Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol.11 , (2022)
https://www.jneonatalsurg.com

OPEN ACCESS

Microbial Mechanisms and Environmental Pathways in the Biodegradation of Synthetic Plastics.

Dufaida K. M[1]

[1]Department of Microbiology,EMEA College of Arts and Science, Kondotty

Email ID : dufudufi@gmail.com

Cite this paper as: Dufaida K. M (2022) Microbial Mechanisms and Environmental Pathways in the Biodegradation of Synthetic Plastics... Journal of Neonatal Surgery, 11, 51-64

ABSTRACT

Plastics are high-molecular-weight synthetic polymers primarily produced from petroleum-derived hydrocarbons. Their versatility, durability, and low manufacturing costs render them indispensable in industrial and domestic sectors. However, these properties are also responsible for their persistence and accumulation in natural ecosystems. This review highlights the origin, classification, and mechanisms of plastic degradation, emphasizing microbial biodegradation as a sustainable solution to plastic pollution. This article summarizes the thermal and chemical properties of plastics, different degradation pathways, and the enzymatic roles of microorganisms involved in the mineralization of polymeric materials. Particular attention has been given to polyethylene (PE), one of the most widely used and environmentally persistent polymers. Current evidence indicates that microbial communities can partially or completely convert synthetic polymers into benign end products, such as carbon dioxide, water, methane, and biomass, through extracellular enzymatic activity. Understanding the physicochemical parameters and microbial mechanisms influencing these processes is essential for developing eco-friendly strategies to mitigate plastic waste accumulation and its ecological impacts...

Keywords: *Plastics, Polyethene, Microbial degradation, Biodegradation mechanisms, Environmental pollution, Enzymatic degradation.*

INTRODUCTION

High-molecular-weight organic polymers, widely known as plastics, are primarily synthesized from hydrocarbons and petroleum derivatives (Ahmed et al., 2018). The term "plastic" originates from the Greek word plastikos, meaning capable of being shaped or molded. This characteristic is central to plastics, which are generally defined as polymers exhibiting thermoplasticity—softening upon heating to allow molding into diverse forms (Kale et al., 2015). Although biodegradable bioplastics have emerged as alternatives, the overwhelming majority of plastics continue to be produced from petrochemical feedstocks (Getachew & Woldesenbet, 2016). These materials are mainly composed of elements such as carbon, hydrogen, oxygen, nitrogen, chlorine, and silicon, with polyethylene being the most extensively manufactured polymer, accounting for approximately 64% of global plastic production and typically represented by the chemical formula CnH2n (Kale et al., 2015).

The extensive utilization of plastics spans numerous industries, including packaging, agriculture, healthcare, construction, and consumer goods, highlighting their versatility and indispensable role in modern society. For instance, plastics are used in products ranging from agricultural films and fishing nets to sanitary fixtures and synthetic leather (Piergiovanni and Limbo, 2016). Such widespread applications reflect their durability, low weight, and adaptability. However, these same properties contribute to significant environmental concerns, as plastics resist natural degradation and accumulate persistently in ecosystems worldwide, thereby posing serious ecological risks (Ahmed et al., 2018; Yang et al., 2020; Al-Thawadi, 2020). Plastics are broadly categorised based on their degradability, which has significant implications for both their use and environmental impact. Despite their utility, the long-term sustainability challenges associated with plastic waste necessitate a thorough understanding of its degradation.

Chemically, plastics fall into two primary groups: degradable and nondegradable polymers (Ghosh et al., 2013) (Figure 1). Biodegradable plastics, often derived from renewable biological resources such as starch, cellulose, and algal matter, can decompose naturally through microbial activity or environmental factors. These bio-based polymers can also be produced by microorganisms, offering a promising alternative to synthetic plastics (Imre & Pukanszky, 2013). In contrast, conventional synthetic plastics are predominantly synthesized from petrochemical sources and are characterized by high molecular weights formed from repetitive monomer units. The environmental persistence of these synthetic polymers underlies the pollution problems associated with plastics.

An emerging concern in plastic pollution is the generation of microplastics (MPs), defined as plastic particles smaller than 5 mm in diameter, which have been identified as ecotoxicological hazards (Zhang et al., 2017; Chen et al., 2020a, 2020b; Wong et al., 2020). Of particular concern are fibrous microplastics, which can be inhaled and accumulate in lung tissues, often carrying hazardous additives such as plasticizers and dyes that may induce carcinogenic and mutagenic effects (Gasperi et al., 2018; Wong et al., 2020). Although incineration is frequently employed for plastic waste disposal, it can leave behind bottom ash containing residual, unburned particles. This ash has been identified as a secondary source of microplastic pollution, capable of releasing thousands of microplastic particles per metric ton (Yang et al., 2021).

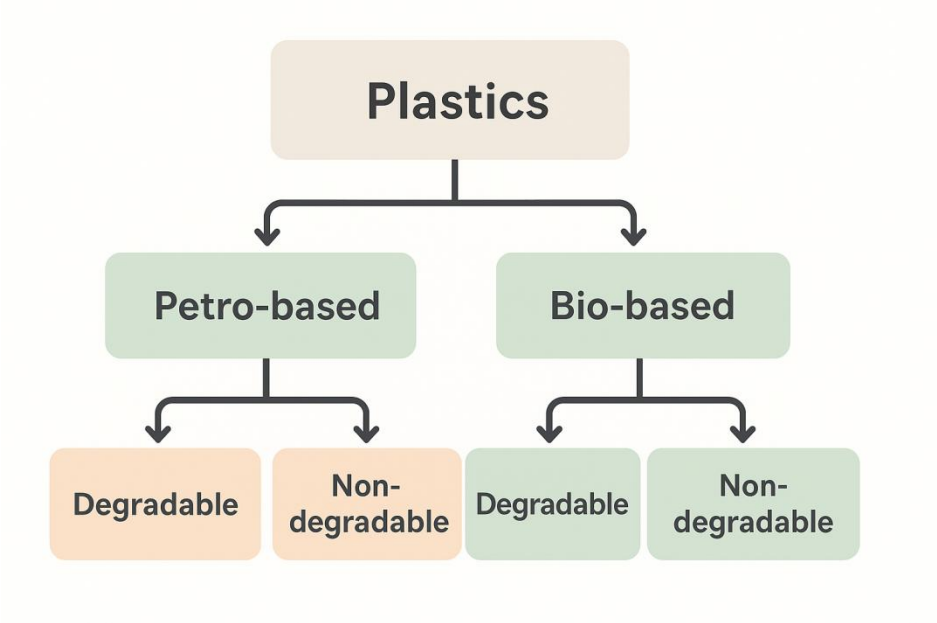

Figure 1. Classification of plastics based on origin and degradability

In aquatic environments, plastic debris undergoes further fragmentation to produce nanoplastics (NPs), which are plastic particles smaller than 100 nm and have been linked to various biological effects (Nolte et al., 2017; Revel et al., 2018). Several studies have demonstrated the detrimental effects of MPs and NPs on aquatic organisms. For example, exposure of test organisms to polystyrene microplastics results in epithelial cell deformation in the midgut (Suman et al., 2020). Similarly, polystyrene microspheres accumulated in the intestines and hepatopancreas of red claw crayfish, inhibiting their growth over a 21-day exposure period (Chen et al., 2020a, 2020b). Moreover, exposure of freshwater microalgae to polystyrene MPs causes vacuole formation and a significant decline in pigment content, further underscoring the ecological impact of these pollutants (Xiao et al., 2020). Plastics degrade in the environment through several pathways, including hydrolytic, photodegradation, thermo-oxidative degradation, and biodegradation. Given the durability and persistence of plastics, their removal from ecosystems is a significant challenge. Biodegradable plastics, which undergo decomposition by microbial action, are eventually converted into carbon dioxide and water, highlighting their potential role in mitigating plastic pollution (Fotopoulou & Karapanagioti, 2017). The biodegradation process can be accelerated by thermo-oxidants and photodegradative agents, which produce free radicals that initiate chain scission within the polymer matrix, leading to a decrease in molecular weight and the formation of carbonyl groups. Thermal oxidation at temperatures above the melting point of the polymer further reduces its heat of fusion and promotes carbonyl compound formation, thereby increasing microbial susceptibility and biodegradation rates (Manzur et al., 2004).

In addition to chemical factors, various intrinsic and extrinsic parameters influence the degradation behavior of plastics in the environment. These include polymer type, prior treatment methods, erosion patterns, phase separation, discoloration, and surface cracking. Together, these factors affect not only the degradation process but also contribute to environmental pollution caused by plastic waste (Thomas et al., 2015). A comprehensive understanding of these degradation mechanisms is crucial for developing effective strategies to manage plastic pollution and enhance the sustainability of plastic materials.

Classification of Plastics Based on Thermal Properties

Plastics are broadly categorized into thermoplastics and thermosetting polymers based on their thermal behaviors. Thermoplastics, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polytetrafluoroethylene (PTFE), soften upon heating and can be reshaped multiple times without chemical transformation. These polymers are typically synthesized through addition polymerization, where small monomers form linear macromolecular chains via the opening of double bonds, often initiated by free-radical reactions. Their molecular weights usually range from 20,000 to 500,000 atomic mass units. In contrast, thermosetting polymers, such as phenol-formaldehyde and polyurethanes, become infusible and cannot be remelted or reshaped after being molded and cured. These are formed via step-growth polymerization, releasing small molecules such as H_2O and HCl as by-products (Ghosh et al., 2013; Singh & Sharma, 2008).

Types of Degradable Plastics

Plastics capable of environmental breakdown are broadly classified into four main categories: biodegradable, bio-based, photodegradable, and compostable (Figure 2). These categories differ in terms of source materials, degradation mechanisms, and environmental impacts. Photodegradable bioplastics contain light-sensitive chemical groups integrated into their polymer backbones. These groups react to prolonged exposure to ultraviolet (UV) radiation, causing the structural degradation of plastics. However, in the absence of UV light, such as in landfill environments, this degradation does not occur (Arikan & Ozsoy, 2015). Additionally, artificial photodegradation can release volatile organic compounds (VOCs), which are potentially toxic and contribute to the environmental deterioration of plastic waste exposed to outdoor conditions (Lomonaco et al., 2020).

Bio-based bioplastics are synthesized entirely from renewable biological sources, with their carbon content derived from biomass-derived sources. Common feedstocks include starch, cellulose, soybeans, and corn, which provide a sustainable alternative to fossil fuel-based plastics (Getachew & Woldesenbet, 2016; Marichelvam et al., 2019; Maraveas, 2020). These materials reduce dependence on non-renewable resources and offer functional versatility comparable to that of conventional plastics. Compostable plastics require specific environmental conditions for effective degradation, such as controlled temperature, humidity, and microbial activity, which are typically found in industrial composting facilities. Under these conditions, they break down into non-toxic components at rates similar to those of organic compost, leaving no harmful residues (Meereboer et al., 2020). To be classified as bio-compostable, plastics must undergo rigorous testing to evaluate their biodegradability, disintegration, and ecotoxicological safety.

Biodegradable plastics are materials that microorganisms enzymatically decompose into simpler natural products, such as carbon dioxide, water, and biomass. This microbial degradation occurs under favorable environmental conditions and is considered complete when no ecological harm results from residual products (Jain et al., 2010). Biodegradability is defined as the ability of these materials to undergo complete microbial breakdown within a reasonable timeframe. Understanding these types of degradable plastics and their distinct characteristics is crucial for developing environmentally responsible materials and managing plastic pollution. Each category offers unique advantages and limitations in terms of environmental sustainability, degradation efficiency, and practical application.

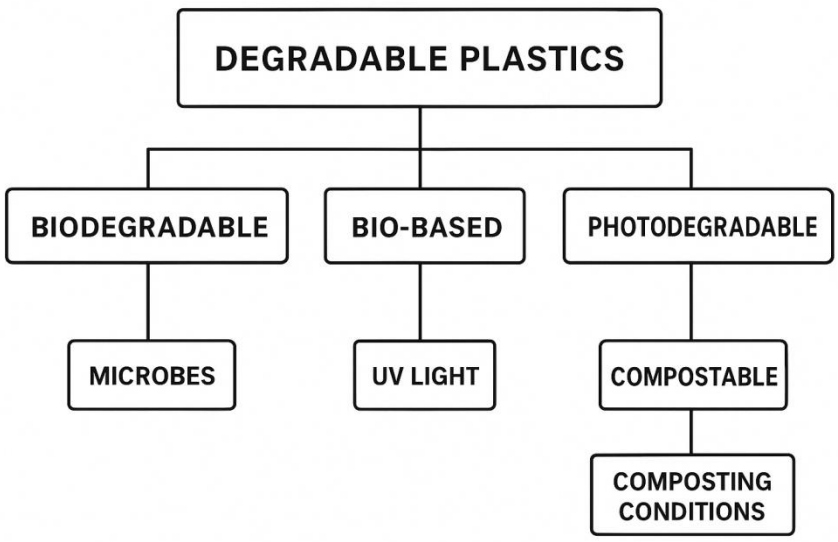

Figure 2. Major categories of degradable plastics and their breakdown mechanisms.

Types of Degradation

Various degradation mechanisms affect polymers, depending on the environmental and chemical conditions. The primary degradation pathways include photo-oxidative, thermal, ozone, mechanochemical, and catalytic degradation, each of which plays a significant role in altering the polymer structure, properties, and lifespan as shown in Table 1 (Figure 3).

Table 1. Comparison of various plastic degradation mechanisms.

Degradation Type	Key Trigger	Mechanism	Common Degradation Products	Environmental Importance
Photodegradation	UV radiation	UV breaks C–C bonds → free radicals → chain scission	Carbonyls, ketones, aldehydes	Initiates abiotic oxidation; weakens polymer surface
Thermal Degradation	High temperature	Bond breakage throughout polymer matrix	Volatile organics, hydrocarbons	Accelerates further biodegradation; occurs during waste burning or heat exposure
Oxidative / Ozone Degradation	Ozone (O_3) or oxygen radicals	Oxidation of polymer chains → carbonyl formation	Ketones, esters, lactones	Increases brittleness and susceptibility to microbial attack
Mechanochemical Degradation	Mechanical stress, abrasion, ultrasonic vibration	Physical cracking → radical formation → chain breakage	Oligomers, fragmented particles	Prominent in marine/soil movement; produces microplastics
Catalytic Degradation	Metal catalysts, zeolites	Catalyst lowers activation energy → rapid chain scission	Oils, gases, waxes	Used in industrial plastic conversion (pyrolysis)
Enzymatic Biodegradation	Microbial enzymes	Enzymes hydrolyze bonds → monomers → mineralization	CO_2, CH_4, H_2O, biomass	Final step of degradation; eco-friendly breakdown

Photo-oxidative degradation is predominantly initiated by light absorption, particularly ultraviolet (UV) radiation, which triggers chain scission at the polymer surface. Unlike thermal degradation, which affects the bulk of the material, photo-induced degradation occurs superficially and leads to the breakdown of chemical bonds, such as peroxides and ethers, especially in defective chain regions (Rånby, 1989; Tyler, 2004). For example, polyethylene (PE) undergoes depolymerization at high temperatures, forming smaller monomeric units. Similarly, polymethylmethacrylate (PMMA) can be almost entirely reverted to its monomer form under thermal influence (Ramis et al. 2004). UV light within the 290–400 nm range, typically from sunlight, facilitates this process by cleaving carbon–carbon bonds and forming degradation products, such as esters, aldehydes, and other oxygenated compounds (Jensen & Kops, 1980; Nagai et al., 2005).

Thermal degradation, often coupled with oxidative reactions, occurs throughout the polymer matrix when it is exposed to high temperatures. It may be triggered unintentionally or as a result of thermal depolymerization, requiring both heat and sometimes ultraviolet (UV) light to initiate the breakdown process (Teare et al., 2000). On the other hand, ozone degradation is induced by reactive oxygen species (ROS) formed through interaction with ozone, which, despite being present in small atmospheric concentrations, has a powerful oxidative effect on polymers. These reactions alter the mechanical and electrical properties of plastics and generate carbonyl compounds, such as ketones, lactones, esters, and aromatic derivatives, particularly affecting unsaturated and aromatic chains (Kefeli et al., 1971; Andrady et al., 1998; Allen et al., 2003).

Mechanochemical degradation, polymers experience chain cleavage owing to mechanical forces, such as stress or ultrasonic vibrations, leading to radical formation and molecular weight reduction (Gol'dberg & Zaikov, 1987; Li et al., 2005). This process alters the polymer's branching structure and double-bond concentrations (Striegel, 2003). For example, in PMMA,

nitroxides act as chain-terminating agents, forming macro-radicals suitable for further polymerization reactions (Schmidt-Naake et al. 2002). Furthermore, in the presence of oxide powders such as SiO_2 or Fe_2O_3, mechanical dechlorination of polyvinyl chloride (PVC) occurs, reducing its molecular weight (Inoue et al., 2004).

Finally, catalytic degradation has been widely explored for its ability to convert waste polymers into useful hydrocarbons, such as oils and gases. This process is driven by various catalysts, including platinum-based systems (e.g., Pt-Mo and Pt-Co supported on SiO_2), transition metal oxides (e.g., chromium, cobalt, and iron), and zeolites (Gimouhopoulos et al., 2000; Lin & Yen, 2005; Kim et al., 2004). Polyolefins, such as polypropylene (PP), degrade through free radical pathways in the presence of catalysts such as Fe/activated carbon (Sekine & Fujimoto, 2003). Heating above 38°C initiates depolymerization, enhancing the product yield and quality of plastic pyrolysis (Wall et al., 1954).

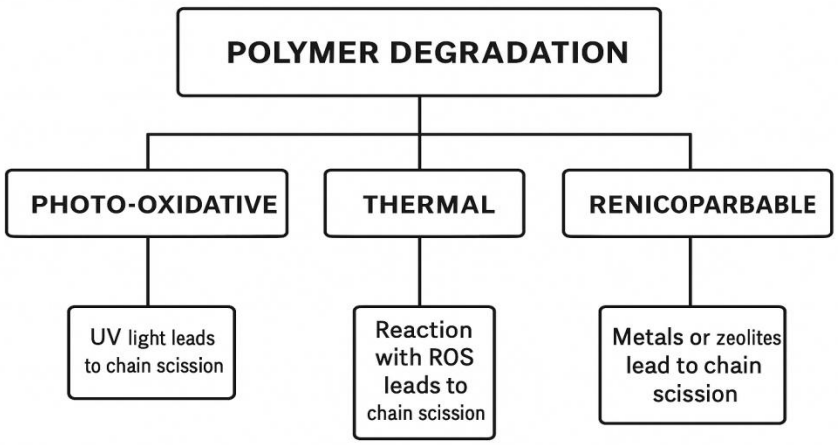

Figure 3. Major polymer degradation pathways

Biodegradation of Plastics

Biodegradation refers to the breakdown of organic substances through the metabolic activities of microorganisms, leading to both physical and chemical changes in the material and ultimately converting it into simpler, environmentally safe compounds. This natural process plays a vital role in managing organic waste and has gained growing importance in addressing the issue of plastic pollution. Both natural and synthetic polymers can undergo biodegradation, though the efficiency and speed of the process depend on factors such as molecular structure, weight, and surrounding environmental conditions. Natural polymers like starch, cellulose, and proteins are more easily decomposed by microbes because they contain functional groups that enzymes can readily act upon. In contrast, synthetic polymers—such as polyethylene, polypropylene, and polystyrene—are more resistant due to their stable carbon–carbon backbones, hydrophobic nature, and lack of degradable sites. Recent innovations in biotechnology and materials engineering, however, have enabled the creation of biodegradable synthetic polymers and bio-based composites that emulate the degradability of natural materials, offering more sustainable solutions for reducing plastic waste.

Microbial Action and Mechanisms

Microbial degradation occurs, although the rate and extent of degradation vary significantly based on the chemical structure of the polymer and environmental conditions (Ishigaki et al., 2004; Alshehrei, 2017). The primary agents responsible for biodegradation are bacteria, fungi, and actinomycetes. These microorganisms employ various enzymatic systems to degrade plastic polymers. However, most polymers are high-molecular-weight, water-insoluble substances that cannot be directly absorbed by microbial cells. To overcome this, microbes secrete extracellular enzymes, also known as exoenzymes, which catalyze the breakdown of complex polymers into smaller, water-soluble molecules that can pass through the semi-permeable cell membrane (Figure 4). Biodegradation typically occurs in two key stages: depolymerization and mineralization (Gu, 2003). During depolymerization, long polymer chains are cleaved into oligomers and monomers, which are sufficiently small and soluble to be transported into the microbial cells. Once internalized, these simpler compounds undergo mineralization,

where microbial metabolic pathways further degrade them into inorganic end products, such as carbon dioxide (CO_2), methane (CH_4), water (H_2O), and microbial biomass, depending on the environmental conditions.

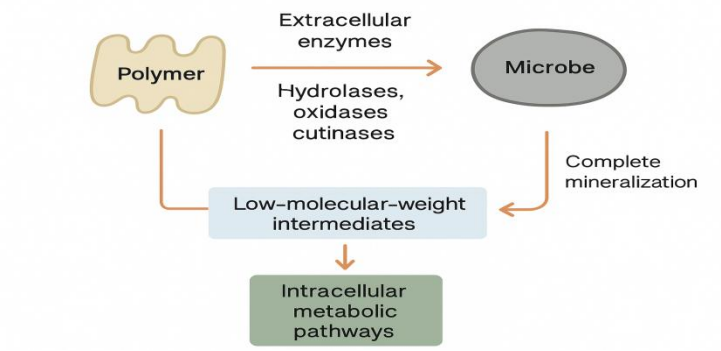

Figure 4: Microbial enzymatic mechanism of plastic degradation

Aerobic and Anaerobic Biodegradation

Biodegradation can proceed under two major types of environmental conditions: aerobic and anaerobic conditions. The presence or absence of oxygen significantly influences the pathway and end-products of the degradation process.

Aerobic biodegradation occurs in environments where oxygen is available. In this scenario, microorganisms use oxygen as the terminal electron acceptor in their respiratory chains. The general reaction involves the breakdown of the carbon backbone of the plastic polymer, yielding carbon dioxide, water, and residual biomass as the primary by-products (Müller, 2005; Priyanka & Archana, 2011). The reaction is summarized as follows:

Carbon (plastic) + O_2 → CO_2 + H_2O + residual carbon.

This type of degradation is commonly observed in composting environments, surface soils and other oxygen-rich habitats. In contrast, anaerobic biodegradation occurs in oxygen-deficient or oxygen-deprived environments, such as deep landfill sites, sediments, and certain industrial bioreactors. Under these conditions, anaerobic microorganisms utilize alternative electron acceptors, such as nitrate (NO_3^-), iron (Fe^{3+}), sulfate (SO_4^{2-}), manganese (Mn^{4+}), or even carbon dioxide (CO_2), to facilitate respiration. The degradation process yields methane (CH_4) as a significant byproduct, along with carbon dioxide, water, and biomass:

Carbon (plastic) → CH_4 + CO_2 + H_2O + residual carbon.

This pathway is particularly relevant in the methanogenic and sulfidogenic environments of engineered and natural anaerobic systems. For instance, in the anaerobic degradation of polyethylene under such conditions, both methane and hydrogen sulfide (H_2S) are detected as terminal products, in addition to carbon dioxide and water (Shahnawaz et al., 2016).

Factors Influencing Biodegradation

The extent and rate of plastic biodegradation depend on several factors, including the type of polymer, molecular weight, crystallinity, presence of additives, and environmental conditions, such as temperature, pH, moisture, and the composition of the microbial community. Polymers with ester, amide, or ether bonds are generally more susceptible to microbial attack than those with stable carbon-carbon backbones.

Moreover, environmental settings such as soil, freshwater, marine environments, compost, and anaerobic digesters provide different conditions that can accelerate or inhibit microbial activity. For example, aerobic composting offers optimal conditions for rapid biodegradation owing to high microbial diversity and elevated temperatures, whereas oceanic environments are typically nutrient-poor and colder, considerably slowing down the process.

Mechanism of Biodegradation

Microbial degradation of polymeric materials typically follows a sequential three-step mechanism: (1) initial attachment of microorganisms to the polymer surface, (2) utilization of the polymer as a carbon and energy source, and (3) enzymatic degradation of the polymer structure (Figure 5).In the first step, microorganisms such as bacteria and fungi adhere to the surface of plastic materials, forming biofilms. Surface colonization is a critical prerequisite for biodegradation, as it enables organisms to remain in close contact with the substrate. Once attached, the microbes initiate degradation by secreting specific

extracellular enzymes capable of hydrolyzing long polymer chains into smaller units (Danso et al., 2018). These enzymes act on the macromolecular structure of plastics, cleaving them into low-molecular-weight oligomers and monomers. Some of these smaller degradation products are small enough to diffuse across the microbial cell membrane and are subsequently absorbed into the cells. Inside microorganisms, these molecules are further metabolized through various biochemical pathways, ultimately supplying energy for microbial growth and maintenance. This stepwise process of depolymerization, followed by assimilation and mineralization, is essential for the complete biodegradation of synthetic and natural polymers.

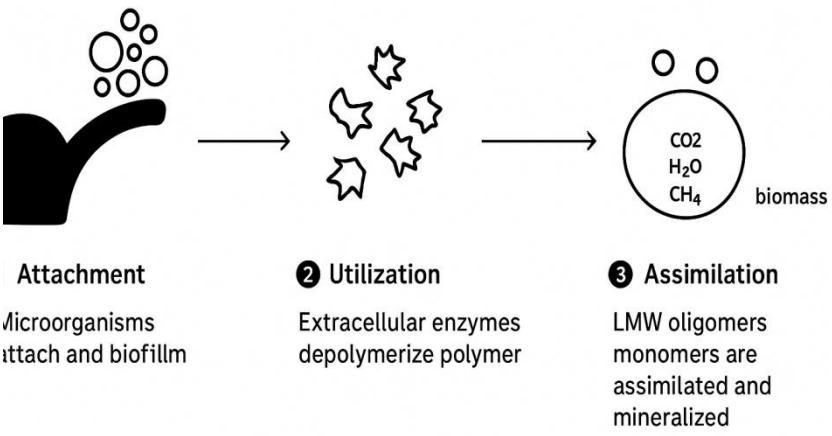

Figure 5: Mechanism of Biodegradation

Assessment Methods for Biodegradability of Polymeric Materials

A diverse range of analytical techniques has been employed to evaluate the biodegradability of polymer-based materials. To ensure standardized testing and comparability across studies, international organizations such as the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have developed several protocols for assessing the biodegradation potential of plastics (Piergiovanni & Limbo, 2016). Among the most widely used methods are gas chromatography–mass spectrometry (GC–MS), stereomicroscopy, and micro-Fourier transform infrared spectroscopy (μ-FTIR), which are effective in identifying molecular-level changes that occur in the polymer during degradation (Lomonaco et al., 2020; Corami et al., 2020). These techniques allow for the precise chemical characterization of byproducts and structural modifications that arise during microbial decomposition. Biodegradation can also be assessed using several physical, chemical, and biological indicators. These include a reduction in mass, changes in tensile strength, alterations in physical dimensions, and modifications in molecular weight distribution. In addition, CO_2 evolution, microbial activity in the soil, and shifts in both chemical structure and surface morphology are critical indicators of degradation (Kathiresan, 2003; Sivan, 2011; Kumar & Maiti, 2016; Chen et al., 2020a; 2020b). Collectively, these evaluation methods provide comprehensive insights into the extent and nature of plastic degradation under different environmental conditions (Figure 6).

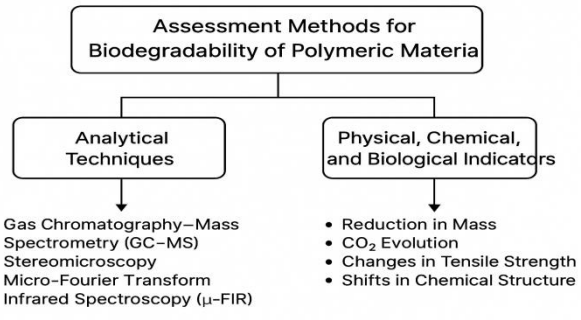

Figure 6. Assessment of Polymer Biodegradation

Microbial Degradation of Polymeric Materials

Polymer degradation by microorganisms is a complex, multistep process involving four primary stages: biodeterioration, biofragmentation, assimilation, and mineralization. Each stage contributes to the progressive breakdown and eventual conversion of polymeric materials into simpler substances that can be utilized by the microbial cells.

Biodeterioration

Biodeterioration refers to the initial alteration of the surface properties of a polymer due to microbial colonization and environmental exposure. This stage results in changes in the mechanical, chemical, and physical characteristics of the material. The extent of these changes is influenced by the chemical structure and composition of the polymer, as well as the surrounding environmental conditions, such as temperature, humidity, and UV exposure (Vivi et al., 2019). The development of substrate microenvironments and the formation of biofilms on plastic surfaces are typical outcomes of this stage.

Biofragmentation

Following biodeterioration, the next critical step is biofragmentation, which involves enzymatic cleavage of the polymer backbone. Microorganisms, primarily bacteria, secrete enzymes such as oxygenases that incorporate oxygen atoms into polymer chains. This oxidative reaction leads to the formation of intermediate compounds, such as alcohols and peroxides, which are less structurally stable and more susceptible to further degradation (Pathak, 2017; Dussud & Ghiglione, 2014). Enzymes such as lipases, esterases, and endopeptidases play vital roles in breaking down specific functional groups, including esters and amides, further facilitating the fragmentation of the polymer into smaller molecular units.

Mineralization

In the final phase, mineralization, the fragmented products, typically small monomers and oligomers, are absorbed by microbial cells via their semi-permeable membranes. Only molecules with sufficiently low molecular weights can be transported into the cell. Once internalized, these monomers undergo oxidative metabolism to generate energy, which is used for cellular growth and biomass production (Lucas et al., 2008; Kale et al., 2015). Larger molecules that cannot cross the cell membrane remain extracellular and may undergo further enzymatic breakdown until they are small enough to be assimilated into the cell.

Assimilation

During assimilation, atoms are incorporated into microbial cells, allowing for the complete breakdown of substances. Some secondary metabolites are either excreted from the cells or passed on to other microorganisms, which continue the degradation process and utilize these intermediates. As these metabolites are further broken down, end products such as carbon dioxide (CO_2), nitrogen (N_2), water (H_2O), and methane (CH_4) are released (Krzan et al., 2006; Lucas et al., 2008).

Enzymatic Degradation of Plastics

Enzymes play a pivotal role in the breakdown of polymers during intracellular and extracellular processes. Specific enzymes, such as hydrolases, lipases, and cutinases, target specific functional groups within polymer chains. These enzymes initiate chain scission, leading to the formation of monomers and oligomers that are suitable for microbial metabolism. In some studies, the degradation of plastics, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), has been directly attributed to the activity of enzymes secreted by soil and compost bacteria (Gu, 2003).

Plastic degradation by microbial enzymes is challenging because of the absence of hydrolyzable groups in the carbon–carbon backbone. Initial breakdown requires molecular weight reduction through abiotic and biotic factors, such as UV exposure, which introduces functional groups, such as carbonyls, making polymers more susceptible to enzymatic attack. Enzymes such as laccase, lipase, urease, protease, and lignin-degrading enzymes contribute to this process, with thermostable laccase shown to degrade polyethylene within 48 h at 37 °C. Biodegradation was assessed by changes in surface morphology, mechanical properties, chemical byproducts, oxygen consumption, CO_2 release, and microbial biomass production. Factors influencing microbial degradation include the presence of functional groups, polymer structure (linear or branched), bond type (e.g., ester > ether > amide > urethane), chemical composition, physical form (films, pellets, powders), density, molecular weight, and the ratio of amorphous to crystalline regions. Amorphous regions are more susceptible to enzymatic activity, whereas high crystallinity and hydrophobicity hinder degradation by limiting water absorption and microbial access. Reduced solubility further lowers the microbial degradation potential by restricting polymer–microbe interactions.

Polyethylene Degradation

Polyethylene (PE) is one of the most widely used plastic materials, particularly in food packaging and storage applications. Common shopping bags are typically manufactured from polyethylene (PE). Owing to the global overuse of such materials, PE-based products account for approximately 10% of the municipal solid waste worldwide (Begum et al., 2015). Annually, it is estimated that between 500 billion and one trillion PE bags are used globally.

The chemical structure of PE renders it highly stable and hydrophobic, which limits its biodegradability, as most microorganisms lack the appropriate enzymatic systems to metabolize this synthetic polymer efficiently (Yoon et al., 2012). Nevertheless, some microorganisms can utilize PE polymers as a carbon source, and signs of degradation include surface erosion, discoloration, cracking, and phase separation (Trivedi et al., 2016).

Polyethylene (PE) degradation is broadly classified into abiotic and biotic processes. Abiotic degradation involves natural environmental factors, such as temperature fluctuations and ultraviolet (UV) radiation, which initiate polymer breakdown. In contrast, biotic degradation involves microbial organisms that alter the physical and chemical properties of plastics to metabolize them (Sen and Raut, 2015). Owing to its low cost, environmental stability, and ease of processing, polyethylene (PE) remains one of the most frequently encountered polymers worldwide. Two main strategies have been proposed to address their persistence in nature: the use of microorganisms capable of degrading the polymer and the engineering of polymers that are inherently more susceptible to microbial attack (Okoh and Atuanya, 2014).

Polyolefins, including low-density polyethylene (LDPE), are chemically nonreactive. While they can endure short-term exposure to temperatures up to 95°C, they are typically stable for longer periods at around 80°C (Billmeyer, 1984). LDPE has an incomplete crystalline structure, ranging from 50% to 60%, which contributes to its specific properties, such as flexibility, tensile strength, rigidity, and resistance to tearing (Ferreira et al., 2005). Oxidation of PE leads to the formation of carbonyl groups, which microorganisms can exploit for degradation (Cornell et al., 1984; Awasthi et al., 2017).

The degradation of non-hydrolysable polymers like PE and polypropylene proceeds primarily through oxidative mechanisms, which result in a significant reduction in molecular weight. A range of oxidative enzymes—such as monooxygenases, peroxidases, manganese peroxidases, dehydrogenases, and oxidases—are involved in targeting ethylenic linkages. Through the action of both extracellular and intracellular enzymes, long polymer chains are converted into smaller units like monomers and oligomers, which microorganisms can subsequently utilize as energy sources (Arkatkar et al., 2009). This microbial degradation pathway bears similarities to β-oxidation of fatty acids, a metabolic process found in both animals and humans (Albertsson et al., 1987).

Various microbial species capable of degrading PE and related polymers have been isolated from natural environments (Table 2). These include bacteria such as *Streptococcus*, *Klebsiella*, *Micrococcus*, *Staphylococcus*, and *Pseudomonas*, which have demonstrated the ability to break down synthetic plastics (Das and Kumar, 2015; Park and Kim, 2019). One effective approach to enhance the biodegradability of PE involves blending it with specific additives. These additives promote the auto-oxidation of the polymer, facilitating molecular weight reduction, and thereby making the material more accessible to microbial enzymatic activity.

Several microbial strains have demonstrated the ability to degrade polyethylene (PE), though the process remains slow due to PE's high molecular weight and chemical stability. For instance, *Bacillus vallismortis* degraded up to 75% of LDPE after 120 days (Skariyachan et al., 2017), while *Aspergillus oryzae* and *Bacillus cereus* strains showed degradation rates of around 36% after 112 days (Muhonja et al., 2018). Fungi such as *Aspergillus flavus* and bacterial strains like *Bacillus siamensis* have also shown modest degradation capabilities of HDPE and LDPE, respectively (Taghavi et al., 2021; Maroof et al., 2021). PE undergoes thermo-photooxidation producing various intermediates like ketones and carboxylic acids, which microbes further degrade through enzymatic oxidation and β-oxidation pathways. Biodegradation requires initial reduction of molecular weight to facilitate microbial uptake and enzyme action, followed by oxidation converting hydrocarbons into metabolizable acids (Yoon et al., 2012; Restrepo-Flórez et al., 2014). Microbial degradation is often evaluated through weight loss, tensile strength reduction, SEM surface analysis, and carbonyl index measurements, with biosurfactants enhancing microbial adhesion and degradation efficiency (Das and Mukherjee, 2005; Sudhakar et al., 2007). Fungal species such as *Aspergillus niger*, *Aspergillus japonicus*, *Trichoderma viride*, and *Aspergillus nomius* have been reported to reduce PE weight and tensile strength significantly within weeks to months of incubation as shown in Table 2 (Raaman et al., 2012; Munir et al., 2018).

Table 2. Major microorganisms involved in plastic degradation and their mechanisms

Microorganism	Type	Target Polymer	Enzyme involved	Reported Diagnosis	References
Bacillus vallismortis	Bacteria	LDPE	Oxidases, peroxidases	75% in 120 days	Skariyachan et al., 2017
Aspergillus oryzae	Fungi	LDPE	Laccase, lipase	36% in 112 days	Muhonja et al., 2018
Klebsiella pneumoniae	Bacteria	HDPE	Laccase, peroxidase	Significant surface erosion	Awasthi et al., 2017
Pseudomonas aeruginosa	Bacteria	PE	Biosurfactants & oxidases	Improved oxidation	Das & Mukherjee, 2005
Trichoderma viride	Fungi	PE	Cutinase	Weight loss & cracks	Munir et al., 2018

Biodegradable plastics types based on the mode of degradation pathway

Biodegradable plastics are commonly divided into oxobiodegradable and hydro-biodegradable types based on their degradation mechanisms. Hydro-biodegradable plastics, such as cellulose, starch, and polyhydroxyalkanoate (PHA), degrade primarily through hydrolysis, whereas oxobiodegradable plastics undergo a two-stage process involving initial abiotic oxidation followed by microbial breakdown. In the case of polyethylene (PE), abiotic photooxidation introduces carbonyl groups into the polymer backbone, which microbes then transform into alcohols, aldehydes, and finally fatty acids via enzymes like monooxygenase, alcohol dehydrogenase, and aldehyde dehydrogenase. These fatty acids enter the β-oxidation pathway for further metabolism. Microbial colonization alters the PE surface by increasing its roughness, fragility, and reducing molecular weight, while also converting its hydrophobic surface into a more hydrophilic one, facilitating degradation. Analytical techniques such as FTIR detect increases in carbonyl groups, ketones, and aldehydes, confirming oxidation, with carbon dioxide and water released as end products. Bacteria like *Klebsiella pneumoniae* contribute significantly to PE degradation by producing enzymes including lipase, tyrosinase, peroxidase, and laccase, along with biosurfactants that help microbes interact with the polymer by improving the exchange between hydrophobic and hydrophilic phases, thus enhancing microbial penetration and accelerating polymer breakdown.

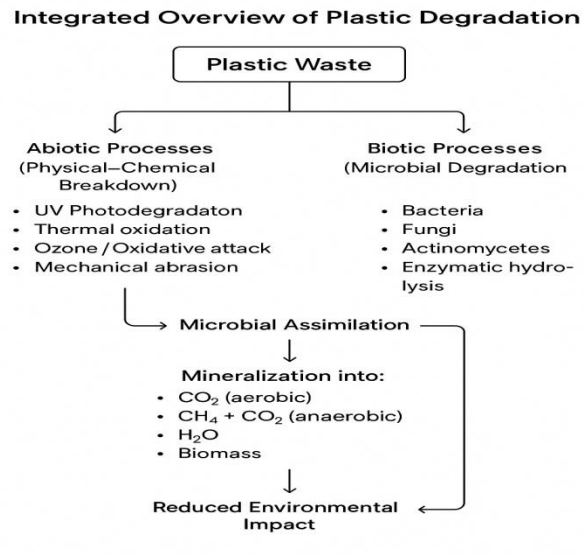

Figure 7: Integrated overview of abiotic and biotic pathways involved in plastic degradation.

CONCLUSION

Plastics, primarily derived from petroleum, are widely used globally, with polyethylene (PE) bags being among the most common. The accumulation of micro- and nanoplastics in aquatic environments has increased significantly due to various degradation processes such as biodegradation, thermo-oxidative degradation, photodegradation, thermal effects, and hydrolysis. This accumulation poses severe threats to freshwater and marine life, as well as to humans through the food chain. Given the persistent, hydrophobic, and chemically inert nature of these polymers, their removal from ecosystems remains challenging. While physical and chemical treatments exist, microbial degradation offers a promising and eco-friendly alternative. However, further research is necessary to assess the efficacy of microbes in treating wastewater contaminated with original plastic polymers, including their ability to remove micro- and nanoplastics and mitigate associated toxicities. Additionally, preventing the transfer of plastics from waste streams into aquatic ecosystems requires strategic management, including proper collection, disposal, or incineration. Long-term, coordinated cleanup efforts are essential to monitor and reduce the ongoing impact of plastic pollution on environmental health.

REFERENCES

1. Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A. A., Noman, M., … & Muhammad, S. (2018). Biodegradation of plastics: Current scenario and future prospects for environmental safety. Environmental Science and Pollution Research, 25(8), 7287–7298.
2. Albertsson, A. C., Andersson, S. O., & Karlsson, S. (1987). The mechanism of biodegradation of polyethylene. Polymer Degradation and Stability, 18(1), 73–87.
3. Allen, N. S., Edge, M., Mourelatou, D., Wilkinson, A., Liauw, C. M., Parellada, M. D., Barrio, J. A., & Quiteria, V. R. S. (2003). Influence of ozone on styrene–ethylene–butylene–styrene (SEBS) copolymer. Polymer Degradation and Stability, 79(2), 297–307.
4. Al-Thawadi, S. (2020). Microplastics and nanoplastics in aquatic environments: Challenges and threats to aquatic organisms. Arabian Journal of Science and Engineering, 45(6), 4419–4440.
5. Alshehrei, F. (2017). Biodegradation of synthetic and natural plastic by microorganisms. Journal of Applied Environmental Microbiology, 5(1), 8–19.
6. Andrady, A. L., Hamid, S. H., Hu, X., & Torikai, A. (1998). Effects of increased solar ultraviolet radiation on materials. Journal of Photochemistry and Photobiology B: Biology, 46(1–3), 96–103.
7. Arıkan, E. B., & Özsoy, H. D. (2015). A Review: Investigation of Bioplastics. Journal of Civil Engineering and Architecture, 9(2), 188–192.
8. Arkatkar, A., Arutchelvi, J., Sudhakar, M., Bhaduri, S., Uppara, P. V., & Doble, M. (2009). Approaches to enhance the biodegradation of polyolefins. The Open Environmental Engineering Journal, 2(1), 68–80.
9. Awasthi, S., Srivastava, P., Singh, P., Tiwary, D., & Mishra, P. K. (2017). Biodegradation of thermally treated high-density polyethylene (HDPE) by Klebsiella pneumoniae CH001. 3 Biotech, 7(5), 332.
10. Begum, M. A., Varalakshmi, B., & Umamagheswari, K. (2015). Biodegradation of polythene bag using bacteria isolated from soil. International Journal of Current Microbiology and Applied Sciences, 4(11), 674–680.
11. Billmeyer, F. W. (1984). Textbook of polymer science (3rd ed.). Wiley-Interscience.
12. Chen, X., Li, Y., Zhang, H., & Wang, J. (2020a). Biodegradation of synthetic polymers by microbial enzymes: Mechanisms and applications. Journal of Environmental Science and Technology, 54(3), 456–468.
13. Chen, Y., Wen, D., Pei, J., Fei, Y., Ouyang, D., Zhang, H., & Luo, Y. (2020b). Identification and quantification of microplastics using Fourier-transform infrared spectroscopy: Current status and future prospects. Current Opinion in Environmental Science & Health, 18, 14–19.
14. Corami, F., Rosso, B., Bravo, B., Gambaro, A., & Barbante, C. (2020). A novel method for purification, quantitative analysis and characterization of microplastic fibers using Micro-FTIR. Chemosphere, 238, 124564.
15. Cornell, R. R., Kaplan, A. M., & Rogers, R. D. (1984). Biodegradation of photo-oxidized polyethylene. Applied and Environmental Microbiology, 47(5), 1271–1275.
16. Danso, D., Chow, J., & Streit, W. R. (2018). Plastics: Environmental and biotechnological perspectives on microbial degradation. Applied and Environmental Microbiology, 85(19), e01095–19.
17. Das, K., & Mukherjee, A. K. (2005). Characterization of biochemical properties and biological activities of biosurfactants produced by Pseudomonas aeruginosa. Applied Microbiology and Biotechnology, 69(2), 192–199.
18. Das, M. P., & Kumar, S. (2015). An approach to low-density polyethylene biodegradation by Bacillus amyloliquefaciens. 3 Biotech, 5(1), 81–86.

19. Dussud, C., & Ghiglione, J.-F. (2014). Bacterial degradation of synthetic plastics in marine environments. Environmental Science and Technology, 48(19), 11288–11289.

20. Ferreira, A., Alves, N. M., & Coelho, J. F. J. (2005). Polyethylene structure and morphology: Influence of crystalline content. Polymer Engineering and Science, 45(4), 571–579.

21. Fotopoulou, K. N., & Karapanagioti, H. K. (2017). Degradation of various plastics in the environment. In Hazardous chemicals associated with plastics in the marine environment (pp. 71–92). Springer.

22. Gasperi, J., Wright, S. L., Dris, R., … & Tassin, B. (2018). Microplastics in air: Are we breathing it in? Current Opinion in Environmental Science & Health, 1, 1–5.

23. Getachew, A., & Woldesenbet, F. (2016). Production of biodegradable plastic by PHB accumulating bacteria using low-cost agricultural waste material. BMC Research Notes, 9(1), 509.

24. Ghosh, S. K., Pal, S., & Ray, S. (2013). Study of microbes having potentiality for biodegradation of plastics. Environmental Science and Pollution Research, 20(7), 4339–4355.

25. Gimouhopoulos, K., Doulia, D., Vlyssides, A., & Georgiou, D. (2000). Optimization studies of waste plastics–lignite catalytic coliquefaction. Waste Management Research, 18(4), 352–357.

26. Gol'dberg, V. M., & Zaikov, G. E. (1987). Mechanochemical degradation of polymers. CRC Press.

27. Gu, J.-D. (2003). Microbiological deterioration and degradation of synthetic polymeric materials: Recent research advances. International Biodeterioration & Biodegradation, 52(2), 69–91.

28. Imre, B., & Pukánszky, B. (2013). Compatibilization in bio-based and biodegradable polymer blends. European Polymer Journal, 49(6), 1215–1233.

29. Inoue, T., Miyazaki, M., Kamitani, M., Kano, J., & Saito, F. (2004). Mechanochemical dechlorination of polyvinyl chloride by co-grinding with metal oxides. Advanced Powder Technology, 15(2), 215–225.

30. Ishigaki, T., Sugano, W., Nakanishi, A., Tateda, M., Ike, M., & Fujita, M. (2004). The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors. Chemosphere, 54(3), 225–233.

31. Jain, R., Kosta, S., & Tiwari, A. (2010). Polyhydroxyalkanoates: A way to sustainable development of bioplastics. Chronicles of Young Scientists, 1(3), 10–15.

32. Jensen, H. M., & Kops, J. (1980). Photo-oxidation of polymer materials: Mechanisms and kinetics. Polymer Photochemistry, 1(1), 1–18.

33. Kale, S. K., Deshmukh, A. G., Dudhare, M. S., & Patil, V. B. (2015). Microbial degradation of plastic: A review. Journal of Biochemical Technology, 6(2), 952–961.

34. Kathiresan, K. (2003). Polythene and plastics-degrading microbes from the mangrove soil. Revista de Biología Tropical, 51(3–4), 629–634

35. Kefeli, A., Razumovskii, S., & Zaikov, G. Y. (1971). Interaction of polyethylene with ozone. Polymer Science, 13(4), 904–911.

36. Kim, J.-R., Van, J.-H., Park, D.-W., & Lee, M.-H. (2004). Catalytic degradation of mixed plastics using natural clinoptilolite catalyst. Reaction Kinetics and Catalysis Letters, 81(1), 73–81.

37. Krzan, A., Hemjinda, S., Miertus, S., Corti, A., & Chiellini, E. (2006). Standardization and certification in the area of environmentally degradable plastics. Polymer Degradation and Stability, 91(12), 2819–2833.

38. Kumar, S., & Maiti, P. (2016). Controlled biodegradation of polymers using nanoparticles and its application. RSC Advances, 6(72), 67449–67480.

39. Li, J., Guo, S., & Li, X. (2005). Degradation kinetics of polystyrene and EPDM melts under ultrasonic irradiation. Polymer Degradation and Stability, 89(1), 6–14.

40. Lin, Y.-H., & Yen, H.-Y. (2005). Fluidised bed pyrolysis of polypropylene over cracking catalysts for producing hydrocarbons. Polymer Degradation and Stability, 89(1), 101–108.

41. Lomonaco, T., Manco, E., Corti, A., La Nasa, J., Ghimenti, S., Biagini, D., Di Francesco, F., Modugno, F., Ceccarini, A., Fuoco, R., & Castelvetro, V. (2020). Release of harmful volatile organic compounds (VOCs) from photo-degraded plastic debris: A neglected source of environmental pollution. Journal of Hazardous Materials, 394, 122596.

42. Lucas, N., Bienaime, C., Belloy, C., Quenedecu, M., Silvestre, J.-E., & Saucedo, N. (2008). Polymer biodegradation: Mechanisms and estimation techniques. Chemosphere, 73, 429–442.

43. Manzur, A., Limón-González, M., & Favela-Torres, E. (2004). Biodegradation of physicochemically treated LDPE by a consortium of filamentous fungi. Journal of Applied Polymer Science, 92(1), 265–271.

44. Maraveas, C. (2020). Production of sustainable and biodegradable polymers from agricultural waste. Polymers, 12(5), 1127.

45. Marichelvam, M. K., Jawaid, M., & Asim, M. (2019). Corn and rice starch-based bioplastics as alternative packaging materials. Fibers, 7, 32.

46. Maroof, L., Khan, I., Yoo, H. S., Kim, S., Park, H.-T., Ahmad, B., & Azam, S. (2021). Identification and characterization of low density polyethylene-degrading bacteria isolated from soils of waste disposal sites. Environmental Engineering Research, 26(3), 200167.

47. Meereboer, K. W., Misra, M., & Mohanty, A. M. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. Green Chemistry, 22, 5519.

48. Muhonja, C. N., Makonde, H., Magoma, G., & Imbuga, M. (2018). Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya. PLoS ONE, 13(7), e0198446.

49. Müller, R. J. (2005). Biodegradability of polymers: Regulations and methods for testing. In Biopolymers Online (pp. 365–374).

50. Munir, E., Harefa, R. S. M., Priyani, N., & Suryanto, D. (2018). Plastic degrading fungi Trichoderma viride and Aspergillus nomius isolated from local landfill soil. IOP Conference Series: Earth and Environmental Science, 126, 012145.

51. Nagai, N., Uedaira, S., & Kinoshita, S. (2005). Photodegradation behavior of polyethylene films under UV irradiation. Polymer Degradation and Stability, 89(1), 1–8

52. Nolte, T. M., Hartmann, N. B., Kleijn, J. M., Garnæs, J., van de Meent, D., Hendriks, A. J., & Baun, A. (2017). The toxicity of plastic nanoparticles to green algae: Influence of surface modification, medium hardness and cellular adsorption. Aquatic Toxicology, 183, 11–20.

53. Okoh, E. B., & Atuanya, E. I. (2014). Impacts of soil composting and poultry manure on biodegradation of polyethylene. International Journal of Applied Microbiology and Biotechnology Research, 2, 18–29.

54. Park, S. Y., & Kim, C. G. (2019). Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium from a landfill. Chemosphere, 222, 527–533.

55. Pathak, V. M. (2017). Review on the current status of polymer degradation: Biodegradation, photodegradation and thermal degradation. Environmental Science and Pollution Research, 24(36), 27867–27884.

56. Piergiovanni, L., & Limbo, S. (2016). Plastic packaging materials. In Food packaging materials (pp. 33–49). Springer.

57. Priyanka, N., & Archana, T. (2011). Biodegradability of polythene and plastic by the help of microorganism: A way for brighter future. Journal of Environmental & Analytical Toxicology, 1(02).

58. Raaman, N., Rajitha, N., Jayshree, A., & Jegadeesh, R. (2012). Biodegradation of plastic by Aspergillus spp. isolated from polluted sites. Journal of Academia and Industrial Research, 1(6), 313–316.

59. Ramis, X., Bou, J. J., Salla, J. M., & Morancho, J. M. (2004). Thermal degradation of poly(methyl methacrylate): Kinetic study. Journal of Thermal Analysis and Calorimetry, 75(3), 979–988.

60. Ranby, B. (1989). Photodegradation and photo-oxidation of synthetic polymers. Journal of Analytical and Applied Pyrolysis, 15, 237–247.

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

62. Revel, M., Châtel, A., & Mouneyrac, C. (2018). Micro(nano)plastics: A threat to human health? Current Opinion in Environmental Science & Health, 1, 17–23.

63. Schmidt-Naake, G., Drache, M., & Weber, M. (2002). Combination of mechanochemical degradation of polymers with controlled free-radical polymerization. Macromolecular Chemistry and Physics, 203(15), 2232–2238.

64. Sekine, Y., & Fujimoto, K. (2003). Catalytic degradation of PP with an Fe/activated carbon catalyst. Journal of Materials Cycles and Waste Management, 5(2), 107–112.

65. Sen, S. K., & Raut, S. (2015). Microbial degradation of low density polyethylene (LDPE): A review. Journal of Environmental Chemical Engineering, 3(1), 462–473.

66. Shahnawaz, M., Sangale, M. K., & Ade, A. B. (2016). Bacteria-based polythene degradation products: GC–MS analysis and toxicity testing. Environmental Science and Pollution Research, 23(11), 10733–10741.

67. Singh, B., & Sharma, N. (2008). Mechanistic implications of plastic degradation. Polymer Degradation and Stability, 93(3), 561–584

68. Sivan, A. (2011). New perspectives in plastic biodegradation. Current Opinion in Biotechnology, 22(3), 422–426.

69. Skariyachan, S., Setlur, A. S., Naik, S. Y., Naik, A. A., Usharani, M., & Vasist, K. S. (2017). Enhanced biodegradation of low and high-density polyethylene by bacterial consortia from plastic-contaminated cow dung. Environmental Science and Pollution Research, 24, 8443–8457.

70. Striegel, A. M. (2003). Influence of chain architecture on the mechanochemical degradation of macromolecules. Journal of Biochemical and Biophysical Methods, 56(1–3), 117–139.

71. Sudhakar, M., Trishul, A., Doble, M., Kumar, K. S., Jahan, S. S., Inbakandan, D., & Venkatesan, R. (2007). Biofouling and biodegradation of polyolefins in ocean waters. Polymer Degradation and Stability, 92(9), 1743–1752.

72. Suman, T. H., Jia, P.-P., Li, W.-G., Junaid, M., Xin, G.-Y., Wang, Y., & Pei, D.-S. (2020). Acute and chronic effects of polystyrene microplastics on brine shrimp. Journal of Hazardous Materials, 400, 123220.

73. Taghavi, N., Singhal, N., Zhuang, W.-Q., & Baroutian, S. (2021). Degradation of plastic waste using stimulated and naturally occurring microbial strains. Chemosphere, 263, 127975.

74. Teare, D., Emmison, N., Ton-That, C., & Bradley, R. (2000). Cellular attachment to UV-ozone modified polystyrene surfaces. Langmuir, 16(6), 2818–2824.

75. Thomas, B., Olanrewaju-Kehinde, D., Popoola, O., & James, E. (2015). Degradation of plastic and polythene materials by microorganisms from soil. World Applied Sciences Journal, 33(12), 1888–1891.

76. Trivedi, P., Hasan, A., Akhtar, S., Siddiqui, M. H., Sayeed, U., & Khan, M. K. A. (2016). Role of microbes in degradation of synthetic plastics and manufacture of bioplastics. Journal of Chemical and Pharmaceutical Research, 8(3), 211–216.

77. Tyler, D. R. (2004). Mechanistic aspects of the effects of stress on photochemical degradation reactions in polymers. Journal of Macromolecular Science, 44(4), 351–388.

78. Vivi, P., Brustolin, G., & Giordani, G. (2019). Microbial colonization and deterioration of polymer surfaces in the environment. Ecological Indicators, 106, 105457.

79. Wall, L., Madorsky, S., Brown, D., Straus, S., & Simha, R. (1954). The depolymerization of polymethylene and polyethylene. Journal of the American Chemical Society, 76(13), 3430–3437.

80. Wong, J. K. H., Lee, K. K., Tang, K. H. D., & Yap, P.-S. (2020). Microplastics in freshwater and terrestrial environments. Science of the Total Environment, 719, 137512.

81. Xiao, Y., Jiang, X., Liao, Y., Zhao, W., Zhao, P., & Li, M. (2020). Adverse physiological effects of polystyrene microplastics on freshwater microalgae. Chemosphere, 255, 126914.

82. Yang, Y., Liu, W., Zhang, Z., Grossart, H.-P., & Gadd, G. M. (2020). Microplastics provide new microbial niches. Applied Microbiology and Biotechnology, 104, 6501–6511.

83. Yang, Z., Lü, F., Zhang, H., Wang, W., Shao, L., Ye, J., & He, P. (2021). Is incineration the terminator of plastics and microplastics? Journal of Hazardous Materials, 491, 123429.

84. Yoon, M. G., Jeon, H. J., & Kim, M. N. (2012). Biodegradation of polyethylene by a soil bacterium and AlkB cloned recombinant cell. Journal of Bioremediation & Biodegradation, 3(4), 145

85. Zhang, C., Chen, X., Wang, J., & Tan, L. (2017). Toxic effects of microplastic on marine microalgae Skeletonema costatum. Environmental Pollution, 220(Pt B), 1282–1288.