result, the resultant compound is acetic acid, which microorganisms may utilise [28].

4.5 Polyacrylic acids

Polyacrylic acid is a synthetic polymer with a wide range of applications, such as personal care, detergents, and wastewater treatment. Due to its high solubility in water, it is simply transported through wastewater treatment systems and, eventually, ends up in the natural environment. While polyacrylic acid demonstrates a tendency to biodegrade under natural conditions, the degradation mechanism is not well defined. In contrast, it has been found that only samples of low molecular weight (less than 4000) are active and biodegradable, while greater ones degrade at a very slow rate [28]. Other researchers have pointed out that the biodegradation process of polyacrylic acid may involve the hydrolysis of the ester bonds or oxidative reactions with enzymatic catalysis. Even though it is necessary to do the research in order to comprehend all the mechanisms of polyacrylic acid biodegradation and identify the microorganisms that have the capability to break down this polymer, this knowledge can help identify feasible alternatives to polyacrylic acid in various sectors.

4.6 Nylon 6,6

Nylon 6 represents a kind of synthetic polymer that is called polyamide polymer. And this is where the name "6,6" comes from: it is a 6 "string" repeated unit form of hexamethylene diamine (HDMA) monomers and adipic acid monomers. Nylon 6, or more generally known as polyamides, serves a wide variety of purposes because of their many desirable properties, like great strength, toughness, and good resistance to heat and chemicals. The structure of nylon 6,6 is formed by a straight chain with amide (-CO-NH-) linkages between the repeating units of HDMA and adipic acid. The molecular organisation of polymers increases the strength of molecules. To give rise to the amide bonds that create polyamide polymers, the HDMA monomer results in the formation of the amine group (-NH-), while the adipic acid monomer leads to the generation of the carboxylic acid groups (-COOH-) [32]. Nylon 6,6 production, for all intents and purposes, has been where it is because of its exceptional properties, its adaptability, and the multiple uses that it has. Nylon 6, which differs from all natural polymers like cellulose by being created from mainly non-renewable resources like oil or natural gas, it is created by complex chemical processes such as the polymerization of hexamethylenediamine and adipic acid. Nylon 6's high manufacturing rate is due to its desired properties, which include high tensile strength, durability, heat resistance, and chemical durability. Such characteristics make it suitable for use in a variety of fields, including fabrics, car accessories, electric insulation, food covering, and mechanical tools. It is due to nylon 6's versatility and high utilization requirements across different sectors and industries. It is important to recycle Nylon 6 as illegible since it does end up becoming an inexorable part of marine life after some time. It entails improper disposal or contamination of the article, which contains Nylon 6 products, and can lead to the collection of these products in marine water and water systems like seas and rivers. Nylon 6,6 waste that may appear as food may be consumed and retained within a fish's belly, seabirds' stomachs, and marine mammals' stomachs, as well as getting entangled in discarded. Fishing nets made from nylon 6,6. It can lead to the mortality or asphyxiation of fish or marine organisms, resulting in significant environmental damage and species extinction. Even despite the concerning issues, the polymer Nylon 6,6 still has wide applications in various areas because of its above merits. It can be said that the textile sector, owing to Nylon 6, which is the major raw material for the manufacture of textiles, threads, and other cloth, forms the largest market. Its heavy tensile strength,

resistance to abrasion, and feasibility for use in dyeing, finishing, and other procedures are vital factors in the popularity of its use for fabrics in carpets, fisheries, and upholstery.

Because nylon 6 is a polymer that embraces multifunctionality, flexibility, and versatility, it has a wide range of applications in various sectors because of its exceptional properties. The utilisation of nylon 6 is not limited to a particular field. Textiles can be made of it for clothes and garments; it can be used as automotive parts, electronics and electrical components, packaging materials, industrial components, consumer goods, filament yarn, and for medical purposes. These applications denote that nylon 6 presents this mildness as a suitable and versatile material with a wide range of qualities and properties that perform optimally within different industries. However, it is also essential to study the environmental consequences of polymer production, examine the sustainability of the polymer itself to lessen the environmental impact of the process, and research for new substitutes for sustainability to replace or at least reduce the polymer's drawbacks on the environment.

Polymer modifications to facilitate biodegradation
With a view to providing "weakly" connected backbones of polymers that may include bond breakage facilitating biodegradation, several approaches have been employed. Polymers like polyvinyl alcohol and others having only C-C– bonds in the main chain backbone have shown that as giant chains, they are resistant to enzymatic breakdown processes in general. As is the case, research efforts have been focused on the development of polymer modifications that are tailor-made to generate polymers with efficient biodegradability. One of the ways to make these materials biodegradable is to put functional groups into the main chain, like the dynamic ester groups that can be broken by chemical hydrolysis. The other strategy is embedding polar groups, and especially carbonyl groups, in or on the main chain of molecules to be exposed to chemical chain cleavage photochemical activations as well [33].

Biodegradable and non-biodegradable polymer blends
The rate at which a blend breaks down that contains both bio- and non-biodegradable polymers can differ tremendously depending on several factors, including how the components are located relative to each other and the mixing process itself. These parameters moderately affect the shape of the blend, which is the focus of the activity to monitor the penetrability of the decomposable component using this shape. Therefore, the process of polymer selection, their ratios, and the blending technique should be carefully selected to maintain these optimal biodegradability aspects alongside those of the desirable physical properties of the blend. Different ways to improve the qualities of biodegradable resins, accelerate the rate of decomposition, increase hydrophilicity, and increase mechanical resistance are through the blending of natural and synthetic polymers. Mixing two or more polymers together is known as polymer blending and is aimed at creating a new super material that will combine the desirable properties of both polymer systems. This kind of biodegradable polymer blend is carried out through the blending of a thermoplastic biodegradable resin with a non-biodegradable one. Those blends are anticipated to be much

more bio-based and break down in nature as opposed to conventional petroleum-based plastic materials [34].

Starch-based plastics are a kind of biodegradable plastic that is extracted from renewable sources; thus, they have gained much attention as an environmentally friendly material instead of oil-based plastics because of their superior environmental properties. Most carbohydrates available today are derived from natural sources. Starch stands out as the most cost-effective and abundant. Starch can be extracted from a variety of sources, including corn, wheat, and potatoes, making it an easily accessible raw material. Due to its availability and biodegradability, starch is widely used in the manufacture of biodegradable plastics. However, starch has limitations in its mechanical properties, such as brittleness and poor water resistance, which restrict its use in many applications. To enhance its properties and make it more suitable for a broader range of applications, starch is often blended with other biodegradable polymers, such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA). These polymers complement starch by providing improved strength, flexibility, and processability, while also maintaining high biodegradability. The blending process creates a composite material that leverages the natural biodegradability of starch and the enhanced physical properties of the synthetic polymers, resulting in a more versatile and sustainable plastic. To further expand the utility of starch-based materials, chemical modifications can be applied to alter the molecular structure of starch. Esterification or etherification is used as a chemical engineering processes. Functional groups of starch can be modified to improve its compatibility with other polymers, increase its water resistance, and enhance its thermal stability. These modifications allow starch-based plastics to be tailored for specific applications such as packaging, agricultural films, and disposable items. Additionally, starch can be transformed into a thermoplastic material through a process known as gelatinization. In this process, starch is mixed with water and subjected to heat and pressure, causing the starch granules to swell and break down into a viscous, moldable mass. This thermoplastic starch (TPS) can then be processed using conventional plastic manufacturing techniques, such as extrusion and injection molding, to produce a variety of biodegradable plastic products. The ability to convert starch into TPS further extends its applicability in the production of eco-friendly plastics [35]. This property can be attained with a small percentage of hydrophobic plastics like polyethylene and poly (methyl methacrylate) blended with plasticized starch, which in turn leads to products with inhibitory degradation and good mechanical features. This class of starch-based polymeric materials can be an eco-friendly alternative to conventionally produced plastics that are not biodegradable and might be the cause of increasing landfill waste. Apart from several studies that have been carried out for the use of starch-based plastics in several applications, such as packaging, agricultural films, and disposable goods, reports show that they can replace the synthetic polymers. In the food industry, they serve this function well; almost every snack, confectionery, and frozen food pack is made of them. They also serve as soil filtration films, adding fertility to agricultural land. Other than this, there has been an exploration of their involvement in biomedical devices (such as drug delivery systems and tissue engineering).

_____

Egypt. J. Chem. **67,** SI: M. R. Mahran (2024)

[36]. The decomposition process of starch-based plastics can be one of the truly desirable alternatives to conventional plastics, which can easily stay alive in nature for many decades. Although the biodegradability of starch-based plastics is influenced by numerous parameters, such as the level of their crystallisation, the type of plasticizers, and the oxygen and humidity levels in the surroundings, it is simply not enough to use this type of material to manufacture packaging. So, given that the starch degradation process is influenced by a lot of variable factors, it is very difficult to track the starch degradability for a particular application and in different disposal conditions [37].

Rate and mechanism of polymer biodegradation

Polymer biodegradation is a complex process that involves several pathways, including hydrolytic degradation, oxidative degradation, and microbial degradation. Each of these pathways is influenced by specific factors such as molecular weight, crystallinity, and cross-linking, which determine the rate and extent of degradation. In comparison to their non-fluid equivalents, liquid-state polymers have faster break-down times in comparison to their equivalents in the non-fluid state. The speed of degradation of polymers associated with the solid state is a multifactorial process that is conditioned by the polymer composition, molecular weight, morphology, crystallinity, and degree of cross-linking. Polymers can provide multiple processing paths that include physical, chemical, and biological degradation. Biodegradation utilizes physical processes to pull down the polymeric chains through friction, water attack, or analysis (chemical breakage). Biodegradation is a chemical process that involves the splitting of the polymer links, which are opened by some chemical reaction like oxidation, reduction, or hydrolysis. Microorganisms degrade plastics in a biological decomposition process, which is mediated by enzymes breaking the polymer chains forming the plastics. For example, in the case of polyester, the hydrolysis of the ester bonds occurs quickly. The pace of biodegradation can be increased by the modification of the polymer with the function group, which is prone to the attack of enzymes or hydrolytic degradation. Alternatively, hydrolytic additives and fillers may be introduced into the polymer matrix. Alongside this, more effective processing techniques, such as blending or copolymerization, could also provide the necessary improvements in the mechanism and breakdown rate of solid polymers [38].

The process of biodegrading polymers in the solid state can be very variable duration-wise, with wide alternative ranges depending on the chemical composition of the polymer and environmental conditions. For example, in soil and compost, the degradation rate of PCL and PLA is higher than in water. The rate of biodegradation is also influenced by the molecular weight of the polymer, with lower-molecular-weight polymers degrading faster than higher-molecular-weight polymers. The physicochemical conditions in the solid phase that control the mechanism of polymer degradation are also dependent on the degree of crystallinity and cross-linking of the polymer. High crystallinity and cross-linking polymer systems, meanwhile, inclusive of amorphous and non-cross-linked ones, are less prone to being degraded. However, a significant concern is that the addition of plasticizers or other structural changes might increase amorphous regions, decrease the extent of cross-linking, and hence reduce the biodegradability of the polymer [39]. In PLA, hydrolytic degradation is the primary pathway for PLA. The degradation rates are strongly influenced by molecular weight and crystallinity. Studies have shown that PLA with lower molecular weight and lower crystallinity degrades more rapidly in composting environments. Polycaprolactone, another biodegradable polyester, exhibits a degradation rate that is inversely proportional to its crystallinity. Highly crystalline PCL degrades slowly, while amorphous PCL can degrade much faster in the presence of microbes. Cross-linked polymers, such as vulcanized rubber, are highly resistant to both oxidative and microbial degradation due to their stable network structure. However, this resistance makes them less suitable for applications where biodegradability is desired.

There are two ways in which the enzymes act on the polymer. In the first approach, it is reared, not particularly with a group of monomers from the polymeric chain. The introductory approach consists of either a diffusion of extracellular hydrolases or hydrolysis of the polymer into water-soluble compounds. This microorganism variably releases an enzyme, which then disintegrates the plastics into microparticles that move in the aquatic environment. In the second, more complicated example, the enzyme relates to or is bonded to the microorganism's outer cover or cell surface, which then attaches itself to the polymer surface, to which the output of the enzyme leads to seeking and binding to that part of the polymer that it can see and may bind to. On the other hand, the enzyme proteins are high-molecular-weight proteins; therefore, they are largely complex with the solid polymer's molecule and lack the capability to penetrate the bulk of the polymers unless the polymers are swollen by solvent [40].

7.1 Mechanism of Biodegradation

Microorganism degradation is how living things break down organic substances into simpler substances, such as carbon dioxide, water, and biomass. It is this process that is of paramount importance regarding carbon cycling and other elements cycling through the environmental ecosystem, and it is also an indispensable feature for the elimination of many pollutants in our environment. The biodegradation process typically involves three key steps: (1) amylase and protease; (2) reduction; and (3) absorption. This is an enzymatic hydrolysis phase in which the microorganisms secrete extracellular enzymes, resulting in the degradation of complex organic compounds into

simpler compounds. The resultant simpler compounds are subsequently allowed to transport into the microbial cells and undergo an oxidation process. The oxidation process is just the opposite of obtaining electrons from exogenous compounds. At last, the oxidised compounds are taken up by the microbial biomass, which is utilised as a source of energy and organic products to be used for cell biochemical processes [41].

The catalysts that participate in biodegradation are generally defined by the types of compounds. For example, lipase breaks down the triglycerides to form two fatty acids and one monoglyceride, and proteases break down proteins into peptide compounds. These are organs that are synthesised by a range of microorganisms, including bacteria, mushrooms, and yeast cells. They are inducible, involving a switch that is 'on' and marking high synthesis levels in the presence of specific compounds in the environment. The reductive biodegradation process has an oxidation step, which works by using oxygen or other electron acceptors to remove electrons. This mechanism usually occurs either at the cell membrane or in the microorganism's cytoplasm, while enzymes such as dehydrogenases and oxygenases are two of the many others mentioned as catalysts of the process [42]. In many cases, the electrons taken away are used in the generation of adenosine triphosphate (ATP), which is the primary cell currency of energy. Also, the integration phase, basically the formation of oxidised compounds that are assimilated by the same biomass, is included in the overall process of biodegradation.

7.2 Kinetics of Biodegradation

Biodegradation kinetics is the study of the intensities and degrees of conversion brought about by the microorganisms, considering the concentration of solutes, temperature, and pH of the medium. The breakdown of an enzyme-polymer system is a result of the bond scission number that the enzyme causes on the molecule prior to disassociating from it; it depends on whether the bond breakup is reversible or not. For different enzyme-polymer bonds, the actual dissimilation procedures can differ. Whether microbial biodegradation is measured through weight loss measurements, gas dispersal, CO_2 emissions, or microbial growth measurements, the rates of these processes can vary significantly. The basis of this rate is calculated by calculating the number of materials that have been reduced over time. This way, researchers would be able to determine how much biodegradation and the rate of the process occurred. The data obtained by this kinetic phenomenon can be studied by implementing different models based on existing theories like first-order, second order, and mixed-order kinetics. They are virtual tools that allow you to access information on the reaction mechanism, how fast the material decays, and how long it takes to decompose. Numerous experiments have been carried out

by various institutions to look at the kinetics of biodegradation of different polymers such as polyesters, polycaprolactone, polyhydroxyalkanoates, and starch plastics. As such, using polycaprolactone as the material for biodegradable purposes can be recommended as it achieves the desired life span of 22 weeks [43]. Research published in 2016 about the biodegradation of bacterial polyhydroxyalkanoates demonstrated that the process was followed by mixed-order kinetics, and the rate constant depended on the molecular weight of the polymer [44].

In their research, the scientists presented a broad general approach to biodegradation kinetics, mediating both single and multi-scission mechanisms, which are common. The concept is based on attack at any selective location on polymeric chains. When the enzyme makes an initial cleavage, it can eventually either disengage from the chains and do a single scission process, or it can stay attached and there can be multiple bond cleavages on the chain as the enzyme keeps moving along it. Three variables are the decent substrate polymer, the fragment size built by the first assault, and the number of repetitive scissions accommodated when the enzyme remains complexed with a fragment of the two produced from the initial polysaccharide molecule, and these elements define the therapy effectiveness [28]. The study other researchers conducted employed a theory that explains the way microorganisms attack and utilise such anaerobic digesters of dead organic matter as cellulose and fatty acids. The notion says that not only enzymes that are in a soluble state are responsible for deterioration, but microorganisms that fix themselves onto the substrate's surface, carry the substrate or molecular fragments into cells, and attack them at the point of adhesion and enzyme assault are also to blame. The contact of the cell with the growth medium, the number of adsorptive points on the growth medium per enzyme complex and attack, the average particle size and total surface area of the medium, cell concentration, and cell loading are the main variables that affect the process under question [28]. This inevitably requires the inclusion of biodegradation kinetics in the list of parameters that a biodegradable product manufacturer must consider when creating and determining its bioavailability for environmental purposes.

Plastic waste management

At present, there are few options for proper disposal of plastic waste other than incineration, burying in landfills, or recycling the material. Conversion is the process of burning down the plastic waste that contains hazardous chemicals in the air. The horizon of plastic burial in landfills has gradually moved from a technically simple way analogous to chemical neutralisation to a biologically active method supported by water that is not far from the landfill surface to have organised microorganism growth. These microorganisms may then retrieve the organic material already present in the waste, which can be driven by the by-

_____

products of water, carbon dioxide, and methane. By recycling plastic waste, we mean that it is processed into materials that can help lower the volume of plastic that is thrown into landfills and burned with other waste. Nevertheless, the recycling of plastic waste is poised to be quite a challenge since the rates for the recycling of such material are generally low, and it might be difficult to recycle certain kinds of plastic [45].

Plastic waste management has become one of the major environmental problems because of the rising quantity of plastic waste produced internationally. This dilemma has been alleviated with numerous methods suggested and implemented, as shown in Figure 3. The single way may be all that is aimed at reducing the waste of plastic by appealing to consumers and governments around the globe to less use of plastics like bags, bottles, and plan containers and even minimising single use of plastics. In addition to these, there is reusing, which refers to turning plastics into other items. Yet, sorting the plastic waste, the high price of recycling, and the few places for recycling equipment are the most evident issues in the plastic recycling efforts. The other ways to deal with this issue should be the raising of biodegradable plastics in the system of nature as well as the implementation of regulations and policies thereby decreasing the amount of plastic waste. In addition to this, innovative technologies are being brought about for plastic waste processing into valuable products, for instance, fuel and chemicals, by simple burning processes such as pyrolysis and gasification [46]. An equal focus is placed on the improvement of the collection and disposal of plastic trash, primarily in countries now in the development stage where waste management is often not up to date. This entails the implementation of municipal waste management systems that promote community involvement in waste collection, in addition to the application of relative waste collection and disposal technologies. Though wise, efficient management of plastics requires a combination of techniques, including reducing waste generation, recycling, using biodegradable plastics, government policies and regulations, technological advancement, and improving waste collection and disposal infrastructure.
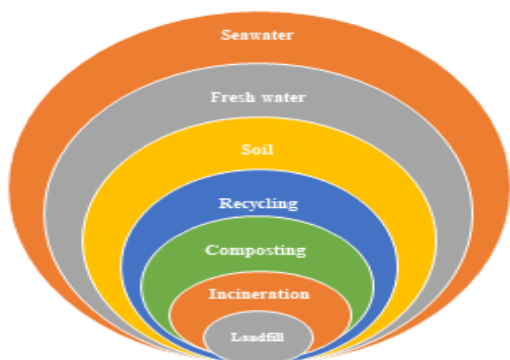

Figure 3 Degradation of polymers in different environments

8.1 Seawater

Oceans occupy 71% of the earth's surface and are home to 97% of the planet's water [47]. The sea water is usually regarded as having a high salt content of 34–37 ppt. Up to 99% of the salts are ionic compounds containing chlorine, sodium, sulphur, magnesium, calcium, and potassium [48]. Surface temperatures range from 30 °C in summer to -1 °C in winter on the seabed, and they depend not only on the season but also on the depth and location [49]. Standard seawater is typically considered to be 15 °C. The pH value of seawater is neutral, 7.5–8.4, a little more in the alkaline milieu [48]. Only very few fungi can withstand seawater, while anaerobic microorganisms dominate among the existing bacteria, especially in deep layers with low oxygen content as compared to aerobic microorganisms [50]. Alongside the temperature, the availability of light is also of paramount importance since it is a resource that is used by photosynthetic microorganisms and algae [51]. Understanding how various factors influence the degradation of polymers in seawater is crucial to mitigating plastic pollution. The type of polymer itself plays a key role, with biodegradable options like polyesters (PLA, PHB) degrading under specific conditions (warm, aerobic environments), while resistant polymers like polyethylene (PE) require significant time (hundreds of years). Abiotic factors like sunlight (UV radiation can break down polymer chains) and temperature (warmer water accelerates degradation) further influence the process. Biotic factors also play a significant role, with marine microbes like bacteria and fungi utilizing enzymes to break down polymers. The specific marine environment (salinity, oxygen levels, and currents) also impacts the degradation rates and distribution of microplastics formed during breakdown. Research is actively developing new, targeted degradable polymers and modifying existing ones for marine applications. By understanding the interplay between these factors, scientists can optimise the degradation behaviour of polymers, minimising their negative impact on marine ecosystems. The degradation of polymers in seawater is a complex process influenced by factors such as salinity, temperature, UV radiation, and microbial activity. The persistence of plastics in the marine environment is a significant concern due to the formation of microplastics, which have detrimental effects on marine life and ecosystems. Polyethylene (PE) and polypropylene (PP) are widely used non-biodegradable polymers that are highly resistant to degradation in seawater. The low water permeability coupled with the lack of functional groups susceptible to hydrolysis means that PE and PP can persist for hundreds of years in marine environments. Physical forces such as wave action and UV radiation cause these plastics to fragment into smaller pieces. This leads to the formation of microplastics. These microplastics can be ingested by marine organisms leading to bioaccumulation and potential harm throughout the food chain. Polylactic

_____

acid (PLA) is a biodegradable polymer designed to degrade under industrial composting conditions. However, its degradation in seawater is slow due to the low temperatures and reduced microbial activity compared to terrestrial environments. Studies have shown that PLA can persist in seawater for several years gradually breaking down into microplastics that pose similar risks to marine life as conventional plastics. Polyhydroxyalkanoates (PHAs) are naturally occurring biopolymers produced by microorganisms. They are more susceptible to microbial degradation in seawater compared to synthetic polymers. The degradation rate of PHAs in marine environments is influenced by factors such as polymer composition, salinity, and the presence of specific marine microbes capable of metabolizing PHA. Although PHAs degrade faster than conventional plastics, the rate is still slow enough that they can contribute to microplastic pollution if not properly managed. Polymers degrade in seawater, they often break down into microplastics—tiny plastic particles less than 5 millimeters in size. These microplastics are ubiquitous in the marine environment and pose a significant threat to marine life. Microplastics can be ingested by a wide range of marine organisms from plankton to large marine mammals. These particles can cause physical harm such as internal injuries and blockages, and can also introduce toxic chemicals into the organism's body. Microplastics can bioaccumulate leading to higher concentrations of harmful substances up the food chain, potentially impacting human health. The widespread presence of microplastics in marine ecosystems can disrupt the balance of these environments. Microplastics can alter sediment properties, affect the behavior and reproduction of marine organisms, and even influence the availability of food resources. The long-term ecological impacts of microplastic pollution are still being studied, but evidence suggests that they contribute to the decline of marine biodiversity and the degradation of ecosystem services.

8.2 Fresh water
The two main types of freshwater bodies are stagnant and dynamic waters. The environmental conditions are like those in seawater, with a salt concentration of less than 1 ppt [52]. Temperatures vary by season, rainfall, location, and depth of water. Lake Constance in Central Europe measures temperatures from 4 to 25 °C [53], while in the African Lake Victoria, temperatures range from 24 to 29 °C [54]. The pH of freshwater ranges from 6 to 9 [52, 55]. It is amazing to learn that bacteria and fungi are the main biological decomposers in fresh water, with fungi located a millimetre or two below the water surface. In freshwater environments, polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and starch-based materials generally exhibit relatively faster degradation rates. This is largely due to the higher levels of microbial activity and the presence of enzymes that can break down polymer chains. For instance, PLA has been shown to degrade within

months in freshwater environments, especially under warm, aerobic conditions. Similarly, PHAs, which are naturally produced by microorganisms, degrade efficiently in freshwater, with complete degradation occurring within a year depending on the specific conditions. In contrast, the degradation of polymers in seawater is often significantly slower. The high salinity, lower temperatures, and reduced microbial activity in seawater can inhibit the breakdown of polymers. For example, PLA, which degrades relatively quickly in freshwater, can take several years to degrade in seawater due to the reduced enzymatic activity and lower temperatures. Additionally, the presence of biofilms on the surface of plastics in seawater can further slow down the degradation process by creating a barrier that limits the exposure of the polymer to degrading agents.

8.3 Soil
The biodegradation within the soil is even more diversified than in other environments. The soil texture can be different in different regions. Densely packed loamy soil with particles < 2 m leaves very little space for gas diffusion with the environment, whereas this process is almost impossible in coarse sand with particle sizes up to 2 m. Depending on precipitation and climate, temperatures and pH values vary; the former may range from 2 to 11 inches. This process at the same time regulates the population density and activity of microorganisms in the soil [56]. Nevertheless, aerobic decomposition is usually postulated in the soil environment [57]. The effectiveness of polymer degradation in soil is influenced by the polymer's chemical structure, the presence of specific microorganisms, and environmental conditions (soil type, moisture, and temperature). Polylactic acid (PLA) is a popular biodegradable polymer that degrades in soil under composting conditions. However, its degradation rate in natural soil environments is slower due to the lower temperatures and variable moisture levels compared to industrial composting settings. It was reported that polylactic acid degradation occurred through hydrolysis where the ester bonds in the polymer backbone were broken down by water followed by microbial assimilation of the resulting lactic acid. Polyhydroxy acids (PHAs) are a class of biodegradable polyesters produced by microorganisms. They are known for their effective degradation in soil particularly in environments rich in organic matter. Soil-dwelling bacteria such as Pseudomonas and Bacillus species can metabolize PHAs, breaking them down into carbon dioxide, water, and biomass. The degradation rate of PHAs in soil is influenced by factors such as polymer composition, crystallinity, and the presence of microbial communities. Blends of starch with other biodegradable polymers such as polycaprolactone (PCL) exhibited good biodegradability in soil. Starch is a natural polysaccharide that is readily consumed by soil microorganisms. The biodegradation of starch-based polymers is initiated by the enzymatic

breakdown of starch into glucose which is then metabolized by microbes, leading to the degradation of the entire polymer blend. Soil microorganisms play a pivotal role in the biodegradation of polymers. The microbial community in soil is diverse. It is consisting of bacteria, fungi, and actinomycetes that produce enzymes capable of breaking down complex polymer structures. Certain bacterial species such as *Pseudomonas*, *Bacillus*, and *Rhodococcus,* are effective at degrading polyesters like PHAs and PLA. These bacteria secrete depolymerases that cleave the polymer chains into smaller oligomers which are further broken down into monomers that can be metabolized. Soil fungi, including species from the genera *Aspergillus and Penicillium* contribute to polymer degradation by producing extracellular enzymes such as *cellulases, lipases, and esterases.* These enzymes are particularly effective at breaking down starch-based polymers and polycaprolactone. The rate of polymer biodegradation in soil is highly dependent on soil type, moisture content, temperature, pH, and the presence of organic matter. Sandy soils with their lower organic content and microbial activity generally exhibit slower biodegradation rates compared to loamy or clayey soils which have higher moisture retention, organic matter, and microbial density. Polyhydroxy acids (PHAs) degrade more rapidly in loamy soils rich in organic carbon which supports a thriving microbial community. Adequate moisture is essential for microbial activity and the hydrolysis of biodegradable polymers. However excessive moisture can lead to anaerobic conditions which may slow down degradation. Optimal temperatures for soil biodegradation are typically in the range of 20 - 30 °C. Degradation rates decrease significantly at lower temperatures as microbial activity slows down. The pH of the soil can influence enzyme activity and microbial growth. Most biodegradable polymers degrade more efficiently in neutral to slightly acidic soils (pH 6-7). High levels of organic matter in the soil provide a rich substrate for microorganisms enhancing the biodegradation of polymers such as starch-based materials and PHAs. The OECD Protocol 307 is a laboratory soil biodegradation test. Here, the temperature is set at 20 °C, an interval of 120 days, and a pH of 5.5–8 [58].

8.4 Composting

The composting environment is frequently looked upon as a homogeneous ecosystem where aerobic conditions govern the ecological niche, and the composting process can be better controlled in terms of composition, pH, humidity, and size than biodegradation in soil [56]. While the composition of compost material varies depending on the source, green waste and agricultural residues are widely used. The purpose is to achieve a relative humidity of 45–60% and a pH value of 6.5–8.0 [59]. No ISO standard or ASTM guidelines are available for home composting conditions. This means polymeric is characterised as home compostable if at least 90% (measured after CO_2 release) is

degraded within 12 months at ambient temperatures of 20–30 °C [60].

8.5 Industrial composting

In contrast to home compost, commercial composting units operate at 50–60 °C [61], which gives a boost to the thermophilic bacteria and fungi at that temperature. This causes the process of biological degradation to take place for a shorter period. Aside from that, the size and structure of the compost pile also play an important role. In addition, regular and thorough aeration are other measures to boost degradation [62]. The temperature set for the industrial composting method mentioned in DIN EN 14855 is 58 °C at a maximum duration of 6 months. Composting and industrial composting are the same word in the same context given the circumstances and are grouped.

8.6 Recycling

Mechanical recycling involves the collection, sorting, and processing of plastic waste into new materials. This method is limited by the quality of the recycled material which often degrades with each cycle reducing its usability for high-performance applications. Contamination, the mixing of different polymer types, and the presence of additives reduce the effectiveness of mechanical recycling. However mechanical recycling remains a cornerstone of current plastic waste management strategies [63-65]. Chemical recycling offers a promising alternative to mechanical recycling by breaking down plastic waste into its monomers or other chemical feedstocks which can then be repolymerized into new plastics [66-67]. This method allows for the recycling of mixed and contaminated plastics that are difficult to process mechanically [68-70]. Emerging technologies such as pyrolysis, gasification, and solvolysis are driving the advancement of chemical recycling. Pyrolysis, for example, converts plastic waste into fuels or raw materials for new plastics, reducing reliance on virgin fossil resources. Gasification transforms plastic waste into syngas, which can be used to produce chemicals and fuels, while solvolysis uses solvents to depolymerize plastics into their constituent monomers [71]. Although chemical recycling holds significant potential, it faces challenges such as high energy requirements and the need for clean feedstock. However, ongoing research aims to improve process efficiency and scalability [72].

8.7 Landfill

Landfilling remains one of the most common disposal methods for plastic waste. However this approach has significant drawbacks, including the long-term persistence of plastics which can take hundreds of years to degrade, and the risk of leachate contamination in surrounding environments and ground water. Like seawater and fresh water, landfills decay under anaerobic conditions. Anaerobic decomposition at first proceeds under dry

conditions with the aid of the microorganisms that come from digestion tanks. To speed up decay, moisture and oxygen can be added during and after the operation of the plant. The pH value lies in the range of 5.8 and 8.5 [56, 73]. The leachate that is collected from the bottom is recycled and then no longer allowed to re-enter the soil and groundwater, which may lead to an increase in the performance of a landfill [74]. Table 3 summarizes the main environmental factors, as well as the most important ones for biological disintegration. The biodegradation of various polymers in all environments is presented in Tables 4 and 5.

8.8 Incineration

Incineration is another widely used method, particularly for reducing the volume of plastic waste. While it provides energy recovery, it also generates harmful emissions such as dioxins and furans, which pose health and environmental risks. The inefficiency of some incineration processes further exacerbates these issues.

Limitations of biodegradable polymers

Biodegradable polymers are an excellent option for removing plastic waste and establishing sustainability.

They have some limitations in comparison with non-biodegradable polymers; understanding allows choosing the right material for the specific purpose.

With advancements in research and development, it is possible to make biodegradable polymers a more attractive and accessible alternative. The benefits of biodegradable polymers include environmental friendliness, which reduces plastic pollution and promotes a more sustainable future, as well as renewable resources. Utilising renewable resources, lessening dependence on fossil fuels, and improving waste management, compost offers a sustainable option for disposal [75]. Biodegradable polymers have limitations: Slower biodegradation rates: biodegradation can differ widely depending on the environment and microorganisms utilized. Lower mechanical strength: This may be inappropriate for applications that require high strength. Production cost may be higher than for non-biodegradable materials [76]. Table 6 provides the comparative analysis.

Table 3 The major environmental variables along with their key degradation parameters.

Environment	Temperature (°C)	pH	Oxygen Availability	Moisture	Key Microorganisms	Ref.
Seawater	30 (surface) -1 (seabed)	7.5-8.4 (alkaline)	Mostly anaerobic (deeper layers)	High	Anaerobic bacteria	[48-50]
Freshwater	4-29	6-9	Variable (aerobic & anaerobic zones)	High	Bacteria, Fungi (limited depth)	[52-55]
Soil	Varies depending on region and depth	2-11	Aerobic (generally assumed)	Variable	Bacteria, Fungi, Archaea (in some cases)	[56-58]
Composting (Home)	20-30 (ambient)	6.5-8.0	Aerobic	Moderate-High (45-60% relative humidity)	Bacteria, Fungi	[59,60]
Composting (Industrial)	50-60	Neutral (around 7)	Aerobic	High	Thermophilic bacteria, fungi	[61,62]
Sewage sludge	37-50	Variable	Variable (aerobic & anaerobic zones)	High	Diverse bacteria, archaea (anaerobic)	[63-65]
Landfill	Varies with depth	5.8-8.5	Anaerobic	Variable (initially dry, moisture added later)	Methanogenic archaea (anaerobic)	[65-67]

Table 4 The polymer degradation in various environments at standard conditions 25°C.

Polymer	Landfill	Soil	Seawater	Compost	Fresh Water	Ref.
PLA	Slow till 11 months	No change	It is not suitable for biodegradation over one year	Minimal change	No change	[68]
PHB	90% after 4 weeks	0.12%/day at 28 °C	7% was detected after 1 year.	6% was observed at 150 days.	7% was measured after 180 days, and 35% after 358 days.	[69-70]
PCL	-	Very Slow	degrades completely in just a few weeks	Degradation can be observed after a few weeks	-	[71-73]
PBS	-	Degradable but after 180 days only 11%	-	-	-	[74]

Table 5 The polymer degradation in various environments.

Polymer	Landfill	Soil	Seawater	Compost	Fresh Water	Ref.
Copolymer of PLA and glycolic acid, poly (lactic-co-glycolic acid) (PLGA)	Slow till 15 months	Degradation occurs at 45ºC after 8 Weeks. At 50 ºC occurs at 5 Weeks	Mass loss after 270 days	High Temp at 45-70 ºC degradation occurs after 17 days	-	[75-77]
PHB (Polyhydroxybutyrate)	13 days at 30 ºC	different pH values at different temperatures and humidity over a period of 200 days	160 days at 29 ºC	temperature of 55 ºC observed nearly 80% biodegradation after 30 days	-	[78-79]
PHBV (Polyhydroxybutyrate-co-valerate)	total mass loss of 60% could be determined after 350 days at 35 ºC	Degradation occurs at different temperature	At 29 ºC, a total mass loss of 46% within 160 days	100% after 70 days at 20–24º C	21 mol% was degraded within 254 days, at 6 ºC	[80-81]

Table 6 A comparative analysis between biodegradable and non-biodegradable polymers

Property	Biodegradable Polymers	Non-Biodegradable Polymers
Origin	Renewable resources (plants, microorganisms)	Fossil fuels
Biodegradability	Degrade by microorganisms into harmless byproducts	Persist in the environment for centuries
Environmental Impact	Reduced reliance on fossil fuels, minimized CO_2 emissions	Contribute to plastic pollution in landfills and oceans
End-of-Life Management	Composting or anaerobic digestion	Landfill disposal, limited recycling options
Mechanical Strength	Can be lower than non-biodegradable counterparts	Generally higher mechanical strength
Cost	Production cost can be higher due to feedstock and processing	Typically, lower production cost
Applications	Suitable for short-lived applications (packaging, food service)	Wide range of applications due to durability (construction, textiles)

Economic and environmental impact analysis
Table 7 displays the selling price of poly lactic acid (PLA) and various PLA composites. The low price of cellulose and lignin reduces the cost of PLA-composite. The selling price of PLA composites with cellulose and lignin at 5–30% is 1.43–1.90 $/kg [77].

Table 7 A selling price of PLA and different composites.

Type	Selling price ($/kg)
PLA	1.99
P_CL_5	1.89–1.90
P_CL_10	1.80–1.81
P_CL_20	1.61–1.64
P_CL_30	1.39-1.43

Commercialization of bioplastics
In recent years, the commercialization of bioplastics has become a topic of great interest as people seek alternatives to address the growing plastic waste problem. Bioplastics constitute less than 1% of the synthetic plastics manufactured every year [78]. Plastic production has been decreasing globally, but bioplastic production has increased. The drivers are the rising awareness among the

masses about the adverse effects of synthetic plastics and different countries imposing stringent rules on the usage of bioplastics. The transition to bioplastics has a few challenges, including the trade-off between biodegradability and reusability, as well as the requirement to meet the same design and formulation standards as conventional plastics [79]. The major companies in the bioplastic manufacturing sector are in several countries, such as the USA, Japan, Germany, and the Netherlands.
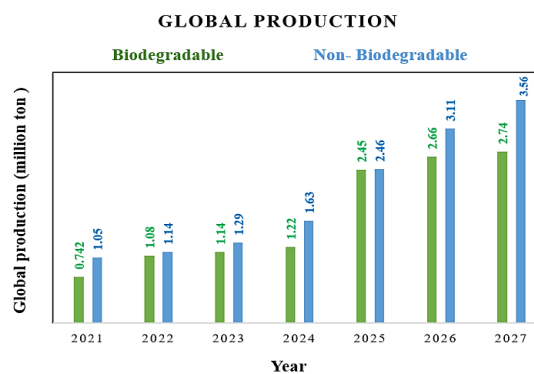

Figure 4

The current global production capacity of bioplastics is estimated to be about 1.05 million metric tonnes in 2021 and 3.11 million metric tonnes in 2026, as shown in Figure 4. The global market value for bioplastics

The Figure 4 The global production capacity of biodegradable and non-biodegradable will grow by about four times. $ 46 billion From $11.2 billion in 2021 to $15.02 percent the usage of biodegradable and bio-based non-biodegradable plastics in 2021 is forecast at 58.3%, 41.7%, and 7%, respectively, reflecting the trend towards the use of biodegradable products. According to the bioplastic market share by region, Europe holds the largest share at 43.5%, followed by North America (19.6%), and Asia (19.6%). In Europe, bioplastics are mostly used for food packaging, plastic mulch for agriculture, and plastic shopping bags and bottles. In addition, the market will be propelled by the increase in the use of bioplastics in key application areas such as packaging, consumer goods, textiles, medical devices, automotive, and transport, among others [80-82].

Conclusions and recommendations

Polymers are materials composed of the unit's monomers. This is a kind of molecule consisting of a repeating structure. Polymers were widely used in many industries as they featured less cost and weight, as well as higher flexibility. It has been argued that there are risks to the environment because most polymers are made in large quantities with low biodegradability. Most of the plastic waste created is incinerated or landfilled, where it stays forever for hundreds or even thousands of years until organic decomposition occurs. Inadequate or deliberate disposal of plastic waste may also result in the release of toxic materials into the environment, making the air and water particularly polluted. To face up to the problems of which disposal of such plastics has become more and more challenging, people have recently become more interested in creating biodegradable polymers that can decompose by natural processes instead. The biodegradable polymers may decompose from their small fragmenting molecules over a longer period. However, making biodegradable plastics from many different materials comes in as an important advantage. These materials are renewable and consist of sources such as starch, cellulose, and vegetable oils, as well as synthesized monomers such as lactic acid and caprolactone. Living up to their name, different kinds of polymers are therefore easily degradable and disintegrate in ways that are either through the digestion of microbes or simply exposure to sunlight, which in the end generates harmless molecules such as water and carbon dioxide. Due to the role of biodegradable plastics in depleting the damage that non-biodegradable plastics due to the environment and advancing the course for sustainability, non-biodegradable polymers have gained so much popularity in recent years due to the harmful effects they pose to the environment. Therefore, biodegradable polymer research, development, and use have been neglected and therefore given much emphasis in recent years. The collective effort of environmentalists and policymakers in each corner of the world is amplified into a unified voice of concern about the consequences of discarded plastics in landfills and the ocean as well.

In this study, extensively described for the degradation process of materials, the biodegradability of polymers in several applications was identified, and factors affecting polymer degradation were described in detail. The discussion included the biodegradation of synthetic polymers. The blending of biodegradable and non-biodegradable polymers and their influence on the biodegradation process were discussed. The consequences of polymer degradation in various environments were investigated. In the fresh water, bacteria and fungi were identified as the main biological decomposers. The optimal pH values for material degradation at the landfill site were between pH 5.8 and 8.5.

Conflicts of interest

"There are no conflicts to declare"

References

[1] Azmi, George E., Aya M. Saada, Eissa M. Shokir, Mohamed S. El-Deab, Attia M. Attia, and Walaa AE Omar. "Adsorption of the xanthan gum polymer and sodium dodecylbenzenesulfonate surfactant in sandstone reservoirs: Experimental and density function theory studies." *ACS omega* 7, no. 42 (2022): 37237-37247.

[2] Reddy, M. S. B., Ponnamma, D., Choudhary, R., & Sadasivuni, K. K. (2021). A comparative review of natural and synthetic biopolymer composite scaffolds. Polymers, 13(7), 1105.

[3] Wang, C., Liu, Y., Chen, W. Q., Zhu, B., Qu, S., & Xu, M. (2021). Critical review of global plastics stock and flow data. Journal of Industrial Ecology, 25(5), 1300-1317.

[4] Kibria, M. G., Masuk, N. I., Safayet, R., Nguyen, H. Q., & Mourshed, M. (2023). Plastic waste: Challenges and opportunities to mitigate pollution and effective management. International Journal of Environmental Research, 17(1), 20.

[5] Rai, P., Mehrotra, S., Priya, S., Gnansounou, E., & Sharma, S. K. (2021). Recent advances in sustainable design and applications of biodegradable polymers. Bioresource Technology, 325, 124739. doi: 10.1016/j.biortech.2021.124739

[6] Siracusa, V., & Blanco, I. (2020). Bio-polyethylene (Bio-PE), Bio-polypropylene (Bio-PP) and Bio-poly (ethylene terephthalate) (Bio-PET): Recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications. Polymers, 12(8), 1641.

[7] Elsaeed, Shimaa M., Elsayed Gamal Zaki, Walaa AE Omar, Ahmed Ashraf Soliman, and Attia Mahmoud Attia. "Guar gum-based hydrogels as potent green polymers for enhanced oil recovery in high-salinity reservoirs." *ACS omega* 6, no. 36 (2021): 23421-23431.

[8] Ouyang, W., Li, X., Xu, J., Pei, Y., & Liu, S. (2020). Comprehensive exploration of natural degradation of poly (lactic acid) blends in various degradation media. Waste Management, 118, 162-171. doi: 10.1016/j.wasman.2020.09.022

[9] Adrah, K., Ananey-Obiri, D., & Tahergorabi, R. (2020). Development of bio-based and biodegradable plastics: novelty, advent, and alternative technology. Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications, 1-25.

[10] Diaz, J. R., Franco, L. T., & Garzón, C. E. (2020). Enhanced biodegradation of poly (lactic acid) (PLA) by blending with starch nanocrystals and fique fibers. Journal of Polymers and the Environment, 28(1), 172-184. doi: 10.1007/s10924-019-01686-9 [doi.org]

[11] Akhir, M. A. M., & Mustapha, M. (2022). Formulation of biodegradable plastic mulch film for agriculture crop protection: a review. Polymer Reviews, 62(4), 890-918.

[12] Jarrar, H., El-Keblawy, A., Ghenai, C., Abhilash, P. C., Bundela, A. K., Abideen, Z., & Sheteiwy, M. S. (2023). Seed enhancement technologies for sustainable dryland restoration: Coating and scarification. Science of the Total Environment, 166150.

[13] RameshKumar, S., Shaiju, P., & O'Connor, K. E. (2020). Bio-based and biodegradable polymers-State-of-the-art, challenges and emerging trends. Current Opinion in Green and Sustainable Chemistry, 21, 75-81.

[14] Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. Progress in Polymer Science, 117, 101395.

[15] Ali, S. S., Elsamahy, T., Al-Tohamy, R., Zhu, D., Mahmoud, Y. A. G., Koutra, E., ... & Sun, J. (2021). Plastic wastes biodegradation: Mechanisms, challenges and future prospects. Science of The Total Environment, 780, 146590.

[16] Bahl, S., Dolma, J., Singh, J. J., & Sehgal, S. (2021). Biodegradation of plastics: A state of the art review. Materials Today: Proceedings, 39, 31-34.

[17] Wei, R., & Wierckx, N. (2021). Microbial degradation of plastics. Frontiers in Microbiology, 12, 635621.

[18] Di Bartolo, A., Infurna, G., & Dintcheva, N. T. (2021). A review of bioplastics and their adoption in the circular economy. Polymers, 13(8), 1229.

[19] Samir, A., Ashour, F. H., Hakim, A. a. A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. Npj Materials Degradation, 6(1). https://doi.org/10.1038/s41529-022-00277-7

[20] Maity, W., Maity, S., Bera, S., & Roy, A. (2021). Emerging roles of PETase and MHETase in the biodegradation of plastic wastes. Applied Biochemistry and Biotechnology, 193, 2699-2716.

[21] Satti, S. M., & Shah, A. A. (2020). Polyester-based biodegradable plastics: an approach towards sustainable development. Letters in Applied Microbiology, 70(6), 413-430.

[22] Tyagi, P., Agate, S., Velev, O. D., Lucia, L., & Pal, L. (2022). A critical review of the performance and soil biodegradability profiles of biobased natural and chemically synthesized polymers in industrial applications. Environmental Science & Technology, 56(4), 2071-2095.

[23] Carmen, S. (2021). Microbial capability for the degradation of chemical additives present in petroleum-based plastic products: A review on current status and perspectives. Journal of hazardous materials, 402, 123534.

[24] Tian, K., Yu, Y., Qiu, Q., Sun, X., Meng, F., Bi, Y., ... & Huo, H. (2022). Mechanisms of BPA degradation and toxicity resistance in Rhodococcus equi. Microorganisms, 11(1), 67.

[25] Feng, S., Yue, Y., Chen, J., Zhou, J., Li, Y., & Zhang, Q. (2020). Biodegradation mechanism of polycaprolactone by a novel esterase MGS0156: a QM/MM approach. Environmental Science: Processes & Impacts, 22(12), 2332-2344.

[26] Atanasova, N., Stoitsova, S., Paunova-Krasteva, T., & Kambourova, M. (2021). Plastic degradation by extremophilic bacteria. International Journal of Molecular Sciences, 22(11), 5610.

[27] Jadaun, J. S., Bansal, S., Sonthalia, A., Rai, A. K., & Singh, S. P. (2022). Biodegradation of plastics for sustainable environment. Bioresource Technology, 347, 126697.

[28] Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. Progress in Polymer Science, 117, 101395.

[29] Dey, S., Veerendra, G. T. N., Babu, P. A., Manoj, A. P., & Nagarjuna, K. (2024). Degradation of plastics waste and its effects on biological ecosystems: A scientific analysis and comprehensive review. Biomedical Materials & Devices, 2(1), 70-112.

[30] Koller, M., Salerno, A., Muhr, A., Reiterer, A., Schober, S., Mittelbach, M., & Braunegg, G. (2017). Production of polyhydroxyalkanoates from agricultural waste and surplus materials. Bioresource Technology, 245, 1525-1533. https://doi.org/10.1016/j.biortech.2017.05.024

[31] Gong, Z., Jin, L., Yu, X., Wang, B., Hu, S., Ruan, H., ... & Jin, F. (2023). Biodegradation of low-density polyethylene by the fungus Cladosporium sp. recovered from a landfill site. Journal of Fungi, 9(6), 605.

[32] Shamsuri, A. A., & Daik, R. (2020). Mechanical and thermal properties of Nylon-6/LNR/MMT nanocomposites prepared through emulsion dispersion technique. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 73(1), 1-12.

[33] Bahl, S., Dolma, J., Singh, J. J., & Sehgal, S. (2021). Biodegradation of plastics: A state of the art review. Materials Today: Proceedings, 39, 31-34.

[34] Rajeshkumar, L. (2022). Biodegradable polymer blends and composites from renewable resources. In Biodegradable polymers, blends, and composites (pp. 527-549). Woodhead Publishing.

[35] Yu, X., Chen, L., Jin, Z., & Jiao, A. (2021). Research progress of starch-based biodegradable materials: A review. Journal of Materials Science, 56, 11187-11208.

[36] Müller, P., González, M., & Báez, G. (2017). Chemical modification of starch for applications in bio-based materials. [Editorial]. Molecules (Basel, Switzerland), 22(1), 74. https://doi.org/10.3390/molecules22010074

[37] Agarwal, S. (2020). Biodegradable polymers: Present opportunities and challenges in providing a microplastic-free environment. Macromolecular Chemistry and Physics, 221(6), 2000017.

[38] Cakmak, O. K. (2024). Biodegradable polymers—A review on properties, processing, and degradation mechanism. Circular Economy and Sustainability, 4(1), 339-362.

[39] Jadaun, J. S., Bansal, S., Sonthalia, A., Rai, A. K., & Singh, S. P. (2022). Biodegradation of plastics for sustainable environment. Bioresource Technology, 347, 126697.

[40] Bher, A., Mayekar, P. C., Auras, R. A., & Schvezov, C. E. (2022). Biodegradation of biodegradable polymers in mesophilic aerobic environments. International Journal of Molecular Sciences, 23(20), 12165.

[41] Sharma, S., & Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environmental Science and Pollution Research, 24(27), 21530–21547. https://doi.org/10.1007/s11356-017-9910-8

[42] Van Der Zee, M., Villaverde, S., & Villacorte, L. O. (2020). Microbial degradation and fate of emerging contaminants. In Microbial Degradation and Bioremediation of Organic and Inorganic Pollutants (pp. 71-104). Elsevier.

[43] Li, M., Ma, Q., Su, T., Wang, Z., & Tong, H. (2024). Effect of polycaprolactone microplastics on soil microbial communities and plant growth. Journal of Polymers and the Environment, 32(3), 1039-1045.

[44] Gahlawat, G., Soni, R., Gupta, R., & Puri, S. K. bass(2016). Kinetics of biodegradation of polyhydroxyalkanoates (PHAs) by bacteria: A review. International Journal of Biological Macromolecules, 90, 451-458. doi: 10.1016/j.ijbiomac.2016.05.067

[45] Aktaş, Ç., Atasoy, M., & Atasoy, A. (2020). Investigation of the factors affecting plastic waste recycling. Journal of Cleaner Production, 272, 122762. https://doi.org/10.1016/j.jclepro.2020.122762

[46] Matjašič, T., Simčič, T., Medvešček, N., Bajt, O., Dreo, T., & Mori, N. (2021). Critical evaluation of biodegradation studies on synthetic plastics through a systematic literature review. Science of the Total Environment, 752, 141959.

[47] Tyagi, P., Agate, S., Velev, O. D., Lucia, L., & Pal, L. (2022). A critical review of the performance and soil biodegradability profiles of biobased natural and chemically synthesized polymers in industrial applications. Environmental Science & Technology, 56(4), 2071-2095.

[48] Da Costa, J. P., Nunes, A. R., Santos, P. S., Girao, A. V., Duarte, A. C., & Rocha-Santos, T. (2018). Degradation of polyethylene microplastics in seawater: Insights into the environmental degradation of polymers. Journal of Environmental Science and Health, Part A, 53(9), 866-875.

[49] Huang, D., Hu, Z. D., Liu, T. Y., Lu, B., Zhen, Z. C., Wang, G. X., & Ji, J. H. (2020). Seawater degradation of PLA accelerated by water-soluble PVA. e-Polymers, 20(1), 759-772.

[50] Wang, G. X., Huang, D., Ji, J. H., Völker, C., & Wurm, F. R. (2021). Seawater-degradable polymers—fighting the marine plastic pollution. Advanced science, 8(1), 2001121.

[51] Kliem, S., Kreutzbruck, M., & Bonten, C. (2020). Review on the biological degradation of polymers in various environments. Materials, 13(20), 4586.

[52] Yi, Y., Guo, S., Li, S., Rahman, M. Z., Zhou, L., Shi, C., & Zhu, D. (2021). Effect of alkalinity on the shear performance degradation of basalt fiber-reinforced polymer bars in simulated seawater sea sand concrete environment. Construction and Building Materials, 299, 123957.

[53] Li, C., Busquets, R., & Campos, L. C. (2020). Assessment of microplastics in freshwater systems: A review. Science of the Total Environment, 707, 135578.

[54] Zhang, B., Chen, L., Chao, J., Yang, X., & Wang, Q. (2020). Research progress of microplastics in freshwater sediments in China. Environmental Science and Pollution Research, 27, 31046-31060.

[55] Sun, X. L., Xiang, H., Xiong, H. Q., Fang, Y. C., & Wang, Y. (2023). Bioremediation of microplastics in freshwater environments: A systematic review of biofilm culture, degradation mechanisms, and analytical methods. Science of The Total Environment, 863, 160953.

[56] Borrowman, C. K., Johnston, P., Adhikari, R., Saito, K., & Patti, A. F. (2020). Environmental degradation and efficacy of a sprayable, biodegradable polymeric mulch. Polymer degradation and stability, 175, 109126.

[57] Beltrán-Sanahuja, A., Benito-Kaesbach, A., Sánchez-García, N., & Sanz-Lázaro, C. (2021). Degradation of conventional and biobased plastics in soil under contrasting environmental conditions. Science of The Total Environment, 787, 147678.

[58] Liao, J., & Chen, Q. (2021). Biodegradable plastics in the air and soil environment: Low degradation rate and high microplastics formation. Journal of hazardous materials, 418, 126329.

[59] Mokobia, K., Jonathan, E. M., Oyiborhoro, G., Maliki, M., & Ifijen, I. H. (2024, February). Environmental degradation of polymer-based composite materials: challenges and mitigation strategies. In TMS Annual Meeting & Exhibition (pp. 1218-1236). Cham: Springer Nature Switzerland.

[60] Brebu, M. (2020). Environmental degradation of plastic composites with natural fillers—a review. Polymers, 12(1), 166.

[61] Bandini, F., Frache, A., Ferrarini, A., Taskin, E., Cocconcelli, P. S., & Puglisi, E. (2020). Fate of biodegradable polymers under industrial conditions for anaerobic digestion and aerobic composting of food waste. Journal of Polymers and the Environment, 28, 2539-2550.

[62] Martín del Campo, A. S., Robledo-Ortíz, J. R., Arellano, M., & Perez-Fonseca, A. A. (2022). Influence of agro-industrial wastes over the abiotic and composting degradation of polylactic acid biocomposites. Journal of Composite Materials, 56(1), 43-56.

[63] Maris, Joachim, Sylvie Bourdon, Jean-Michel Brossard, Laurent Cauret, Laurent Fontaine, and Véronique Montembault. "Mechanical recycling: Compatibilization of mixed thermoplastic

wastes." *Polymer Degradation and Stability* 147 (2018): 245-266.

[64] Ragaert, Kim, Laurens Delva, and Kevin Van Geem. "Mechanical and chemical recycling of solid plastic waste." *Waste management* 69 (2017): 24-58.

[65] Schyns, Zoé OG, and Michael P. Shaver. "Mechanical recycling of packaging plastics: A review." *Macromolecular rapid communication* 42, no. 3 (2021): 2000415.

[66] Huang, Jijiang, Andrei Veksha, Wei Ping Chan, Apostolos Giannis, and Grzegorz Lisak. "Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes." *Renewable and Sustainable Energy Reviews* 154 (2022): 111866.

[67] Solis, Martyna, and Semida Silveira. "Technologies for chemical recycling of household plastics–A technical review and TRL assessment." *Waste Management* 105 (2020): 128-138.

[68] Martínez-Narro, Gerardo, Samaila Hassan, and Anh N. Phan. "Chemical recycling of plastic waste for sustainable polymer manufacturing-A critical review." *Journal of Environmental Chemical Engineering* (2024): 112323.

[69] Kulikova, Yuliya, Galina Ilinykh, Natalia Sliusar, Olga Babich, and Mohamed Bassyouni. "Life cycle assessments of biofuel production from beach-cast seaweed by pyrolysis and hydrothermal liquefaction." *Energy Conversion and Management: X* 23 (2024): 100647.

[70] Elhenawy, Yasser, Kareem Fouad, Amr Mansi, M. Bassyouni, Mamdouh Gadalla, Fatma Ashour, and Thokozani Majozi. "Experimental analysis and numerical simulation of biomass pyrolysis." *Journal of Thermal Analysis and Calorimetry* (2024): 1-15.

[71] Elhenawy, Yasser, Kareem Fouad, M. Bassyouni, O. A. Al-Qabandi, and Thokozani Majozi. "Yield and energy outputs analysis of sawdust biomass pyrolysis." *Energy Conversion and Management: X* 22 (2024): 100583.

[72] Aboelela, Dina, Habibatallah Saleh, Attia M. Attia, Yasser Elhenawy, Thokozani Majozi, and Mohamed Bassyouni. "Recent advances in biomass pyrolysis processes for bioenergy production: optimization of operating conditions." *Sustainability* 15, no. 14 (2023): 11238.

[73] Mateo-Sagasta, J.; Raschid-Sally, L.; Thebo, A. GlobalWastewater and Sludge Production, Treatment and Use. In Wastewater: Economic Asset in an Urbanizing World; Qadir, M., Wichelns, D., Drechsel, P., Eds.; Springer: Dordrecht, The Netherlands; Heidelberg, Germany; New York, NY, USA, 2015; pp. 15–38. ISBN 978-94-017-9545-6.

[74] Belone, M. C. L., Kokko, M., & Sarlin, E. (2021). Degradation of common polymers in sewage sludge purification process developed for microplastic analysis. Environmental Pollution, 269, 116235.

[75] Xu, Z., & Bai, X. (2022). Microplastic degradation in sewage sludge by hydrothermal carbonization: Efficiency and mechanisms. Chemosphere, 297, 134203.

[76] Xochitl, Q. P., María del Consuelo, H. B., María del Consuelo, M. S., Rosa María, E. V., & Alethia, V. M.

(2021). Degradation of plastics in simulated landfill conditions. Polymers, 13(7), 1014.

[77] Canopoli, L., Coulon, F., & Wagland, S. T. (2020). Degradation of excavated polyethylene and polypropylene waste from landfill. Science of the Total Environment, 698, 134125.

[78] Aisha, S., Chin, P. S., Baharuddin, A. T., & Peng, L. C. (2018). Production of bio-based plastics from renewable resources and their future prospects. Progress in Polymer Science, 87, 112-142.

[79] Kim, P. Do, Park, H., Rajendran, N., Yu, J., Min, J., Kim, S. K., & Han, J. (2023). Economic and environmentally viable preparation of a biodegradable polymer composite from lignocellulose. Journal of Industrial and Engineering Chemistry, 122, 221–230. https://doi.org/10.1016/j.jiec.2023.02.023

[80] Thomas, A. P., Kasa, V. P., Dubey, B. K., Sen, R., & Sarmah, A. K. (2023). Synthesis and commercialization of bioplastics: Organic waste as a sustainable feedstock. Science of the Total Environment, 904(September), 167243. https://doi.org/10.1016/j.scitotenv.2023.167243

[81] Rosenboom, J.G., Langer, R., Traverso, G., 2022. Bioplastics for a circular economy. Nat.Rev. Mater. 7, 117–137. https://doi.org/10.1038/s41578-021-00407-8.

[82] Bioplastics Market, 2022. Bioplastics Market (By Product: Biodegradable, Nonbiodegradable; By Application: Packaging, Consumer Goods, Agriculture, Agriculture, Textile, Building & Construction, Others) - Global Industry Analysis, Size, Share, Growth, Trends, Regional Outlook, and Forecast 2023-2032. http s://www.precedenceresearch.com/bioplastics-market.