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## Opinion paper

# Biodegradation: A Priority Research Area in Sustainable Development Goals Perspective

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In the present climate change adaptation scenario, it will be important to prioritize the research areas for present and the times ahead. While prioritizing research areas in developing countries in sustainable development goals perspective, focus should be on the issues like health, food security, clean water, renewable energy, air pollution etc. Further, the emphasis should be on strengthening the local research capacity and the locally relevant research initiatives. It is more pertinent in developing countries where the funds and technologies are limited. In India, one of the major challenges in prioritized research will be the management of waste materials. The preference to the use of plastics has generated serious environmental and human health problems.

Microbes have been our companions since ages, both as friends or foes. They have been taking care of the overall ecology through biogeochemical cycling and biodegradation in all the environmental conditions. Their applied value in medicine, agriculture, and industry is well recognized. The challenges in microbiology over the next few decades are tightly intertwined with the pressing global need for sustainable waste management and environmental conservation. One of the most critical areas in this context will undoubtedly be biodegradation. As human societies continue to generate vast amounts of solid wastes, including a wide range of chemically complex and often non-biodegradable materials, soil microbes will play an increasingly vital role in addressing these issues (Abdel-Shafy and Mansour, 2018).

Solid wastes contain diverse components that pose significant challenges to microbial degradation. Plastics, for instance, are among the most persistent pollutants in the environment due to their strong chemical structures and resistance to natural decomposition. Common plastics like polyethylene (PE) and polypropylene (PP) feature simple yet highly durable carbon-carbon backbones, making them particularly difficult for microbes to break down. Polyethylene terephthalate (PET), used extensively in bottles and packaging, has ester bonds that are theoretically biodegradable but require specific enzymes to hydrolyze effectively (Gilani *et al.*, 2023). Even more complex are materials like polyvinyl chloride (PVC), which not only resist degradation but can also release toxic chlorine

*Table 1. Challenges vs. potential solutions in soil biodegradation*

| Major challenges | Description | Potential solution |
|---|---|---|
| Microbial adaptation & variability | Natural genetic changes can impact degradation efficiency. | Use of synthetic biology to enhance microbial degradation potential. |
| Environmental stressors | Temperature, pH, and pollutants affect microbial activity. | Isolation of extremophiles and genetic modifications for resilience. |
| Horizontal gene transfer | Spontaneous genetic exchange may alter biodegradation efficiency. | CRISPR-based control of gene transfer for stability. |
| Biotechnological limitations | Current tools (synthetic biology, CRISPR) have practical constraints. | AI-driven optimization and predictive modeling. |
| Detection & monitoring challenges | Difficulty in tracking microbial populations and degradation efficiency. | Multi-omics approaches (metagenomics, proteomics, metabolomics). |
| Regulatory and policy constraints | Strict environmental policies may limit bioremediation applications. | Development of improved regulatory frameworks and policies. |
| Field application limitations | Lab-based success does not always translate to field performance. | Advanced bioreactor technologies and *in-situ* biostimulation. |

compounds, further complicating microbial intervention. Alongside plastics, synthetic chemicals (all types of persistent organic pollutants) such as pesticides, dyes, and flame retardants also present challenges (Table 1) due to their stable molecular structures, aromatic rings, and halogenated compounds, which are often toxic to soil microbial communities.

The solutions to these challenges lie in leveraging advancements in microbial biotechnology and soil microbiology. Recent discoveries have identified microbial enzymes like PETase, which specifically targets PET, and other hydrolases that can degrade similar polymeric materials. Developing microbial consortia groups of microbes working synergistically to tackle different steps in the breakdown process can enhance degradation efficiency for complex materials (Table 2). Genetic engineering offers another promising avenue, where microbes can be tailored to produce specific enzymes or adapt to degrading otherwise recalcitrant compounds. Such engineered systems could also help overcome limitations in natural soil environments, where factors like nutrient availability, pH, and competing organisms might restrict microbial activity.

Beyond plastics and synthetic compounds, the broader issue of solid waste management

*Table 2. Potential of microorganisms in biodegradation*

| Microorganisms | Degraded compound(s) | Source/Environment | Reference |
|---|---|---|---|
| *Pseudomonas putida* | Aromatic hydrocarbons, BPA | Contaminated soils, wastewater | (Ratheesh and Shibli, 2024) |
| *Bacillus subtilis* | Pesticides, phenols | Agricultural soil, wastewater | Chen *et al.*, 2023 |
| *Rhodococcus erythropolis* | Alkanes, PAHs | Oil-contaminated sites | Liu *et al.*, 2011 |
| *Sphingomonas* sp. | Polychlorinated biphenyls (PCBs) | Polluted sediments, soil | Abraham *et al.*, 2002 |
| *Deinococcus radiodurans* | Heavy metals, radiation-resistant degradation | Extreme environments | Liu *et al.*, 2023 |
| *Mycobacterium* sp. | Petroleum hydrocarbons | Crude oil spills, soil | Aziz *et al.*, 2024 |
| *Acinetobacter* sp. | Pharmaceutical pollutants | Hospital wastewater | Męcik *et al.*, 2024 |
| *Phanerochaete chrysosporium* | Lignin, PAHs, dyes | Decaying wood, soil | Pozdnyakova, 2012 |
| *Novosphingobium* sp. | Pharmaceutical compounds | Contaminated water, soil | Liu *et al.*, 2023 |
| *Comamonas testosterone* | Steroid hormones, BPA | Activated sludge, soil | Li *et al.*, 2024 |
| *Achromobacter xylosoxidans* | Pesticides, heavy metals | Industrial wastewater | Muhammad *et al.*, 2024 |
| *Alcaligenes faecalis* | Naphthalene, phenol | Wastewater, soil | Essam *et al.*, 2010 |
| *Cupriavidus necator* | Polychlorinated compounds | Contaminated groundwater | Wittich and Wolff 2007 |
| *Methylibium petroleiphilum* | Petroleum hydrocarbons | Oil spills, contaminated sites | Nakatsu *et al.*, 2006 |
| *Burkholderia cepacia* | Herbicides, pesticides | Agricultural runoff | Maharana *et al.*, 2025 |

includes organic waste materials like agricultural residues, food waste, and lignocellulosic biomass. These are more biodegradable but still require efficient microbial processing for sustainable recycling into bioenergy or biofertilizers. Harnessing microbial communities capable of breaking down cellulose, hemicellulose, and lignin into usable components will be critical (Fig. 1). Composting and bioreactor technologies already utilize such processes, but optimization for scale, efficiency, and integration with other waste streams remains an active area of research.

Plastic degradation deserves special attention due to the sheer scale of the problem and its implications for both soil health and global ecosystems. While natural degradation rates for plastics in soil are negligible, advances in bioformulations could offer transformative solutions. Bioformulations are engineered blends of microbes, enzymes, and carriers that can be applied to soils or waste dumps to enhance biodegradation processes (Khan *et al.*, 2023). These formulations could be optimized for specific environments or waste types, ensuring targeted action while minimizing unintended ecological impacts. Additionally, promoting biodegradation in natural settings will require a deep understanding of microbial ecology, as the interactions between native and introduced microbes can significantly affect outcomes.

Looking forward, soil microbiology must integrate with other disciplines, such as materials science and environmental engineering, to develop comprehensive strategies for waste degradation. For example, producing biodegradable plastics that are more compatible with microbial enzymes or designing hybrid systems combining mechanical recycling and microbial degradation could accelerate waste management solutions. Furthermore, research into naturally occurring plastic-degrading microbes, particularly in extreme environments such as landfills or deep-ocean sediments, could uncover novel mechanisms and enzymes with broad applicability.

Climate change and soil degradation further complicate the role of microbes in

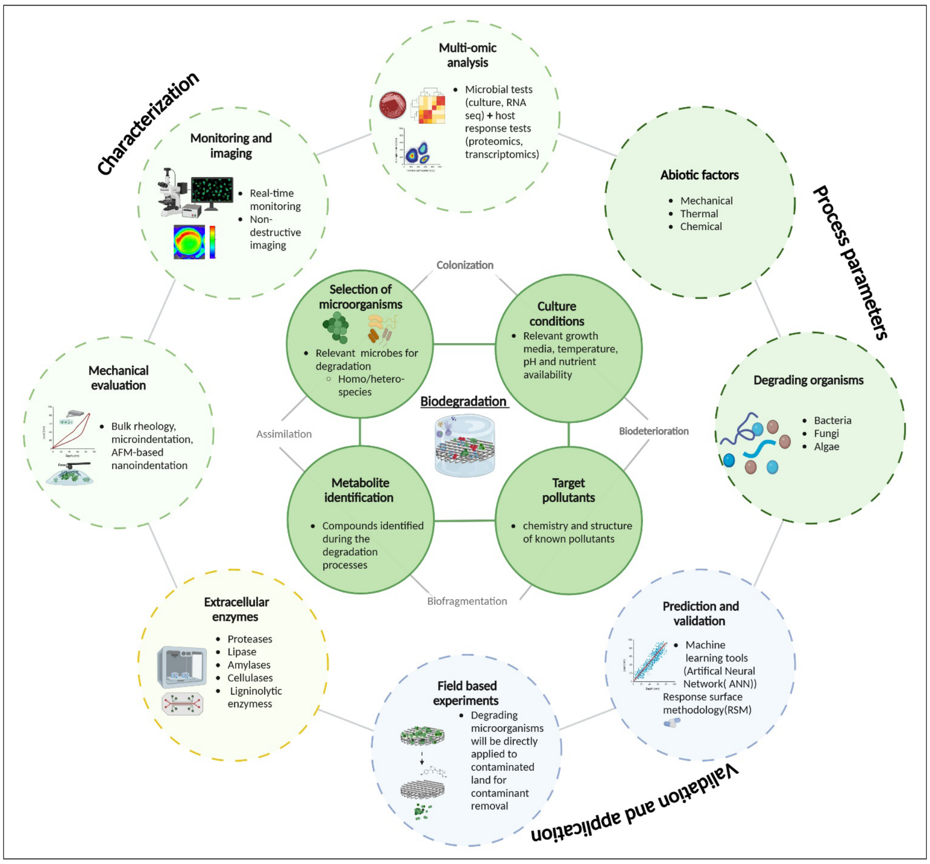


*Fig. 1. Processes involved in biodegradation.*

biodegradation. As soil environments become increasingly stressed by rising temperatures, altered moisture levels, and pollution, microbial activity may decline or shift, potentially reducing the efficiency of natural biodegradation processes. Adaptive strategies, such as engineering resilient microbial strains or protecting soil health through better land management practices, will be essential to maintain biodegradation capacity under changing conditions.

The path forward in addressing these challenges is multifaceted. Biodegradation research must not only focus on identifying efficient microbial solutions but also ensure their scalability, safety, and environmental compatibility. Bioformulations, microbial consortia, and enzyme engineering hold immense promise, but their success will depend on sustained investment in research, interdisciplinary collaboration, and global policies supporting sustainable waste management practices. By rising to these challenges, soil microbiology can play a pivotal role in restoring balance to Earth's ecosystems while addressing one of humanity's most pressing environmental crises.

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