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Bacterial Biodegradation in Plastic Waste Management: An Insight

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Abstract:

This comprehensive overview explores the multifaceted nature of plastics, highlighting their classification, benefits, and environmental challenges. It discusses the origins of plastics, including thermoplastics, elastomers, and bioplastics, and examines harmful additives such as phthalates, BPA, and flame retardants that pose health risks. The review also addresses the environmental impact of plastic waste, particularly microplastics, and the processes of photodegradation and ozone degradation that contribute to plastic fragmentation. Furthermore, it explores the role of bacteria in bioplastics production and biodegradation, emphasizing microbial mechanisms such as adhesion, hydrolysis, and bioassimilation. Understanding these processes is critical for developing sustainable solutions to plastic pollution and promoting environmentally friendly practices.

Keywords*: Plastics, Bioplastics, Elastomers, Additives, Plastic Degradation, Microbial Biodegradation, Bacteria, Plastic Pollution*

1.Introduction

Plastics are polymers made from various monomers that are diversely used in human endeavors. Plastics are cheap, malleable, ductile, lightweight, and versatile. The wide range of applications encourages pollution and adamant persistence in the environment while dissipating harmful chemicals (Asmonaite & Bethanie, 2019; Vincent et al., 2023). Making more plastics attracts more pollution which is deadly because of hyper utilization of fuels, and dissipation of chemicals that are affecting biological systems at cellular, molecular, organ, and system levels. Innovative alternatives are bioplastics made from biobased materials (Sarkingobir & Lawal, 2021; Stancey et al., 2025. Making bioplastics through use of bacteria or other microbe to act upon agricultural or food waste is a more innovative and sustainable option. Bacteria use the waste to gain carbon and apply enzymes to synthesize polymers like bioplastics (Irawan et al., 2024). The objective of this paper is to lay an insight on the role of bacteria in plastic degradation.

2. The meanings of Plastics

Currently, this century is regarded as plastic age, because plastics make a lot of wonders such as durability, and are linked to improper disposal or management. Plastics cause extensive problem in our natural habitats, large plastics tend to fragments to become tiny ones (microplastics) that are ingested by biological systems and in turn bioacumulate to pollute the food chain (Saskatchewan Ministry of Environment , 2012; Wagner et al., 2014). Plastic are from the word borrowed from Greek, namely, "*plastikos*" which means fit to be molded. Equally, the other original word is the "*plastos*" which means molded. Thus, the term plastics in talking about material polymer that is ductile during manufacture. Therefore, the material has been characterized with ability to be turn to shapes during production (Lusher et al., 2017; Pizzorno, 2024). Plastics are catch-all name referring to all polymers that are molded upon addition of specific pressure and temperature to make different end-products. Plastics are made either as synthetic or semi-synthetic from oil, gas, coal, petroleum, etc. Organic plastics come from organic materials like corn, sea weeds, cellulose, starch, cane, etc (Lusher et al., 2017; Stancey et al., 2025). There are certain categories of names given to plastics such as the followings:

- Thermoplastics- Thermoplastics soften once they are made (molded), for instance, polyester resins, polyurethane, Bakelite.
- Elastomers- Elastomers are categories of plastics that are elastic in nature, after stretching they can be able to return to original (initial) shape.
- Bioplastics- Bioplastics are categories of plastics that are of different types consisting of examples like biodegradable, biobased, and oxo-biodegradable. However, their main trait is they are made from biological materials with a view that they can be comparatively degraded by biological beings more than their counterparts. Biobased plastics are products of biological renewable sources. Oxobiodegradable plastic contains metal(s) that act as catalyst to aid degradation under suitable conditions (Lusher et al., 2017; Alabi et al. 2019).

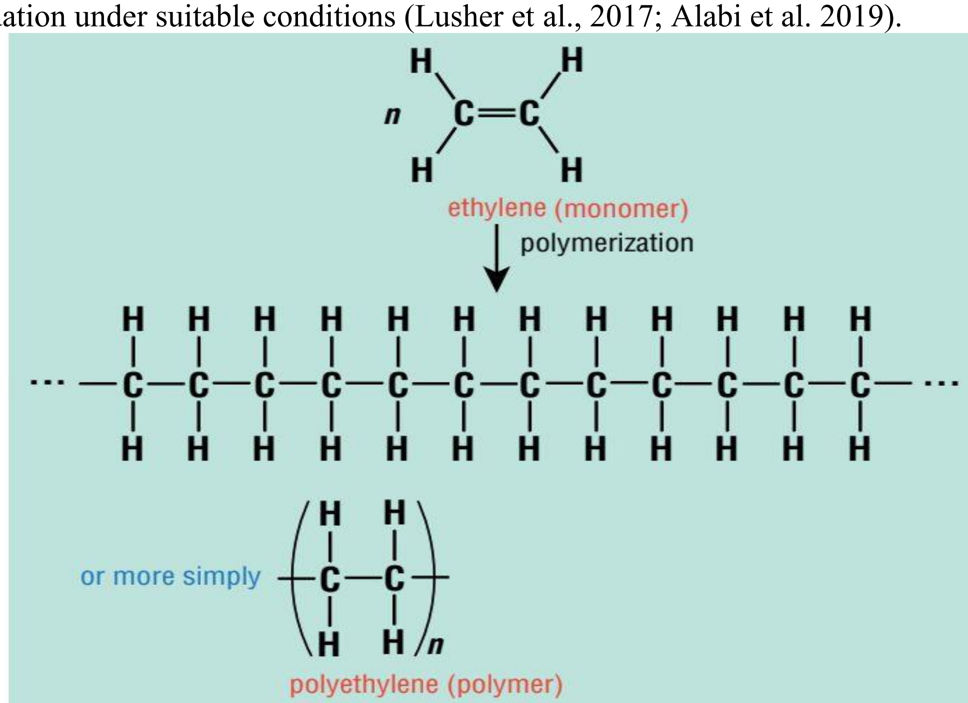

Figure 1Typically example of synthetic plastic; Source: Washam (2010)

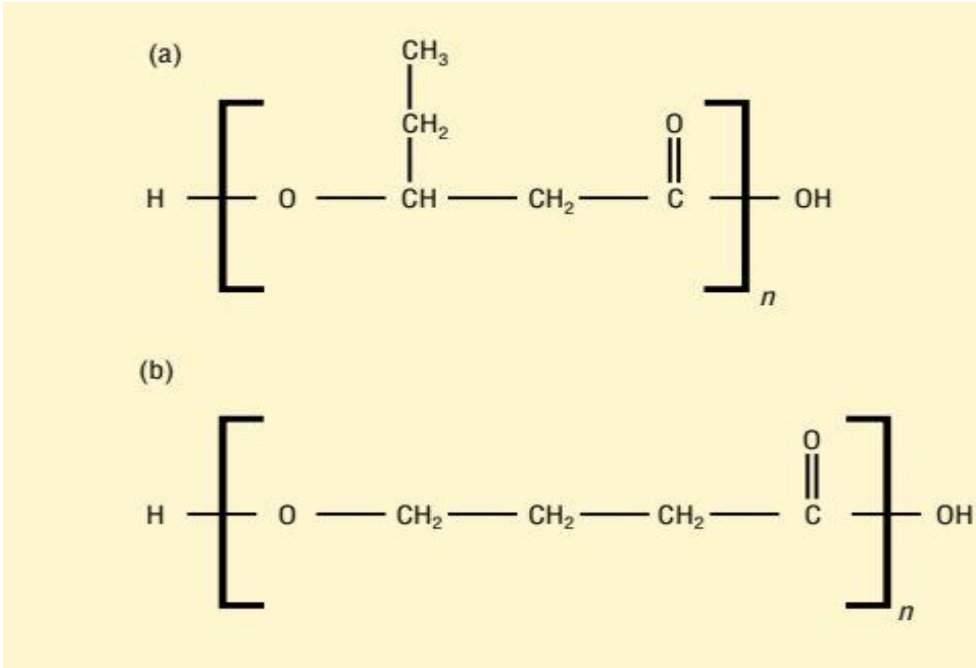

Figure 2Typically examples of bioplastics; Examples of two PHA molecules: (a) poly-3-hydroxyvalerate; (b) poly-4 hydroxybutyrate (n is a large number.) Source: Washam (2010)

However, in plastics, some of the monomers are harmful (example vinyl chloride) and many of the additives are harmful to humans and biological systems. Some of the harmful additives of plastics include the followings:

- Pthalates- Pthalates are utilized to ensure flexibility and resistant to breakage in plastics. Examples of pthalates include Dibutyl phthalate (DBP), and Diethyl phthalate (DEP), and these molecules are considered to be endocrine disruptors. Pthalates are highly present in PVC plastics and are able to leach from the main polymer chain to food, water, and environment (EPA, 2016; Oghenekohwiroro et al., 2015).
- Bisphenol A (BPA)- Bisphenol A (BPA) was about 5.2 million tons made in 2008. Bisphenol A (BPA) is a leading chemical manufactured in the world nowadays. BPA is utilized in epoxy resins and polycarbonate and has the tendency to leach into the environment. PP, PVC, and PE contain BPA as well. BPA too is a categorical example of endocrine disruptors known currently (Lusher et al., 2017; Ncuebe et al., 2021).
- Flame retardants (FRs)- FRs are utilized in plastics of electronics, furniture, fabrics, etc to minimize flammability. Examples of FRs include hexabromocyclododecane (HBCD), and polybrominated diphenyl ethers (PBDEs). These chemicals are designed as examples of endocrines disruptors. Other effects of FRs include developmental problems, teratogenicity and kidney or liver poisoning (Hahladakis et al., 2018).
- Nonylphenols (NPs)- NPs typically include the precursors of nonylphenol ethoxylate and nonylphenol, that are utilized as antioxidants. These are typical endocrine disruptors of concern (Lusher et al., 2017; Alabi et al., 2019).
- Harmful byproducts of burning- Plastics make several harmful substances upon burning (as disposal method) therefore this approach is of concern to environment and health (Hahladakis et al., 2018). Some of the harmful products obtained upon burning of plastics are in Table 1.

Table 1: Harmful products obtained upon burning of plastics

S/N	Substance	Health effects

1	Acetaldehyde	Damages nervous system, and induce lesions
2	Acetone	Causes irritation in eyes, and respiratory system
3	Benzaldehyde	Causes irritation in skin, and limit brains activity
4	Toluene	Causes depression and irritation of the yes
5	Xylene	Irritates the human eyes, and affect the nervous system as well
6	Propylene	Damages the central nervous system and reduces consciousness
7	Vinyl chloride	Causes cancer, irritates the skin, eye, and respiratory system
8	Phosgene	It is corrosive to skin, eyes, and respiratory system
9	HCl	Corrosive to eyes, skin, and respiratory system
10	Formaldehyde	Carcinogenic, and damages the eye
11	Benzole	Affects liver, immunity, and bone marrow

Source: Alabi et al. (2019); Children's Environmental Health Network (2010).

3. Plastics management and concerns

- Plastics are posing several daunting changes to all. More especially improper management of plastic waste is significantly consequential as well be disposed in this section:
- Persistence- Plastics are highly persistent in the environment. Normally, plastics bottles take about 450 years before been completely degraded; bags take 20 years before decomposing, fishing line stay for about 600 years, with the effort of mechanical pressure, heat, smaller fragments emerge to make micro or nanoplastics (EarthDay Network, 2018; Valentine, 2018).
- Serving as vector of pollutants-There are myriad arrays of pollutants in the environment that can reach-out to the plastics. In this vein, plastics (especially the tiny ones) are capable of carrying along several chemicals to the parts of the environment. Some chemicals adhere to plastic surface (adsorption), some gets into the inner part (absorption) and some combine the duo (permeation) (Gazal & Gheewala, 2020; Rist & Hartmann, 2017; Havern, 2022).
- Leaching of pollutants or additives-Plastics can be able to release its folds (such as copollutants and additives) to the environment, actions such as pressure, heat, and ultraviolet, mechanical, and microbial activity. This begets pollution of land, water, and biota (Lyon, 2004; Libroin, 2015: Katsara et al., 2025; Petrulioniene, 2025).
- Effects on biological systems- Different additives and co-pollutants in plastics cause a number of hazardous effects on the hormone (s) or endocrine system in turn resulting in effects of nervous system, reproduction, etc. Some chemicals such as heavy metals exhibit diverse effects. More critically, plastics exert inflammation and oxidative stress on biological systems (Hahladakis et al., 2018). Some effects of plastics are in Table 2.

Table 2: Effects of plastics on different biological levels

S/N	Level of organization	Effects
1	Molecular level	Oxidative stress, cell damage, impaired metabolism
2	Tissue level	Histopathological changes, damage and transfer of tissues
3	Organism	Impaired respiratory, insatiation, impaired growth, development, and reproduction, behavioral changes

Source: Rist & Hartmann (2017).

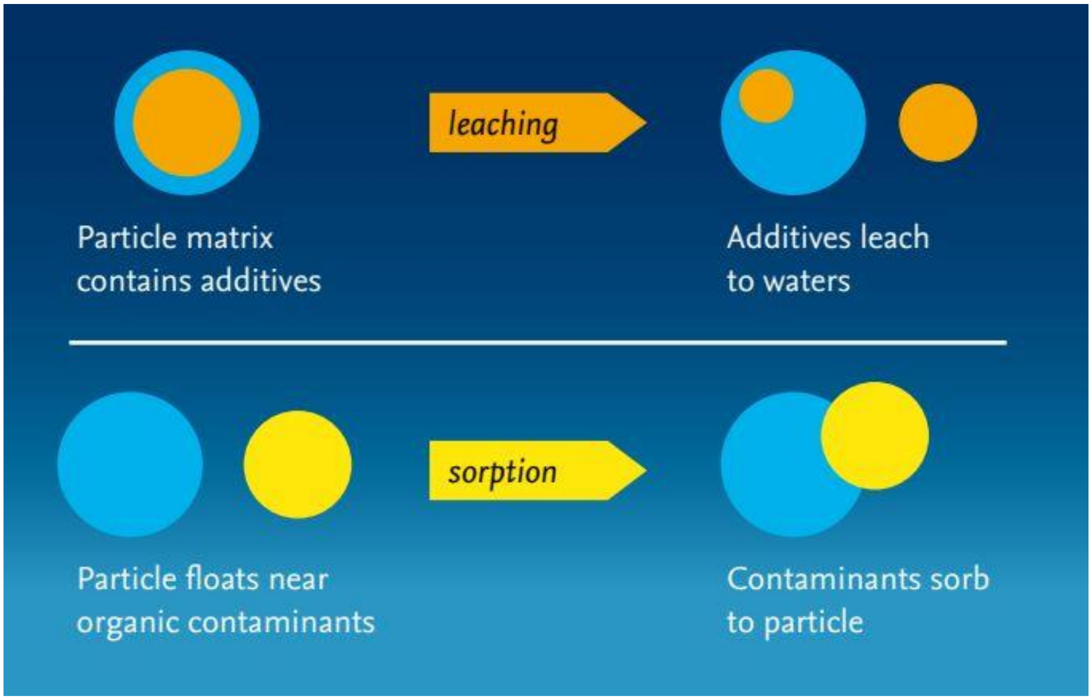

Figure 3Typical leaching behavior of plastics; Source; Lusher et al. (2017)

4.Bioplastics

Bioplastics are group of types of plastics that are supposed to be biodegradable and biobased or both (Bhatt, 2023). Often bioplastics are made using the machinery of microbes under various conditions and are therefore coined as biomaterials. Presently, the bioplastics make about 1% or more of the general plastics produced every year. Bioplastics can be starch-based, cellulose-based, protein-based, and microbially-based (when microbes such as bacteria or fungi are utilized to polymerize simple carbon units to larger extensive units) (Bhatt, 2023). The procedural steps of synthesize bioplastics in bacteria include the followings:

- Substrate selection- Substrate is the carbon source for the bacteria that is mostly drawn from agricultural source or wasted food materials. The carbon source is utilized by the bacteria to make polymers.
- Microbe selection- At this stage, the specific microbial strain is carefully selected for its tendency to synthesize desired bioplastics polymer from carbon sources (smaller units of monomers).
- Fermentation- Under this step, microbe is made to grow in a bioreactor under specific controlled conditions using carbon feedstock.
- Bioplastics accumulation- In the course of fermentation, the microbe transforms the carbon source into bioplastics of need. The bioplastics accumulates in the cells.
- Harvesting and extraction- Therewith, sufficient quantity of bioplastics is harvested, extracted, in turn purified.
- Processing- At this terminal step, the bioplastic may be further converted to form products like sheets, films, and pellets (Bhatt, 2023).

5.Macromolecules degradation or fragmentation

- Before the actual fragmentation or biodegradation carried out by bacteria or microbes take place, some prior or initial manipulations of the large plastics materials is under taken in real life situations. Some of these processes are under listed below:
- Photodegradation- Photodegradation occurs because the sunlight acts upon large molecules of plastics and in turn resulting in smaller fragments of the plastics materials. The UV light breaks carbon-carbon bonds and makes esters, aldehydes, formate, and propyl groups, among others (Bordoloi et al., 2024).
- Ozone degradation- Ozone degradation has the ability to transform large plastics to smaller fragments because generated reactive oxygen species are ensured (Bordoloi et al., 2024).

6.Bacteria and plastic degradation

Usually, several bacterial species are capable of making bioplastics in the ongoing innovative researches towards better sustainable products. Plastics made from biobased materials are more susceptible to easy degradation; therefore searching in this raged is intensified (Washam, 2010; Sangeetha & Kiruthika, 2025). Some bacterial species producing plastics are as follows:

- *Bacillus* species such as gram positive are promising sources of polyhydroxylalkanoates (PHAs) are made by bacteria under nutrient limited conditions. PHAs are about 150 bioplastics of different categories.
- *Cupriavidus necator* is another bacterium that is capable of gathering PHA as 8% of its dry weight.
- *Pseudomonas* species make medium-chain-length PHAs plastics of different types.
- Recombinant *E. coli* is another bacterium that is engineered form and is able to make biosynthetic plastics (Mandal et al., 2024; Sangeetha & Kiruthika, 2025).

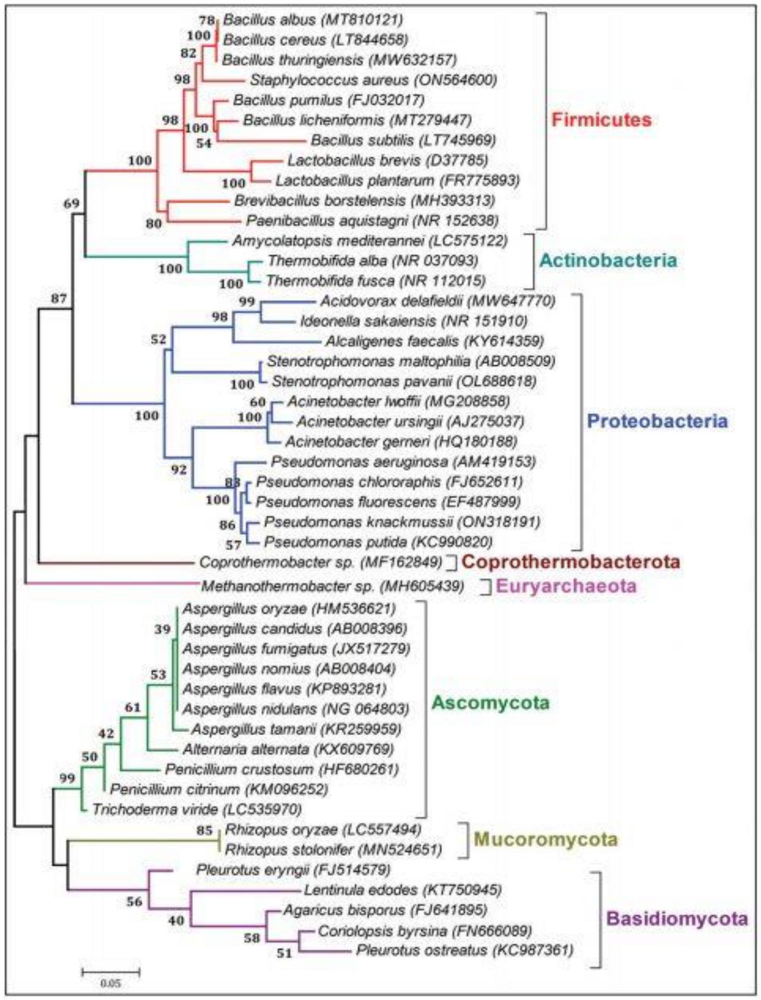

Figure 4Phylogenic tree of microbes (including bacteria) with ability to degrade plastics; Source: Kour et al. (2023)

However, mostly three enzymes participate in bacteria in the making of bioplastics. The enzyme includes 3-ketothiolase (phaA) which condenses 2 acetyl CoA to make acetoacetyl CoA. A reductase (acetyl-coA reductase) act to form 3-hydroxybutyryl-coA. PHA synthase (phaC) ensure the polymerization of 3-hydroxybutyryl-coA to make PHB (Sangeetha & Kiruthika, 2025). Indeed, bacteria are suitable microbes for bioremediation of plastics and other pollutants. There is a growing trend of studies trying to understand the possible role of bacteria in biodegradation of plastic waste nowadays. For instance, bacteria such as *Acinetobacter*, *Pseudomonas, Bacillus,* and typically *Klebsiella* are been studied gradually for exploitation against plastic polymers (Kour et al., 2023). In this vein, a lot of studies are ongoing to ascertain the ability of bacteria and other microbes on degradation of plastics. Patel et al. (2024) assessed the ability of *Bacillus sp., Pseudomonas sp., Proteus sp.*, and *Salmonella* sp., on low density polyethylene and high density polyethylene, and the results indicate varying degree of weight loss of the plastics (over too months). Mohanan et al. (2020) suggested that, after consumption of the degraded plastic byproducts, the short materials (intermediates) have been proposed to be channeled to TCA cycle for subsequent release of CO_2 and H_2O and this mostly undergoes under aerobic condition. Ullah et al. (2025) reported some different plastic polymers acted upon by different bacterial species as revealed in Table 3.

Table 3Typical bacterial microbes capable of degrading some plastics

S/N	Type of polymer	Microbe
1	PET	*Pseudomonas mendocina*
2	PET	*Staphylococcus aureus*
3	PET	*Staphylococcus pyogenes*
4	LDPE	*E. coli*
5	LDPE	*Bacillus weihenstephanensis*
6	PP	*Bacillus aereus*
7	PHAs	*Pseudomonas species*
8	PE	*Pseudomonas alcaligens*
9	PET	*Ideonella sakaiensis*

Source: Ullah et al. (2024).

7.Microbial mechanism of microbial eating of plastics (biodegradation)

Biodegradation is the process whereby decay of plastics or other synthetic material (or chemicals) is elicited (or conducted) by bacteria or fungi or relevant microbe into harmless product such as water, carbon dioxide, methane, etc (de Souza & Gupta, 2024; Sangeetha & Kiruthika, 2025). Plastics are made from crude oils (in some frequent circumstances), a component derived anciently through accumulation of algae and plant materials acted upon by environmental pressure overtime. The products utilized to make fuels or oils are initially made through use of sunlight energy via photosynthesis to make foods (carbon compounds) (Kour et al., 2023). Therefore, the fuels or oils (utilized in making plastics) are a good source of fuels and carbon sources, and energy to the microbes, hence the reason they act upon them and decompose them (Kour et al., 2023). Kour et al. (2023) specifically contemplated that PET is acted upon by PETase, and PVC is acted by catalase-peroxidase, in the extracellular domain of the bacteria to make smaller units. The byproducts of the initial steps of PVC degradation are further acted by laccase, monooxygenases, and other specific enzymes before being taken into the intracellular medium. Within the cell, absorbed or consumed units are further degraded to carbon units that are further turned to alpha-ketoglutarate (for example) or acetyl CoA to enter the TCA cycle. However, the laconic view of the degradation is seen underneath. Verily, some given microbes act upon plastic materials and result in cutting down polymers into smaller units that are potentially harmless. This activity may be represented in form of stages viz:

- Adhesion-Adhesion is the act whereby the microbe stick on the plastic surface and resulting into a thin layer denoted as biofilm (Wagner et al., 2014; Kour et al., 2023).
- Hydrolysis- Hydrolysis is a process whereby special enzymes use water to split plastics into fragments or units.
- Consumption or bioassimilation- In a process known as consumption stage, microbe take-in the smaller units made from hydrolyzing plastics and use the byproducts for food and (or energy) (Kour et al., 2023; De Jesus & Alkendi, 2023).

Microbes involves in plastics degradation

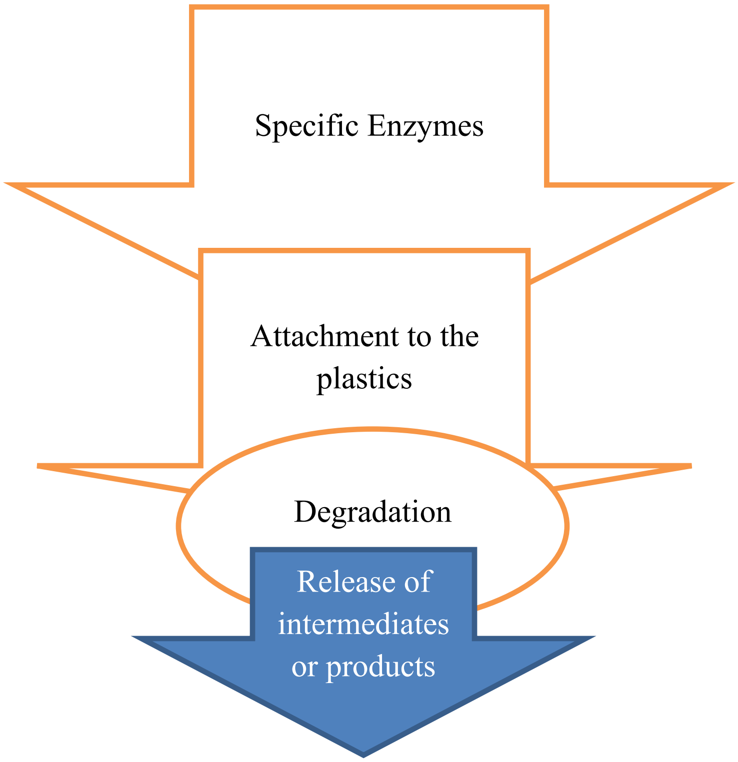

Figure 5: Diagrammatic representation bacterial degradation of plastics

8.Conclusion

The pervasive presence of plastics in our environment poses significant ecological and health challenges, primarily due to their durability and resistance to natural degradation. While plastics offer numerous benefits across industries, their improper disposal has led to the accumulation of microplastics and long-lasting pollution that threatens ecosystems and human well-being. Understanding the various pathways of plastic degradation such as photodegradation, ozone degradation, and microbial biodegradation is crucial for developing sustainable waste management strategies. Microbial bioremediation emerges as a promising solution, leveraging bacteria capable of producing bioplastics and breaking down existing plastic waste through enzymatic processes. Advances in understanding microbial mechanisms such as adhesion, hydrolysis, and bioassimilation highlight the potential of harnessing bacteria like *Bacillus*, *Pseudomonas*, and *Ideonella sakaiensis* to mitigate plastic pollution effectively. However, challenges remain in optimizing these biological processes for large-scale application and ensuring environmental safety. In conclusion, integrating microbial biodegradation into comprehensive waste management frameworks offers a sustainable pathway to reduce plastic pollution. Continued research and innovation are essential to harness the full potential of microbes, develop eco-friendly plastics, and promote responsible usage and disposal practices, ultimately safeguarding our environment for future generations.

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