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# Classification and microbes involved in Plastic biodegradation: A review

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## Abstract

Plastic is composed of synthetic and semi-synthetic compounds with immense applications. While Plastics are dangerous and harm the environment, their practice is causing their ingesting to grow. Outdated methods of plastic degradation through physical and chemical means like landfill, incineration, and recycling are expensive and perilous and release hazardous chemical substances to the environment. Thus, proper approaches are required to overcome this trick. Biodegradation through microbes on the other hand offers a hopeful solution. Presently, numerous categories of bacteria and other microbial species degrade plastic materials. Several steps are required in plastic biodegradation like biodeterioration, depolymerization, assimilation and mineralization. These processes will result in secretion of enzymes that degrade plastics and converts it into gasses and biomass along other biproducts.

**Keywords:** Plastics; Biodegradation; microplastics; Microbes; Types

## 1. Introduction

Plastics synthetic or semi-synthetic organic compounds of long-chain polymeric molecules. They are mostly composed of elements such as carbon, hydrogen, nitrogen, oxygen, chlorine and bromine [1]. Plastics replaced old methods like wood, glass etc and due to their strength, low cost and durability [2]. Plastic is the third most production material worldwide [3]. In current times, approx. 450M metric tons of plastics are produced annually [4]. Due to stable nature of the plastic it last for decades in the environment [5]. Plastics can be broken down to micro or even Nano plastics using UV, thermal degradation, mechanical and human activities [6]. These microplastic are causing serious threats to marine organisms' health [7]. Plastics chemical additives alter their properties and cause environmental threats [8].

Plastic waste treatment involves different approaches like, incineration, chemical recycling, landfilling and mechanical processing [9]. Plastics are divided into two categories, Biodegradable and non-biodegradable [10]. Conventional plastics include, polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR) [11]. Synthetic polymers include plastic foams, nylons, polyethylene, polystyrene and polyurethane etc. [12]. Large scale plastic wastes generally end up in landfills or in oceans. This large-scale amount of plastic waste has one of the environmental problems that are challenging the present society [13].

Mechanisms such as chemical, thermal, photooxidation and biodegradation are responsible for the degradation of plastics. 90 plus genera of bacteria, fungi and actinomycetes play a vital role in biodegradation of polymers. Degradation by microorganisms occurs very slowly [14]. Plastic microbial degradation involves the following stages. Biodeterioration, bio fragmentation, assimilation and mineralization [15]. Biodegradable plastics are formulated from materials that can be easily degraded under environmental conditions. Industrial biological waste treatment facilities open the way for new waste management strategies. Bio plastic such as Polyhydroxy Alkenoates (PHAs), which has no toxic effects and is safe, can be easily biodegraded. They are generally produced by some strains of microorganisms [14].

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## 2. Plastic types

Plastics are divided into two main types on the basis of physical properties, that is thermosets and thermoplastics.

### 2.1. Thermoplastics

Thermoplastic, is solidified when temperature is low i.e. cooled, and melted when the temperature is high i.e. melted. The high profiled examples of thermoplastics are Polyvinyl chloride, polycarbonate, polypropylene (PP), polylactic acid (PLA), polyethylene terephthalate (PET), polyethylene (PE), low-density polyethylene (LDPE), high-density polyethylene, polystyrene (PS), polystyrene (PS), and polyhydroxyalkanoates (PHA).

### 2.2. Thermosets

Another type of plastic, cannot be remelted as excessive heating can change its chemical structure. Examples include, Polyurethane (PUR), phenolic resins, epoxy resins, silicone, vinyl ester, acrylic resins, and urea formaldehyde (UF) [36]. A figure of types of plastics on the basis of physical properties are as below. Figure 1

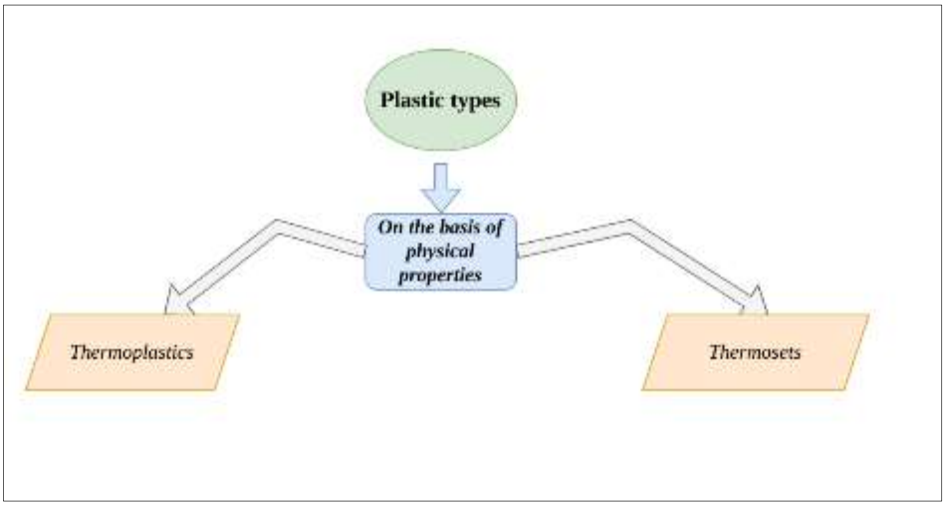


**Figure 1** Types of plastics

Plastics can also be divided on the basis of commonly uses in daily life. The examples of these plastics are in the figure 2, given below.

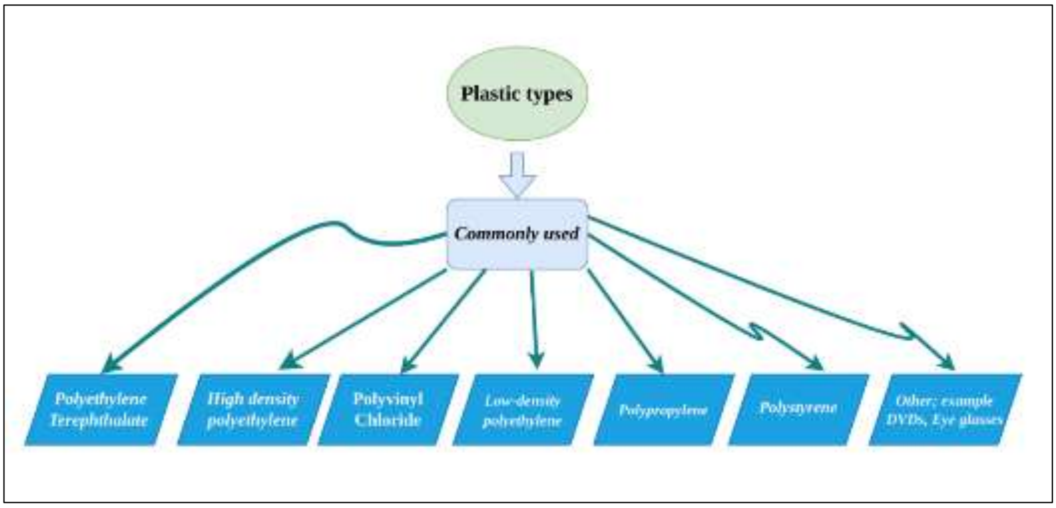


**Figure 2** Different types of plastics on the basis of daily use.

## 3. Uses of plastics

There are different uses of different plastics for example, Polyethylene terephthalate, which is a thin, translucent plastic, used to covering a diversity of foods and beverages. Low-density polyethylene, which is a multipurpose and sturdy is usually used to grip drinks. HDPE, derived heat-resistant petroleum, used for Plastic bags. Polyvinyl chloride (PVC) is a synthetic plastic that contains chemical additives, usually, phthalates, dioxins, BPA, and heavy metals, all these chemicals can cause cancer and bronchitis, among other related health issues. PVC used as a wrapper. Polypropylene (PP) is used for package medications. Polystyrene (PS) typically used as a recyclable container [37]. Mostly used plastics globally are LDPE, HDPE, PET, PS, EPS, and PP [36].

Currently, biodegradable plastics are being in use in addition to nonbiodegradable ones. Most of the industries manufacture biodegradable plastics. The usage of biodegradable polymers is directly linked to environmental issues. The two examples of biodegradable plastics are Polylactic acid (PLA) and polybutylene adipate-co-terephthalate [38]. PLA, being biodegradation, still takes a long time for the polymer to break down naturally. In nature environment, a biodegradable polymer's biodegradation process may take months or even years [39].

### 3.1. Plastics classification based on biodegradability

### *3.2.* Non-biodegradable plastics

Non-biodegradable plastic is a material which cannot be degraded by living organisms and acts as a environmental pollution source [16]. It comprises fossil-based and bio-based polymers. Fossil-based synthetic polymers are most used non-biodegradable plastics and are hydrocarbons and petroleum derivatives. They are made up of a small repeating subunit, they have high molecular weight and stability due to which they do not easily undergo degradation cycles. Commonly Used non-biodegradable plastics include Polyvinyl Chloride, Polypropylene, PS, Polyethylene, PUR and Polyethylene terephthalate. They accrued in the environment and became a threat. Some of them are chemically inactive and resistant to microbial attack [17]. The term "Bio" in bio-based polymers stands for carbon source or its biodegradability. Sources of non-biodegradable plastics are usually green plants such as corn, sugarcane and biomass. The process of manufacturing involves pretreatment, hydrolysis, fermentation and some important steps of organic reactions [18].

### 3.3. **Biodegradable plastics**

Biodegradable plastics are degradable and can be broken down when exposed to UV light, sunlight, microorganisms, certain enzymes or insect attack [19]. Biodegradable plastics include bio-based and fossil-based polymers. Plastic biodegradation includes enzymatic and non-enzymatic hydrolysis. Microorganisms release exoenzymes, which degrade polymer complexes into smaller components such as dimers and monomers, allowing them to readily flow through a bacterial cell's semipermeable membrane. Bacterial cells employ these monomers as an energy and carbon source. This process includes both aerobic and anaerobic processes [17]. Certain petroleum-based polymers are also biodegradable. Polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) are major biodegradable plastics. The most well-known polymers from polyhydroxyalkanoates are poly-3-hydroxyvalerate and poly-4-hydroxybutyrate. Because of their hydrophilic properties, these polymers allow for hydro-degradation. The bacterial fermentation of carbohydrates produces polyhydroxyalkanoates and polylactic acid. However, this technique may have an impact on the food industry because sugars are still produced from crops that compete with food sources. Despite this, biodegradability is intimately tied to the biochemical interaction between polymers and microorganisms [20]. Biodegradable plastics also increased soil fertility, decreased the amount and degradation time of plastic materials on earth [21].

### 3.4. Different microorganisms involved in Biodegradation

Microorganisms have a vital role in biodegradation owing to their variety. Bacteria, fungi, and other microorganisms possess the potential because to their tiny size, rapid absorption, metabolism, adaptability, and spread [22]. Microorganisms can tolerate extreme circumstances, adapt to new settings, and release enzymes that allow them biodegrade plastic as their only supply of carbon [23]. Streptococcus, Bacillus, Pseudomonas, and Staphylococcus are the most predominant bacterial species involved in plastic biodegradation [24]. Enzymes involved in plastic biodegradation are classified into two types: extracellular and intracellular. Extracellular enzymes are selected due to their reactivity and oxidative-hydrolytic functionality [22]. Several effective attempts have been made using various molecular approaches to modify the genes encoding plastic degrading enzymes in order to boost their activities and raise the production level [25]. Some plastic degrading microbes are as follows in table 1.

**Table 1** Plastic degrading microorganisms

| S.no | Type of plastic | Microorganisms | References |
|---|---|---|---|
| 1) | Polyethylene terephthalate | Ideonella sakaiensis | [26] |
| 2) | Polyethylene | Bacillus amylolyticus | [40] |
| 3) | PE | Pseudomonas Alcaligenes | [40] |
| 4) | Polyethylene terephthalate (PET) | Thermomonospora fusca | [26] |
| 5) | PET | Pseudomonas mendocina | [26] |
| 6) | PET | Staphylococcus aureus | [41] |
| 7) | PET | Staphylococcus pyogenes | [41] |
| 8) | PET | Candida antarctica | [26] |
| 9) | Polyurethane | Pseudomonas protegens strain | [27] |
| 10) | PUR | Thermobifida fusca | [27] |
| 11) | LDPE | Escherichia coli | [42] |
| 12) | LDPE | Burkholderia cepacia | [42] |
| 13) | LDPE | Bacillus weihenstephanensis | [42] |
| 14) | PUR | Pestalotiopsis microspore | [27] |
| 15) | PUR | Candida rugosa | [27] |
| 16) | Polyethylene (PE) | Pseudomonas putida | [28] |
| 17) | HDPE | Ochrobacterum anthropi | [43] |
| 18) | PP | Bacillus cereus | [43] |
| 19) | PP | Sporosacrina globispora | [43] |
| 20) | PHAs | Pseudomonas species | [28] |
| 21) | PVC | white-rot fungi | [28] |
| 22) | PLA | Cryptococcus sp. Strain S-2 | [44] |
| 23) | PBS | Pichia pastoris | [44] |
| 24) | PBS | Candida rugosa | [44] |

## 4. Factors affecting the degradation of plastics:

Factors that influence biodegradation are polymer properties and environmental factors [29].

### 4.1. Polymers characteristics

The characterization of polymers including the arrangement, mobility, crystallinity, molecular weight, type of functional group and additives or plasticizers [30].

### 4.2. Polymer size

Smaller plastics degraded faster than larger plastics. Microorganisms decay slowly due to high molecular weight polymers. Polymer solubility reduces as molecular weight increases, making it less susceptible to microbial attack. Polymers, such as monomers, dimers, and oligomers, degrade and mineralize easily [31]. Abiotic hydrolysis, photo-oxidation, and physical breakdown also increase the polymer's surface area and diminish the plastic's molecular weight [30]. Glucose is an essential carbon source than plastic, its availability reduces the rate of deterioration, if found on the surface of plastic material [32].

### 4.3. Colors and packaging

These are two non-polymeric pollutants that reduce biodegradability. Biosurfactants are compounds utilized in polymer biodegradation due to their low toxicity and high biodegradability ratios. It enhances biodegradation under extreme temperatures, pH, and salinity because to the presence of distinct functional groups [33]. Microplastics' ability to degrade completely relies on their kind. For example, petrochemical-based polymers in the marine environment degrade more slowly than on land [34].

### 4.4. Atmospheric conditions

It can influence biodegradation, both high temperatures and high humidity increases deterioration. On the other hand, cold and dry environments keep plastics around longer [35].

### 4.5. Enzymes

Both internal and external microbial cells possess enzymes that breakdown polymers. It degrades polymer chains, releasing metabolic byproducts as CO2, H2O, CH4, and N2. Algae, actinomycetes, bacteria, and fungi are among the microorganisms utilized to extract enzymes involved in plastic biodegradation. All enzymes involved in the degradation of plastics belong within the "Hydrolases" class, with exceptions such cutinase, lipase, and PETase [32].

## 5. Challenges in Biodegradation of Plastics

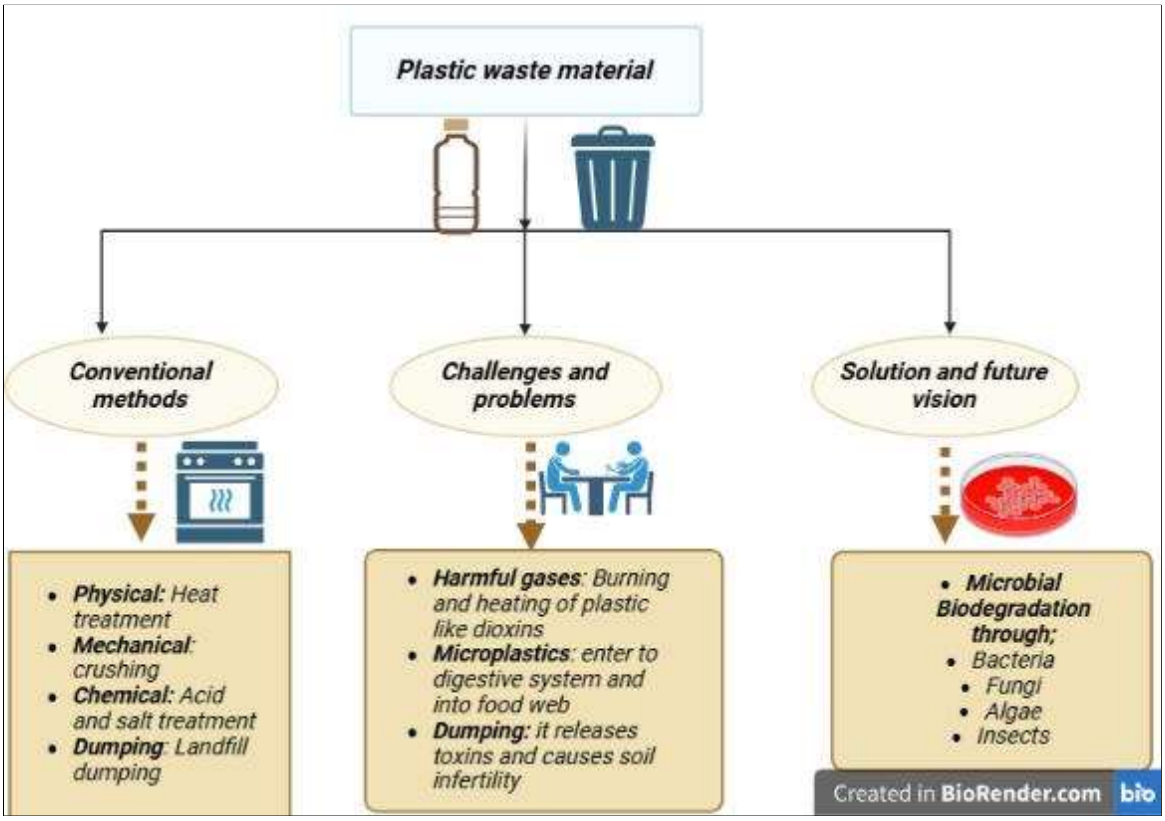


**Figure 3** Overview of plastic conventional methods and future possibility, adapted from [51].

Plastic biodegradation faces several challenges. Traditional plastics like polyethylene (PE) and polypropylene (PP) resist microbial attack due to their high molecular weight and hydrophobic nature. These properties hinder enzymatic breakdown and microbial access [45]. Another challenge in plastic decomposition is the specific environmental conditions needed. Factors like temperature, pH, and oxygen levels must align perfectly for microorganisms to effectively break down plastics. These ideal conditions are often missing in places like landfills or oceans, leading to slower decomposition [46]. Also, many places lack the specific microbes needed to break down plastics. Even if introduced, plastic-degrading bacteria often struggle to thrive because they face competition from local microorganisms [47]. Additionally, breaking down plastics requires a lot of energy, making it hard for bacteria to sustain the process without extra nutrients [48]. A big issue with plastic degradation is the creation of microplastics. Partial breakdown often leads to these tiny particles lingering in the environment, posing serious health risks to both marine and land ecosystems. This highlights the need to fully understand and improve biodegradation methods to achieve complete degradation, not just partial [49]. Finally, the different compositions of plastics make biodegradation tougher. Plastics often contain stabilizers, fillers, and additives to enhance durability but hinder microbial breakdown. These additives can also release harmful substances during decomposition, causing more environmental issues [50].

### 5.1. Approaches needed to tackle plastic degradation

The development of Biodegradable plastics is needed and for that, biodegradable plastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), are designed to degrade plastics speedier under natural environmental conditions. Conditions will help composting and give exposure to microbes. Researchers are working continuously into producing new types of biodegradable plastics that degrade quicker without releasing harmful biproduct substances during breakdown. There are some microbes and related enzymes have been discovered that have the ability to break down plastics. For example, PETase are enzymes produced by bacteria that degrades polyethylene terephthalate (PET). Optimizing theses enzymes are crucial for industrial use. Certain microorganisms such as bacteria and fungi have the ability to degrade plastics in landfills or treatment plants. Although, it must be further explored and scaled up for practical application. Incapacitating plastic degradation requires a complicated approach that includes novelties in material science, enhancements in recycling technologies, biological solutions, and supportive policy agendas. In order to make significant progress in plastic pollution crisis, there must be collaboration between industries, researchers, and governments.

## 6. Conclusion

Plastic is one of the problems of the recent era. Deprived administration of authorities leads to a high jeopardy of plastic pollution. Plastic treatment through biodegradation is the promising way ahead as their biproducts are more useful and less hazardous to the environment than conventional methods used for plastic degradation including incarnation. Conventional methods need to be converted into new biodegradable methods to slow down environmental pollution. With the few steps of biodegradation including biodeterioration, assimilation and mineralization and their useful biproduct results, the future of plastics are bright.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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