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MICROBIAL AND ENZYMATIC PLASTIC BIODEGRADATION: AN INTEGRATIVE REVIEW OF STUDIES FROM THE UNITED STATES, CHINA, AND BRAZIL

BIODEGRADAÇÃO MICROBIANA E ENZIMÁTICA DE PLÁSTICOS: UMA REVISÃO INTEGRATIVA DE ESTUDOS DOS ESTADOS UNIDOS, DA CHINA E DO BRASIL

BIODEGRADACIÓN MICROBIANA Y ENZIMÁTICA DE PLÁSTICOS: UNA REVISIÓN INTEGRATIVA DE ESTUDIOS DE ESTADOS UNIDOS, CHINA Y BRASIL

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ABSTRACT

The widespread use of plastics, combined with low recycling rates, has intensified concerns about the accumulation of plastic waste in the environment. This integrative review aimed to examine evidence on the microbial and enzymatic biodegradation of plastics in studies published between 2015 and 2023, focusing on the United States, China, and Brazil. Articles were searched in Scopus and Web of Science, and patents were searched in the Brazilian National Institute of Industrial Property (INPI) database. After the selection criteria were applied, 45 articles and four patents were included. The studies mainly addressed the action of bacteria, fungi, and their enzymes on polymers such as polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS). The findings indicate potential for the biodegradation of these materials, but results vary according to the polymer, microorganism, experimental conditions, and indicators used to assess degradation. The evidence comes predominantly from laboratory studies conducted under controlled conditions and does not support general claims of complete mineralization or effectiveness at a large scale. Microbial and enzymatic biodegradation is a promising research area, although its application to plastic waste management still requires more consistent assessment methods and studies under conditions closer to real-world use.

KEYWORDS: *Polymers. Biodegradation. Sustainability. Microorganisms. Plastic Recycling.*

RESUMO

O uso amplo de plásticos, associado às baixas taxas de reciclagem, tem intensificado a preocupação com o acúmulo desses resíduos no ambiente. Esta revisão integrativa teve como objetivo analisar as evidências sobre a biodegradação microbiana e enzimática de plásticos em estudos publicados entre 2015 e 2023, com recorte para Estados Unidos, China e Brasil. A busca de artigos foi realizada nas bases Scopus e Web of Science, e a busca de patentes, no Instituto Nacional da Propriedade Industrial (INPI). Após a aplicação dos critérios de seleção, foram incluídos 45 artigos e quatro patentes. Os estudos abordaram principalmente a ação de bactérias, fungos e suas enzimas sobre polímeros como o tereftalato de polietileno (PET), o polietileno (PE) e o poliestireno (PS). Os resultados indicam potencial para a biodegradação desses materiais, mas variam conforme o polímero, o microrganismo, as condições experimentais e os indicadores utilizados para avaliar a degradação.

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As evidências provêm predominantemente de estudos laboratoriais conduzidos sob condições controladas e não permitem generalizar a ocorrência de mineralização completa ou a eficácia dos processos em larga escala. Conclui-se que a biodegradação microbiana e enzimática é uma linha promissora de pesquisa, embora sua aplicação ao gerenciamento de resíduos plásticos ainda dependa de métodos de avaliação mais consistentes e de estudos em condições próximas às de uso real.

PALAVRAS-CHAVE: Polímeros. Biodegradação. Sustentabilidade. Microrganismos. Reciclagem de plásticos.

RESUMEN

El uso generalizado de plásticos, junto con las bajas tasas de reciclaje, ha intensificado la preocupación por la acumulación de estos residuos en el medio ambiente. Esta revisión integrativa tuvo como objetivo analizar las evidencias sobre la biodegradación microbiana y enzimática de plásticos en estudios publicados entre 2015 y 2023, con un enfoque en Estados Unidos, China y Brasil. La búsqueda de artículos se realizó en Scopus y Web of Science, y la de patentes, en la base de datos del Instituto Nacional de la Propiedad Industrial de Brasil (INPI). Tras aplicar los criterios de selección, se incluyeron 45 artículos y cuatro patentes. Los estudios abordaron principalmente la acción de bacterias, hongos y sus enzimas sobre polímeros como el tereftalato de polietileno (PET), el polietileno (PE) y el poliestireno (PS). Los resultados indican un potencial para la biodegradación de estos materiales, pero varían según el polímero, el microorganismo, las condiciones experimentales y los indicadores utilizados para evaluar la degradación. Las evidencias proceden predominantemente de estudios de laboratorio realizados en condiciones controladas y no permiten generalizar la ocurrencia de una mineralización completa ni la eficacia de los procesos a gran escala. La biodegradación microbiana y enzimática constituye una línea de investigación prometedora, aunque su aplicación a la gestión de residuos plásticos todavía requiere métodos de evaluación más consistentes y estudios en condiciones más próximas a las de uso real.

***PALABRAS CLAVE**: Polímeros. Biodegradación. Sostenibilidad. Microorganismos. Reciclaje de plásticos.*

INTRODUCTION

Plastics are widely recognized as essential materials in contemporary society because of their broad applicability in areas such as consumer products, packaging systems (Tuo et al., 2026), construction (Gupta et al., 2024), and biomedical applications (Ornaghi et al., 2023). Consequently, global plastic production reached approximately 489.14 million tons in 2023, while plastic waste generation totaled about 389.33 million tons in the same year (Guha et al., 2025), highlighting the magnitude of plastic consumption and its associated environmental burden. Recent research has explored several strategies, including recycling (Chen & Hu, 2024), reuse and valorization of plastic residues in construction materials (Knopik et al., 2025), and biodegradation of plastics (Lv et al., 2024), as promising approaches to reduce their adverse environmental impacts. However, recycling strategies alone are not sufficient to effectively

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address the growing environmental challenges associated with plastic pollution (Shukla et al., 2025). Therefore, the limitations of recycling approaches highlight the urgent need for alternative and complementary strategies capable of improving plastic waste management and reducing its long-term environmental impacts.

Biodegradation mediated by microorganisms such as bacteria, fungi, and algae has emerged as a promising approach for reducing the persistence of synthetic plastics in the environment (Faszczewska et al., 2026). In addition, enzymes act in the depolymerization of polymers, promoting the formation of monomers (Suresh et al., 2025). Furthermore, adequate pretreatment methods can modify the characteristics of polymers, thereby enhancing their susceptibility to enzymatic and microbial degradation (Ciuffi et al., 2024). However, important constraints affecting microbial microplastic biodegradation include incomplete mineralization, the formation of toxic intermediate products, and slow degradation kinetics (Yadav et al., 2025). Thus, progress in understanding and applying plastic biodegradation may represent a key strategy for addressing the plastic waste crisis and promoting more sustainable practices.

In this context, reviews are essential to consolidate current knowledge, identify emerging trends, and highlight knowledge gaps. This integrative review examines advances in microbial and enzymatic plastic biodegradation reported between 2015 and 2023, with a particular focus on biological mechanisms, technological innovations, and patented applications. By critically assessing the progress and challenges in the field, this study provides insights into the potential of biotechnological solutions to mitigate plastic pollution and support the transition toward a circular economy.

1. MATERIALS AND METHODS

1.1. Study design

This study was designed as a mixed-method integrative review, following the qualitative–quantitative approach described by Sandelowski (2000), which combines the collection and analysis of both qualitative and quantitative data. This design allowed the construction of numerical and classificatory data to support the quantitative synthesis, and descriptive interpretations to strengthen the qualitative discussion.

1.2. Literature search

The literature search was conducted in the Scopus and Web of Science databases, accessed through the CAPES Periodicals Portal, covering publications from January 2015 to

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December 2023. According to the original search records, the terms “degradation”, “plastic”, and “microbial” were combined using the Boolean operator AND. The initial search retrieved 2,255 records from Scopus and 1,959 records from Web of Science. After applying the publication-period restriction (2015–2023), the number of records was reduced to 1,412 in Scopus and 1,278 in Web of Science. The results were subsequently restricted to articles, resulting in 900 records from Scopus and 947 from Web of Science. A geographical filter including China, the United States, and Brazil was then applied, resulting in 403 records from Scopus and 427 from Web of Science, for a total of 830 records before duplicate removal. After identification and removal of 80 duplicate records, 750 unique articles remained for screening.

The geographical restriction reflected the scope originally adopted for the study and, therefore, the results should be interpreted as a comparative synthesis of research retrieved for these three countries rather than as a comprehensive global assessment of plastic biodegradation research. References published after 2023 were used exclusively to provide updated background information in the Introduction and were not included in the review corpus.

Because the original search was performed using the three terms documented above, enzyme-specific descriptors were not independently included in the search strategy. Therefore, studies addressing enzymatic degradation were identified within the records retrieved by the original search rather than through a dedicated enzymatic search string. This represents a methodological limitation, as studies indexed exclusively under terms such as enzyme, enzymatic, PETase, MHETase, cutinase, esterase, laccase, biodegradation, or depolymerization may not have been retrieved.

1.3. Inclusion and exclusion criteria

The screening process considered studies addressing microbial or enzymatic degradation of synthetic polymers and their relationship with sustainability or environmental implications. Studies written in English, Portuguese, or Spanish and included within the geographical scope of China, the United States, and Brazil were considered. Duplicate records and studies that did not specifically address the subject of the review or did not discuss sustainability were excluded. Literature reviews were also excluded from the final analytical corpus.

After screening, 143 articles were selected for full-text assessment, comprising 80 records retrieved from Scopus and 63 from Web of Science. Following full-text assessment and application of the eligibility criteria, 45 articles were included in the final analysis, of which 27 were retrieved from Scopus and 18 from Web of Science.

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1.4. Patent search

In addition to the scientific literature, a patent search was conducted using the database of the Brazilian National Institute of Industrial Property (INPI) to identify technological developments related to plastic degradation. The documented search used the combinations “Degradação AND Plástico” and “Degradation AND Plastic”, considering the period from 2015 to 2023. The search retrieved 41 patent records. After screening, 37 patents were excluded because they did not specifically address the scope of the review, and four patents were retained for detailed analysis.

1.5. Data screening and analysis

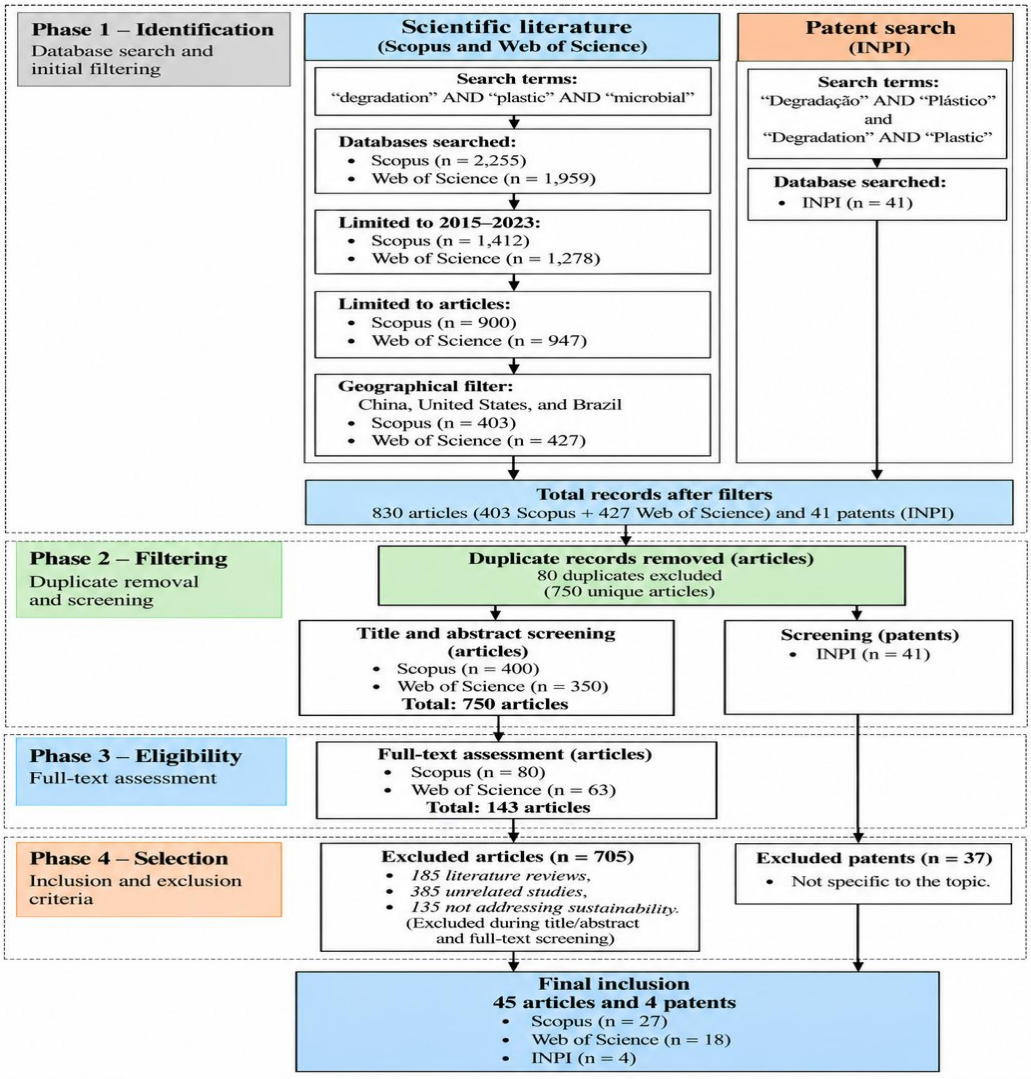
The selected studies were analyzed qualitatively by full-text reading, with attention to the type of polymer investigated, the microbial or enzymatic agents involved, the experimental conditions, and the main results. The analysis also considered the geopolitical context of the countries where the studies were conducted. For each article, information such as title, year of publication, type of microorganism or enzyme used, polymer studied, country of research, and main outcomes was extracted and organized. For patents, the data collected included the title, year, microbial or enzymatic component employed, and the main technological contributions.

1.6. Flowchart

The entire selection process of articles and patents followed rigorous inclusion and exclusion criteria to ensure the scientific quality and relevance of the data. This process is summarized in Figure 1, which illustrates the stages of identification, screening, eligibility, and inclusion that guided the methodological framework of this study.

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Figure 1. Flow diagram of the study selection process, showing identification, filtering, and final inclusion of articles and patents (2015–2023)



2. RESULTS AND DISCUSSION

2.1. Publication Trends and Geographical Distribution (2015–2023)

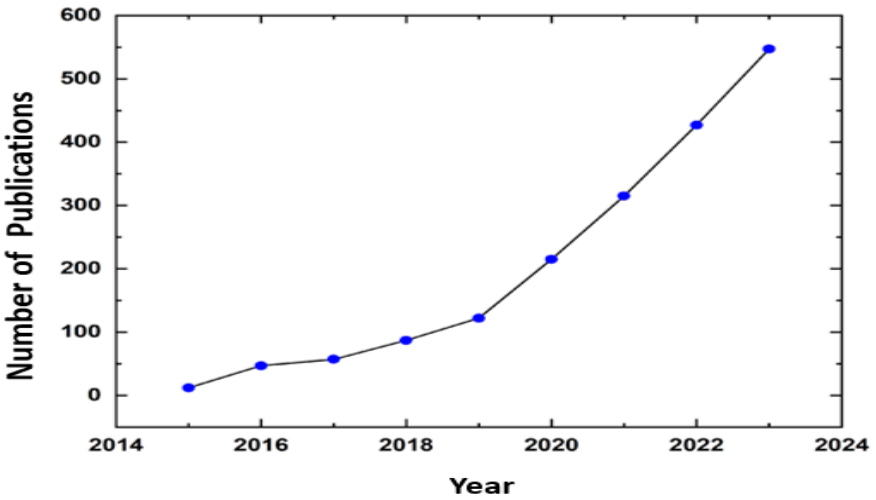
Analysis of publication trends (Figure 2) revealed a substantial growth in the number of studies addressing plastic biodegradation between 2015 and 2023. This increasing body of literature may reflect the growing global concern with plastic waste management and the search

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for sustainable alternatives to conventional disposal strategies. The environmental relevance of this issue is reinforced by the limitations of traditional disposal methods such as landfilling, recycling, and incineration, which are associated with restricted landfill availability, air pollution emissions, and the limited adoption of recycling worldwide (Luyt & Malik, 2019). In this context, increasing attention has been directed toward the development of environmentally friendly strategies for plastic degradation, particularly those based on biological and enzymatic processes.

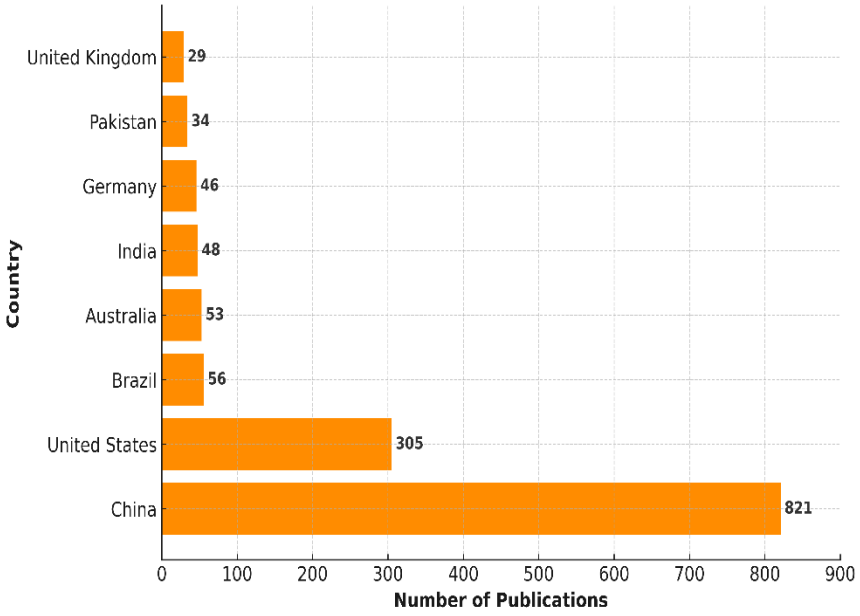
China and the United States dominate the field (Figure 3), with China surpassing the US by approximately 169%. China's prominence in the publication data can be considered alongside its substantial role in the global plastics sector. Jiang et al. (2020) describe China as the world's largest producer and consumer of plastics, accounting for nearly one-third of the global plastic flow. Chen et al. (2019) also report that China leads global plastic production, consumption, and waste recycling. These findings indicate that the country not only leads research on plastic biodegradation but also plays a proactive role in waste recycling and management, reinforcing its position as a key player in environmental sustainability practices.

Figure 2. Publications on biological degradation of plastics identified in Scopus and Web of Science databases between 2015 and 2023



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Figure 3. Leading countries publishing on the topic “Degradation and Plastic and Microbial” in Scopus and Web of Science databases between 2015 and 2023 (Phase 1 of the analysis)



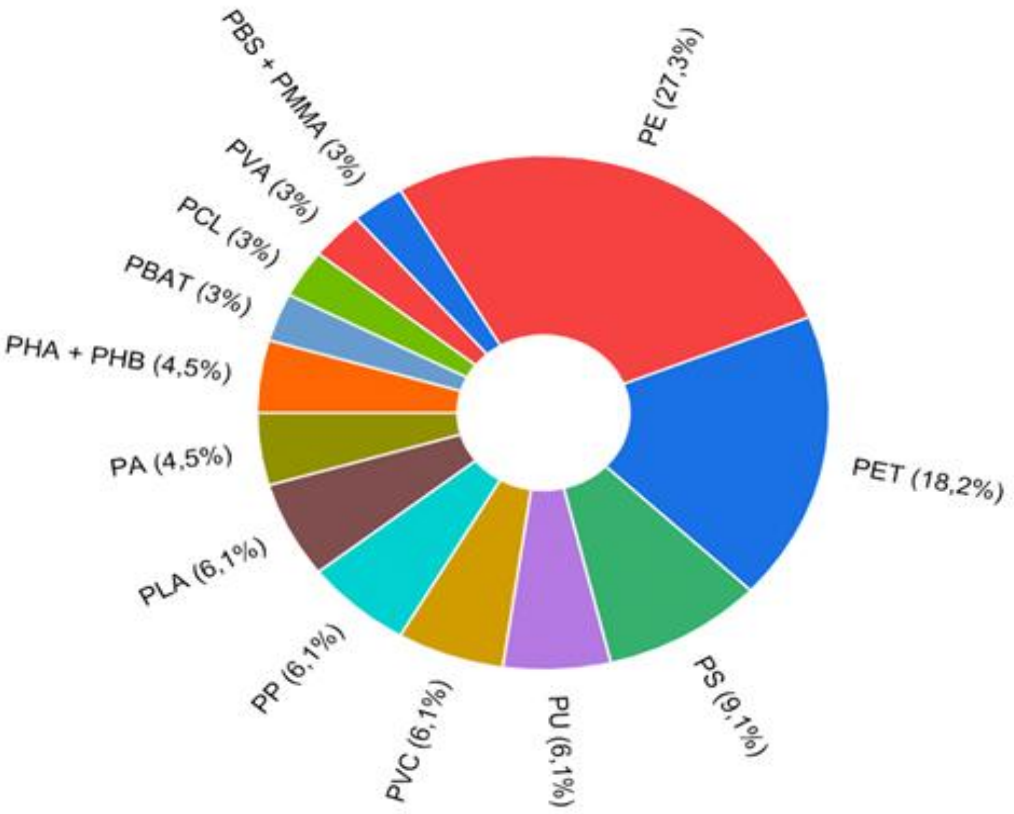
The United States ranked second in research on plastic degradation, following China. Together, these countries account for most of the scientific contributions in the field, highlighting their pivotal role in advancing technologies for sustainable plastic management. Although Brazil produces fewer studies than leading countries such as China and the United States, it remains an important country for research due to its ecological and socioeconomic characteristics, including its high biodiversity, significant plastic waste generation, and the need for sustainable waste management solutions, particularly within the Latin American context.

2.2. Most Investigated Polymers

Among the polymers studied, polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS) are predominant (Figure 4). These materials are widely used, highly resistant to biodegradation, and constitute a significant portion of plastic waste accumulation. Research has therefore focused on developing microbial and enzymatic approaches to accelerate their degradation.

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Figure 4. Distribution of the most investigated plastics in the final selection of studies addressing biological degradation (Distribution of plastic types investigated in the 45 articles included in the final review)



Zhao et al. (2023) used microorganisms such as *Marinobacter*, *Thalassospira*, *Nocardioides*, and *Alcanivorax*, isolated from deep-sea sediments. In tests with four selected strains, the authors observed PET weight loss ranging from 1.3% to 1.8% after 30 days of incubation, accompanied by the formation of polymer degradation products, confirming the occurrence of depolymerization. Additionally, Shingwekar et al. (2023) used orange peel ash to catalyze PET depolymerization into BHET, which was subsequently degraded by a bacterial consortium, resulting in an overall degradation efficiency of 33% after 10 weeks. These findings suggest that bacterial strains and microbial consortia have potential for PET degradation, including in approaches that combine biological and chemical treatments. Together, these studies illustrate distinct approaches to PET transformation. Because the experimental procedures and

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reported outcome measures differ, the percentages should not be interpreted as directly comparable measures of PET biodegradation.

Regarding polyethylene (PE), Devi et al. (2023) demonstrated that the indigenous bacterial strain *Alcaligenes faecalis* ISJ128 exhibits degradation capacity toward low-density polyethylene (LDPE). In the same context, Tao et al. (2023) reported that *Rhodococcus sp*. promoted approximately 1% PE weight loss after 30 days of incubation. Similarly, Ruan et al. (2023) demonstrated that the fungus *Trichoderma harzianum* is capable of promoting polyethylene (PE) degradation, likely due to the activity of laccase produced by this fungus. These findings indicate that both bacterial and fungal microorganisms contribute to polyethylene biodegradation, although the process remains limited and may involve enzymatic activity.

In the case of polystyrene (PS), Peng et al. (2019) evaluated the degradation capacity of larvae of two species, *Tenebrio obscurus* and *Tenebrio molitor*. The results showed that *Tenebrio obscurus* exhibited a higher PS degradation capacity than *Tenebrio molitor.* Additionally, Wang et al. (2020) demonstrated that an *Acinetobacter* strain isolated from the gut of *Tribolium castaneum* shows the potential to degrade polystyrene (PS).

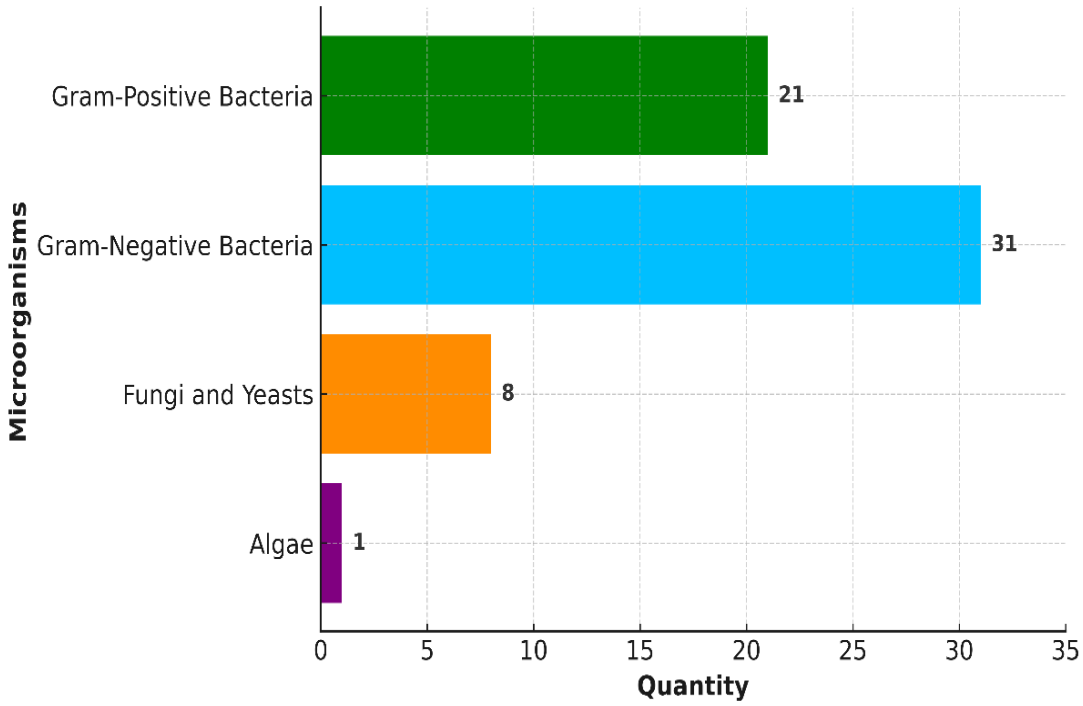
Overall, the studies report different forms of evidence for the transformation of PET, PE, and PS, including polymer weight loss, detection of degradation products, and changes associated with microbial or enzymatic activity. These findings should be interpreted according to the methods and experimental conditions of each study, rather than as directly comparable measures of biodegradation. Further research is needed to establish the extent of polymer degradation and assess its potential beyond controlled laboratory conditions.

2.3. Microorganisms and Mechanisms of Biodegradation

Microorganisms are central to plastic biodegradation, with bacteria being the most frequently studied group, followed by fungi, yeasts, and algae (Figure 5). A previous study (Roberts et al., 2020) used a bacterial consortium composed of *Pseudomonas* and *Bacillus* species and observed synergistic growth in the presence of PET, along with evidence of partial degradation of the polymer.

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Figure 5. Distribution of microorganisms identified in the final selection of studies addressing biological plastic degradation



Fungal species such as *Coniochaeta hoffmannii* and *Pleurostoma richardsiae* have demonstrated activity on polypropylene (PP), with evidence of structural modifications in the polymer (Porter et al., 2023), while the microalga *Chlorella vulgaris* demonstrated potential in PET degradation when combined with pretreatments (Falah et al., 2020). Additionally, Ali et al. (2023) demonstrated that bacteria associated with the gut microbiota of wax moth larvae (*Achroia grisella*) have the ability to promote polyethylene degradation. Collectively, these results demonstrate the expanding potential of biological systems as sustainable alternatives for the degradation of persistent plastic polymers in the environment.

From a mechanistic perspective, according to Pathak and Navneet (2017), the biodegradation of polymers by microorganisms involves changes in the chemical and physical properties of the material, followed by the breakdown of polymer chains, the uptake of the resulting molecules, and the production of byproducts such as CO_2, CH_4, and H_2O. Taken together, these findings highlight the complexity of microbially mediated plastic biodegradation

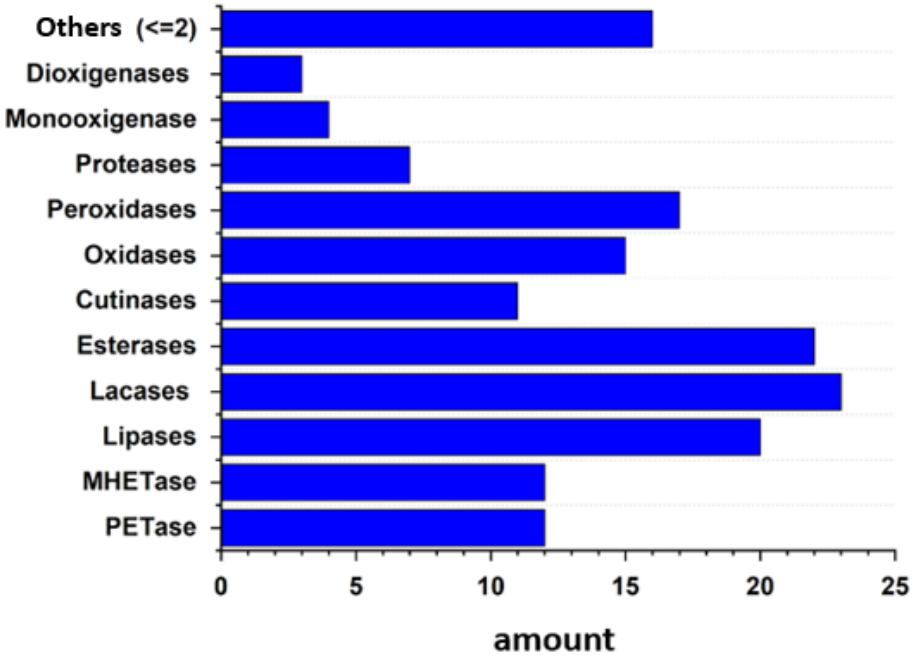
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and reinforce the importance of identifying specific metabolic pathways and enzymes involved in polymer depolymerization to better assess their environmental and technological potential.

2.4. Enzymes Involved in Plastic Degradation

The enzymatic repertoire involved in plastic biodegradation is diverse, including laccases, esterases, lipases, peroxidases, oxidases, PETases, and MHETases (Figure 6). PETases, in particular, have attracted significant attention since the discovery of *Ideonella sakaiensis*, with subsequent studies identifying putative PETase-like enzymes from environmental metagenomes (Karunatillaka et al., 2022).

Figure 6. Distribution of enzyme types identified in the final selection of studies addressing biological plastic degradation



These enzymes act to break down complex polymers into smaller oligomers and monomers, which can then be metabolized by microorganisms. However, challenges remain in optimizing enzyme activity under environmental conditions and scaling up production for industrial applications. Advances in protein engineering and synthetic biology are expected to play a pivotal role in overcoming these barriers.

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2.5. Patents and Technological Perspectives

Table 1 presents the patents related to plastic biodegradation identified in the database of the Brazilian National Institute of Industrial Property (INPI). The records were selected using the same inclusion and exclusion criteria previously applied to the scientific literature. The search methodology may partly explain the marked difference between the number of patents and the number of scientific articles retrieved from the Scopus and Web of Science databases. Another possible explanation is that the INPI database covers patent applications filed for protection in Brazil, whereas Scopus and Web of Science index scientific publications from around the world.

Table 1. Patent applications related to plastic biodegradation identified through the Brazilian National Institute of Industrial Property (INPI) database (2016–2021)

Patent	Applicants	Polymer	Microorganisms/Enzymes	Country/Organization	Reference	Main Outcomes
Plastic degradation solution	Buonamici, Guglielmo	PE, PP, PVC, PET, PS	Flavobacterium, Enterobacter asburiae, Ideonella sakaiensis, Sphingomonas, Bacillus subtilis; fungi: Fusarium oxysporum, Purpureocillium lilacinum, Pestalotiopsis microspora, Trichoderma harzianum, Alcaligenes eutrophus	Italy	Buonamici (2021)	The invention proposes a plastic-degrading solution containing selected bacterial and fungal extracts to promote plastic degradation.
Improved plastic-degrading proteases	Alain Marty; Sophie Duquesne; Marie Guicherd; Marlène Vuillemin; Maher Ben Khaled	PLA	Protease enzyme	European Patent Organization	Marty et al. (2020)	The invention proposes the development of protease variants that exhibit superior performance in PLA degradation compared with the original enzyme.
Masterbatch composition comprising a high concentration of biological entities	Michel Chateau; Jean-Philippe Rousselle	PBAT, PLA, PCL, PE, PET	Actinomadura keratinilytica, Laceyella sacchari	European Patent Organization	Chateau & Rousselle (2022)	Development of a composition containing high concentrations of biological entities to produce plastic articles with improved biodegradability.
Liquid composition comprising biological entities and uses thereof	Guémard; Dalibey	PLA, PCL, PBAT, PHA, PBS, PET, PBT, PEF, PEA, PEN, PE, PP, PMP, PA6, PA66, PA11, PA12, PVC, PS, EVA, PVOH	Various bacteria, fungi, and yeasts	European Patent Organization	Guémard and Dalibey (2023)	The invention proposes a liquid composition containing biological entities to increase the biodegradability of plastic articles.

Notable innovations include the combination of bacteria and fungi for plastic degradation (Buonamici, 2021). Additionally, Marty et al. (2020) present in their patent an innovation in the use of proteases to degrade polymers. Furthermore, enzyme-enriched masterbatch compositions have been proposed for producing more degradable plastics (Chateau & Rousselle, 2022). Patents related to plastic biodegradation represent an important contribution to the advancement

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of sustainable development, particularly in countries such as Brazil, where plastic waste management still presents considerable challenges. The innovations reported in the patents of Buonamici (2021), Chateau and Rousselle (2022), Guémard and Dalibey (2023), and Marty et al. (2020) demonstrate continuous progress toward the development of more efficient and economically viable strategies for polymer degradation. These approaches include the application of microbial consortia, the use of specific enzymes, and modifications designed to enhance both the mechanical performance and the degradability of polymeric materials. Collectively, these technological developments offer promising alternatives to minimize plastic waste accumulation and encourage the valorization of residual materials, contributing to the implementation of circular economy principles.

3. CONCLUSIONS

This review highlights the potential of microbial and enzymatic approaches for the degradation of different plastic polymers. Differences in the polymers, experimental conditions, and methods used to assess biodegradation should be considered when comparing their results and discussing applications in natural environments or at industrial scale.

The findings should be interpreted in light of the review's scope. The literature search covered two bibliographic databases, used a limited set of search terms, and focused on three countries. The included studies also reported biodegradation using different metrics, while the patent search was limited to a national database. These factors may have influenced the range of evidence identified.

Suggestions for future research include evaluating these approaches under environmentally relevant conditions, using more comparable measures of biodegradation, and examining their economic feasibility and performance at larger scales. These efforts may help clarify their practical potential for plastic waste management.

DECLARATION

During the preparation of this manuscript, the authors used ChatGPT (GPT-5, OpenAI) to assist with English-language editing and enhance the clarity of the text. The authors subsequently checked and revised all AI-assisted content and assume full responsibility for the final version of the article.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript.

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