

A Review of Microbial Degradation of Plastic: Enzymes and Organisms

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Abstract

This review synthesizes research on systematic analysis of microbial applications in degrading plastic and microplastic waste, focusing on bacteria, fungi, actinomycetes, and enzymes such as PETase, cutinase, and laccase to address persistent plastic pollution and remediation challenges. The review aimed to evaluate microbial taxa involved in biodegradation, benchmark enzymatic activities, identify consortia strategies, elucidate metabolic pathways, and assess environmental influences on degradation efficiency. Literature was selected based on comprehensive inclusion of experimental, metagenomic, enzymatic, and biotechnological studies spanning global environmental microbiology and synthetic biology, analyzed through comparative and critical frameworks. Findings reveal diverse microbial communities, including key bacterial and fungal genera, with consortia exhibiting synergistic enzymatic cooperation that enhances polymer breakdown. Enzymatic mechanisms of PETase, cutinase, and laccase demonstrate variable catalytic efficiencies, improved by protein engineering and immobilization, though challenges remain for non-PET plastics. Metabolic pathways for monomer assimilation and gene regulation are partially elucidated, with environmental factors such as temperature and pH critically modulating microbial and enzymatic performance. Integration of multi-omics and synthetic biology advances supports enhanced biodegradation but highlights scalability and methodological standardization gaps. These findings collectively underscore the potential of microbial and enzymatic systems for sustainable plastic waste remediation while emphasizing the need for integrative approaches to optimize efficacy and application in diverse environmental contexts.

Keywords: Plastic Degradation; Microorganisms; Bioremediation; Environmental Microbiology

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INTRODUCTION

Research on microbial applications in degrading plastic and microplastic waste has emerged as a critical area of inquiry due to the escalating environmental and health impacts of persistent plastic pollution worldwide. Since the mid-20th century, plastic production has surged from 1.5 million metric tons in 1950 to over 360 million tons annually, with microplastics (<5 mm) becoming ubiquitous contaminants in terrestrial, aquatic, and atmospheric ecosystems [1]; [2]. The durability and resistance of synthetic polymers such as polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) have led to their accumulation, threatening biodiversity and human health through bioaccumulation and toxic effects [3]; [4]. The growing recognition of these impacts has driven research toward sustainable biodegradation strategies, particularly focusing on microbial consortia and enzymatic pathways that offer eco-friendly alternatives to conventional recycling and disposal methods [5]; [6].

Despite advances in identifying plastic-degrading microorganisms and enzymes, significant challenges remain in understanding and optimizing biodegradation processes. Current knowledge gaps include the limited efficiency of microbial degradation under environmental conditions, the complexity of microbial consortia interactions, and the scarcity of well-characterized enzymes capable of degrading recalcitrant plastics [7]; [8]; [2]. Moreover, while bacteria, fungi, and actinomycetes have demonstrated plastic degradation capabilities, the mechanisms underlying enzyme specificity, synergistic microbial metabolism, and environmental factors influencing degradation rates are not fully elucidated [9]; [10]; [11]. Controversies persist regarding the scalability of microbial biodegradation and the relative contributions of isolated strains versus consortia, with some studies emphasizing the superiority of engineered consortia for enhanced degradation [12]; [8]. The consequences of these gaps include limited practical application of microbial degradation technologies and continued environmental accumulation of plastic waste [13]; [6].

The conceptual framework for this review integrates the roles of microbial taxa—bacteria, fungi, and actinomycetes—and key enzymes such as PETase, cutinase, and laccase in plastic biodegradation. These enzymes catalyze polymer depolymerization through hydrolytic and oxidative mechanisms, facilitating microbial assimilation of plastic-derived monomers [14]; [15]; [16]. Understanding the interplay between microbial diversity, enzymatic activity, and environmental parameters is essential to advancing biodegradation strategies and developing robust biotechnological applications [17]; [2].

The purpose of this systematic review is to comprehensively analyze current research on microbial degradation of plastic and microplastic waste, emphasizing bacterial, fungal, and actinomycete contributions alongside enzymatic mechanisms involving PETase, cutinase, and laccase. This review aims to bridge existing knowledge gaps by synthesizing findings on microbial consortia, enzyme engineering, and biodegradation pathways, thereby informing future research and practical applications in sustainable plastic waste management [8]; [14].

This review employs a systematic approach, incorporating peer-reviewed studies from diverse environments and methodologies, including culture-dependent and metagenomic analyses. Inclusion criteria focus on microbial taxa and enzymes relevant to plastic degradation, while exclusion criteria omit studies lacking mechanistic insights or quantitative degradation data. The findings are organized to address microbial diversity,

enzymatic functions, consortia dynamics, and biotechnological advancements, providing a structured overview of the field [18]; [19].

METHODS

Research Design

This study uses a literature analysis approach through a query transformation process. The authors take the author's original research question – "systematic analysis of the application of microbes in degrading plastic and microplastic waste. Focus on bacteria, fungi, actinomycetes, and enzymes like PETase, cutinase, and laccase." – and expand it into a few more specific search statements.

By systematically expanding broad research questions into a few targeted questions, we ensure that your literature search is comprehensive (you won't miss out on specific specialized studies or jargon) and manageable (each query returns a set of papers that are closely aligned with a particular aspect of your topic).

The queries that were changed were:

1. Systematic analysis of microbial applications in degrading plastic and microplastic waste. Focus on bacteria, fungi, actinomycetes, and enzymes such as PETase, cutinase, and laccase.
2. Investigate the role of genetically engineered microbial and enzyme consortiums in the biodegradation of plastics and microplastics, focusing on their synergistic effects and mechanisms of action.
3. Explores the role of microbial interactions, environmental factors, and novel enzymatic pathways in the biodegradation of plastics and microplastics, with a focus on diverse microorganisms such as bacteria, fungi, and actinomycetes.
4. Explores the potential of microbial consortiums and novel enzyme metabolic pathways in the biodegradation of diverse plastics and microplastics, with a focus on the role of bacteria, fungi, actinomycetes, and their associated enzymes.
5. Investigating the metabolic pathways and new enzymatic mechanisms used by diverse microorganisms, including actinomycetes and fungi, in the biodegradation of various plastics and microplastics, highlights the diversity of enzymes such as PETase, cutinase, and laccase.

Research Time and Place

The research was conducted through a literature search using a database that has a collection of more than 270 million research papers. The process was carried out in the range of the publication year 2015 to 2025, in accordance with the set inclusion criteria

Research Target/Subject

The subject of the research is in the form of scientific papers relevant to the topic of plastic and microplastic biodegradation by microorganisms, including bacteria, fungi, actinomycetes, as well as enzymes such as PETase, cutinase, and laccase. The papers used are papers that meet the following inclusion criteria: Papers from the range of 2015 to 2025.

Research Procedure

The research procedure includes several stages:

1. Query Transformation

Develop the research question into several more specific search queries.

2. Identification and Implementation of Inclusion & Exclusion Criteria

We analyzed the research questions to extract inclusion/exclusion criteria so that the database returned only matching studies.

3. Paper Screening

Each search query is run with inclusion-exclusion criteria to generate a candidate paper. During this process, 375 papers were found.

4. Chain Quote

a) Backward citation tracking (looking at references from the core paper).

b) Forward citation tracking (looking at papers that cite the core paper).

From this process, 36 additional papers were found.

5. Relevance Assessment and Sorting

A total of 411 candidate papers (375 + 36) were then selected so that the following were obtained:

a) 398 levant papers

b) 50 highly relevant papers

Instruments, and Data Collection Techniques

The instrument used is a search system on a scientific literature database. Data collection techniques include:

1. Search using a query that has already been transformed
2. Screening by inclusion criteria
3. Forward and backward quote chain search
4. Collection of all papers included in the range of 2015–2025

Data analysis technique

The analysis was carried out by assessing the relevance of the papers, comparing the main themes, and identifying the contribution of each paper to the issue of plastic and microplastic biodegradation. The results of the screening and relevance assessment are then used to produce a collection of core papers that correspond to the research questions.

RESULTS AND DISCUSSION

Descriptive Summary of the Studies

This section maps the research landscape of the literature on systematic analysis of microbial applications in degrading plastic and microplastic waste. Focus on bacteria, fungi, actinomycetes, and enzymes like PETase, cutinase, and laccase. The reviewed studies encompass a broad scope, including microbial diversity, enzymatic mechanisms, consortia interactions, metabolic pathways, and environmental factors influencing biodegradation. Methodologies range from metagenomics and enzyme engineering to systematic reviews and experimental biodegradation assays, with geographic and disciplinary focuses spanning global environmental microbiology, biotechnology, and synthetic biology. This comparative analysis is crucial for addressing research questions on microbial roles, enzyme efficiencies, consortia synergy, metabolic insights, and operational conditions affecting plastic biodegradation.

Table 1. Descriptive Summary

No	Study	Biodegradation Agents	Degradation Mechanisms	Environmental Influences
1	Cao et al. [12]	Bacterial-fungal consortia for complex compound degradation	Enzyme complementarity in consortia enhances breakdown; biodegradation pathways supported by consortia	Synthetic biology tools improve robustness and enzyme environment
2	Majumdar [9]	Bacteria, fungi, actinomycetes in microplastic degradation; limited consortia focus	PETase, cutinase, laccase enzymatic mechanisms; broad enzymatic degradation mechanisms	Factors affecting microbial degradation efficiency analyzed
3	Getino et al. [13]	Bacteria, fungi, actinomycetes degrading major petrochemical plastics; microbial consortia for in situ remediation	Degradation rates and enzymatic mechanisms for PE, PP, PET, PVC; metabolic pathways and gene expression	Temperature and pH variability challenges highlighted
4	Nguyen et al. [20]	Diverse microbes including bacteria, fungi, algae, cyanobacteria; microbial cooperation noted	Enzymes decomposing various plastics including laccase and cutinase; microbial-mediated degradation mechanisms	Ecological factors influencing biodegradation outcomes
5	Chigwada & Tekere [21]	Bacterial genera involved in plastic biodegradation; bacterial consortia for enhanced degradation	Bacterial enzymes like proteases, esterases, lipases; molecular methods to analyze biodegradation	Biotechnological methods improving bacterial degradation
6	Qi et al. [22]	Engineered microbes and artificial consortia for PET degradation	PET hydrolases and enzyme modifications; metabolic pathways for PET monomer utilization	Synthetic biology strategies for enzyme and chassis Engineering
7	Gilani et al. [23]	Microbial roles including bacteria and fungi; microbial enzyme roles in biotic degradation	Enzymatic and abiotic degradation mechanisms; biotechnological implications for enzyme use	Gene manipulation and anaerobic biotechnology highlighted
8	Sahu et al. [24]	Bacteria, fungi, algae in microplastic bioremediation; microbial consortia and biofilm synergy	Enzymatic degradation and biofilm-based systems; natural metabolic pathways for microplastic degradation	Enzyme immobilization and eco-engineering techniques noted
9	Krueger et al. [7]	Microbial taxa involved in plastic degradation, noting recalcitrance; limited effective consortia	Enzymatic hydrolysis and oxidation mechanisms; analytical challenges in biodegradation studies	Environmental constraints limiting microbial degradation
10	Kumar et al. [18]	Diverse bacterial and fungal plastic degraders via metagenomic analysis; bacterial-fungal consortia importance in landfill soil	Genes encoding enzymes for PVC, PE, PET, polyurethane; pathway curation for plastic biodegradation	Depth-dependent environmental effects on microbial activity
11	Kulkarni et al. [25]	Microorganisms degrading PET microplastics, focusing on bacteria and fungi; limited consortia discussion	PETase and MHETase enzymatic steps in PET degradation; metabolic conversion of PET monomers	Temperature, pH, and crystallinity effects on degradation examined
12	Pires et al. [26]	Landfill and estuarine microbiomes with bacteria and fungi; bacterial-fungal cooperation in aerobic PCL degradation	Enzymatic hydrolysis of PCL, limited PE and PET degradation; enzymes like esterase and lipase in PCL breakdown	Aerobic vs anaerobic and thermophilic conditions impact assessed
13	Cao et al. [27]	Bacteria (Proteobacteria, Firmicutes) and fungi (Ascomycota) identified; microbial colonization and biofilm formation	Hydrolase, oxidative, depolymerization enzymes as key; degradation processes and molecular mechanisms	Research trends and environmental factors affecting degradation
14	Adamu et al. [28]	Microbial enzymes including cutinase, PETase, laccase in soil MPs degradation; enzyme consortia development	Enzyme engineering and immobilization for enhanced activity; enzymatic pathways and gene expression	Soil environmental parameters and photocatalytic remediation emphasized
15	Shokunbi et al. [8]	Microbial consortia of bacteria and fungi for plastic degradation	Enzyme complementarity and cross-feeding in consortia; synergistic metabolism and metabolic interactions	Design principles for stable, scalable consortia
16	Lv et al. [29]	Marine bacteria, fungi, actinomycetes involved in plastic degradation; microbial biofilm formation on marine plastics	Enzymes like esterase, cutinase, laccase on PET, PE, PS, PVC, PP; gene expression and metabolic pathways	Adaptation to marine environmental factors highlighted
17	Ramos et al. [30]	Bacteria, fungi, consortia degrading LDPE; efficient microbial consortia identified	Degradation efficiencies and techniques like SEM, FTIR; biodegradation time and weight loss data	Environmental isolation sources and operational parameters
18	Yagnik & Das [10]	Actinomycetes isolated from plastic dumping sites for LDPE degradation; individual actinomycetes focus	Weight loss and chemical changes via FTIR; alkane and polymer degradation pathways confirmed	Incubation conditions and degradation confirmation assays
19	Bi et al. [31]	PET-degrading enzymes	Enzyme thermostability and	Temperature optima and protein

No	Study	Biodegradation Agents	Degradation Mechanisms	Environmental Influences
		from actinomycetes genera; limited consortia focus	enhanced depolymerization rates; enzyme structure-function and substrate specificity	engineering improvements
20	Jiang et al. [16]	Fungal strain <i>Blastobotrys</i> sp. degrading polyurethane and PBAT; enzyme-centric study	Novel cutinase BaCut1 with efficient polyester degradation; substrate-binding modes and degradation products	Incubation temperature and enzyme dosage effects examined
21	Gambarini et al. [32]	Fungal <i>Clonostachys rosea</i> degrading PCL and PET; single strain molecular mechanisms	Cutinase activity and gene expression regulation; gene upregulation and metabolic pathways	Glucose inhibition of degradation process noted
22	Souza et al. [33]	Fusarium cutinases for PET biodegradation; enzyme structural study	Molecular dynamics exploring enzyme conformational dynamics affecting catalysis; enzyme structure to PET hydrolysis efficiency	SEM to observe plastic surface interactions
23	Sui et al. [15]	Cutinase-like enzymes for PET biodegradation; enzyme-focused	Protein engineering for improved PET hydrolysis; ligand-protein interactions and catalytic mechanisms	Fusion proteins and engineered enzyme applications
24	Hong et al. [34]	Plastic-degrading enzymes in <i>Pseudomonas stutzeri</i> ; single species study	PETase-like and MHETase-like enzyme activity; bioinformatics and assays to confirm degradation	Growth on polystyrene and polyurethane substrates reported
25	Choi [14]	Plastic-degrading enzymes including PETase, cutinase, laccase; synthetic consortia integration	Enzyme discovery, engineering, and immobilization; enzyme catalytic mechanisms and substrate specificity	Enzyme stability and biotechnological applications
26	Phillip & Chauhan [6]	Biotechnological approaches using microbial enzymes; challenges in consortia and GMO applications	PETase, MHETase, laccase catalytic roles; enzymatic degradation pathways and gene editing	Environmental parameters affecting enzyme function emphasized
27	Pham et al. [35]	Extremophilic bacteria producing multiple enzymes; synergistic enzyme systems	Multi-enzyme synergy in extremophiles; unknown bioproducts and metabolic pathways	Environmental adaptation factors like hydrophobicity emphasized
28	Fan et al. [4]	Aerobic and anaerobic microbial degradation of microplastics; microbial community structure differences	Enzymatic degradation under different redox conditions; metabolic pathways under aerobic vs anaerobic conditions	Environmental distribution and physical-chemical influences
29	Kolipaka et al. [36]	Bacterial and fungal contributions to plastic biodegradation; limited consortia discussion	PETase discovery and enzymatic mechanisms; enzymatic pathways and degradation factors	Environmental and operational factors affecting biodegradation
30	Akram et al. [5]	Microbial and enzymatic plastic biodegradation for circular economy; microbial consortia and isolated enzymes	Enzyme interaction with plastic surfaces; enzymatic hydrolysis and microbial metabolism	Sustainable valorization and scaling challenges
31	Kumar et al. [18]	Microbial PET degradation by bacteria and fungi; limited consortia focus	Cutinase and PETase enzymatic roles; biochemical processes and degradation obstacles	Environmental and operational conditions for PET degradation
32	Wongsatit et al. [37]	PET-degrading enzymes and microbial consortia engineering; bottom-up and top-down consortia construction	Protein design and synthetic biology tools; metabolic pathways and enzyme auxiliary functions	Bioengineering for enhanced PET circularization
33	Vaishnav et al. [17]	Microbial enzymes and their modifications; genetic and protein engineering to improve enzymes	Enzyme hydrolysis and oxidation mechanisms; molecular mechanisms and gene cloning	Challenges and opportunities in enzyme modification
34	Basene & Pillai [11]	Microbial enzymes from bacteria and fungi; limited consortia discussion	Enzyme sources and degradation capabilities; enzymatic breakdown pathways	Environmental impact and traditional method drawbacks
35	Pérez-García et al. [2]	Microbial enzymes and pathways for plastic biodegradation; challenges in identifying degraders	Over 255 verified plastic-active enzymes; metabolic pathways and gene expression	Biotechnological applications and measurement methods
36	Gurme [3]	Microplastic degradation chemistry and microbial roles; limited consortia focus	Enzymatic degradation and secondary pollutant formation; degradation pathways and environmental behavior	Mitigation strategies including enzymatic degradation reviewed
37	Li et al. [38]	Single-cell approach to identify microplastic-degrading microbes; cultivates rare, active degraders	Enzymes involved in polystyrene degradation stages; key enzymes and degradation stages mapped	Insect gut microbiota and functional screening highlighted
38	Wani et al. [1]	Metagenomics for discovering plastic-degrading microbial communities;	Gene mining for plastic-degrading enzymes; functional genetics and gene prediction	Bioinformatics tools and in situ remediation potential

No	Study	Biodegradation Agents	Degradation Mechanisms	Environmental Influences
		microbial consortia characterization		
39	Kour et al. [39]	Microbial roles in plastic degradation focusing on bacteria and fungi; microbial enzymatic degradation	Enzymatic mechanisms and microbial metabolism; enzymatic pathways and microbial action	Environmental impact and sustainability aspects
40	Dailin et al. [40]	Biodegradation and abiotic degradation of plastics; microbial strains and plastic types compared	Bioprocesses and degradation products described	Operational feasibility and environmental impact
41	Jahanshahi et al. [19]	Metagenomic catalog of plastic-contaminated environments; microbial taxa and plastizymes diversity	Hydrolases, peroxidases, cutinases as dominant enzymes; gene and protein annotations for degradation	Sequence and structural enzyme validation
42	Xu [41]	Directed evolution of PET-degrading enzymes; enzyme engineering centered	Enhancing catalytic efficiency and thermostability; engineered variants like HotPETase and LCC mutants	Protein engineering techniques for improved activity
43	Gates & Crook [42]	Biochemical mechanisms of plastic biodegradation; ranks effective biodegraders	Metabolic routes for industrial plastics categorized; experimental techniques in biodegradation research	Challenges in plastic biodegradation efficacy
44	Rosini et al. [43]	Enzymatic breakdown of oil-based polyesters and bioplastics; enzyme-embedded bioplastics and microbial platforms	Enzyme discovery, screening, and biocatalyst design; enzymatic depolymerization and upcycling pathways	Circular economy and kinetic standardization emphasized
45	Zhang et al. [44]	Engineered biopolymer-immobilized enzymes for PET degradation; enzyme immobilization study	Enhanced thermostability and reusability of enzymes; near-complete PET depolymerization and product recovery	Techno-economic and life cycle assessments included
46	Garg et al. [45]	Biomass integration to enhance plastic degradation; bioreactor and genetic engineering applications	Enzymes like PETase and laccase and microbes; enzymatic and microbial degradation processes	Environmental and economic benefits emphasized

Microbial Diversity:

1. Over 40 studies identified diverse bacteria, fungi, and actinomycetes as key plastic degraders, with genera such as *Pseudomonas*, *Bacillus*, *Aspergillus*, and actinomycetes frequently reported [21]; [18]; [30].
2. Several studies emphasized the importance of microbial consortia combining bacteria and fungi for enhanced degradation, highlighting synergistic interactions [12]; [8]; [26].
3. Marine and landfill environments were common sources of plastic-degrading microbes, with metagenomic approaches revealing complex microbial communities [29]; [18]; [1].
4. Extremophilic microbes and insect gut microbiota were noted as promising but less explored sources of plastic degraders [35]; [38].
5. Some reviews pointed out the limited knowledge on microbial diversity for highly recalcitrant plastics like PE and PP [7]; [2].

Enzymatic Activity:

1. PETase, cutinase, and laccase enzymes were consistently identified as primary catalysts for PET and other polyester degradation [9]; [15]; [14].
2. Engineered enzymes with improved thermostability and catalytic efficiency, such as HotPETase and LCC mutants, showed significant advances [41]; [31]; [44].
3. Enzymatic degradation rates varied widely depending on enzyme source, plastic type, and environmental conditions [13]; [16]; [33].
4. Immobilization and fusion protein strategies enhanced enzyme stability and reusability in several studies [28]; [44].
5. Some studies highlighted the challenges in degrading non-PET plastics enzymatically due to structural recalcitrance [7]; [6].

Consortia Synergy:

1. Multiple studies demonstrated that microbial consortia outperform single strains by providing complementary enzymatic activities and metabolic cooperation [12]; [8]; [26].
2. Synthetic biology approaches enable the design of stable, robust consortia tailored for complex polymer degradation [22]; [37].
3. Cross-feeding and enzyme complementarity within consortia accelerate polymer depolymerization and mineralization [8]; [12].
4. Some research noted the scarcity of well-characterized consortia for certain plastics, indicating a gap in applied consortia engineering [6]; [2].
5. Environmental consortia from landfill and estuarine sites showed natural synergistic interactions important for biodegradation [18]; [26].

Metabolic Pathways:

1. Studies elucidated pathways for PET monomer utilization, including conversion to terephthalic acid and ethylene glycol entering central metabolism [22]; [25] [32].
2. Gene expression analyses revealed upregulation of cutinase and other hydrolase genes during plastic degradation [32]; [42].
3. Metagenomic and transcriptomic approaches identified genes encoding enzymes for PVC, PE, PET, and polyurethane degradation [18]; [19].
4. Some studies highlighted metabolic inhibition by preferred carbon sources like glucose, affecting degradation efficiency [32].
5. Pathway curation and enzyme-substrate interaction studies informed protein engineering and biodegradation optimization [33]; [15]

Environmental Influence:

1. Temperature, pH, crystallinity, and oxygen availability were frequently reported as critical factors affecting microbial and enzymatic degradation [13]; [25]; [4].
2. Engineered enzymes and microbial chassis showed improved stability under variable environmental conditions [22]; [41]; [44].
3. Soil, landfill, marine, and insect gut environments presented distinct operational challenges and microbial adaptations [18]; [35]; [38].
4. Photocatalytic and immobilization techniques were explored to enhance enzyme activity and degradation rates in situ [28]; [24].
5. Several studies emphasized the need to integrate microbial biodegradation with existing waste management systems for scalability [13]; [14].

Critical Analysis and Synthesis

The reviewed literature collectively advances the understanding of microbial and enzymatic degradation of plastics and microplastics, highlighting significant progress in identifying diverse microbial taxa and enzymes such as PETase, cutinase, and laccase. Strengths include comprehensive characterization of microbial consortia and enzymatic mechanisms, as well as innovative biotechnological approaches to enhance degradation efficiency. However, limitations persist in the scalability of biodegradation processes, variability in environmental conditions, and incomplete elucidation of metabolic pathways. Methodological inconsistencies and challenges in verifying degradation efficacy also constrain the comparability and applicability of findings. Overall, the synthesis underscores the promise of

microbial applications while emphasizing the need for standardized methodologies and integrative approaches to overcome current bottlenecks.

Comprehensive Analysis of Microbial Plastic Degradation: Strengths and Weaknesses

Microbial Diversity and Roles:

Extensive identification of bacteria, fungi, and actinomycetes involved in plastic degradation has been achieved, with studies demonstrating the adaptability of microbial communities in diverse environments such as landfills and marine ecosystems. The recognition of key genera like *Pseudomonas*, *Bacillus*, *Aspergillus*, and actinomycetes highlights the broad taxonomic range capable of polymer breakdown [18,30,10,36]. Metagenomic and metataxonomic analyses provide detailed insights into microbial community structures and functional gene abundance related to plastic degradation [18,1]. However, despite this taxonomic breadth, many studies rely on culture-dependent methods that may overlook unculturable or rare taxa, limiting the full understanding of microbial diversity. Environmental variability and microbial competition complicate the extrapolation of laboratory findings to natural settings [13,7]. Furthermore, the ecological roles and interactions within microbial consortia remain insufficiently characterized, hindering the optimization of biodegradation consortia [8,18].

Enzymatic Mechanisms and Catalytic Efficiency:

Detailed biochemical characterization of enzymes such as PETase, cutinase, and laccase has elucidated substrate specificities and catalytic pathways, with advances in protein engineering enhancing thermostability and activity, including notable examples such as HotPETase and engineered LCC variants [31,15,41]. Structural studies and molecular dynamics simulations have provided mechanistic insights facilitating rational enzyme design [33,15]. The discovery of novel enzymes from diverse microbial sources, including actinomycetes and fungi, expands the enzymatic repertoire for plastic degradation [31,32,17]. Nevertheless, native enzymes often exhibit limited catalytic efficiency and stability under environmental conditions, restricting practical applications [13,41]. Many studies focus predominantly on PET degradation, with less attention to other recalcitrant polymers like PE and PP, where enzymatic mechanisms remain poorly understood [2,6]. Additionally, enzyme-substrate interactions in complex polymer matrices are not fully elucidated, and the impact of polymer crystallinity and additives on enzymatic activity is underexplored [25,18].

Microbial Consortia and Synergistic Interactions:

Research demonstrates that microbial consortia outperform single strains by providing complementary enzymatic activities and metabolic cooperation, enhancing degradation rates and stability [12,8,5]. Studies highlight cross-feeding and enzyme complementarity as key factors in consortium efficiency, with synthetic biology enabling the design of robust artificial consortia [12,8,37]. The co-existence of bacteria and fungi in consortia facilitates degradation of complex polymers under varying environmental conditions [26,8]. Despite these promising results, the design and control of stable consortia remain challenging due to complex interspecies interactions and environmental fluctuations [12,8]. There is a lack of standardized protocols for consortium construction and evaluation, limiting reproducibility and scalability [8]. Moreover, the metabolic pathways and gene regulation within consortia are not fully mapped, impeding targeted optimization [18,8].

Metabolic Pathways and Molecular Mechanisms:

Several studies have identified key metabolic routes for polymer monomer assimilation, such as the conversion of PET hydrolysis products into TCA cycle intermediates [22,32,42]. Genomic and transcriptomic analyses reveal upregulation of genes encoding cutinases and other hydrolases during plastic degradation [32,18]. Enzymatic pathways involving ester bond hydrolysis and oxidative mechanisms are well characterized for certain polymers [17,2]. However, comprehensive understanding of metabolic pathways is limited by incomplete genomic data and insufficient functional validation of candidate genes [42,18]. The influence of environmental factors on gene expression and enzyme regulation is underexplored, and the fate of degradation intermediates and potential toxic byproducts remains unclear [13,32]. This gap restricts the development of fully integrated biodegradation models and bioprocesses.

Environmental and Operational Factors:

Studies acknowledge the significant impact of parameters such as temperature, pH, oxygen availability, and polymer properties, particularly crystallinity, on microbial degradation efficiency and enzyme stability [9,25,4]. Research into extremophiles and engineered enzymes addresses some environmental constraints [35,41]. Bioreactor and immobilization technologies have been explored to enhance enzyme performance and process scalability [28,44]. Nonetheless, environmental heterogeneity and fluctuating conditions in natural and engineered systems pose challenges for consistent biodegradation performance [13,4]. Many laboratory studies do not replicate field conditions, limiting ecological relevance [7,4]. The stability and activity of enzymes and microbes under operational stresses require further optimization, and the economic feasibility of large-scale applications remains uncertain [6,44].

Methodological Approaches and Data Quality:

The integration of multi-omics, metagenomics, and advanced analytical techniques such as FTIR and SEM has improved the detection and quantification of plastic degradation and microbial activity [18,30,19]. Functional assays and molecular docking complement structural studies to validate enzyme-substrate interactions [16,33]. Systematic reviews and bibliometric analyses provide comprehensive overviews of research trends [27,30]. However, methodological inconsistencies, such as variable degradation assays, lack of standardized metrics, and insufficient controls, complicate cross-study comparisons [7,30]. Gravimetric and spectroscopic methods may not fully capture mineralization or distinguish between surface erosion and true biodegradation [30,40]. The scarcity of long-term field studies and in situ validations limits the robustness of conclusions and practical applicability [7,4].

Biotechnological Advancements and Scalability:

Synthetic biology, protein engineering, and enzyme immobilization have yielded enhanced enzymes and microbial chassis with improved degradation capabilities [12,31,37,44]. Artificial consortia and bioengineered systems show promise for industrial applications and circular economy integration [5,37,44]. Emerging approaches such as single-cell sorting and metagenomic mining accelerate discovery of novel degraders [38,1]. Despite this technological progress, challenges remain in scaling laboratory successes to environmental or industrial scales due to process complexity, cost, and regulatory hurdles [13,6]. The ecological safety and stability of genetically modified organisms in open environments are concerns [6]. Furthermore, the translation of enzyme improvements into economically viable and sustainable processes is still in early stages [6,44].

Thematic Review of Literature

Research on microbial applications for degrading plastic and microplastic waste predominantly focuses on the diversity of microorganisms involved, including bacteria, fungi, and actinomycetes, alongside the roles of key enzymes such as PETase, cutinase, and laccase. Significant attention has been given to elucidating enzymatic mechanisms, metabolic pathways, and the synergistic effects of microbial consortia in enhancing degradation processes. Environmental factors and biotechnological interventions, including enzyme engineering and consortia design, are also crucial themes that influence the efficiency and scalability of biodegradation strategies. Together, these themes reveal an evolving interdisciplinary approach integrating microbiology, enzymology, and synthetic biology to address plastic pollution sustainably.

Table 2. Thematic Review

No	Appears In	Theme	Theme Description
1	38/50 Papers	Microbial Diversity in Plastic and Microplastic Degradation	This theme highlights the extensive variety of bacteria, fungi, and actinomycetes capable of degrading plastics, with frequent identification of genera such as <i>Pseudomonas</i> , <i>Bacillus</i> , <i>Aspergillus</i> , and <i>Streptomyces</i> . Studies report microbial adaptability in diverse environments, including marine, landfill, and insect gut ecosystems, underscoring their roles in colonization and biofilm formation for plastic degradation [9,21,18,29,4,39].
2	35/50 Papers	Enzymatic Mechanisms and Key Plastic Degrading Enzymes	Investigations focus on enzymes like PETase, cutinase, laccase, and hydrolases that catalyze polymer depolymerization, detailing substrate specificity, catalytic pathways, and enzyme-substrate interactions. Advances in structural biology and protein engineering, including directed evolution and immobilization, have enhanced enzyme efficiency and thermostability, particularly for PET degradation [22,31,33,15,17,41,44].
3	22/50 Papers	Microbial Consortia and Synergistic Interactions	Research supports that microbial consortia comprising diverse taxa exhibit superior degradation efficiency compared to single strains, owing to complementary enzymatic repertoires and metabolic cross-feeding. Synthetic biology approaches enable the design of stable, robust consortia tailored for complex polymer breakdown, demonstrating improvements in adaptability and biodegradation rates [12,26,8,37].
4	20/50 Papers	Biotechnological Advances and Enzyme Engineering	Studies emphasize protein engineering, gene editing, and synthetic biology techniques to optimize enzymes and microbial hosts for enhanced plastic biodegradation. Innovations include fusion proteins, immobilized enzymes, and genetically modified strains, aiming to improve catalytic activity, stability, and industrial applicability within circular economy frameworks [28]; [31]; [15]; [14]; [37]; [41]; [44].
5	19/50 Papers	Metabolic Pathways and Molecular Mechanisms of Biodegradation	Research elucidates metabolic routes for plastic polymer breakdown, including hydrolysis of ester bonds and subsequent assimilation of monomers via pathways like the TCA cycle. Genomic and transcriptomic analyses reveal key genes and regulatory mechanisms involved in biodegradation, with fungal and bacterial systems showing diverse enzymatic gene expression profiles [18,32,2,42].
6	18/50 Papers	Environmental and Operational Factors Affecting Biodegradation	Studies identify parameters such as temperature, pH, oxygen availability, plastic crystallinity, and pollutant presence that influence microbial degradation efficiency and enzyme activity. Both aerobic and anaerobic conditions are considered, with implications for natural and engineered bioremediation systems [9,20,25]; [4]; [30].
7	15/50 Papers	Microplastic-Specific Biodegradation Challenges and Solutions	Focus on microplastic degradation addresses unique challenges due to size and environmental distribution, highlighting microbial capabilities, enzyme activities, and remediation technologies such as bioreactors and biofilms. Emerging techniques include single-cell analyses and metagenomics to uncover novel degraders and enzymatic functions [24,27,38,1,40].
8	11/50 Papers	Actinomycetes as Specialized Plastic Degraders	Actinomycetes are recognized for their potent degradation of plastics like LDPE and PET, producing thermostable enzymes such as cutinases with substantial weight loss in plastics. Isolation from plastic-contaminated sites and enzyme

No	Appears In	Theme	Theme Description
9	10/50 Papers	Analytical and Experimental Methodologies in Biodegradation Research	engineering have advanced understanding of their biodegradation role [10,31,34]. Techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), gravimetry, metagenomics, and molecular dynamics simulations are widely employed to assess microbial degradation, enzyme activity, and polymer structural changes. These methods facilitate mechanistic insights and verification of biodegradation efficacy [18,30,33].

Chronological Review of Literature

Research on microbial degradation of plastics has evolved significantly over the last decade, focusing initially on identifying plastic-degrading microorganisms and enzymatic activities. Early works emphasized the potential of bacteria, fungi, and actinomycetes to biologically break down persistent polymers. Subsequent studies expanded into enzyme characterization, molecular mechanisms, and the design of microbial consortia for enhanced degradation. Recent advances highlight synthetic biology, enzyme engineering, and metagenomic approaches to improve biodegradation efficiency and scalability, aiming to integrate these innovations into sustainable plastic waste management.

Table 3. Chronological Review

No	Year Range	Research Direction	Description
1	2015 - 2016	Foundational Understanding of Microbial Plastic Degradation	Initial studies mapped the scope of plastic pollution and explored the limited but promising potential of microbes to degrade plastics. Emphasis was placed on identifying microbes capable of enzymatic hydrolysis or oxidation and understanding the recalcitrance of common plastics. Analytical challenges and environmental factors influencing degradation were also discussed.
2	2020 - 2022	Emerging Bioremediation Technologies and Microbial Roles	Research focused on eco-friendly bioremediation and the role of bacteria, fungi, and algae in degrading microplastics. Advances included enzyme immobilization, biofilm based systems, and integrating bioremediation with eco-engineering for enhanced degradation. The multifaceted roles of microbes and their enzymatic mechanisms began to be elucidated.
3	2023	Expanding Microbial Diversity and Enzyme Characterization	Studies reported extensive microbial taxa involved in plastic degradation, including bacteria, fungi, actinomycetes, and extremophiles. Focus was given to enzymes such as PETase, cutinase, and laccase, their catalytic mechanisms, and environmental influences. Metagenomic and bioinformatics approaches emerged to discover novel plastizymes and microbial consortia.
4	2024	Mechanistic Insights and Enzyme Engineering	Research advanced into detailed metabolic pathways, gene regulation, and molecular dynamics of plastic-degrading enzymes. Emphasis was placed on enzyme modification and protein engineering for enhanced catalytic efficiency and stability. Microbial consortia and synergistic interactions became a focal point for improving biodegradation of complex polymers, including PET and LDPE.
6	2025	Synthetic Biology and Scalable Biotechnological Applications	The latest research highlights the integration of synthetic biology, directed evolution, and metagenomic mining to develop highly efficient enzyme variants and robust microbial consortia. Innovations include in vivo enzyme immobilization, single-cell approaches to cultivate rare degraders, and biotechnological platforms supporting circular plastic economy principles. Challenges of environmental scalability and techno economic feasibility are being addressed.

Agreement and Divergence Across Studies

Most studies agree that a diverse range of microbes including bacteria, fungi, and actinomycetes play significant roles in plastic and microplastic degradation, with enzymes

like PETase, cutinase, and laccase being central to these processes. There is consensus on the advantages of microbial consortia over isolated strains due to synergistic metabolic interactions enhancing degradation efficiency. However, divergences arise concerning the scalability of biodegradation under environmental conditions, with some studies emphasizing challenges such as enzyme stability and varying environmental parameters. Differences in focus, ranging from soil, landfill, marine environments, to engineered systems, contribute to variability in reported efficiencies and microbial communities.

Table 4. Agreement and Divergence

No	Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
1	Microbial Diversity and Taxonomy	Broad consensus that bacteria (notably <i>Pseudomonas</i> , <i>Bacillus</i> , <i>Enterobacter</i> spp.), fungi (<i>Aspergillus</i> , <i>Trichoderma</i>), and actinomycetes (<i>Streptomyces</i> , <i>Rhodococcus</i>) are key plastic degraders [9,21,18,30,10,36]. Marine-derived microbes are highlighted specifically for adaptability to fluctuating conditions [29]. Metagenomic and single-cell methods reveal diverse microbial communities with functional plastic-degrading genes [18,38,1].	Variation exists in reported dominant taxa depending on environment: landfill vs. marine vs. insect gut microbiota [18,26,38]. Some studies emphasize extremophiles in plastic degradation while others focus on common soil or landfill isolates [35,10].	Differences stem mainly from sampling environments, methodologies (culture dependent vs. omics), and microbial isolation techniques. Environmental conditions select for specific taxa.
2	Enzymatic Activity and Efficiency	PETase, cutinase, and laccase are consistently identified as pivotal enzymes for degrading plastics like PET, PE, and PU, with high catalytic activity reported especially for engineered or modified enzymes [22,31,33,15,14,41,44]. Engineering advances, including directed evolution and immobilization, improve enzyme stability and efficiency [37,41,44].	Discrepancies in reported degradation rates and enzyme efficiencies exist, particularly with non-PET plastics where enzymatic activity is often limited [6,2]. Some studies highlight lack of effective enzymes for specific polymers such as PE and PP [7,2].	Variability arises from different enzyme sources, substrate types, assay conditions, and degree of enzyme engineering. The inherent recalcitrance of certain plastics impacts enzymatic effectiveness.
3	Consortia Synergy and Stability	Several papers underscore the superior performance of microbial consortia over single strains due to complementary enzyme repertoires and metabolic cooperation, enhancing degradation pathways [12,8,5,37]. Consortia improve adaptability and robustness in diverse environments [18,26].	Some reports note challenges in maintaining stability and consistency of consortia under environmental conditions and bioprocess scale-up, with less clarity on consortia design principles [6,8].	Differences are due to diversity in consortium composition, environmental variability, and nascent state of engineering microbial consortia for controlled applications
4	Metabolic Pathway Elucidation	Studies collectively highlight enzymatic hydrolysis of ester bonds (PETase, cutinase) and oxidative mechanisms (laccase), with metabolic pathways involving monomer assimilation into central metabolism like the TCA cycle [22,32,42]. Gene expression analyses and genome sequencing elucidate specific plastic degrading genes and regulation [18,32].	Some papers emphasize fungal metabolic pathways and gene regulation, while others focus mainly on bacterial enzymatic mechanisms [32,17]. The influence of carbon source repression varies, e.g., glucose inhibition in fungi [32].	Variation reflects organismal differences (fungi vs bacteria), distinct polymer substrates, and methodological approaches (genomic, proteomic, transcriptomic)
5	Environmental and Operational Influences	Temperature, pH, and substrate crystallinity are widely recognized as key factors affecting microbial degradation rates and enzyme stability [9,25,28,6,4]. Engineered enzymes and microbial chassis show improved tolerance to	Disagreements exist regarding the scalability of biodegradation in natural environments, with some studies emphasizing challenges like microbial competition, toxic intermediates, and variable physicochemical conditions [13,7,6,2].	Divergence arises from differences in lab-scale vs field conditions, complexity of environmental matrices, and variation in biotechnological adaptations deployed in studies

No	Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
		environmental stresses [22,31,41,44]. Bioreactor and immobilization techniques enhance operational stability [28,44].		

Theoretical and Practical Implications

Theoretical Implications:

The synthesized findings reinforce the concept that microbial diversity, including bacteria, fungi, and actinomycetes, plays a crucial role in plastic and microplastic biodegradation, supporting the theory that complex microbial consortia outperform single strains due to synergistic enzymatic activities and metabolic interactions [12]; [8]; [18]. This aligns with emerging ecological models of plastisphere communities where cooperative metabolism enhances polymer breakdown. Enzymatic mechanisms involving PETase, cutinase, and laccase are increasingly understood at molecular and structural levels, confirming their substrate specificity and catalytic pathways, which supports existing biochemical theories of ester bond hydrolysis and oxidative depolymerization in synthetic polymers [15]; [33]; [14].

Protein engineering and directed evolution studies further validate the adaptability of these enzymes to improve efficiency and thermostability [41]. The elucidation of metabolic pathways and gene expression profiles in microbes degrading plastics, such as those revealed by metagenomic and transcriptomic analyses, advances theoretical frameworks on microbial plastic metabolism and gene regulation under environmental conditions [18]; [32]; [1]. These insights challenge earlier assumptions about the recalcitrance of plastics by demonstrating active microbial adaptation and enzymatic evolution. Environmental and operational factors such as temperature, pH, and substrate crystallinity are confirmed to significantly influence microbial degradation rates and enzyme stability, supporting ecological theories on niche specialization and enzyme-substrate dynamics in biodegradation processes [25]; [4]; [17].

This highlights the complexity of biodegradation in situ compared to controlled laboratory conditions. The integration of synthetic biology and microbial consortia engineering introduces a novel theoretical paradigm for designing robust biodegradation systems, emphasizing enzyme complementarity, cross-feeding, and metabolic cooperation, which extends classical microbiological degradation models [12]; [8]; [37]. Despite advances, the limited biodegradation of highly recalcitrant plastics such as polyethylene and polypropylene remains a theoretical challenge, underscoring gaps in understanding microbial enzymatic capabilities and evolutionary constraints [7]; [2].

Partical Implications:

The demonstrated efficiency of microbial consortia and engineered enzymes in degrading plastics suggests practical applications in bioremediation technologies, offering scalable and eco-friendly alternatives to conventional mechanical and chemical recycling methods [12]; [5]; [44]. This supports industry shifts toward bio-based plastic waste management solutions. Advances in enzyme engineering, including immobilization and directed evolution, provide pathways to develop industrially viable biocatalysts with enhanced activity and stability, facilitating enzymatic recycling processes that can recover high-purity monomers for circular economy applications [41]; [44]; [15].

The identification of key microbial taxa and enzymes through metagenomics and single-cell approaches enables targeted bioprospecting and microbial resource management, which can inform policy frameworks for environmental monitoring and biotechnological deployment in contaminated sites [18]; [38]; [19]. Understanding environmental parameters that affect biodegradation efficiency informs the design of optimized bioreactors and in situ remediation strategies, allowing for tailored interventions in diverse ecosystems such as landfills, aquatic environments, and soils [4]; [26]; [24].

The recognition of microbial plastic degradation as a multi-factorial process involving microbial ecology, enzymology, and environmental chemistry underscores the need for interdisciplinary regulatory policies that support research, development, and safe application of genetically modified organisms and synthetic consortia [6]; [8]; [11]. Practical challenges remain in scaling microbial degradation technologies due to variability in environmental conditions and the persistence of certain plastics, indicating that combined approaches integrating microbial degradation with physical and chemical methods may be necessary for comprehensive waste management [7]; [2]; [6].

Table 5. Limitations

No	Area of Limitation	Description of Limitation	Papers Wich Have Limitation
1	Limited Environmental Scalability	Many studies focus on laboratory or controlled conditions, limiting the external validity of findings when applied to complex natural environments. This constraint affects the generalizability of microbial degradation efficiencies and enzyme stability under variable environmental parameters.	[13]; [24]; [4]
2	Insufficient Diversity of Microbial Strains	Research often emphasizes a narrow range of microbial taxa or enzymes, which restricts understanding of the full microbial diversity involved in plastic degradation. This limitation hinders the discovery of novel degraders and enzymes with potentially superior capabilities.	[9]; [27]; [34]; [36]
3	Methodological Constraints in Biodegradation Assessment	Variability and limitations in analytical techniques such as gravimetry, SEM, FTIR, and molecular assays reduce the reliability and comparability of biodegradation results across studies, impacting the robustness of conclusions.	[21]; [30]; [30]
4	Focus on PET and Limited Plastic Types	A disproportionate focus on polyethylene terephthalate (PET) biodegradation leaves other prevalent plastics like polyethylene (PE),	[13]; [6]; [2]

No	Area of Limitation	Description of Limitation	Papers Wich Have Limitation
		polypropylene (PP), and polystyrene (PS) underexplored, limiting comprehensive understanding of microbial degradation across plastic types.	
5	Lack of Long-Term and Field Studies	The scarcity of long-term and in situ field investigations restricts insights into the sustained performance and ecological impacts of microbial consortia and enzymes, thereby limiting practical application and environmental relevance.	[7]; [18]; [26]
6	Limited Integration of Multi-Omics Approaches	Few studies comprehensively integrate metagenomics, metatranscriptomics, and metabolomics, which constrains the elucidation of complex microbial interactions and metabolic pathways critical for effective plastic biodegradation.	[18]; [1]
7	Challenges in Enzyme Engineering and Stability	Despite advances, engineered enzymes often face challenges related to catalytic efficiency, thermostability, and substrate specificity, which limit their practical deployment in diverse environmental and industrial settings.	[31]; [15]; [41]; [44]
8	Geographic and Habitat Bias	Research predominantly samples microbes from specific environments such as landfills or aquatic systems, leading to geographic and habitat biases that reduce the representativeness of microbial diversity and degradation potential globally.	[30]; [35]; [39]

Table 6. Gaps and Future Research

No	Gap Area	Description	Future Research Directions	Justification
1	Limited enzymatic degradation of recalcitrant plastics	Enzymatic mechanisms and efficient degradation pathways for highly recalcitrant plastics like PE and PP remain poorly understood and underexplored compared to PET	Investigate and characterize novel enzymes and microbial strains capable of degrading PE and PP; apply protein engineering and directed evolution to enhance catalytic efficiency for these polymers	Most studies focus on PET degradation due to its ester bonds, while PE and PP lack efficient enzymatic degradation routes, limiting biotechnological applications for these dominant plastics [13,7,6,2].
2	Incomplete understanding of microbial consortia dynamics	The metabolic interactions, gene regulation, and stability mechanisms within microbial consortia for plastic degradation are insufficiently characterized	Employ multi-omics (metagenomics, transcriptomics, metabolomics) and synthetic biology to map metabolic pathways and regulatory networks in consortia; develop standardized protocols for consortium design and	Synergistic consortia outperform single strains, but lack of detailed mechanistic understanding hinders rational design and scalability of effective consortia [12,18,8,37].

No	Gap Area	Description	Future Research Directions	Justification
3	Environmental variability effects on biodegradation efficacy	The impact of fluctuating environmental parameters (temperature, pH, oxygen, crystallinity) on microbial and enzymatic degradation performance is not fully elucidated	Conduct systematic in situ and controlled environment studies to quantify effects of environmental factors; develop robust enzymes and microbial chassis tolerant to variable conditions	Environmental heterogeneity causes inconsistent degradation rates and limits field applicability of lab optimized strains and enzymes [13,25,4,41].
4	Scarcity of standardized biodegradation assessment methods	Lack of uniform, validated protocols and metrics for measuring plastic biodegradation impedes cross-study comparability and reliability	Develop and adopt standardized assays combining gravimetry, spectroscopy, mineralization tracking, and molecular markers; validate methods across laboratories and environmental contexts	Current methods often fail to distinguish surface erosion from true biodegradation, complicating efficacy evaluation and technology development [7,30,40].
5	Limited exploration of extremophilic and rare microbial degraders	Extremophiles and rare taxa, such as insect gut microbiota, are underexplored sources of plastic-degrading microbes and enzymes	Apply single-cell sorting, metagenomics, and functional screening to isolate and characterize extremophilic and rare plastic degraders; explore their enzyme systems for novel catalytic properties	Extremophiles offer enzymes with enhanced stability and activity under harsh conditions, promising for industrial applications [35,38,1].
6	Insufficient integration of biodegradation with waste management systems	Microbial degradation processes are rarely integrated with existing recycling or waste treatment infrastructures for practical scalability	Design pilot-scale bioreactors and hybrid systems combining microbial consortia and enzymatic treatments with mechanical recycling; perform techno-economic and life cycle assessments	Integration is critical to translate biodegradation advances into sustainable, scalable plastic waste management solutions [13,14,44].
7	Undercharacterized enzyme-substrate interactions in complex polymers	Molecular details of enzyme binding and catalysis on heterogeneous, additive-containing plastics are not fully resolved	Use molecular dynamics, structural biology, and biochemical assays to elucidate enzyme interactions with diverse polymer matrices and additives; guide rational enzyme engineering	Understanding substrate complexity is essential to improve enzyme efficiency and broaden substrate range beyond model polymers [33,15,18].
8	Limited knowledge on degradation intermediates and byproducts	Fate, toxicity, and metabolic assimilation of plastic degradation intermediates and byproducts remain poorly understood	Investigate metabolic pathways and environmental fate of degradation products using metabolomics and ecotoxicological assays; assess potential secondary pollution risks	Incomplete knowledge of intermediates limits safe application and optimization of biodegradation processes [13,32,3].
9	Challenges in genetic and protein engineering for environmental application	Engineered enzymes and microbes often face stability, regulatory, and ecological safety challenges in open environments	Develop containment strategies, inducible expression systems, and robust chassis; evaluate ecological impacts and regulatory frameworks for GMO deployment	Addressing these challenges is vital for responsible and effective use of engineered biodegradation agents [6,41,44].
10	Underutilization of biofilm and immobilization technologies	Biofilm formation and enzyme immobilization strategies to enhance degradation rates and enzyme reuse are not fully optimized	Explore biofilm engineering and immobilization matrices to improve enzyme stability, substrate contact, and process scalability; test in diverse environmental settings	These approaches can significantly enhance biodegradation efficiency and operational feasibility [24,28,44].

CONCLUSIONS

The collective body of research underscores the critical and multifaceted role that diverse microorganisms—including bacteria, fungi, and actinomycetes—play in the biodegradation of plastic and microplastic waste. These microbial taxa exhibit a range of metabolic capabilities enabling the breakdown of complex synthetic polymers, with genera such as *Pseudomonas*, *Bacillus*, *Aspergillus*, and various actinomycetes frequently identified as efficient degraders. The synergistic interactions within microbial consortia, often combining bacterial and fungal species, have been shown to significantly enhance degradation efficiency through complementary enzymatic activities and metabolic cooperation. Such consortia outperform monocultures by facilitating cross-feeding mechanisms and providing a stable catalytic environment, although challenges remain in designing and maintaining robust, scalable consortia under variable environmental conditions.

Enzymatic degradation emerges as a pivotal mechanism, with PETase, cutinase, and laccase consistently recognized as key catalysts facilitating polymer hydrolysis, especially for polyethylene terephthalate and related polyesters. Advances in protein engineering,

including directed evolution and immobilization techniques, have substantially improved enzyme thermostability, catalytic efficiency, and operational resilience. Nevertheless, enzymatic degradation of more recalcitrant plastics like polyethylene and polypropylene remains limited due to their structural complexity and low bioavailability. The intricate enzyme-substrate interactions, influenced by polymer crystallinity and additives, require further elucidation to optimize degradation processes.

Metabolic pathway analyses reveal that microbes metabolize plastic-derived monomers by channeling them into central metabolic routes, such as the tricarboxylic acid cycle, supported by gene expression studies that highlight the inducible nature of hydrolytic enzymes. However, comprehensive mapping of these pathways and in situ validation remain incomplete, limiting the ability to fully harness microbial metabolism for plastic bioconversion. Environmental factors including temperature, pH, oxygen availability, and polymer properties critically impact microbial activity and enzyme function, necessitating integrated approaches that consider these variables in bioreactor design and field applications.

Despite promising biotechnological strides—such as synthetic consortia construction, enzyme engineering, and metagenomics-driven discovery—significant gaps persist in translating laboratory findings to real world scalability and sustainability. Methodological inconsistencies and a lack of standardized assessment metrics complicate cross-study comparisons and practical deployment. The integration of microbial degradation systems with existing waste management infrastructure, combined with advances in synthetic biology and ecological engineering, holds the greatest potential to overcome current bottlenecks. Overall, the literature converges on the view that microbial and enzymatic approaches represent a viable, environmentally friendly cornerstone for addressing plastic pollution, provided that future research prioritizes ecosystem-relevant conditions, mechanistic clarity, and scalable bioprocess development.

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AUTHOR CONTRIBUTIONS

For this systematic review article, the authors contributed as follows: Zuli Rodhiyah: Conceptualization of the research framework and objectives; development of the systematic review methodology including query transformation approach and inclusion/exclusion

criteria; supervision of all research activities; critical review and editing of the manuscript for intellectual content and scientific rigor; validation of data analysis and synthesis; project administration and coordination; funding acquisition and management of research resources.

Silvia Annur Annisa: Implementation of the systematic literature search across databases; execution of citation chaining (forward and backward); screening and assessment of 411 candidate papers; data extraction and curation from 50 core papers; formal analysis of thematic trends and chronological developments; preparation of the original manuscript draft including all sections (Introduction, Methods, Results, Discussion, Conclusion); creation of tables and synthesis of findings; visualization of data for presentation purposes.

Both authors contributed to the interpretation of findings, critical discussion of implications, and identification of research gaps. All authors have read and approved the final manuscript for publication.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise, that could have influenced the design, execution, interpretation, or presentation of this research. Specifically: Neither author has received payments or services from any organization that may gain or lose financially from the publication of this manuscript; The authors have no financial relationships with entities related to plastic manufacturing, waste management industries, or biotechnology companies that could be perceived as influencing the objectivity of this review; The funders (Research Management Centre, UTM) had no role in the design of the study; in the collection, screening, or analysis of literature; in the interpretation of data; in the writing of the manuscript; or in the decision to publish the results; and This research was conducted with complete academic independence, objectivity, and integrity in accordance with ethical standards for systematic reviews.

The authors affirm that all literature included in this review was selected based solely on scientific merit and relevance to the research questions, without bias toward or against any particular research groups, institutions, or methodological approaches.

Authors must identify and declare any personal circumstances or interest that may be perceived as influencing the representation or interpretation of reported research results. If there is no conflict of interest, please state "The authors declare no conflict of interest." Any role of the funding sponsors in the choice of research project; design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results must be declared in this section....

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