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Review

THE ROLE OF MICROORGANISMS IN THE BIOREMEDIATION OF MICROPLASTICSIN SOIL: SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

The Role of Microorganisms In The Bioremediation of Microplasticsin Soil: Systematic Literature Review. *Microplastic (MP) pollution is an environmental crisis that threatens the balance of ecosystems and biodiversity. This systematic review aims to examine the role of microorganisms in the bioremediation of microplastics in soil through biodegradation mechanisms. The method used was a systematic literature review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A total of 40 articles from reputable Scopus-indexed journals were selected based on keywords related to "soil contamination," "bioremediation," "microbes," "microplastics," "enzymatic degradation," "bacteria," "fungi," "algae," and "analytical methods." Unlike conventional methods, microbial bioremediation utilizes enzymatic activity, biofilm formation, and specific metabolic pathways to break down MP into simpler compounds that are harmless to the environment. The efficiency of MP degradation is influenced by various factors, such as polymer crystallinity, molecular weight, surface properties, and environmental conditions. Analytical approaches such as FTIR, SEM, TGA, GC-MS, HPLC, and gravimetric analysis play a crucial role in monitoring changes in polymer structure and identifying microbial biodegradation pathways. The results of the study indicate that bacteria, fungi, and algae are capable of degrading MP through enzymatic activity, biofilm formation, and specific metabolic pathways that convert complex polymers into simpler compounds.*

INTRODUCTION

Soil contamination is a serious environmental problem caused by the introduction of liquid, solid, or gaseous waste into the soil, particularly from human activities. This contamination can pose various ecological and health risks, while also leading to a decline in soil quality or fertility. Contaminated soil can disrupt biogeochemical cycles, reduce crop productivity, and harm biodiversity [(1)]. Soil contamination is one of the factors driving environmental degradation, including through pollution by microplastics (MP). MP are plastic particles smaller than 5 mm derived from synthetic fibers or the degradation of larger plastic items. MP can enter the soil through various pathways, such as the use of plastic mulch in agricultural activities, irrigation with domestic wastewater, and atmospheric deposition. The presence of MP has the potential to damage soil structure and fertility, affect microbial diversity, and disrupt nutrient cycles [2].

Microplastics are highly resistant and widespread in both terrestrial and aquatic ecosystems. Microplastics can settle from the air onto the ground, thereby increasing contamination levels [3]. One of the largest sources of microplastics is the abrasion of vehicle tires during use, which releases significant amounts of particles [4]. Asphalt containing plastic polymers also contributes to MP formation through wear and degradation [5]. Additionally, plastic waste such as bags and bottles fragments into MP over time due to environmental exposure [6]. The use of plastic film in agriculture also contributes to MP pollution as the material degrades. Everyday activities such as washing clothes and disposing of household waste are also sources of MP release into the environment [7].

Microplastic (MP) removal techniques are a critical aspect of efforts to address environmental pollution, particularly in terrestrial ecosystems. Various methods have been developed to remove MP, each with different mechanisms of action and levels of efficiency. Currently, spectroscopic techniques are the most commonly used methods for detecting and characterizing MP, although the technology's ability to detect and remove extremely small particles remains limited. In addition, several MP removal methods have been implemented, including filtration, electrocoagulation, biodegradation, adsorption, and coagulation-flocculation. These methods show potential for reducing MP concentrations in the environment, although their effectiveness depends heavily on particle size, polymer type, and environmental conditions. Various MP remediation efforts have shown promising results; however, challenges remain in their large-scale implementation and in maintaining efficiency under diverse environmental conditions.

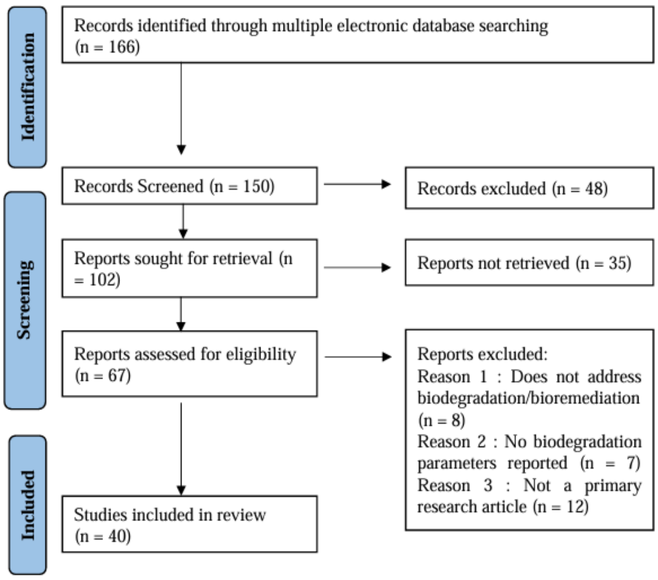
Previous review articles have focused only on specific groups of microorganisms, particularly bacteria, and have addressed only the general mechanisms of MP biodegradation [7]. Studies that integrate the roles of bacteria, fungi, and algae in the bioremediation of MP in soil and discuss the factors affecting degradation efficiency and the analytical methods used in the biodegradation process remain relatively limited. Therefore, further research is needed to optimize these methods so they can be widely applied. One emerging approach is the removal of MP through bioremediation, which is viewed as an environmentally friendly method with the potential to effectively address MP contamination in various ecosystems, particularly terrestrial ecosystems. Bioremediation harnesses the natural ability of microorganisms to degrade plastic materials through enzymatic processes, thereby offering a more sustainable alternative to traditional remediation techniques. Several studies have shown that various microorganisms play a role in the MP bioremediation process, including bacteria, fungi, and algae, which have the ability to degrade plastic polymers through specific biochemical mechanisms [8].

Bioremediation has a number of advantages that make it a potential alternative for addressing MP pollution. From an economic perspective, this method is generally more efficient than other remediation techniques because it does not require complex equipment, saves costs, and does not produce secondary pollutants [9]. Recent studies show that bioremediation can achieve more than 95% efficiency in removing MP from wastewater [10]. Furthermore, bioremediation offers a sustainable solution by harnessing the ability of microorganisms to degrade plastic polymers through environmentally friendly biological processes. In line with this, the objective of this Systematic Literature Review (SLR) is to identify and analyze the effectiveness of bioremediation by various types of microbes against diverse types of MP, as well as the enzymes used in the MP degradation process.

MATERIALS AND RESEARCH METHODS

A comprehensive literature search was conducted using the ScienceDirect electronic database, focusing on articles indexed in Scopus. The following keywords and phrases were

used: “soil contamination,” “microbial bioremediation,” “microbials” combined with “microplastics,” “enzymatic degradation,” “bacteria,” “fungi,” “algae,” “analytical methods,” and “biodegradation efficiency.” The selected studies were systematically reviewed for relevance, quality, and alignment with the objectives of the systematic review and inclusion criteria; Articles highlighting cases of MP contamination in soil, the role of microorganisms such as bacteria, fungi, and algae in MP degradation, exploring enzymatic degradation mechanisms and microbial metabolic pathways involved in plastic biodegradation, as well as articles published between 2021 and 2025.
Articles that met the inclusion criteria were then evaluated based on topic relevance, clarity of research methodology, and the alignment of research findings with the study’s objectives. Data from each article were then systematically extracted, including author names, year of publication, types of microorganisms studied, types of microplastics, biodegradation mechanisms, and key findings relevant to the study’s objectives. These extracted data served as the basis for the analysis to identify the role of microorganisms in the bioremediation of MP in soil. Forty articles were analyzed using parameters identified based on the PRISMA framework, as presented in Figure 1.



Source: PRISMA 2020 flow diagram
Figure 1. PRISMA Flowchart for the Article Review Process

RESEARCH RESULTS AND DISCUSSION
Bioremediation has emerged as a sustainable and environmentally friendly method for minimizing the negative impacts of MP and addressing the ecological consequences it causes. Unlike physical and chemical approaches, biological methods rely on milder operating conditions, require low energy consumption, and produce fewer and non-hazardous byproducts, making them better suited to the balance of natural ecosystems [(11)]. The bioremediation process leverages the degradation capabilities of microbes and flexible enzymatic activity, as microorganisms can adapt to various environmental conditions and target a wide range of polymer types. Furthermore, bioremediation aligns with the principles of the circular economy because it converts MP waste into valuable products, such as bioenergy and biomass, thereby offering a cost-effective solution that can be implemented on a large scale, particularly in areas with limited resources [(12)].

MP consists primarily of polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (Table 1), and is highly durable due to its stable chemical structure and additional additives. Suboptimal waste management, low recycling rates, and excessive plastic use can lead to its accumulation in terrestrial ecosystems, thereby adversely affecting biodiversity and human health [(13)]. Microbial bioremediation is increasingly being reported as a promising approach for MP degradation, with bacteria, fungi, and algae demonstrating enzymatic potential in breaking down polymers. However, degradation efficiency is influenced by the type of polymer, the degree of crystallinity, and surface functional groups [(14)]. Efforts to enhance microbial activity through bioaugmentation and biostimulation have shown positive results [(15)]. Thus, bioremediation serves as a sustainable alternative that supports environmental resilience and pollution mitigation.

Table 1. Types of Microplastics (MP) and Physical Characteristics

No.	MP Type	MP Form	MP Size(μm)	References
1	PVC	Spherical	0,1–1,0	(16)
2	PET	Amorf	75–300	(7)
3	PE, PP, PET, PVC, PS	Fragment	< 5000	(17),(18),(19)
7	Polyester, acrylic, PET, PS, nylon, PVA.	Film	100–5000	(20),(21),(22)
8	PE, PP, PET, PS, PVC	Film, fiber, fragment, styrofoam	100–5000	(23),(24),(23),(25)
9	PE, PP, PS, PET, PVC, PUR, PVA, PLA	Particle, fragment, fiber	< 5000	(26)
10	PVC	Pristine & aged	1	(16),(27),(28),(8)
12	Polyester, acrylic, PET, PS, nylon, PVA.	Fragment	< 5000	(29),(30),(9),(10)
13	PVC	Film	< 5000	(12),(31)
14	PET	Film, pellet, foam	< 5000	(32)
15	PP	Fragment	±1000	(33), (34)

Based on Table 1, it is evident that the MP reported in various studies exhibit high diversity in terms of polymer type, morphological form, and particle size. The most commonly found polymers include PVC, PET, PE, PP, PS, as well as other synthetic polymers such as polyester, acrylic, nylon, PVA, PUR, and PLA. The dominance of these polymers reflects global consumption patterns, particularly packaging plastics (PE, PP, PET, PS) and construction or industrial materials (PVC), indicating that the primary sources of MP in the environment are closely linked to everyday anthropogenic activities. Fragments, particles, and fibers are the most commonly reported forms, followed by films and styrofoam. This suggests that the majority of MP originates from the fragmentation of large-sized plastics due to physical, chemical, and biological processes in the environment.

The presence of fibers, which are commonly associated with polyester, acrylic, and nylon, indicates a significant contribution from textile waste and laundry activities, particularly in terrestrial and aquatic ecosystems near residential areas. Meanwhile, the recorded size range of microplastics is very broad, ranging from the submicron scale (0.1–1.0 μm) to <5 mm, which is the general threshold for defining microplastics. The discovery of very small particles, approaching nanoplastic size, in spherical PVC confirms that microplastics have the potential for a high specific surface area, making them more chemically reactive and more likely to interact with microorganisms and other contaminants. In contrast, larger microplastics ranging from hundreds of micrometers to millimeters generally retain their original polymer characteristics and exhibit lower levels of degradation.

Interestingly, several studies have also distinguished between pristine (pure) and aged (processed) PVC with different particle sizes (1 µm and 150 µm). These conditions indicate that the aging process resulting from UV exposure, oxidation, and environmental abrasion plays a significant role in altering the physical and chemical properties of MP, including increasing surface roughness and introducing a functional group into a molecule (compound) through chemical reactions [16]. These changes have the potential to increase the susceptibility of MP to microbial colonization and biological degradation; thus, aging can be viewed as a crucial initial stage before bioremediation can proceed effectively.

The diversity of polymers and MP morphologies (Table 1) indicates that bioremediation cannot be viewed as a single universal process but rather depends heavily on the intrinsic characteristics of the MP. Polymers such as PET and PVC, which have more stable chemical bonds, tend to be more resistant to biological degradation than PE or PP, thus requiring specific microorganisms or enzymes. Similarly, fiber and film forms with high surface-area ratios are potentially more easily colonized by microbes than fine spherical particles. Particle size also has a direct impact on bioremediation efficiency. Small-sized MP provide a larger contact area for enzymes, but at the same time can disperse more easily and are difficult to separate from the environmental matrix. The following section will describe the mechanisms of MP degradation from various polymer sources through bioremediation by microorganisms.

Mechanism of MP Biodegradation by Bacteria

The degradation of MP in the environment is a biological process involving several stages, including microbial colonization, enzymatic activity, and intracellular metabolism. These stages are influenced by environmental factors as well as the physicochemical properties of each type of MP. Microorganisms secrete various enzymes, such as esterases, lipases, oxygenases, laccases, and peroxidases, which contribute to the fragmentation and functionalization of plastic polymers. This entire degradation process is influenced by environmental factors such as nutrient availability, oxygen levels, and polymer surface characteristics, which ultimately determine the rate of MP biodegradation. This process is based on enzymatic activity, biofilm formation, and microbial metabolism [9]. Enzymatic degradation (Table 2) is generally mediated by hydrolases, oxidases, and peroxidases. For example, esterases and lipases target polyester-based plastics, while oxygenases trigger the oxidation of polyolefin-based plastics such as PE and PP, facilitating further degradation [6]. These processes are often accelerated when microorganisms form biofilms on the surface of microplastics, creating a microenvironment rich in enzymes and metabolites that accelerate degradation [3].

Table 2. Mechanisms of MP Degradation by Bacteria

No.	Bacteria	MP Type	Degradation Mechanisms	Enzymes	Efficiency (%)	Duration (Days)	Analytical Instruments	References
1	Achromobacter	PET	Hydrolysis of ester bonds	Esterase	5	14–60	Penurunan massa, FTIR	(17),(35)
2	Rhodococcus sp. XY-1	PE, PS	Surface oxidation is followed by enzymatic depolymerization	Oxygenase	8	30–180	FTIR, SEM, GC-MS	(19),(20),(21)

No.	Bacteria	MP Type	Degradation Mechanisms	Enzymes	Efficiency (%)	Duration (Days)	Analytical Instruments	References
3	Pseudomonas sp.	PE, PP	Polymer chain cleavage through biofilm oxidation	Laccase, peroksidase	10	30–120	SEM, FTIR	(27)
4	Ideonella sakaiensis	PET	Enzymatic hydrolysis, assimilatory depolymerization	PETase, MHETase	30	7–30	FTIR, TGA, DSC, enzim assay;	(16),(36)
5	Comamonas acidovorans	PUR	Depolymerization of urethane bonds	Urethanase esterase	40–60	7–21	FTIR, GPC, gravimetri	(22),(23),(25)
6	Bacillus sp	PE, PS, PET	Enzymatic degradation of biofilm surfaces	Esterase,lipase, oxidoreductase	8	30–180	FTIR, SEM, GC–MS	(37),(1)
7	Bacillus cereus	LDPE	Enzymatic degradation by biofilms	Esterase, lipase	78,62 ± 2,16	21	Gravimetri	(38)
8	Streptomyces sp.	PE, PS	Surface oxidation modification	Peroxidase, oxidase	5	60–180	SEM, FTIR, gravimetri	(16),(28)
9	Pseudomonas knackmussii	PE	Oxidation of C–C bonds	Hydroxylase, monooxygenase	5.95	56	FTIR	(10)
10	Lysinibacillus sp.	PP	Surface erosion and oxidation	Hydrolase, esterase	9	26	SEM	(26),(12)
11	Pseudomonas sp.	PE	Oxidation of the C–C bond-breaking surface	Alkane monooxygenase, peroksidase	±5–15	30-90	FTIR, SEM,	(31)
12	Rhodococcus ruber	PE	Plastisphere biofilm, oxidation, and partial depolymerization	Oxygenase, dehydrogenase	±8–20	60-90	FTIR, SEM, GC-MS	(32),(6),(15)
13	Bacillus cereus	PET	Ester hydrolysis, monomer	*Esterase,cutinase*	±10–18	60–90	FTIR, HPLC	(39),(33)
14	Sphingomonas sp.	PS	Oxidation of aromatic rings	*Dioxygenase, laccase-like*	±5–10	60–120	FTIR, GC-MS	(12)
15	Bacillus flexus	PET	Hydrolysis of ester bonds	*Lipase, cutinase*	±12–18	60–90	FTIR, HPLC	(34),(40)

The degradation of MP by bacteria is greatly influenced by the type of polymer, its chemical structure, and the metabolic capacity of the bacteria to initiate polymer chain activation. In polyethylene (PE) polymers, the biodegradation process generally begins with surface oxidation involving oxygenase enzymes, followed by chain fragmentation and the bioassimilation of low-molecular-weight fragments (<500 g/mol). Theoretically, PE degradation requires the conversion of an inert hydrophobic structure into more reactive polar compounds, which can then be metabolized via the β-oxidation pathway [41]. A number of bacteria, particularly those from the genera Rhodococcus, Pseudomonas, and Bacillus, demonstrate a significant ability to initiate this process through biofilm formation and the production of oxidative enzymes such as alkane monooxygenases, peroxidases, and dehydrogenases.

Rhodococcus ruber consistently demonstrates the best performance compared to other bacteria. This bacterium is capable of achieving degradation efficiencies in the range of 8–20% within 60–90 days, which is higher and more stable than that of Pseudomonas spp. or Bacillus spp. The superiority of R. ruber is primarily attributed to its ability to form a robust biofilm on polymer surfaces and to produce oxidative enzymes, including laccase and oxygenase, which play a role in the partial cleavage of C–C bonds. Furthermore, the laccase produced by Rhodococcus has been reported to contribute to the formation of carbonyl groups on the PE surface, thereby increasing the polymer's susceptibility to further degradation [8].

In polypropylene (PP), which has a structure similar to PE but with a higher degree of crystallinity due to the presence of methyl groups, biodegradation efficiency is generally lower. PP degradation is also dominated by oxidative mechanisms, beginning with bacterial colonization of the surface and the introduction of polar functional groups through the activity of oxygenases and oxidoreductases. Among the reported bacteria, Pseudomonas spp. exhibit relatively better PP degradation efficiency (approximately 5–15%) compared to other genera. The advantage of Pseudomonas lies in its metabolic flexibility and its ability to produce various oxidative enzymes, including alkane monooxygenases and dehydrogenases, which enable the initial activation of the polymer chain and gradual fragmentation. These findings reinforce previous reports that Pseudomonas putida, Bacillus cereus, and Rhodococcus ruber are the primary early colonizers on PP surfaces in biodegradation systems [24].

Unlike PE and PP, ester-bond-based plastics such as polyethylene terephthalate (PET) and polyurethane (PUR) exhibit much higher rates of biodegradation. In PET, the degradation mechanism is dominated by the hydrolysis of ester bonds catalyzed by specific enzymes such as PETase and MHETase. In this regard, Ideonella sakaiensis is the most efficient bacterium reported in the literature, with PET degradation efficiency reaching approximately 30% in a relatively short time (7–30 days). This high effectiveness is due to the presence of a well-defined degradation pathway, in which PET is directly depolymerized into terephthalate monomers and ethylene glycol, which can be immediately assimilated by bacterial cells.

Meanwhile, PUR degradation showed the highest efficiency compared to other types of MP, particularly by Comamonas acidovorans, which was able to achieve degradation efficiencies of up to 40–60%. This success is closely related to the bacteria's ability to produce urethanase and esterase, which directly break urethane bonds, allowing the degradation process to proceed more quickly and efficiently than with hydrocarbon plastics. Overall, findings from various studies indicate that the most effective bacteria for MP biodegradation depend heavily on the compatibility between the types of enzymes produced and the chemical structure of the target polymer. Rhodococcus ruber stands out as the best degrader for PE, Pseudomonas spp. for PP, Ideonella sakaiensis for PET, and Comamonas acidovorans for PUR; thus, these four bacteria have great potential for further development in MP bioremediation strategies through microbial degradation by bacteria.

Although various bacteria have shown potential in degrading microplastics, their application on a field scale still faces a number of limitations. Complex and heterogeneous natural environmental conditions such as variations in temperature, pH, humidity, and UV radiation as well as the physicochemical characteristics of microplastics (size, shape, density, and hydrophobicity) can affect bacterial colonization and the efficiency of the biodegradation process. Small microplastics tend to migrate to deeper soil layers, making them less accessible to bacteria. Furthermore, the uneven distribution of MP and its interaction with soil particles can reduce contact between bacteria and the plastic substrate [17]. These factors cause the rate of biodegradation in the environment to be generally slower than the results obtained under controlled laboratory conditions.

Mechanisms of MP Biodegradation by Fungi

Fungi play a key role in the initial depolymerization stage, primarily due to their ability to produce large quantities of nonspecific extracellular enzymes. The mechanism of polymer degradation by fungi begins with the adhesion and penetration of hyphae onto the polymer surface, followed by the secretion of oxidative and hydrolytic enzymes such as laccase, lignin peroxidase (LiP), manganese peroxidase (MnP), cutinase, esterase, and urethanase. These enzymes are capable of oxidizing or hydrolyzing polymer bonds in both hydrocarbon-based plastics (PE, PP, PS) and ester-based plastics (PET, PUR).

Fungi show significant potential for the biodegradation of MP through enzymatic and biofilm-mediated degradation mechanisms, with degradation efficiency strongly influenced by the type of polymer and the enzymes produced (Table 3). Based on the analyzed literature, Fusarium solani and Aspergillus tubingensis are the fungi with the highest degradation efficiency, particularly against ester-based polymers such as PET and PUR, with efficiencies reaching 20–50% within a relatively short time. This advantage is primarily due to the ability of these two fungi to produce specific hydrolytic enzymes, such as cutinase, esterase, and urethanase, which can directly break ester and urethane bonds, thereby accelerating the depolymerization of MP.

Table 3. Mechanisms of MP Degradation by Fungi

Fungi	MP Type	Degradation Mechanisms	Enzymes	Efficiency (%)	Duration (Days)	Instruments	References
Lasiodiplodia theobromae	PP	Oksidasi & Fragmentasi rantai polimer	Laccase	1,3	90	FTIR, SEM, DSC, viskositas, BM rata-rata	(4),(39)
Aspergillus niger	PE, PP	Oksidasi permukaan & depolimerisasi parsial melalui penetrasi hifa	Laccase, esterase, peroxidase	3-15	30-90	FTIR, SEM, gravimetri	(34),(19)
Penicillium simplicissimum	PE	Degradasi oksidatif yang dimediasi oleh biofilm	Laccase,	5-12	60-120	FTIR, SEM, XRD	(17),(19),(25)
Fusarium solani	PET, PUR	Hidrolisis ikatan ester	Cutinase, esterase, urethanase	20-50	14-60	FTIR, HPLC	(23),(38),(16)
Aspergillus tubingensis	PET	Depolimerisasi enzimatik	Cutinase-like enzyme	25-35	14-30	FTIR, HPLC, TGA	(8),(29),(9)
Penicillium sp.	LDPE	Biofilm	Laccase	5.25	30	SEM, FTIR	(18),(36),(10),(40)
Fusarium oxysporum	LDPE	Kolonisasi	Laccase	2,4	30	SEM	(24),(34),(25)
Fusarium solani	PP	Depolimerisasi enzim oksidatif	Laccase	2.36	30	GPC	(37),(1),(27)
Penicillium olsonii	PP	Bioflm	Laccase	2.94	30	FTIR	(28),(26)

In contrast, fungi that degrade hydrocarbon polymers such as PE, PP, and LDPE including Penicillium sp. and Laccidiodendron theobromae generally exhibit lower degradation efficiency (<10%). This is related to the stability of the C–C bonds in these polymers, which are difficult to break down enzymatically. Nevertheless, biofilm formation and initial oxidation processes carried out by these fungi play a crucial role in modifying the surface of microplastics (MP), thereby increasing their susceptibility to further degradation by other microorganisms.

Fungi act as active degraders through enzymatic mechanisms and have the potential to be applied in the bioremediation of microplastics (MP) on a field scale, particularly through their association with plants. Mycorrhizal fungi, such as Arbuscular Mycorrhizal Fungi (AMF), which are found in approximately 90% of plant species, are known to enhance phosphorus uptake and help plants cope with various environmental stresses, including plastic and heavy metal contamination. Several soil fungi, such as Laccaria laccata, have been reported to degrade various types of microplastics including polystyrene (PS), polylactic acid (PLA), and polyethylene terephthalate (PET) through enzymatic activity that breaks the polymer's carbon chains [17].

The ability of fungi to colonize plant root systems, produce extracellular enzymes, and interact synergistically with other microorganisms indicates that fungi have the potential to serve as effective and sustainable bioremediation agents for application in agricultural land and soil ecosystems contaminated with microplastics. This is further supported by the use of analytical instruments on various fungal species; several studies report that FTIR is frequently used in microplastic (MP) remediation studies because it can detect specific chemical structural changes in polymers, allowing for comparisons of pre- and post-treatment conditions, and is relatively fast and non-destructive for analyzing MP degradation. These findings confirm that an effective MP bioremediation strategy must combine fungi with direct degradation mechanisms and supporting microorganisms within a consortium system.

Mechanisms of MP Biodegradation by Algae

The types of polymers most frequently reported to interact with algae are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), which are conventional plastics with stable carbon–carbon bond structures and hydrophobic properties. The predominance of these polymer types indicates that research has focused primarily on the most persistent plastics commonly found in the environment. The identified degradation mechanisms generally include biofouling, surface colonization by algae, biofilm formation, oxidative stress resulting from photosynthetic activity, and physical erosion of the plastic surface. Algae act as initiators of early degradation by modifying the physical and chemical properties of the microplastic surface, rather than as agents that directly break the polymer chains. Algae contribute to PP degradation through the secretion of oxygenases and hydrolases that oxidize the polymer surface and promote subsequent microbial attack [42].

Algae are rarely reported to produce specific enzymes capable of directly breaking polymer bonds, but they play a crucial role in the conditioning stage of MP degradation. The mechanisms involved include biofouling, the formation of photosynthetic biofilms, and photobiological oxidation (Table 4). In terms of organism type, green algae (Chlorophyta) such as Chlorella vulgaris, Scenedesmus obliquus, and Dunaliella salina are the most promising group for supporting MP biodegradation. This group has a high capacity to produce Extracellular Polymeric Substances (EPS), which enhance biofouling and biofilm formation on plastic surfaces. In addition, the photosynthetic activity of green algae can produce reactive oxygen species (ROS) that trigger polymer surface oxidation, thereby increasing the susceptibility of MP to further degradation.

In addition to playing a role in the oxidation of MP, ROS are also known to form as a biological response to MP exposure. MP exposure can trigger increased ROS production, leading to oxidative stress in various organisms. In microalgae, ROS are not only produced during photosynthesis, but their production can also increase when cells experience environmental stress, including as a result of interactions with MP (1). Thus, the presence of ROS in the alga–MP system serves a dual role: as an agent that accelerates changes in MP surface properties and as an indicator of the alga's physiological response to MP exposure.

Table 4. Mechanisms of MP Degradation by Algae

Algae	MP Type	Degradation Mechanisms	Enzymes	Efficiency (%)	Duration	Analytical Instruments	References
Chlorella vulgaris	PE, PP	Biofouling	NA	2–10	30-120	FTIR, SEM	(9)
Scenedesmus obliquus	PE	Algal Colonization	NA	NA	14–30	SEM, FTIR	(30)
Alga hijau & alga merah.	PVC, PET	Biofilm, EPS secretion	Enzim hidrolitik	NA	NA	SEM, FTIR	(7)
Chlamydomonas reinhardtii	PS	Oxidative stress induced by photosynthesis	NA	NA	7–21	SEM, FTIR	(10)
Nannochloropsis sp.	PE	Biofilm formation and (non-degradative) adsorption	NA	NA	14	SEM	(35)
Dunaliella salina	PE	Algal buildup and physical surface erosion	NA	NA	21–30	SEM	(6)

The lack of information in some table columns, such as enzymes and degradation efficiency, reflects the limitations of the methodological approaches in existing studies. Most studies do not report specific enzymes because algae are generally not the primary producers of plastic depolymerase enzymes, unlike bacteria and fungi. This situation opens opportunities for further research to identify the possible involvement of other mechanisms in MP degradation by algae. Research has focused more on indirect indicators, such as changes in surface morphology and plastic functional groups, which were analyzed using SEM and FTIR. Furthermore, MP degradation efficiency is rarely reported quantitatively due to the lack of established standards for measuring MP biodegradation by algae; consequently, researchers tend to be cautious when drawing conclusions about the extent of degradation.

Cyanobacteria and other photosynthetic algae also play an important role in creating microhabitats that support the colonization of degrading bacteria, although their contribution to direct degradation is relatively limited. Microalgae such as Chlorella vulgaris and Scenedesmus obliquus have often been reported to cause physical and chemical changes in PE, PP, and PS microplastics during long-term incubation. Algae act as facilitators of degradation by altering the surface and environmental conditions of the microplastics.

Overall, bacteria, fungi, and algae play complementary roles (Figure 2) in the bioremediation of MP. Bacteria play a primary role in biodegradation through the production of various extracellular enzymes capable of breaking down polymer chains into simpler compounds. Fungi contribute by penetrating with their hyphae and producing oxidative enzymes that are effective in degrading complex polymers, thereby accelerating the fragmentation and mineralization of MP. Meanwhile, algae play a role primarily during the initial stage (conditioning stage) through biofilm formation, biofouling, and photobiological oxidation processes that alter the surface properties of MP, making it easier for other microorganisms to colonize and degrade it. Thus, the success of MP bioremediation does not depend on a single group of microorganisms, but rather on the synergistic interaction between bacteria, fungi, and algae within a microbial community.

Although it shows promising potential, the application of MP bioremediation on a field scale still faces various challenges. Degradation effectiveness is greatly influenced by environmental conditions, such as temperature, pH, salinity, nutrient availability, light intensity, and the type of MP exposed. In addition, the stability of the microbial community during the bioremediation process must be maintained so that degradation activity can proceed consistently. Other challenges include the low degradation rates of certain highly resistant polymers and the limited information regarding the long-term efficiency and sustainability of the process. Therefore, further research is needed to optimize environmental conditions, enhance the stability of the bioremediation system, and evaluate its effectiveness on a larger scale and over a longer period of time.

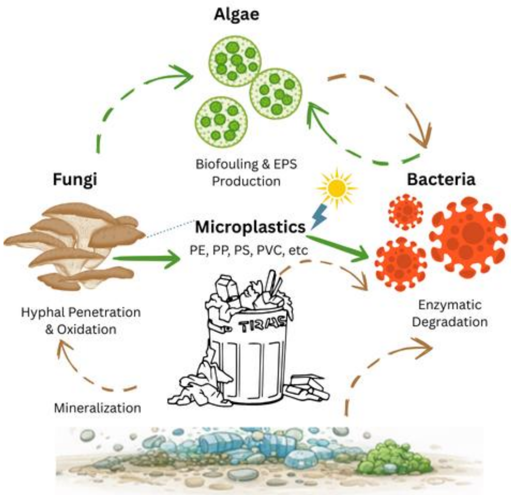


Figure 2. Illustration of the Synergistic Interaction Model of Microorganisms in Biodegradation

CONCLUSIONS AND RECOMMENDATIONS

Based on a systematic review of 40 selected articles, it can be concluded that microbial bioremediation is a promising and sustainable approach to addressing MP contamination in soil. Bacteria, fungi, and algae exhibit specific capabilities in degrading MP through a combination of enzymatic activity, biofilm formation, and specific metabolic pathways that enable the transformation of complex polymers into simpler compounds. Among these three groups of microorganisms, bacteria are the most frequently reported and demonstrate the most consistent biodegradation effectiveness, particularly through the production of extracellular enzymes that play a role in breaking polymer chains. The effectiveness of the biodegradation process is determined not only by the type of microorganism but is also significantly influenced by the physicochemical characteristics of MP, such as crystallinity, molecular weight, and surface properties, as well as the environmental conditions under which degradation occurs. Thus, these findings confirm that microbial bioremediation holds great potential as an environmentally friendly alternative solution; however, its application requires a comprehensive understanding of the interactions between microorganisms, MP, and the environment.

Nevertheless, this review has several limitations. The study was based only on articles that met the selection criteria in the databases used, so it is possible that relevant research from other sources was not included. In addition, variations in research methods, types of MP, environmental conditions, and biodegradation measurement parameters across studies limit the ability to directly compare results. Therefore, future research is recommended to focus on optimizing various types of microorganisms to improve the efficiency and stability of the MP biodegradation process, as well as standardizing biodegradation evaluation methods to produce more comparable data. Future research is also recommended to focus on optimizing other types of microorganisms to improve the efficiency and stability of the MP biodegradation process on a larger scale.

ETHICAL APPROVAL

This study did not require formal ethical approval because it is a systematic literature review based exclusively on published scientific literature. No human participants or personal data were involved in this research.

CONFLICT OF INTEREST

The author declares that there are no financial, institutional, commercial, or personal interests that could influence the design, analysis, interpretation, or publication of this study. All findings and conclusions in this article are based on scientific evidence obtained from a systematic review of the literature. The author assumes full responsibility for the content and scientific quality of this manuscript.

AUTHOR CONTRIBUTIONS

Rahma Fauziah Herlanda (RFH): research conceptualization, literature review, article selection and extraction, data analysis, manuscript drafting, and manuscript revision. Fitri Khoerunnisa (FK): supervision, methodology validation, critical review, editing, and manuscript refinement. All authors have read and approved the final version of the manuscript.

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