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Bacterial biodegradation of synthetic plastics: a review

Yousef Sefidi Heris[1*]

Abstract

Background Plastics are synthetic polymers that are reluctant to degradation. Therefore, their unlimited use has caused environmental problems. The reuse, reduce, and recycle methodology can solve these problems. However, this method is not efficient for mixed plastic wastes. As a result, more efficient and eco-friendly methods are necessary to remove these pollutants.

Main body of the abstract Biodegradation is a more effective and operative method for resolving the global plastic waste problem. This method is defined as breaking down chemical compounds by the enzymes released by organisms. Bacteria are among the plastic-degrading organisms. Plastic biodegradation by bacteria occurs in four successive steps: biodeterioration, depolymerization, assimilation, and mineralization. Plastic biodegradation by these microorganisms includes different enzymatic reactions, converting synthetic plastics into simple mineral materials. These enzymes are part of metabolic pathways that use these polymers as primary substrates. Several factors, including the chemical structure of synthetic plastics, can affect their biodegradation efficacy.

Short conclusion Although it is a promising solution for a global problem, bacterial biodegradation of synthetic plastics suffers from limitations such as slowness. The aim of the present study is to examine different aspects of bacterial biodegradation of synthetic plastics. These include the introduction of important plastic-degrading bacterial genera and enzymes involved in this biodegradation process. Additionally, metabolic pathways of synthetic plastic biodegradation, factors controlling this process, and limitations of this eco-friendly solution are examined.

Keywords Biodegradation, Bacteria, Plastic waste, Synthetic polymers

Background

Plastics are synthetic polymers composed of several organic monomers covalently bound together. They are high-molecular-weight organics derived from petroleum (Atanasova et al. 2021; Puja Asiandu et al. 2021). Their chemical composition includes carbon and hydrogen, supplemented with sulfur, nitrogen, and other organic/inorganic materials (Kumar et al. 2013; Chaurasia 2020). Plastics are reluctant to biodegradation, and their degradation or decomposition takes several thousand years (Chaurasia 2020; Kale et al. 2015). They are a versatile group of solid materials that are durable, lightweight, and moisture-resistant. Based on the chemical structure, synthetic plastics fall into the following categories: polyethylene (PE), polystyrene (PS), polypropylene (PP), polyurethane (PUR), low-density polyethylene (LDPE), and high-density polyethylene (HDPE). Due to their low cost and durability, synthetic plastics are used in several contexts, like telecommunication, agriculture, medicine, building and construction, and packaging. Despite being reusable products, they are among the major environmental pollutants, threatening living beings and humans (Drzyzga and Prieto 2019; Sowmya et al. 2014).

Unlimited plastic use has led to environmental problems caused by their degradation reluctance. The resistance against degradation leads to plastic accumulation in natural habitats. The accumulated plastics are ingested by

*Correspondence:
Yousef Sefidi Heris
yousefidi@yahoo.com
[1] Department of Biology, Shiraz University, Shiraz, Iran

living beings and disturb their population balance. When accumulated in oceans, plastic wastes threaten marine flora and fauna by mechanisms like inhibiting or limiting their movement. Plastics are usually burned to prevent their ecological accumulation. However, this combustion process releases carbon dioxide, toxic compounds, and dioxins, which can cause pulmonary diseases and lung cancer (Kale et al. 2015). These hazardous materials pollute the air, land, and aquatic ecosystems (Soud 2019). As a result, plastic waste should be appropriately processed to minimize this risk (Sowmya et al. 2014).

Reuse, reduce, and recycle methodology can prevent the problems caused by plastic waste. However, this method is inefficient for mixed plastic wastes (Drzyzga and Prieto 2019). In addition, plastic waste processing needs large areas of space and introduces toxic gases to the environment (Kumar et al. 2017). Consequently, more efficient and eco-friendly methods of plastic waste processing seem necessary. Plastic degradation can happen through photooxidation, chemical degradation, thermal degradation, and biodegradation (Mahdiyah and Mukti 2013).

Biodegradation is an effective and operative method for resolving the global plastic waste problem. It breaks down chemical compounds by the enzymes released from living organisms (Fachrul et al. 2021). There are several kinds of plastic-degrading microorganisms (Okmoto et al. 2003; Agrawal and Singh 2016), including bacteria (Chaurasia 2020; Begum et al. 2015). Microorganisms produce several extra or intracellular enzymes that can degrade plastic polymers (Okmoto et al. 2003; Agrawal and Singh 2016; Hedayati 2022). In addition to enzymatic processing, biodegradation may include chemical and physical action of microorganisms (Jamee and Siddique 2019). The enzymatic degradation products may be oligomers, dimers, and monomers. These products are consequently used as microbial carbon and energy sources. In some cases, carbon dioxide and water are produced as the final products of plastic biodegradation (Hedayati 2022; Siracusa 2019; Danso et al. 2019; Riaz et al. 2019; Fesseha and Abebe 2019; Urbanek et al. 2018; Glaser 2019). Plastic biodegradation leads to changes in mechanical properties, changes in chemical bonds, and the appearance of new functional groups (Arutchlevi et al. 2008).

Plastics fall into two categories: biodegradable and non-biodegradable. Biodegradable plastics have a higher rate of biodegradation. However, non-biodegradable ones possess a slow or unknown biodegradation rate. Most of the plastics currently in use, like polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC), are non-biodegradable (Dussud and Ghiglione 2014).

Plastic biodegradation includes four stages: biodeterioration, depolymerization, assimilation, and mineralization. Biodeterioration is a kind of cooperation between the microbes and abiotic factors and breaks the polymers down into smaller molecules. It is followed by depolymerization, in which catalytic compounds released from the microbes (such as enzymes and free radicals) break down the polymers progressively (Puja Asiandu et al. 2021). The biodeterioration causes physicochemical and mechanical changes in plastic polymers (Arutchlevi et al. 2008) and is accelerated by microbial biofilms (Kumar et al. 2017). Depolymerases catalyze depolymerization reaction. Its products are oligomers, dimers, or monomers. The fate of these smaller molecules depends on the presence of oxygen molecules. Aerobic degradation produces CO_2 and H_2O (Fig. 1), while anaerobic metabolism ends in CO_2, H_2O, CH_4, and H_2S (Tiwari et al. 2018). Microbial extracellular and intracellular depolymerase enzymes are necessary for plastic biodegradation. They decompose polymers to form smaller and simpler intermediates. These intermediates are easily dissolved in water and then absorbed by the microbial cells. Assimilation occurs in the cytoplasm of microbial cells through metabolic processes producing energy, biomass, and primary/secondary metabolites (Puja Asiandu et al. 2021). The next and final metabolic process in plastic biodegradation is mineralization. This step changes the hazardous toxic compounds produced during the biodegradation of plastics into safer compounds (Alshehrei 2017). Mineralization is defined as the process of converting biomass

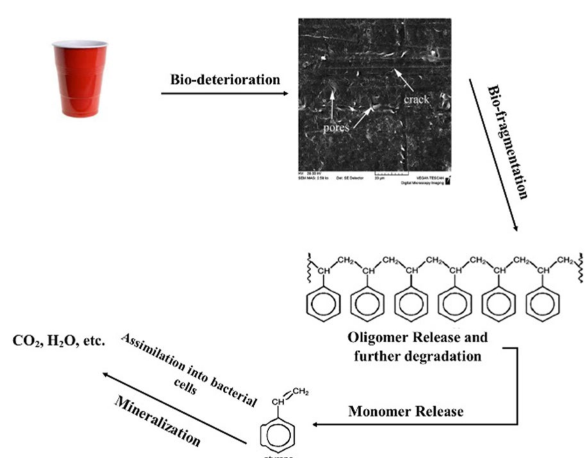

Fig. 1 The four stages of bacterial plastic biodegradation are biodeterioration, depolymerization, and assimilation. During these stages, the synthetic plastics are finally converted into carbon dioxide, water, and other simple compounds. Biodeterioration turns polymers into smaller molecules. Depolymerization releases oligomers, dimers, and monomers. Finally, the monomers are assimilated into bacterial cells and mineralized to form CO_2, H_2O, and other inorganic compounds

or biodegradable substances into gas, water, minerals, etc. The gases include CO_2, CH_4, and nitrogenous compounds. This process ends when the microorganisms consume the biodegradable compounds, and all carbon atoms are converted into carbon dioxide (Serwansks-Leja and Lewandowicz 2010; Kyrikou and Briassoulis 2007). As a net result of these steps, the plastic pollution chain is broken in the air, land, and water (Sowmya et al. 2014).

As a group of microorganisms, bacteria can degrade synthetic plastics through different pathways (Puja Asiandu et al. 2021). The present study examines several aspects of synthetic plastic biodegradation by bacteria. First, different bacterial plastic degraders are introduced. Then, the enzymatic sides of this biodegradation process are discussed. Furthermore, the metabolic pathways used for bacterial biodegradation of synthetic plastics are shortly introduced. Next, the factors controlling the synthetic plastic biodegradation by bacteria are summarized. Finally, the limitations of this eco-friendly solution for plastic waste removal are debated.

Main text

Plastic-degrading microbes

Abiotic degradation of plastics is a primary step caused by physical and chemical factors. It causes mechanical damage in the polymers, which enhances the surface area and decreases the molecular weight (Thew et al. 2023). The microorganisms then grow on the polymers and start their biological degradation. The microbial enzymes depolymerize large polymeric molecules into smaller monomers, which then act as carbon and energy sources for microbial cell growth (Thew et al. 2023; Mishra et al. 2020).

During biodegradation, living organisms convert large polymer molecules into smaller molecules, including oligomers and monomers. These products are used by other organisms and converted into even simpler compounds. Microbes are among the most important living organisms with a high biodegradation potential. These organisms and their enzymes convert the carbon backbone of polymers into smaller biologically important molecules or CO_2 and H_2O (Mir et al. 2017). This way, they can remove plastic wastes from the environment and participate in soil fertility (Tokiwa et al. 2009). The microbial enzymes produced by plastic-degrading microorganisms help them adapt to the environment since they convert substrates into simpler compounds (Fachrul et al. 2021).

Large molecules of plastic polymers cannot enter the microbial cells directly. As a result, plastic-degrading microorganisms responsible for the initial steps of biodegradation exploit extracellular biodegradation strategies. Further biodegradation is accomplished by secondary degraders (Dussud and Ghiglione 2014). Microorganisms are ideal plastic degraders since they have the required enzymes, and their small size enables them to contact plastics.

Bacteria and fungi are among the microbial plastic-degrading organisms. Among bacterial plastic degraders are some members of *Bacillus*, *Pseudomonas*, and *Corynebacterium* genera (Mahdiyah and Mukti 2013; Devi et al. 2016; Roohi et al. 2017). Some fungal plastic-biodegrading examples are *Aspergillus*, *Penicillium*, and *Alternaria*. Fungal biodegradation of plastics is limited to aerobic conditions, while bacterial biodegradation can occur under both aerobic and anaerobic conditions (Kumar et al. 2011). Aerobic biodegradation produces CO_2 and H_2O by using oxygen as an electron acceptor. But, anaerobic biodegradation yields CO_2, H_2O, and CH_4 as end products (Mishra et al. 2020). Polymer decomposition produces compounds used as nutrients to support microbial cell growth (Restrepo-Florez et al. 2014). Microbial biodegradation of plastics is usually a slow process, and some plastics are not biodegradable (Singh and Gupta 2014). Plastic-degrading microorganisms live in various habitats like seawater, soil, activated sludge, and compost. Microorganisms form an association with material surfaces. The adherence of complex microbial communities on the plastic surface is called biofilm formation or microfouling. This process includes the extracellular polysaccharides synthesized by microbial cells. Biofilms are common in water and soil environments (Roohi et al. 2017).

One of the challenges of plastic biodegradation in natural environments is the close contact between the plastic and microorganisms so that the enzymes can find their substrates. Biofilms set the stage for such close contact (Ganesh et al. 2020). Biofilms are microbial consortia where bacteria serve as primary colonizers and capture other organisms, such as diatoms and fungi (Ghosh et al. 2019). Consequently, the biofilm community shows significant differences with free-living microorganisms in the surroundings (Jacquin et al. 2019). Biofilms provide spatial proximity for the immobile microbial cells. On the other hand, the low diffusion rate of extracellular enzymes in biofilms facilitates the biodegradation process (Pinto et al. 2019).

Synthetic plastic-biodegrading bacteria

Bacteria (both Gram-positive and Gram-negative) are among the most efficient degraders of synthetic plastics. Members of species *Arthrobacter*, *Bacillus*, *Corynebacterium*, *Micrococcus*, *Pseudomonas*, *Rhodococcus*, *Staphylococcus*, *Streptococcus*, and *Streptomyces* are some examples of established bacterial plastic degraders (Jacquin et al. 2019; Sharma et al. 2018). Although several studies have shown bacterial biodegradation of synthetic plastics by pure bacterial cultures, this process occurs by synergistic bacterial consortia in the natural context (Amobonye et al. 2021). Bacterial species remineralize the organic carbon in wastes. Therefore, they are saprophytic scavengers. The main hydrocarbons found in plastics are degraded by some specialized bacteria (Yoshida et al. 2016). Plastic-degrading bacteria use the end products of plastic biodegradation as food sources (Austin et al. 2018).

Photolysis, thermolysis, thermooxidation, and radiolysis degrade plastics in natural environments. These events break the polymer chain into lower-weight molecules and release free radicals. The mechanical properties of plastics change as well, and the macrosized particles are converted into tiny ones (Cuadri and Martín-Alfonso 2017). It aids in the process of biodegradation. Bacterial biodegradation of plastics includes four stages: biological deterioration, biological fragmentation, assimilation, and mineralization. In the biological deterioration step, biofilms form around the plastics to help initiate the degradation process. Then, bacterial cells release extracellular enzymes to convert plastic polymers into oligomers, dimers, or monomers, which could be ingested by bacterial cells. In the third step (assimilation), oligomers, dimers, or monomers assemble on the surface of bacterial cells and are absorbed through simple/facilitated diffusion. Finally, these particles are metabolized and converted into CO_2, H_2O, and CH_4 (Cuadri and Martín-Alfonso 2017; Jeyavani et al. 2021).

Some bacterial enzymes, such as alkaline hydroxylase, alkaline monooxygenase, rubredoxin, and rubredoxin oxidase, participate in the biodegradation of synthetic plastics. In addition, lipases, esterases, and cutinases may also take part in this process. Bacterial species residing in plastic-polluted sites have adapted to feed on these materials. This adaptation is interesting on the genomic level and helps produce enzymes capable of synthetic plastic biodegradation (Jeyavani et al. 2021). Bacteria can produce these degradative enzymes continually or in response to their needs in plastic biodegradation (Roohi et al. 2017). Bacterial biodegradation of plastics can take place both aerobically and anaerobically. Under anaerobic conditions, iron, sulfate, nitrate, manganese, and carbon dioxide can act as electron acceptors to decompose plastics (Sharma et al. 2018). Plastic polymers with high-molecular weight are unsuitable for bacterial biodegradation since they should be phagocytosed and then biodegraded by intracellular enzymes (Roohi et al. 2017). Bacterial biodegradation of synthetic plastics is based on the ability of bacterial cells to degrade the long-chain fatty acids (Amobonye et al. 2021).

Bacterial biodegradation is an eco-friendly method of plastic waste management. Nevertheless, this is a slow process, which can yield better results. Designing recombinant bacteria with higher viability in different environmental conditions (pH, temperature, etc.) could be promising (Jeyavani et al. 2021). Bacteria can degrade several types of synthetic plastics (Begum et al. 2015). In some cases, bacterial biodegradation of synthetic plastics produces ubiquitous compounds such as esters, hydrocarbons, and alcohols (Ren et al. 2019). However, some bacteria are not able to degrade synthetic plastic completely. They do not use these materials as the sole carbon source (Cregut et al. 2013). Plastic polymers resistant to bacterial biodegradation are major environmental threats because of the long periods necessary for their complete degradation (Venkatesan et al. 2022).

Enzymatic aspects of bacterial plastic biodegradation

Several enzymes take part in the bacterial biodegradation of plastics, including esterase, lipase, amylase, laccase, manganese peroxidase, and lignin peroxidase (Matsumura and Smith 2005; Ganesh et al. 2017). Manganese peroxidase, lignin peroxidase, and laccase are three major lignolytic enzymes (Hofrichter et al. 2001; Bhardwaj et al. 2012). Hydrolysis and oxidation are two types of reactions involved in polymer biodegradation by bacteria. Hydrolysis breaks the polymers down by hydrolases, while biodegradation through oxidation involves the oxidoreductase function. Hydrolases degrade amides, esters, carbonates, and glycoside bonds to produce monomers from polymers. Oxidoreductases catalyze oxidation–reduction reactions of urethane, amides, ethylene, and carbonates (Matsumura and Smith 2005; Ganesh et al. 2017).

Three amino acid residues, serine, histidine, and aspartate, participate in the polymer hydrolysis. Aspartate forms hydrogen bonds with the histidine ring, and the histidine ring interacts with serine. Histidine conducts the deprotonation with serine to produce the nucleophilic alkoxide group, which attacks the ester bonds. These steps give rise to an acyl-enzyme complex and an alcohol tip. Water attacks the acyl-enzyme complex to form a carboxyl end and free enzyme (Tiwari et al. 2018; Lucas et al. 2008).

Some enzymes cannot degrade some polymers. Here, the other relevant enzymes cooperate to degrade those polymers, a process known as oxidation. For example, monooxygenase and dioxygenase enzymes fuse to form peroxyl or alcohol groups. Peroxidase enzymes catalyze further reactions to degrade these compounds into smaller parts. Peroxidases catalyze reactions between the peroxyl and electron acceptor groups such as amino, phenyl, phenol, thiol, carboxyl, or unsaturated aliphatic groups (Tiwari et al. 2018; Lucas et al. 2008). Some bacteria release extracellular enzymes catalyzing polyethylene

(PE) biodegradation. These enzymes are hydrolases and can catalyze C–O and C–N bond cleavage. This group includes esterase and lipase enzymes (Venkatesan et al. 2022).

Enzymes involved in plastic biodegradation fall into two major categories: extracellular and intracellular enzymes. Extracellular enzymes are well-studied and have versatile functions from oxidation to hydrolysis. These enzymes convert the long carbon backbones of plastic polymers into a mixture of oligomers, dimers, and monomers. These extracellular enzymes catalyze reactions happening at the liquid/solid interface and degrade macromolecules at the solid surface of the plastic. Other enzymes functionalize the hydrophobic surfaces of plastics, convert plastic degradation intermediates into monomers, and finally mineralize these monomers. Intracellular enzymes are involved in aerobic and anaerobic processes, converting degradation intermediates into chemicals that can be assimilated by the microbial cells. However, we must learn a lot about the biochemistry of plastic-degrading enzymes and their structural aspects. Some bacterial plastic-degrading enzymes are involved in polyethylene, polyurethane, polyethylene terephthalate, polystyrene, and nylon degradation (Amobonye et al. 2021).

Enzymes catalyzing polyethylene degradation

Bacterial enzymes involved in polyethylene biodegradation belong to the laccase, peroxidase, hydroxylase, and reductase categories (Amobonye et al. 2021). Alkane hydroxylase is one of these enzymes found in some *Pseudomonas* species (Yoon et al. 2012). Sometimes, this enzyme is presented in a system together with rubredoxin reductase. This system degrades low-molecular-weight polyethylene (Jeon and Kim 2015). Laccase enzyme in some bacteria also degrades polyethylene (Gomez-Mendez et al. 2018). These enzymes seemingly function via the oxidation of hydrocarbon chains in polyethylene molecules (Amobonye et al. 2021).

Enzymes catalyzing polyurethane degradation

Protease, laccase, urease, lipase, cutinase, esterase, and peroxidase can degrade polyurethane (Magnin et al. 2020). Esterase and amidase activities are presented in some polyurethane-degrading bacteria (Magnin et al. 2019). Metagenomics analyses show a broad spectrum of enzymatic activities in polyurethane degradation. These enzymes metabolize different polyurethane intermediates. They include isomerases, hydrolases, decarboxylases, dehydrogenases, dioxygenases, peroxidases, and ligases (Gaytán et al. 2020). Most polyurethane-degrading enzymes act on ester-linked polyurethane. They do not act on polyurethane ethers (Danso et al. 2019). Unlike ether-linked polyurethanes, the carbonyl groups of ester-linked polyurethanes facilitate their enzymatic hydrolysis (Amobonye et al. 2021).

Enzymes catalyzing polystyrene degradation

Although some bacteria can degrade polystyrene, enzymes involved in the initial steps of bacterial biodegradation of polystyrene are partially described (Amobonye et al. 2021). Some depolymerases degrade polystyrene in *Bacillus* and *Pseudomonas* species (Mohan et al. 2016). Phenylacetyl coenzyme A ligase, phenylacetaldehyde dehydrogenase, styrene monooxygenase, and styrene oxide isomerase metabolize styrene—building blocks of polystyrene—before it enters the tricarboxylic acid (TCA) cycle (Ho et al. 2018). These enzymes catalyze some reactions that depolymerize polystyrene to styrene, oxidize styrene to phenylacetate, and introduce phenylacetate to the Krebs cycle (Amobonye et al. 2021).

Enzymes catalyzing polyethylene terephthalate degradation

Polyethylene terephthalate (PET) biodegradation was first reported in *Thermobifida fusca* (Müller et al. 2005). Esterases, cutinases (Jabloune et al. 2020), carboxylesterases, and lipases (Danso et al. 2019; Jabloune et al. 2020; Ru et al. 2020) are involved in the bacterial biodegradation of PET. PETase is one of the most important enzymes in PET biodegradation. It is an aromatic polyesterase found in *Ideonella* species with a basic alpha/beta hydrolase fold. PETase converts PET to bis(2-hydroxyethyl)-TPA (BHET), MHET, and terephthalic acid (TPA). MHETase converts MHET into terephthalic acid and ethylene glycol (Austin et al. 2018).

Enzymes catalyzing nylon degradation

Some bacterial species possess enzymes catalyzing nylon biodegradation (Yamano et al. 2019). Some species of *Pseudomonas* and *Flavobacterium* metabolize intermediates of nylon metabolism with the aid of three different hydrolase enzymes: 6-aminobenzoate-cyclic-dimer hydrolase, 6-aminohexoate-dimer hydrolase, and endo-type 6-aminohexoate-oligomer hydrolase. These enzymes act in tandem to convert the nylon intermediates into 6-aminohexoate monomers. Some *Arthrobacter* species also have similar enzymatic activities (Amobonye et al. 2021).

Metabolic pathways of synthetic plastic biodegradation

Polyethylene is a synthetic plastic degradable by some bacterial strains (Ali et al. 2021). Many polyethylene-biodegrading species can also consume linear n-alkanes. Some n-alkanes (such as hexadecane) are structurally identical to polyethylene and can be model compounds to shed more light on their biodegradation process

(Montazer et al. 2020). The initial step of hexadecane biodegradation occurs with carbon–carbon bond hydroxylation. This step produces primary or secondary alcohols. These alcohols are then oxidized to aldehydes or ketones. These intermediates finally form carboxylic acids (Fig. 2). This oxidation decreases the number of carbonyl groups by forming carboxylic acids. Carboxylated n-alkanes resemble fatty acids and can enter the β-oxidation pathway in bacterial cells (Yoon et al. 2012; Jeon and Kim 2015; Álvarez 2003; Eubeler et al. 2010; Gewert et al. 2015). Some studies have reported that alkane hydroxylase (AlkB) system pathways degrade linear alkanes. Enzymes of this system take part in polyethylene biodegradation through the β-oxidation pathway (Jeon and Kim 2015). Monooxygenases are enzymes critical for the alkane hydroxylase pathway. Different bacterial species have different numbers and types of alkane hydroxylases. Induction conditions and the amount of target carbon in the alkane chain differ drastically for these alkane hydroxylases (Jeon and Kim 2016). *Pseudomonas* species express a broad spectrum of alkane hydroxylases. They participate in the first step of the n-alkane oxidation pathway through hydroxylation of the terminal carbon. These enzymes are the central components of mineralizing polyethylene into carbon dioxide (Bhardwaj et al. 2012). *Rhodococcus rubber* expresses laccase (phenol oxidase) enzymes with multiple copper atoms in their structure. These laccases play a critical role in polyethylene biodegradation (Santo et al. 2013).

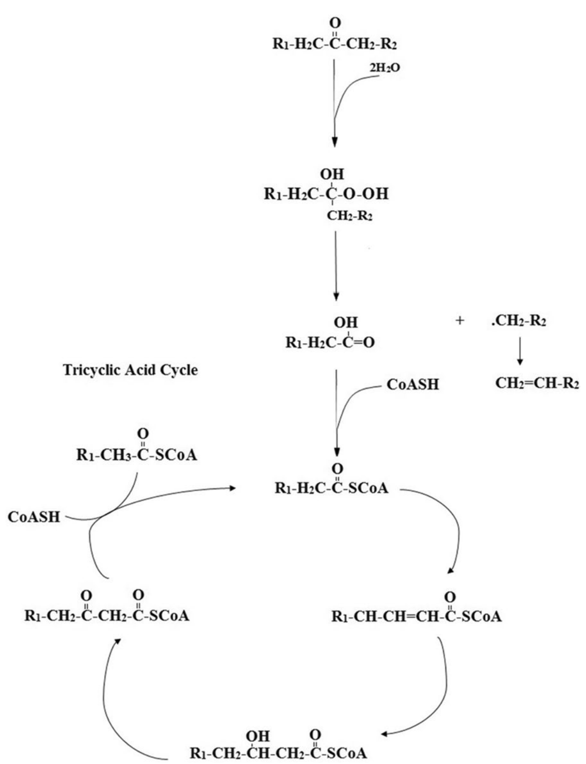

Fig. 2 Bacterial metabolism of polyethylene. First, the hydroxylation of carbon–carbon bonds generates primary or secondary alcohols. These alcohols are then oxidized to aldehydes or ketones, which ultimately give rise to carboxylic acids

Factors controlling biodegradation of synthetic plastics

Several factors can affect the biodegradation of synthetic plastics (Yoshida et al. 2016; Nakkabi et al. 2015; Torena et al. 2021). These include the polymer's chemical structure and the mixability of polymer compartments. In addition, oxidized or hydrolyzed substances can influence the bacterial biodegradation of these plastics. The nutritional state of biodegrading microbes, the hydrophobic or hydrophilic nature of polymers, the type of chemical bonds in polymers, and the roughness of the plastic surface can also influence this process (Puja Asiandu et al. 2021).

Limitations of bacterial biodegradation of synthetic plastics

Bacterial bioremediation of plastic wastes can remove plastic pollution from natural environments. It is a cost-effective and eco-friendly way to solve this problem. It is because bacteria use these pollutants as a food source and convert them into safe compounds. Several studies have reported bacterial biodegradation of synthetic plastics. However, this process suffers from some drawbacks. First, most synthetic plastics are resistant to the biodegradation process. Second, bacterial biodegradation of plastics under natural conditions has still so much to achieve. Third, there is no working definition for the biodegradation of synthetic plastics that can give rise to testable hypotheses. Therefore, developing a biochemical foundation for mechanisms of synthetic plastic biodegradation still has a long way to go. Fourth, plastic biodegradation is very slow, sometimes taking years to complete. Finally, bacterial biodegradation of synthetic plastics has usually been studied through culture-based methods with constant conditions. It is while the conditions of natural habitats in which the biodegradation process takes place can be dramatically different (Montazer et al. 2020). As a result, although several studies have proved the biodegradability of some synthetic plastics, there still must be more detailed investigations to pave the way for the real application of the biodegradation process in fighting against the global plastic waste problem.

Conclusions

Plastics are synthetic polymers known for their resistance against degradation in natural surroundings. The unlimited use of these degradation-resistant synthetic polymers has led to their accumulation in the environment, which is the origin of subsequent environmental problems. Reuse, reduce, and recycle methodology and plastic waste processing can partly prevent this disaster. However, reuse, reduce, and recycle methodology is partially effective. On the other hand, plastic waste processing requires large areas of land and can produce potentially dangerous compounds. Here, biodegradation emerges as a better solution for plastic waste management. This method uses living beings to remove plastic pollution from the environment. These organisms can use plastic pollutants as a food source and convert them into non-toxic materials. Several organisms can degrade synthetic plastics biologically, among which bacteria can be named. Several studies have suggested bacterial biodegradation of plastics as a solution for the environmental problem of synthetic plastics. Bacterial plastic degraders seem to be a promising option to fight against global plastic pollution. Although several lines of evidence have proved the biodegradation of synthetic plastics by different types of bacterial species, this process is slow and incomplete. Therefore, there is a need for more detailed investigations to shed more light on various aspects of this process, particularly in terms of metabolic pathways and enzymatic reactions involved. In addition, through reviewing the related literature, it was discovered that biodegradation seems an appealing solution for plastic waste removal. However, there is little or no information about the commercial use of plastic-degrading bacteria. As a result, there is a need to shed more light on the possibility of developing commercial products that use bacterial plastic degraders to remove these pollutants.

Abbreviations

PE	Polyethylene
PS	Polystyrene
PP	Polypropylene
PUR	Polyurethane
LDPE	Low-density polyethylene
HDPE	High-density polyethylene
TCA	Tricarboxylic acid
BHET	Bis(2-hydroxyethyl)-TPA
MHET	Mono(2-hydroxyethyl)-TPA
TPA	Terephthalic acid
AlkB	Alkane hydroxylase B

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