# Bio Degradation of Polymers and Metal Pollutants by Different Microorganisms: A Mini Review on Biodegradation: An Eco-Friendly Approach

**Ankita B (Botta Ankita)[1], Pandey AR (Archana R Pandey)[2]**

[1]Reserarch Scholar, Department of Microbiology, Atal Bihari Vajpayee Vishwavidyalaya, Bilaspur, Chhattisgarh, India
ankitadora249[at]gmail.com
[2]Head of Department of Microbiology, D.L.S. P.G. College, Atal Bihari Vajpayee Vishwavidyalaya, Bilaspur Chhattisgarh, India
archupandey02[at]gmail.com

**Abstract:** ***Biodegradation, the microbial breakdown of organic materials, offers an eco-friendly solution to the growing challenge of polymer waste. This mini review explores the role of microorganisms in degrading aromatic hydrocarbons and synthetic polymers, emphasizing biodegradation's cost-effectiveness in tackling xenobiotics. It outlines the process's three key stages—biodeterioration, bio fragmentation, and assimilation—alongside the critical roles of enzymes, microbes, and environmental conditions. The review also highlights methods to assess polymer biodegradability, underscoring the importance of integrating new materials into biogeochemical cycles for sustainable waste management. It also emphasizes different microorganisms along with polymers and heavy metals that is degraded by the respective microbes.***

**Keywords:** Biodegradation, Biodeterioration, Bio fragmentation, Assimilation, Polymer degradation, Xenobiotics

## 1. Introduction

As technology has advanced and the global population has grown, plastics have become increasingly prevalent in a wide range of products, whether for everyday domestic or commercial use. Numerous discarded polymer products pose a serious threat to the environment. Polymer products that contribute to ecological pollution and landfill waste that eventually finds its way into an open and uncontrolled environment, given the sharp rise in demand for these polymers and their supply. It is generally acknowledged that traditional plastics, which are usually derived from fossil fuels, can persist in the marine environment for hundreds of years. Additionally, additives related to plastic products, like phthalate plasticizers, can adsorb onto and leak out of degraded plastic marine debris, leading to a build-up of toxicity in the marine food web. Exposure to phthalate plasticizers during a plastic product's use is known to have detrimental effects on human neurodevelopment and reproductive health before disposal.[1, 2] Two new pollutants that interact with one another in designed and environmental systems are micro plastics and organic micro pollutants. The bioavailability and biodegradation of micro plastics can be altered by the sorption of organic micro pollutants, including industrial chemicals, pesticides, and medications.[3] The process by which microorganisms like bacteria and fungi break down organic matter is known as biodegradation.[4] It is considered a natural process, which sets it apart from composting. Composting is a human-driven process where biodegradation takes place under particular conditions.[5] Chemical design and use must shift to a sustainable approach in light of chemical pollution, which poses a serious threat to our ecology. Early in the design phase, the end-of-life and environmental fate of a chemical must be considered if it is necessary for a specific purpose. Fewer researches have examined the environmental biodegradation of natural compounds, despite the fact that many have examined their activity. [6]The detrimental effects of polyaromatic hydrocarbons (PAHs) on a variety of ecosystems make them a global hazard to both industrialized and developing nations. Frequently utilized in daily life, low molecular weight (LMW) PAHs have the potential to be harmful substances. They require an efficient biodegradation system because they are extremely volatile and frequently absorbed by plants and make their way into the food chain.[7]When compared to thermoplastics, thermosets are exceptional polymeric materials that are typically distinguished by their higher modulus and stress at break, chemical resistance, and thermal stability. There are many uses for thermosets, particularly in the construction of long-lasting items including electrical components, storage boxes, medical equipment, pipelines, and parts of automobile. A lot of work has recently gone into redesigning the chemical structure of thermosets by substituting dynamic covalent linkages, such ester and ammine bonds, among others, for some of the permanent covalent bonds. Under the right circumstances, this can allow for reprocessing.[8]Unlike thermoplastics, which only have secondary contacts between neighboring macromolecule chains, thermostats have superior characteristics mostly due to the presence of covalent cross links between the macromolecule chains, which cause a network to develop. Thermostats, especially those made from bio based resources, have the disadvantage of not meeting the standards of a circular economy because of their low capacity for recycling, which at best results in energy recovery or down cycling. Materials made of polymers are now necessary for our daily existence. Therefore, it is not feasible to completely eliminate them from our way of life, but there are steps that may be taken to slow the rapid accumulation of synthetic polymers. Less than 10% of the 460 million tons of plastic produced year worldwide, according to recent figures, is recycled. The remainder is either burned (19%), dumped in landfills (50%), or left as environmental litter (22%).70% of the plastics that end up in the environment through trash or landfills stay there for hundreds of years after they are thrown away. Both biotic and abiotic processes cause these plastics to break down in the environment, which can result in the creation of microplastics that can be carried by wind and rain far from the original plastic's source. The ability of microplastics to get into the food chain also puts ecosystems, animals, and people at danger. [9] Scientists and businesspeople have long struggled with the biodegradation of polymer materials because of their growing production, which poses a serious risk to the environment at all scales. The creation of bio-reinforced materials is one of the suggested environmentally acceptable solutions that researchers are searching for as a result of this. As a result, the new material needs to be made with the same level of quality as the original and, most importantly, with a slightly eco-friendly appearance. [1]Carbon-neutral polymer life cycle: Creating a carbon-neutral polymer life cycle, in which microbes transform plant matter into chemicals that are then utilized to create biodegradable polymers that eventually aid in the nutritional requirement of new plants, is one possible remedy. The integration of knowledge from organic chemistry, materials science, microbiology, and bioengineering is necessary to realize a circular carbon life cycle, but this has slowed down significant industrial advancements.[9] The purpose of this mini review is to synthesize current knowledge on biodegradation as an eco-friendly strategy for mitigating polymer waste, highlighting its mechanisms, influencing factors, and practical applications in environmental sustainability. This review is significant as it addresses the urgent need for sustainable solutions to plastic pollution, a global environmental crisis, by showcasing biodegradation's potential to reduce landfill waste and toxicity in ecosystems.

Sometimes, the terms biodegradation and composting cause slight confusion to be the synonyms. To clarify that below table and set diagram will definitely beneficial.

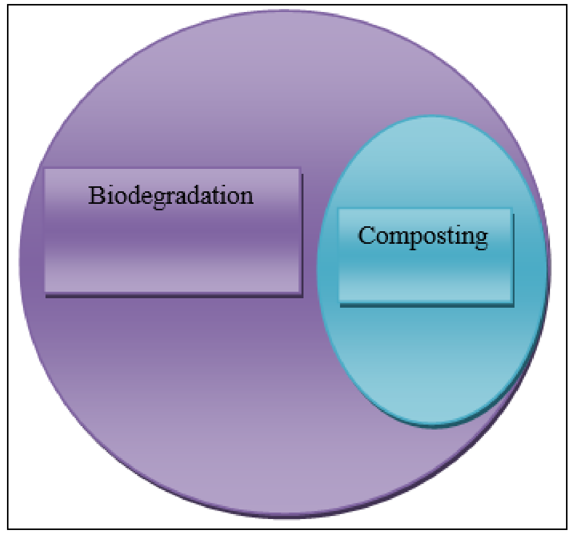
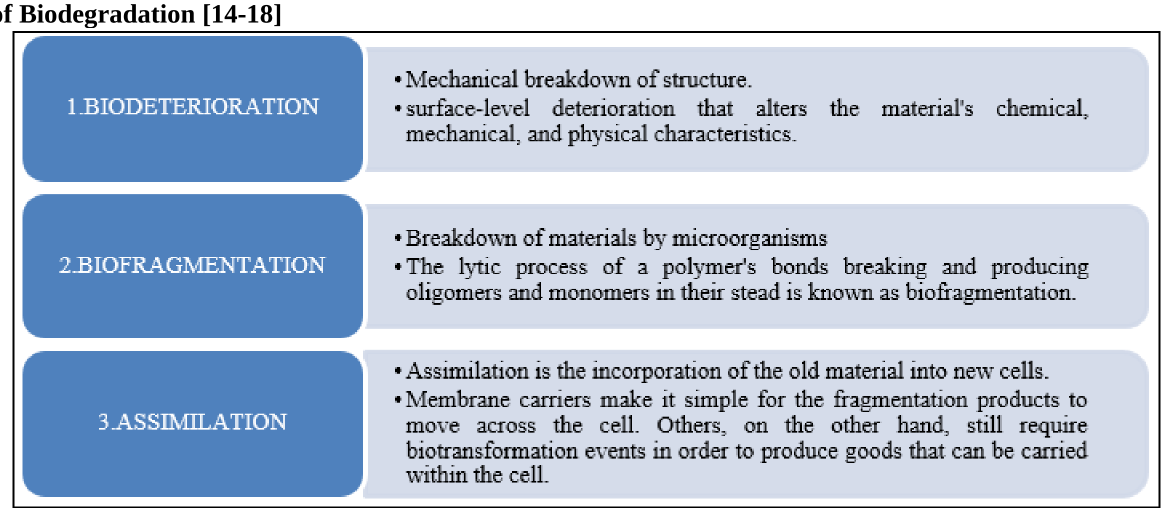



**Table 1:** Showing the difference between the process of Biodegradation and Composting [10-13]

| Biodegradation | Composting |
|---|---|
| Biodegradation is a natural process.<br>By means of metabolic or enzymatic activities, microorganisms such as bacteria and fungus decompose organic materials into smaller molecules.<br>Circumstances for biodegradation are natural.<br>Time period for the process of biodegradation is undefined.<br>End product of the process of biodegradation is carbon dioxide, water, and biomass. | Composting is human driven process.<br>Composting is a type of accelerated biodegradation.<br>Time period for composting is comparatively less than that of biodegradation.<br>End product of composting adds humus to soil. |

**Stages of Biodegradation [14-18]**



[14]

**1) Biodeterioration**

This phase begins when abiotic factors weaken the material's structure in the outside world, permits more degradation by undermining the material's structural integrity. Additional abiotic elements affecting these early alterations include light, temperature, equipment pressure, and environmental pollutants. Even while biodeterioration often happens as an early stage of environmental degradation, biofragmentation can occasionally accompany it. Nevertheless, Hueck defined biodeterioration as an undesirable biological action on the human element, encompassing things like the decay of frontal structures, the microbial rusting of metals, or even aesthetic alterations brought about by man-made buildings.[14-18]

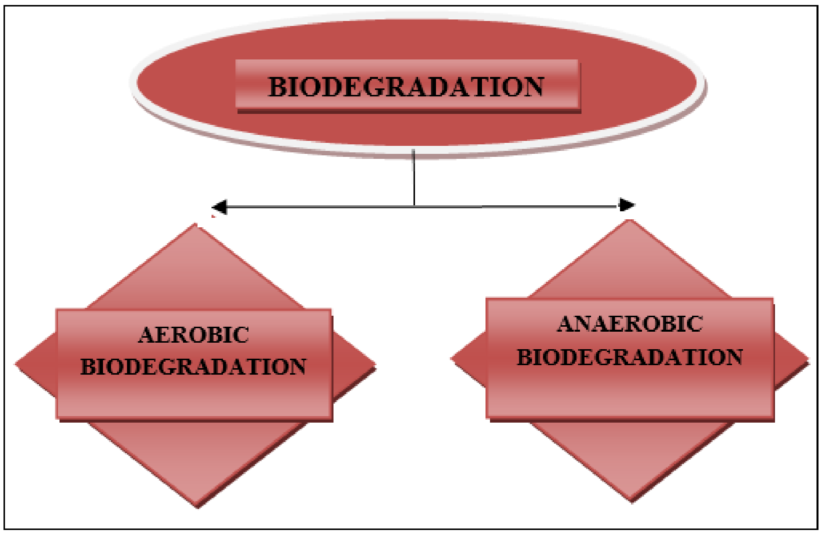
**2) Biofragmentation**

Polymer biofragmentation is a lytic process that creates oligomers and monomers in place of the links that hold a polymer together. The procedures used to separate these resources also change according to whether oxygen is present in the system. Anaerobic digestion involves the breakdown of substances without oxygen, while aerobic digestion involves the separation of microorganisms with oxygen. Both processes produce carbon dioxide, water, and new biomass, with anaerobic digestion also yielding methane. Anaerobic digestion decreases the substance's weight and volume more effectively than aerobic digestion, but aerobic digestion often happens considerably faster. [14-18]

**3) Assimilation**

The results of biofragmentation are then formed into smaller cells during the simulation phase. Membrane carriers make it simple to move some of the separation's products into the cell. To create goods that can be carried within a cell, some still need to undergo biotransformation. The products enter the catabolic pathways within the cell, which can result in the cellular structure or adenosine triphosphate (ATP) being produced.[14-18]

**4) Types of Biodegradation**




1. Aerobic Biodegradation

$$C_{polymer} + O_2 \longrightarrow C_{residue} + C_{biomass} + CO_2 + H_2O$$

2. Anaerobic Biodegradation

$$C_{polymer} \longrightarrow C_{residue} + C_{biomass} + CO_2 + CH_4 + H_2O$$ [14-16, 19, 20]

## 2. Factors Affecting Biodegradation

Environmental elements including soil, water, and nutritional needs affect the biodegradation of materials and the pace at which microorganisms break them down. The chemicals' concentration, type, bioavailability, and physicochemical characteristics all affect how quickly and efficiently they degrade. [17, 18, 21, 22]

### 2.1 Biological factors

Predation by bacteriophages, protozoa, or competition among microbes for the limited carbon sources can both inhibit enzymatic activity. Degradation rate is also influenced by the amount of the contamination in the environment and the quantity of microorganisms that can create the enzymes needed to break it down. Pollutant metabolism by organisms can be accelerated by the contaminant's affinity for certain enzymes. Temperature and moisture have an impact on the pace of metabolism, amounts of soluble materials, and osmotic pressure in both terrestrial and aquatic systems. The ideal pH range for biological enzyme-catalyzed biodegradation processes is around 6.5 to 8.5.[23-27]


Paper ID: SR25316210352 DOI: https://dx.doi.org/10.21275/SR25316210352

### 2.2 Environmental factors

The percentage of metabolic breakdown is lowered when the pollutant is absorbed by the soil matrix, which also lowers the bioavailability to microorganisms. Variations in porosity may be observed in the saturated and unsaturated zones of the aquifer matrix, which can impact the migration and fluid flow of contaminants in groundwater. Water-saturated fine-grained soil slows down the biodegradation process by reducing the transfer of gases including CO2, methane, and oxygen. Pollutants in soil with higher redox potential can be oxidized by microbes, which increase electron transport. This suggests low electron density, which is a sign of aerobic circumstances. The soil has a high electron density under anaerobic circumstances, showing the microbes' capacity for reduction.[23-27]

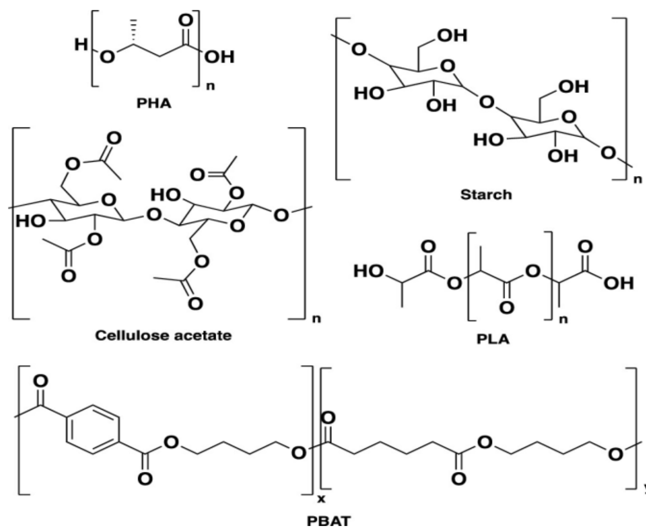
### 2.3 Indicators of Biodegradation

Prior research has employed changes in mass, molecular weight, functional groups, contact angle, mechanical, thermal, or surface characteristics to quantify the biodeterioration of a polymer. Disintegration kinetics validated these findings and demonstrated that the films degraded from the outside in.[28][29]. However, these traits alone don't fully prove polymer biodegradability. The amount of polymer that remains in the test environment can be more accurately measured by measuring the conversion of polymer carbon into carbon dioxide using standardized protocols developed by the Internat ional Organization for Standardization (ISO) and the America n Society for Testing and Materials (ASTM).Additionally, it e nables more consistent comparisons of the biodegradability of polymers across circumstances.[30-34]. The carbon from polymers that is transformed into microbial biomass, however, is not taken into consideration in this analysis.

Thus, the most efficient way to evaluate polymer biodegradability is to utilize isotope-labeled polymers to detect the conversion of the polymer carbon into carbon dioxide and microbial biomass, but this approach is more costly and challenging than the ASTM and ISO approaches.[9],[35],[36],[37] [38]

### 2.4 Examples of Different Polymers and their Degradation

Almost all compounds have been gone through the process of biodegradation. Many of the components (pollutants) has been discussed under table number 02. Few structures have been shown below for structural study. Different polymers are PBAT is petroleum-based, while PLA, cellulose acetate, PHA, and starch are bioplastics. Apart from polymer some natural elements also play toxic role in natural ecosystem.




Typical biodegradable plastic structures. PBAT is petroleum-based, while PLA, cellulose acetate, PHA, and starch are bioplastics. [9, 30, 31, 34]

### 2.5 Different microorganisms involved in the process of biodegradation

Many prokaryotes (algae, fungai and bacteria) separately or mix sludge effective for biodegradation of respective pollutants. The data taken from different study can be useful for different industrial applications.

**Table 2:** Showing different microorganism that is potentially useful for degradation of respective pollutants

| S. No. | Microorganism | Remediated pollutants |
|---|---|---|
| | ALGAE | |
| 01 | *Microcystis aeruginosa, Chlamydomonas reinhardtii and Scenedesmus* almeriensis | Arsenic |
| 02 | *Microcystis aeruginosa, Cyclotella sp., Scenedesmus accuminatus, Scenedesmus protuberans* | Cadmium |
| 03 | *Chlamydomonas reinhardtii* | Cadmium and Chromium |
| 04 | *Fucus vesiculosus* | Cadmium, Chromium, Lead and Nickel |
| 05 | *Ulothrix tenuissima, Ulothrix tenuissima, Spirulina sp.* | Chromium |
| 06 | *Cystoseira aurantia* | Cadmium and Nickel |
| 07 | *Chlorococcum humicola* | Iron |
| 08 | *Spirogyra insignis* | Lead |
| 09 | *Chlorella sp., Spirulina sp* | Lead, Nickel, Dichromate |
| 10 | *Chlorella sp., Isochrysis galbana, Phaeodactylum tricornutum* | Phenol |
| 11 | *Fucus vesiculosus* | Zinc |
| | BACTERIA | |
| 01 | *Mycobacterium sp., Pseudomonas sp., Acinetobacter sp, Ralstonia sp.* | Aromatic hydrocarbons |


Paper ID: SR25316210352 DOI: https://dx.doi.org/10.21275/SR25316210352

| | | |
|---|---|---|
| 02 | *Pseudomonas aeruginosa XJ16, Bacillus cereus XJ20, Acinetobacter lwoffii XJ19, Xanthobacter autotrophicus, Pseudomonas pseudoalcaligenes, Bacillus megaterium, Dietzia sp. and Acinetobacter sp, Bacillus licheniformis, Pseudomonas putida, Paenibacillus glucanolyticus* | Alkane |
| 03 | *Mycobacterium sp., Micrococcus sp., Bacillus sp., Shigella sp.* | Arsenic, Uranium |
| 04 | *Aerococcus sp., Rhodopseudomonas palustris* | Cadmium, Chromium and Lead |
| 05 | *Methyloversatilis sp.* | Cresyl Diphenyl Phosphate |
| 06 | *Pseudomonas sp., Bacillus sp., Escherichia sp., Shewanella sp., Enterobacter sp., Thermus sp.* | Chromium |
| 07 | *Pseudomonas aeruginosa, Aeromonas sp.* | Chromium, Copper, Nickel and Uranium |
| 08 | *Bacillus licheniformis, Pseudomonas putida, Paenibacillus glucanolyticus* | Crude oil |
| 09 | Pseudomonas cepacia, *Bacillus coagulans, Bacillus cereus, Serratia ficaria* | Disel oil |
| 10 | *Bacillus licheniformis* | Dyes |
| 11 | *Escherichia coli* | Hexavalent chromium |
| 12 | *Bacillus sp., Rhodopirellula sp., Rhodovibrio sp.and Formosa sp.* | Hydrocarbon |
| 13 | *Pseudoalteromonas sp., Agarivorans sp.* | Hydrocarbons |
| 14 | *Bacillus subtilis, Pseudomonas fluorescens* | Iron and zinc |
| 15 | *Oscillatoria laetevirens, Arthrospira platensis, Pseudochlorococcum typicum,* | Lead |
| 16 | *Bacillus licheniformis JUG GS2* (*MK106145*) and Bacillus sonorensis | Nephthalene |
| 17 | *Pseudomonas aeruginosa, Corynebacterium propinquum Alcaligenes sp.* | Oils |
| 18 | *Pseudomonas aeruginosa, Corynebacterium propinquum, Alcaligenes* ***Sp., Bacillus subtilis*** | Phenol |
| 19 | *Klebsiella oxytoca, Bacillus firmus, Bacillus macerans, Staphylococcus aureus* | Vat dyes |
| | FUNGI | |
| 01 | *Aspergillus versicolor, Cladosporium sp. , Paecilomyces sp., Aspergillus fumigatus, Paecilomyces sp., Trichoderma sp., Cladosporium sp.* | Cadmium |
| 02 | *Fusarium sp.* | Oils |
| 03 | *Saccharomyces cerevisiae,Cunninghamella elegans* | Heavy metals and mercury |
| 04 | *Phanerochaete chrysosporium* | N-heterocyclic explosives, benzene, xylene, ethylbenzene, tolvene, organochlorines, |
| 05 | *Phanerochaete chrysosporium* | 4,4-dibromodiphenyl ether, |
| 06 | *Saccharomyces cerevisiae, Aspergillus sp.* | Arsenic |
| 07 | *Coprinus comatus* | 4-hydroxy-3,5-dichlorobyphenyl |
| 08 | *Aspergillus sp. and Penicillium sp.* | Aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, chlorophenols |
| 09 | *Aspergillus sp.* | N-hexadecane |
| 10 | *Phomopsis liquidambari* | Phenanthrene |
| 11 | *Ganoderma lucidum* | Pyrene |
| 12 | *Trichoderma sp., Penicillium sp. Aspergillus sp.* | Cobalt and Copper |

[6, 38-47]

## 3. Conclusion

Biodegradation, driven by co-metabolism and catabolic processes, offers a promising eco-friendly approach to polymer waste management. Enhancing microbial activity through directed adaptation could boost bioremediation in polluted environments. This review underscores biodegradation's potential to not only reduce waste but also integrate synthetic materials into sustainable cycles, paving the way for greener industrial practices. Increasing the biotransformation of polymers can be achieved by stimulating the development and activity of degraders at exposure concentrations high enough. Directed microbial adaptation might therefore be a way to enhance polymer bioremediation in polluted settings in the future. In mixed microbial cultures, it can be difficult to attribute an increase in biotransformation to particular degraders or functional enzymes, even when distinct trends in the biotransformation kinetics of polymers are evident.[48] Biodegradation followed by photo degradation is also effective process to deal with polymer degradation.[49]

## References

[1] Oulidi, O., et al., *Enhancing and hindering biodegradation: A comparative study on polyamide 6 reinforced with bio-fillers (peanut shell, olive pomace, and plaster).* Sustainable Chemistry for the Environment, 2024. **7**: p. 100116.

[2] Read, T., et al., *The effect of additives on the biodegradation of polyhydroxyalkanoate (PHA) in marine field trials.* Science of The Total Environment, 2024. **931**: p. 172771.

[3] Poursat, B.A., et al., *Effect of ultra-high-density polyethylene microplastic on the sorption and biodegradation of organic micropollutants.*

Ecotoxicology and Environmental Safety, 2024. **279**: p. 116510.
[4] Young, R., et al., *Improved reference quality genome sequence of the plastic-degrading greater wax moth, Galleria mellonella.* G3: Genes, Genomes, Genetics, 2024: p. jkae070.
[5] Gómez, E.F. and F.C. Michel Jr, *Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation.* Polymer Degradation and Stability, 2013. **98**(12): p. 2583-2591.
[6] Schnarr, L., O. Olsson, and K. Kümmerer, *Biodegradation of flavonoids–Influences of structural features.* Chemosphere, 2024. **359**: p. 142234.
[7] Manaswini, G., et al., *Biodegradation of Low Molecular Weight Polycyclic Aromatic Hydrocarbons in Soil: Insights into Bacterial Activities and Bioremediation Techniques.* Sustainable Chemistry for the Environment, 2024: p. 100146.
[8] Liguori, A., et al., *Bio-based ester-and ester-imine resins for digital light processing 3D printing: The role of the chemical structure on reprocessability and susceptibility to biodegradation under simulated industrial composting conditions.* European Polymer Journal, 2024. **219**: p. 113384.
[9] Mubayi, V., et al., *Toward a Circular Bioeconomy: Designing Microbes and Polymers for Biodegradation.* ACS Synthetic Biology, 2024. **13**(7): p. 1978-1993.
[10] Gioia, C., et al., *End of life of biodegradable plastics: composting versus Re/upcycling.* ChemSusChem, 2021. **14**(19): p. 4167-4175.
[11] Jayasekara, R., et al., *Biodegradation by composting of surface modified starch and PVA blended films.* Journal of Polymers and the Environment, 2003. **11**: p. 49-56.
[12] Ren, X., et al., *The potential impact on the biodegradation of organic pollutants from composting technology for soil remediation.* Waste management, 2018. **72**: p. 138-149.
[13] Song, J.H., et al., *Biodegradable and compostable alternatives to conventional plastics.* Philosophical transactions of the royal society B: Biological sciences, 2009. **364**(1526): p. 2127-2139.
[14] Lucas, N., et al., *Polymer biodegradation: Mechanisms and estimation techniques–A review.* Chemosphere, 2008. **73**(4): p. 429-442.
[15] Elisangela, F., et al., *Biodegradation of textile azo dyes by a facultative Staphylococcus arlettae strain VN-11 using a sequential microaerophilic/aerobic process.* International Biodeterioration & Biodegradation, 2009. **63**(3): p. 280-288.
[16] Ponsá, S., T. Gea, and A. Sánchez, *Different indices to express biodegradability in organic solid wastes.* Journal of environmental quality, 2010. **39**(2): p. 706-712.
[17] Schievano, A., et al., *Two-stage vs single-stage thermophilic anaerobic digestion: comparison of energy production and biodegradation efficiencies.* Environmental science & technology, 2012. **46**(15): p. 8502-8510.
[18] Silva, R.R.A., et al., *Biodegradation of polymers: stages, measurement, standards and prospects.* Macromol, 2023. **3**(2): p. 371-399.
[19] Abbasian, F., et al., *A comprehensive review of aliphatic hydrocarbon biodegradation by bacteria.* Applied biochemistry and biotechnology, 2015. **176**: p. 670-699.
[20] Imron, M.F., et al., *Future challenges in diesel biodegradation by bacteria isolates: a review.* Journal of Cleaner Production, 2020. **251**: p. 119716.
[21] Shimao, M., *Biodegradation of plastics.* Current opinion in biotechnology, 2001. **12**(3): p. 242-247.
[22] Zheng, Y., E.K. Yanful, and A.S. Bassi, *A review of plastic waste biodegradation.* Critical reviews in biotechnology, 2005. **25**(4): p. 243-250.
[23] Bacosa, H.P., et al., *From surface water to the deep sea: a review on factors affecting the biodegradation of spilled oil in marine environment.* Journal of Marine Science and Engineering, 2022. **10**(3): p. 426.
[24] Fannin, T.E., et al., *Use of a fractional factorial design to evaluate interactions of environmental factors affecting biodegradation rates.* Applied and Environmental Microbiology, 1981. **42**(6): p. 936-943.
[25] Fernandes, M., et al., *Factors affecting polyhydroxyalkanoates biodegradation in soil.* Polymer Degradation and Stability, 2020. **182**: p. 109408.
[26] Koh, L.M. and S.M. Khor, *Biodegradation process: basics, factors affecting, and industrial applications*, in *Handbook of biodegradable materials*. 2022, Springer. p. 1-39.
[27] Liu, D., et al., *Factors affecting chemical biodegradation.* Environmental Toxicology: An International Journal, 2000. **15**(5): p. 476-483.
[28] La Fuente Arias, C.I., C. González-Martínez, and A. Chiralt, *Biodegradation Behavior of Poly (3-Hydroxybutyrate-Co-3-Hydroxyvalerate) Containing Phenolic Compounds in Seawater in Laboratory Testing Conditions.* Available at SSRN 4745230.
[29] Arias, C.I.L.F., C. González-Martínez, and A. Chiralt, *Biodegradation behavior of poly (3-hydroxybutyrate-co-3-hydroxyvalerate) containing phenolic compounds in seawater in laboratory testing conditions.* Science of The Total Environment, 2024. **944**: p. 173920.
[30] Kunal, K., et al., *Role of chemical structure in fragility of polymers: a qualitative picture.* Macromolecules, 2008. **41**(19): p. 7232-7238.
[31] Mandelkern, L., *The relation between structure and properties of crystalline polymers.* Polymer Journal, 1985. **17**(1): p. 337-350.
[32] Mottet, A., et al., *Estimating anaerobic biodegradability indicators for waste activated sludge.* Chemical engineering journal, 2010. **160**(2): p. 488-496.
[33] Raymond, J.W., et al., *A review of structure-based biodegradation estimation methods.* Journal of hazardous materials, 2001. **84**(2-3): p. 189-215.
[34] Strobl, G.R. and G.R. Strobl, *The physics of polymers*. Vol. 2. 1997: Springer.
[35] Folino, A., D. Pangallo, and P.S. Calabrò, *Assessing bioplastics biodegradability by standard and research methods: Current trends and open issues.* Journal of

Environmental Chemical Engineering, 2023. **11**(2): p. 109424.

[36] Zumstein, M.T., et al., *Dos and do nots when assessing the biodegradation of plastics*. 2019, ACS Publications.

[37] Ruggero, F., R. Gori, and C. Lubello, *Methodologies to assess biodegradation of bioplastics during aerobic composting and anaerobic digestion: A review*. Waste Management & Research, 2019. **37**(10): p. 959-975.

[38] Sridhar, S., et al., *Removal of microplastic for a sustainable strategy by microbial biodegradation.* Sustainable Chemistry for the Environment, 2024: p. 100088.

[39] Sanjana, M., et al., *Bioremediation–the recent drift towards a sustainable environment.* Environmental Science: Advances, 2024. **3**(8): p. 1097-1110.

[40] Costa, C. and N. Millán, *Differential biodegradation of alkanes in crude oil by three oleophilic strains.* International Biodeterioration & Biodegradation, 2024. **194**: p. 105864.

[41] Jiang, C.-x., et al., *Biodegradation of cresyl diphenyl phosphate in anaerobic activated sludge: Degradation characteristics, microbial community succession, and toxicity assessment.* Water Science and Engineering, 2024.

[42] Xiao, L., et al., *Biodegradation and adsorption of benzo [a] pyrene by fungi-bacterial coculture.* Ecotoxicology and Environmental Safety, 2024. **283**: p. 116811.

[43] Razia, S., T. Hadibarata, and S.Y. Lau, *A review on biodegradation of Bisphenol A (BPA) with bacteria and fungi under laboratory conditions.* International Biodeterioration & Biodegradation, 2024. **195**: p. 105893.

[44] Aziz, Z.S., et al., *Bacterial biodegradation of oil-contaminated soil for pollutant abatement contributing to achieve sustainable development goals: A comprehensive review.* Results in Engineering, 2024: p. 102083.

[45] Gao, Z., et al., *Biochemical insights into the biodegradation mechanism of typical sulfonylureas herbicides and association with active enzymes and physiological response of fungal microbes: A multi-omics approach.* Environment International, 2024. **190**: p. 108906.

[46] Fernandes, M., A.F. Salvador, and A.A. Vicente, *Biodegradation of PHB/PBAT films and isolation of novel PBAT biodegraders from soil microbiomes.* Chemosphere, 2024. **362**: p. 142696.

[47] Salvador, A.F.F. and A. Vicente, *Biodegradation of PHB/PBAT films and isolation of novel PBAT biodegraders from soil microbiomes.* 2024.

[48] Seller-Brison, C., et al., *Adaptation towards catabolic biodegradation of trace organic contaminants in activated sludge.* Water Research, 2024. **266**: p. 122431.

[49] Geng, Y., et al., *Efficient and harmless removal of insecticide diazinon via the stepwise combination of biodegradation and photodegradation.* Ecotoxicology and Environmental Safety, 2024. **281**: p. 116599.