International Journal of Education, Modern Management, Applied Science & Social Science (IJEMMASSS)
An International Quarterly bi-lingual Multidisciplinary Double Blind Open Access Peer Reviewed Refereed Journal
ISSN :2581-9925, Impact Factor (Cosmos: 7.555 & I2OR: 5.105), Volume 08, No. 02(II), April- June, 2026, pp. 163-170

A Comprehensive Review on Polymer and Plastic Decomposition: Mechanism, Environmental Impact and Sustainable Approaches

Ms. Manisha Yadav[1*] | **Dr. Manisha Sheoran**[2]

[1]Research Scholar, Department of Chemistry, Dr. KN. Modi University Newai, Tonk, Rajasthan, India.
[2]Professor, Department of Chemistry, Dr. KN. Modi University Newai, Tonk, Rajasthan, India.

[*]Corresponding Author: kplyadav007@gmail.com

Citation: Yadav, M. & Sheoran, M. (2026). A Comprehensive Review on Polymer and Plastic Decomposition: Mechanism, Environmental Impact and Sustainable Approaches. International Journal of Education, Modern Management, Applied Science & Social Science, 08(02(II)), 163–170. https://doi.org/10.62823/IJEMMASSS/8.2(II).9098

ABSTRACT

Plastic waste is very harmful burdens on the environment. Chemical recycling do not decrease quality repeated regeneration, but it is requires harsh reaction conditions, this is environmentally unfriendly. Under the mild conditions recycling is possible for enzymatic catalyst, Despite its environmental advantages, enzymatic degradation suffers from drawbacks such as low stability, expensive enzymes production and limited substrate range. Bioinspired catalysis represents an innovative solution by combining enzyme- inspired catalytic activity with the durability of inorganic material. plastic degradation from biomimetic perspectives: the imitation of active centers and substrate-binding clefts. Similarity between biomass and plastics, relevant work is discussion to draw inspiration. The is achieving sustainable plastic recycling remains challenging due to the complexity and diversity of plastic waste. Nature inspired catalysis provides new opportunities by enhancing degradation efficiency under environmentally friendly conditions. Furthermore, chemical depolymerization enables recovery of high – purity monomers from waste plastics, making it a valuable option for recycling materials that cannot be efficiently treated by mechanical recycling processes.

***Keywords**: Enzymatic Catalysis, Plasticdegradation, Polymer, PET, Sustainable, PVC.*

Introduction

Polymer: This is a large molecule ,it is made up combine of small units .

First Synthetic Polymer: Bakelite (1907)

These materials have become an integral part of modern life due to their unique properties are such as light weight, flexibility strength and resistance to corrosion.

The rapid increase plastic manufacturing and the improper disposal of plastic waste have become major environmental concern worldwide. Traditional waste management method such as landfilling incineration are insufficient to handle the growing volume of plastic waste and my create additional environmental problems. Mechanical recycling is commonly used for thermoplastic material; however repeated processing often leads to a decline in the quality and performance of recycle products. As a result chemical recycling has gained significant attention as an alternative strategy for plastic waste management. Chemical recycling involves the breakdown of polymer chains into smaller molecules, monomers, or other valueable chemicals that can be reused for the production of new materials. Different processes including hydrolysis, solvolysis, hydrogenolysis have been successfully applied to convert waste plastic into usefl production such as fuels, lubricants, monomers, alcohol and amines.[2]

The production and consumption of plastics have increased dramatically over the past several Decades. Global plastic production has risen forma relatively small scale in the mid –twentieth century to hundreds of millions of tones annually. Creating serious challenges for waste management and environmental protection. Unfortunately only a limited fraction of plastic waste is effectively recycled while a significant amount is disposal of through incineration landfilling or uncontrolled release in to the environment.

Once released ,plastic materials can be transported over long distances by wind ,rivers, and ocean current ,allowing them to accumulate in diverse ecosystems, including ocean , fresh water bodies, soils, and even remote polar regions. Continuous fragmentation of larger plastic item leads to the formation of microplastics, which have been detected in air, water and terrestrial environments worldwide. These particles pose potential risk to ecological system and living organism.

Commonly used plastic such as Polythylene (PE) ,Polypropylene (PP), Polythyleneterephthalate (PET),Polystyrene (PS), and Polyvinyl chloride (PVC) account for a major share of global plastic consumption. Due to their high molecular weight , chemical stability and resistance to natural degradation processes, these materials can persist in the environment for extremely long period.

Types of Polymers

Polymers can be classified in different ways — based on **origin, composition, structure,** and **mode of polymerization.**

On the Basis of Origin

- **Natural Polymers**

  These polymers occur naturally in plants and animals.

  Examples:

  - **Proteins** – silk, wool, collagen
  - **Polysaccharides** – cellulose, starch
  - **Natural rubber** – obtained from latex

- **Synthetic Polymers:**

  These are man-made polymers prepared by chemical reactions.

  Examples:

  - Polyethylene (PE)
  - Polyvinyl chloride (PVC)
  - Polystyrene (PS)
  - Bakelite, Nylon, Teflon

- **Semi-synthetic Polymers:**

  These are chemically modified natural polymers.

Examples

  - **Cellulose acetate** – used in photographic films
  - **Vulcanized rubber** – modified form of natural rubber

Based on Composition

- **Homopolymers**

  Formed from only one type of monomer unit.

  Examples

  - Polyethylene → from ethene
  - Polystyrene → from styrene

Representation

$A + A + A \rightarrow (A)n$

- **Copolymers**

  Formed from two or more different monomer units.

Examples

- Buna-S → Butadiene + Styrene
- Nylon-6,6 → Adipic acid + Hexamethylenediamine
- PET → Terephthalic acid + Ethylene glycol

Representation

A + B + A + B → (AB)n

Based on Intermolecular Forces

- **Elastomers**

  These polymers can stretch and return to their original shape.

  Examples: Natural rubber, Neoprene, Buna-S
- **Fibres**

  These polymers have strong intermolecular hydrogen bonding and high tensile strength.

  Examples: Nylon-6,6, Terylene, Silk, Cotton
- **Thermoplastics**

  These soften on heating and harden on cooling — reversible process.

  Examples: Polyethylene, PVC, Polystyrene
- **Thermosetting Polymers**

  Once hardened, these cannot be softened again — irreversible process.

  Examples: Bakelite, Urea-formaldehyde resin, Melamine
- **Condensation Polymers**

  Formed by the combination of two different monomers with the elimination of a small molecule (like H_2O, HCl, etc.).

  Examples:

  - Nylon 6,6 (from adipic acid and hexamethylenediamine)
  - Terylene (from terephthalic acid and ethylene glycol)
  - Bakelite (from phenol and formaldehyde)

  Reaction

  Monomer + Monomer → Polymer + H_2O

Decomposition Mechensm

The decomposition of polymers involves the breaking of long-chain macromolecules into smaller fragments through physical, chemical, or biological processes. Biodegradation, on the other hand, is facilitated by microorganisms that secrete enzymes to convert polymers into carbon dioxide, water, and biomass. In thermal degradation, high temperature causes chain scission and the release of volatile compounds. Chemical degradation occurs mainly via hydrolysis, oxidation, or photo degradation, depending on environmental conditions. The overall decomposition rate depends on polymer structure, crystallinity, temperature, moisture, and the presence of catalysts or microbes.

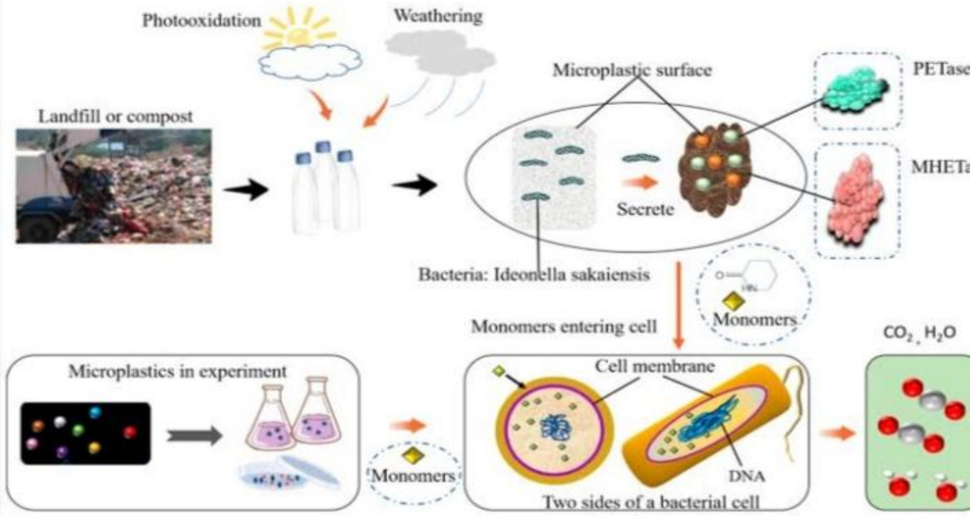
- **Biodegradation and Microbial Decomposition**

Many conventional plastic are highly resistant to biological degradation because their molecular structures contain very few reactive functional group can be easily attacked by microorganisms or enzymes. Their high molecular weight, hydrophobic, nature, strong chemical bonds, and crystalline structure reduce microbial colonization and limit enzymatic activity on the polymer surface.

Before microorganism can effectively utilize plastic materials, the polymer chains often need to undergo preliminary fragmentation through environment factors such as ultraviolet radiation, heat, oxidation, and mechanical stress. These abiotic processes reduce the size of plastic particles and increase their surface area, making them more accessible to microbial action.

PET is one of the most widely studied plastic in biodegradation research. A significant breakthrough was the discovery of the bacterium ideonellasakaiensis, which produces PET degrading enzymes known as PETase and MHETase. These enzymes hydrolyze PET into smaller intermediate compound and monomer that can be transported into microbial cells and further metabolized into carbon dioxide, water, and biomass.

Therefore, improving microbial efficiency, developing engineered enzymes and optimizing environmental conditions are important research directions for enhancing the biological of plastic waste and promoting sustainable waste management.



.This diagram clearly illustrates the biodegradation sequence of PET, beginning with abiotic fragmentation followed by enzymatic hydrolysis by Ideonellasakaiensis. The enzymes PETase and MHETase break PET into monomers, which are transported into microbial cells and metabolized into CO_2 and H_2O. However, due to the high crystallinity, hydrophobicity, and limited functional groups in plastics, the biodegradation rate is extremely slow, supporting the recalcitrant nature described above.

Thermal and Photodegradation

Photocatalytic degradation is an advanced oxidation process in which a catalyst, usually a semiconductor material accelerates chemical reaction when exposed to light energy. During the degradation of microplastics the photocatalyst absorbs light and generates highly reactive species known as reactive oxygen species (ROS). These include hydroxyl radical (OH), Superoxide radical (O_2•) and other oxidizing agents that actively attack polymer chains.

- TiO_2 hv→ H+ VB + e CB
- H + VB + H_2O → •OH + H+
- O_2 + e CB → O_2•
- O_2• + H+ → HOO•
- 2HOO• → O_2 + H_2O_2
- H_2O_2 → 2OH•

The photo catalyst produces hydroxyl radicals (•OH) that react with adsorbed pollutants that are adhered to or in close vicinity to the photo catalyst's surface without showing any preference. The pollutants miner alize as are sult of this reaction. TiO_2 is one of the most widely used photocatalytic performance under ultraviolet and in some cases, visible light irradiation. when TiO_2 absorbs light energy, electrons are excited from the valance band to the conduction band , creating electron hole pairs. The excited electron react with dissolved oxygen molecules to generate super oxide radicals. Eq. (4) illustrate show the produced O2• radical is protonated to create the hydro per oxy radical (HO2•). Eq. (5) there for estates that hydrogen per oxide (H2O2) is produce by there action of the hydro per oxy radical (HO2•).Eq.(6)illustrates how H2O2dissociatestoproduce•OHradicalsasaresult.

The following Eq. (7)–(9)provide an illustration of the general response to plastic degradation in order to aid understanding.

- H + VB+ MPs →oxidize products
- •OH+MPs→CO_2+H_2O
- e +MPs → reduced products

Additionally, MPs are somewhat directly degraded by TiO_2 under visible light. Under visible light irradiation, micro plastic particles can be absorb energy and transition from their ground state to an existed state in this condition, electrons may be transferred from the polymer surface to the condition band of the photo catalyst generating positively charged radical species on the polymer chains .the transferred electrons subsequently react with dissolved oxygen molecules to form superoxide radicals.

These highly reactive species initiate oxidative degradation of polymer chains, resulting in chain scission and the formation of lower molecular weight product. Studies have shown have indirect photo catalytic oxidation mediated by reactive oxygen species is generally more effective then direct photolysis of plastic.

For polymer such as low density LDPE, reactive oxygen species attack vulnerable sites within the polymer structure producing alkyl radical and oxygenated intermediates.

Even in the absence of a photo catalyst, prolonged exposure to sunlight can contribute significantly to plastic degradation. Ultraviolet radiation promotes oxidation hydrogen abstraction and cleavage of chemical bond within polymer chains. These reaction may cause physical change such as surface cracking fragmentation, coloration and flaking.

Laboratory studies have demonstrated that artificial light exposure can induce the formation of oxygen containing functional group and surface fissure on micro plastic. Reactive oxygen species generated during irradiation are believed to play a crucial role in the aging process of plastic material.

Chemically Degradation

- **Hydrolysis**

Hydrolysis is an important chemical degradation pathway for PET in which water molecules cleave the ester bonds present in the polymer chain, producing TPA and EG. IN natural aquatic environments, hydrolysis contributes to the gradual breakdown of PET ;However , the process is generally very slow and may require long period to achieve significant degradation.

  - **Neutral Hydrolysis**

It is typically perform at approximately neutral PH without the addition of chemical catalyst because water is relatively weak nucleophile high temperature and pressure are usually required to promote deploymerization. Research has shown that increasing temperature and optimizing water face can significant improve PET conversion. An important advantage of neutral hydrolysis is the elimination of catalyst related contamination , which simplify product purification and reduce waste.

  - **Acidic Hydrolysis**

IN acidic Hydrolysis, hydrogen ions act as catalyst by activating the ester groups present in PET. Protonation of the carbonyl oxygen increase the susceptibility of the ester bond toward nucleophilic attack by water molecules ultimately leading to polymer chain and monomer formation.

  - **Basic Hydrolysis**

It is employs strong alkaline reagent such as sodium hydroxide to break the ester bond of PET. The reaction initially produces terephthalates salts, which are subsequently converted into terephthalic acid through acidification.

  - **Enzymatic Hydrolysis**

It is emerged as an environmentally friendly alternative to conventional chemical methods. This process utilize specific enzymes to selectively depolymerize PET under relatively mild operating conditions, thereby minimizing energy consumption and reducing the use of hazardous chemicals . Significant interest in this field arose following the discovery of Ideonellasakaieness a bacterium capable of degrading PET through the action of PETase and related enzymes.

- **Oxidative Degradation**

Oxidative degradation is one of the most common chemical degradation pathway for plastic such as polyethylene(PE) and polypropylene(PP). It occurs in the presence of oxygen, often acceleration by heat, UV radiation, or metal catalysts. The process involve free radical formation, peroxide generation and subsequent chain scission reaction.

The degradation mechanism typically includes initiation, propagation, and termination steps, leading to the formation of oxygen containing functional group such as carbonyls, alcohols, and acid.

- **Glycolysis**

This is the most widely studied chemical recycling methods for PET. It involves a transesterification reaction between PET and a glycol, most commonly EG, resulting in the formation of BHET .

A variety of catalytic system have been developed to improve glycolysis efficiency. These catalyst generally promote the reaction by activating both the ester group present in PET and the hydroxyl group groups of theglycol . one of the major challenges association with glycolysis is the limited solubility of PET in ethylene glycol under ambient condition.

To further increase reaction rates and product yield researcher have investigate the use of co-solvent such as DMSO, NMP and other solvents. these addictive improve PET dissolution and facilitate more efficient conversion into monomeric product.

Environmental Impact

Plastic degradation's environmental impact is severe, creating persistent microplastics that harm wildlife through ingestion and entanglement, contaminating ecosystems, and releasing greenhouse gases as they break down, disrupting food chains, soil health, and potentially human health as these tiny particles enter water, air, and food. While plastics don't fully biodegrade quickly, they fragment into microplastics, which become pervasive carriers for toxins, impacting everything from marine birds and terrestrial insects to humans.

- **Microplastic Pollution** Larger plastics break down (often via sunlight/heat) into microplastics (<5mm), entering soil, water, and air, and getting ingested by organisms.
- **Wildlife Harm:** Animals mistake plastics for food or get entangled, causing injury, starvation, or death; ingestion blocks digestive tracts and affects reproduction.
- **Ecosystem Disruption:** Plastic debris smothers habitats like coral reefs, altering natural processes and reducing ecosystem resilience to climate change.
- **Chemical Release:** As plastics degrade, they leach harmful chemicals (additives, adsorbed pollutants) into the environment, making them toxic carriers in ecosystems.
- **Climate Change Contribution:** Plastic production (from fossil fuels) and incineration release significant greenhouse gases (CO_2, dioxins).
- **Food Chain Contamination:** Microplastics and associated toxins accumulate up the food chain, from plankton to humans, with unknown long-term health effects.
- **Soil Degradation:** Accumulation in soil reduces fertility and harms soil organisms like earthworms and microbes, impacting plant growth.

Future Prospects

Polymer decomposition involves physical, chemical (photo, thermo-oxidative, hydrolytic), and biological breakdown, leading to harmful microplastics and toxic substances that contaminate ecosystems, harming wildlife and human health. Sustainable solutions focus on biodegradable alternatives, advanced recycling (chemical/mechanical), enzyme-based biodegradation, and waste management to reduce pollution, while future prospects involve integrated circular economy models and policy.

- **Biodegradable Polymers**: Developing plastics from bio-resources (e.g., PLA, PHA) with controlled degradation.
- **Advanced Recycling:** Chemical recycling to break polymers into monomers for virgin-quality materials.

- **Enzymatic Degradation:** Using specific enzymes (like PETase) for targeted breakdown.
- **Waste Management:** Improved collection, reduction (lifestyle changes), and reuse.
- **Circular Economy:** Designing for reuse, repair, and recycling to minimize waste.
- **Policy & Regulation:** Implementing frameworks to manage plastic production and disposal.

In essence, understanding degradation is key to mitigating pollution, with future success relying on integrated strategies that blend material innovation, better waste management, and circular economic models.

Conclusion

Plastic degradation has emerged as a crucial strategy for addressing the global plastic waste crisis and moving toward a sustainable circular economy. Conventional mechanical recycling, although widely used, is limited by quality loss, contamination issues, and inefficiency in handling mixed plastic waste. Chemical degradation methods offer the advantage of converting polymers back into valuable monomers or chemicals, but their reliance on harsh reaction conditions, high energy input, and toxic reagents raises concerns regarding environmental and economic sustainability.

Enzymatic degradation provides a greener alternative by operating under mild conditions; however, its large-scale application remains constrained due to enzyme instability, slow reaction rates, and high production costs. In this context, biomimetic catalysis has emerged as a promising and innovative approach that bridges the gap between chemical and biological methods. By mimicking enzyme active sites and substrate-binding environments, biomimetic catalysts can achieve high catalytic efficiency while maintaining structural robustness and recyclability.

Overall, no single degradation method alone can provide a complete solution to the plastic waste problem. A synergistic integration of mechanical, chemical, enzymatic, and biomimetic strategies is essential for efficient, scalable, and environmentally responsible plastic recycling. Future research should focus on developing cost-effective, durable, and scalable catalytic systems capable of degrading complex and mixed plastic waste under mild conditions. With continued advancements, plastic degradation technologies have the potential to significantly reduce environmental pollution, conserve resources, and contribute to a truly sustainable materials economy.

Reference

1. Clark, R. A., & Shaver, M. P. (2023). Depolymerization within a circular plastics system. *Chemical Reviews*. Virtual special issue “The Future of Plastics Sustainability”.
2. Wu, Y., Hu, Q., Che, Y., & Niu, Z. (2023). Opportunities and challenges for plastic depolymerization by biomimetic catalysis. *Journal of Catalysis Studies*.
3. Cai, Z., Li, M., Zhu, Z., Wang, X., Huang, Y., Li, T., Gong, H., & Yan, M. (2023). Biological degradation of plastics and microplastics: A recent perspective on associated mechanisms and influencing factors. *Microorganisms, 11*(1661). https://doi.org/10.3390/microorganisms11071661 (doi.org in Bing)
4. Vohlídal, J. (2020). Polymer degradation: A short review. *Polymer Science Review*, 45(2), 101–115.
5. Zhang, X., Liu, Y., Chen, H., & Wang, J. (2024). Degradation of polymer materials in the environment and its impact on the health of experimental animals. *Environmental Toxicology Review*, 58(3), 233–250.
6. Jiang, L., Patel, R., & Singh, A. (2025). A systematic review of plastic recycling. *Waste Management & Research*, 43(1), 12–34.
7. Anonymous. (2024). Status and enhancement techniques of plastic waste degradation in real environments. *Journal of Environmental Studies*, 39(4), 455–472.
8. Dhali, T., Kumar, R., & Sharma, P. (2024). Recent trends in microbial and enzymatic plastic degradation. *Biotechnology Advances*, 62, 108–120.
9. Singh, R. (2005). *Plastic waste and its impact on terrestrial animals*. Journal of Environmental Studies, 12(3), 45–52.

10. Bonhomme, S., Cuer, A., Delort, A. M., Lemaire, J., Sancelme, M., & Scott, G. (2003). Environmental biodegradation of polyethylene. *Polymer Degradation and Stability, 81*(2), 441–452. Bonhomme et al. 2003; Sen and Raut 2015

11. Bryant, J., Morley, N., & Hobson, J. (2016). Toxic chemical accumulation from plastic pollution in marine environments. *Marine Pollution Bulletin, 102*(1), 12–20.

12. Usha, R., Sangeetha, V., & Palaniswamy, M. (2011). Screening of polyethylene degrading microorganisms from garbage soil. *Libyan Agriculture Research Center Journal International, 2*(4), 200–204

13. Sen, S., & Raut, S. (2015). Microbial degradation of plastics: A review. *International Journal of Environmental Research, 9*(3), 231–242.

❑❑❑