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REVIEW ARTICLE

The plastisphere: from microbial pollution to biodegradable solution

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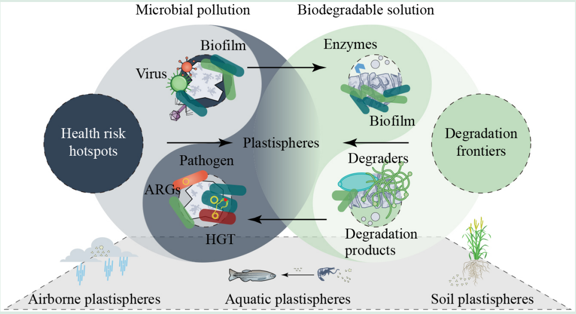
HIGHLIGHTS

- The plastisphere enriches pathogens and antimicrobial resistance genes.
- Microplastics pose serious ecological risks, ultimately threatening human health.
- Biodegradation is a promising technology for mitigating plastic pollution.
- A dual-dimensional framework for sustainable biodegradation.



ABSTRACT: Microplastic pollution is threatening planetary health and sustainable development. The microbiota colonizing microplastic surfaces, termed the plastisphere, has emerged as artificial niches that harbor both microbial risks and novel biodegradation potential. However, these two aspects of the plastisphere have often been investigated in isolation. In this review, we first elaborate on how microplastics act as vectors in facilitating the enrichment and dissemination of pathogens, antibiotic resistance genes (ARGs), and even virus, thereby causing serious microbial and ecological risks, and eventually impacting human health. To address the potential risks, the key plastic-degrading resources, the underlying mechanisms, and recent advances in biodegradation technologies are synthesized. Given

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the dual roles of plastisphere microbes, we therefore propose a two-dimensional screening framework to identify safer and more efficient degraders. This review aims to guide the selection or synthesis of safe and highly efficient degrading microbial consortia, thereby providing sustainable and eco-friendly strategies for mitigating plastic pollution.

KEYWORDS: Plastisphere, Microbial risks, Ecological impacts, Human health, Biodegradation

1 Introduction

Plastics, as typical synthetic polymers, have been extensively used in daily life and industrial applications since the 1950s due to their low cost, light weight, and durability (Geyer et al., 2017). Global plastic production reached 430.9 million tons in 2024 and is projected to increase to 1.231 billion tons by 2060 (Choi et al., 2023). This rapid growth has led to severe plastic waste pollution (Pottinger et al., 2024), which is now widely recognized as a planetary boundary threat (Steffen et al., 2015; Arp et al., 2021).

Plastics break down into microplastics (< 5 mm) through physical, chemical and biological processes, which have become pervasive across aquatic (Thompson et al., 2004, 2024), terrestrial (Büks and Kaupenjohann, 2020; Hanif et al., 2024), and atmospheric ecosystems (Prata, 2018; Peijnenburg, 2025). These particles provide a distinct ecological niche for microbial colonization, forming the "plastisphere" (Zettler et al., 2013; Amaral-Zettler et al., 2020). Studies indicate that this niche contributes to biogeochemical cycling (Wang et al., 2024a), also serving as a vector for potential pathogens (e.g., some species from *Vibrio*, *Pseudomonas*, and *Acinetobacter* genera) and antibiotic resistance genes (ARGs) (Flemming and Wingender, 2010; Zettler et al., 2013; Sun et al., 2025). Notably, biofilms on microplastics enhance the adsorption of metals and organic pollutants (Li et al., 2018, Li et al., 2024a; Mao et al., 2020; Bhagwat et al., 2021), which may further facilitate the dissemination of antibiotic resistance and induce serious microbial risks.

Moreover, microplastics pose multidimensional and complex ecological risks across various environmental compartments. For instance, in aquatic ecosystems, they not only cause direct physical harms to organisms (Eerkes-Medrano et al., 2015), but also leach inherent chemical additives (e.g., plasticizers, flame retardants) and serve as carriers for adsorbed environmental contaminants (Godoy et al., 2019; Ivleva, 2021; Gulizia et al., 2023), thereby triggering synergistic effects. In terrestrial ecosystems, long-term microplastic exposure alters soil physical structure and chemical properties, disrupts microbial community composition and metabolic functions, and further impedes key nutrient cycling processes (Hanif et al., 2024; Wang et al., 2024a). All these consequences negatively affect the health of plants and animals and destabilize ecosystem populations. Particularly concerning is the capacity of microplastics to migrate across environmental media, propagate through food webs, and ultimately pose potential risks to human health (Seltenrich, 2015; Ivleva et al., 2017; Liu and You, 2023). Therefore, it is critical to carry out a comprehensive evaluation of microplastics' multidimensional risks including their environmental and health impacts.

Given the challenge of global plastic pollution, microbial degradation offers a promising mitigation strategy. This review synthesizes current understanding of the microbiota on microplastic surfaces and provides a comprehensive overview of the plastisphere's role as a vector for microbial risks and its function as a vital resource for novel biodegrading enzymes. By addressing the current challenges and highlighting the dual roles of these microbial communities, this review aims to provide a more holistic risk assessment framework and to facilitate the development of safe and effective bioremediation strategies to safeguard the planetary health.

2 Microbial risks of plastisphere

The plastispheres provide unique ecological niches for microbial colonization and biofilm growth, in which microbial communities are embedded in a matrix of extracellular polymeric substances (EPS), thus providing refuges for diverse microorganisms, including harmful pathogens and antibiotic resistant bacteria (ARB). Additionally, pollutants that accumulate on this surface, such as heavy metals and antibiotics, can drive the co-selection of antibiotic resistance and promote its dissemination via horizontal gene transfer. Consequently, the plastisphere acts not only as a reservoir for diverse microbes but also as a potential vector for their transport across different environments, thereby posing significant microbial risks.

2.1 Antimicrobial resistance in plastisphere

2.1.1 Abundance of antimicrobial resistance in plastisphere

Plastispheres are reported as important reservoirs for antimicrobial resistance (AMR) in various environments. For instance, several studies have revealed that aquatic plastispheres harbor ARGs and ARB (Yang et al., 2020a; Sathicq et al., 2021; Luo et al., 2023; Li et al., 2024b). The abundance of ARGs in the plastispheres was reported to be about 3-fold higher than that in surrounding water, while no significant differences were observed between plastispheres and natural surfaces (i.e., rock and leaf) (Wu et al., 2019). Moreover, soil plastispheres showed 2–3 fold higher abundance of ARGs than bulk soil (except for polyvinyl chloride (PVC)) across various microplastics and soil types, especially under some global change factors (Zhu et al., 2022). A previous study showed that microplastic diversity including variations in color, shape, and polymer types, significantly increased ARG abundances (Wang et al., 2024c). Furthermore, degradable and non-degradable microplastics were found to enrich distinctly different ARG patterns (Sun et al., 2021b). In addition to the plastispheres in water and soil environments, air plastispheres also enriched ARGs, with notably a significantly higher abundance found on biodegradable plastispheres than on conventional ones (Peng et al., 2022).

2.1.2 Factors influencing antimicrobial resistance dissemination

The plastisphere is usually considered a hotspot for gene transfer because the embedded bacteria are enclosed within a matrix of EPS and in closer contact with each other compared to those in aquatic or soil environments. It was reported that higher gene exchange frequency was found in the plastisphere compared to free-living microbes in the aquatic environment (Arias-Andres et al., 2018; Yang et al., 2025a). As a hydrophobic substrate, microplastics can readily accumulate inorganic and organic micropollutants in the environment, such as heavy metals (Ashton et al., 2010; Mao et al., 2020), antibiotics (Gouin et al., 2011; Li et al., 2018), PAHs (Teuten et al., 2007), and other persistent organic pollutants (POPs) (Rios et al., 2007). These chemicals were documented to drive the co-selection of antibiotic resistance (Ye et al., 2017; Arias-Andres et al., 2018; Murray et al., 2024), thus making microplastics a specific and even favorable niche for dissemination of antibiotic resistance.

However, it should be noted that microplastic-mediated HGT was highly dependent on microplastic size and plasmid type (Hu et al., 2022; Wang et al., 2022b; Kang et al., 2025). For example, polystyrene (PS) with nanosize significantly impacts the transformation and conjugation process. Recent study revealed that PS particles with 500 nm size created steric effects to impede bacterial interactions, thus decreasing conju-gation frequency of plasmid pYYD01 (Liu et al., 2023). In addition, PS particles promoted the transformation frequency of high replicate plasmid pUC19, but decreased that of the low replicate plasmid pSTV29 and pBR322 (Hu et al., 2022). The proposed enhancing mechanism was that PS particles damaged the lipids membrane and induced pore formation on the cell membrane (Liu et al., 2023). Microplastics can also stimulate the expression of conjugal genes and SOS response genes, thus promoting the HGT of antibiotic resistant plasmids (Yang et al., 2025b). Furthermore, microplastics significantly extended the phylogenetic range of the transconjugal pool, posing additional AMR challenges by increasing the spread of plasmids across natural bacterial populations (Yang et al., 2025b).

2.1.3 Risk assessment of antimicrobial resistance

The AMR risks in plastisphere are governed by a complex interplay of factors related to the properties of plastics and the surrounding environment. The physicochemical properties of the plastic, including polymer type, surface roughness, and chemical additives, influence the initial microbial colonization and subsequent biofilm development (Su et al., 2021; Lin et al., 2024; Pang et al., 2024). For instance, a previous study reported that the microplastic types significantly affected the distribution and dissemination risk of ARGs. Among five commonly used microplastics including polyethylene (PE), polypropylene (PP), PS, polyethylene-fiber (PEF), and polyethylene-fiber-polyethylene (PFP), PP exhibited the highest ARG abundances and dissemination risk (Li et al., 2021). The long-term weathering process increased the release of chemical additives (e.g., plasticizer, antioxidants, and metals) and the generation of nanoplastics (Luo et al., 2023). Recent studies have reported that plasticizers and nanoplastics could promote the HGT of ARGs (Liu et al., 2023; Wu et al., 2023, 2024). In addition, many environmental factors can also affect the AMR risks in the plastispheres, including salinity, pH, nutrient levels, and coexisting contaminants (Wang et al., 2020; Zadjelovic et al., 2023; Joannard and Sanchez-Cid, 2024). Therefore, it is particularly important to conduct risk assessments for AMR in the plastispheres.

Current studies on the distribution of ARGs still heavily rely on molecular approaches such as metagenomic and high-throughput qPCR (HT-qPCR). Leveraging the vast and readily available genomic data, an omics-based framework has been proposed to assess the health risk of AMR, incorporating considerations of human-associated enrichment, gene mobility, and host pathogenicity (Zhang et al., 2021). In addition, the health risks of samples can be quantitatively evaluated based on risk factors of clinical availability, human pathogenicity, human accessibility, and mobility of ARGs (Zhang et al., 2022d). However, genomic information only reflects the potential rather than the actual AMR in real environment (Dantas and Sommer 2012). A recent study integrated phenotypic and genotypic AMR analysis via single-cell spectroscopy and HT-qPCR to systematically compare AMR risks on plastispheres and natural surfaces, and found that plastispheres exhibited ten times higher AMR risk compared to natural surfaces (Yang et al., 2025a). In future, comparative studies across ecosystems and pollution gradients are needed to fully understand how environmental context influence the AMR health risks in different microplastics.

2.2 Pathogenic bacteria in plastisphere

2.2.1 Hotspots of pathogenic bacteria

Plastispheres have emerged as critical environmental interfaces, facilitating the persistence and dissemination of pathogenic bacteria across various ecosystems (Amaral-Zettler et al., 2020; Yang et al., 2020a). Studies have shown that plastispheres often enriched abundant and diverse pathogenic bacteria from surrounding environments (Pham et al., 2021; Zhu et al., 2022; Wang et al., 2024b), including those belonging to the genera *Pseudomonas*, *Aeromonas*, *Vibrio*, *Mycobacterium*, *Listeria*, *Bacillus*, *Acinetobacter*, *Achromobacter*, *Legionella*, *Neisseria*, and *Arcobacter* (Zettler et al., 2013; Yang et al., 2020a; Bhagwat et al., 2021; Wang et al., 2021, Wang et al., 2024b; Sun et al., 2025).

2.2.2 Pathogenic bacteria in various environmental settings

In aquatic environments, microplastics can travel long distances by hydraulic action due to the persistent and buoyant nature, and carry the inhabiting microbes from source or upstream to new habitats (Amaral-Zettler et al., 2020). For example, the *Vibrio* species, which can cause diseases to marine life (e.g., fish, shellfish, and corals), have been found abundant in the marine plastisphere, which can alter their distribution and pose potential threats to aquaculture and aquatic ecosystems (Amaral-Zettler et al., 2020; Sun et al., 2025).

In terrestrial ecosystems, potential pathogens were also enriched in the plastisphere compared to bulk soil but varied across microplastics and soil types. Especially, the increased soil moisture and temperature significantly enhanced the abundance of potential pathogens (Zhu et al., 2022). In addition to bacterial pathogens, the soil plastisphere is also reported to select pathogenic fungi, posing potential risks to human and ecological health (Gkoutselis et al., 2024).

While studies of pathogens in airborne plastispheres are still very limited, it has been reported that in indoor environments, they could adsorb bioaerosols and selectively enrich harmful bacteria and ARGs compared to inorganic particles; moreover, positive correlations between microplastics and pathogenicity have also been found in ambient atmospheric environments (Xu et al., 2024). The ingestion of microplastics particles colonized by pathogens represents a direct route for disease transmission and entry into the food chain, ultimately posing a risk to human health (Li et al., 2025a).

2.2.3 Mechanisms of pathogenic bacteria assembling in plastisphere

Most of pathogens in the environment exist in the form of biofilm, in which the microbial cells are attached to surfaces and embedded within a matrix of EPS. The biofilm environment provides vital advantages to pathogens, such as increased access to nutrients, protection against toxins (e.g., antibiotics, biocides, and heavy metals) and hostile conditions (e.g., desiccation and ultraviolet radiation), and refuge from predation (Flemming and Wingender 2010). In the plastisphere, pathogens are tightly attached to other bacterial cells, increasing the opportunity for the emergence of antibiotic-resistant pathogens, and posing a critical challenge to One Health.

To date, studies on the ecological mechanisms underlying the assembly of pathogens in the plastisphere remain limited (Yang et al., 2019, 2020a; Sathicq et al., 2021; Beloe et al., 2022; Zhang et al., 2022b; Luo et al., 2023). More comprehensive investigations are therefore needed to elucidate the recruitment processes of pathogens on MP surfaces, which will inform effective strategies for mitigating the risks associated with MP pollution.

2.3 Virus in plastisphere

2.3.1 Types of viruses

Most studies of the plastisphere largely focused on bacteria, fungi, and protists, while the knowledge of viruses in the plastispheres is an important yet overlooked area of interest. Metagenomic and viromic analysis have confirmed that viruses are ubiquitous and abundant in the plastisphere (Witsø et al., 2023; Li et al., 2024b; Xia et al., 2025), underscoring the potential for plastic debris to act as a vector for viral pathogens. Human viruses, such as enterovirus and norovirus, have been identified in the plastisphere in wastewater treatment plants (Skraber et al., 2009), highlighting the potential of microplastics as a vector for viral diseases. In addition, studies have shown that viruses can hitchhike on microplastics and prolong their infectivity by adhering to the microplastic surface (Lu et al., 2022b). Recent study reported that SARS-CoV-2 was more stable on plastics compared to metal and cardboard surfaces (Van Doremalen et al., 2020; Zhang et al., 2022a). Theoretical investigations indicated that electrostatic and hydrophobic processes were the underlying mechanisms for the stronger interactions (Zhang et al., 2022a).

2.3.2 Impacts of viruses in plastisphere

Viruses can interact with communities in the plastispheres, infecting a variety of bacterial and eukaryotic hosts, affecting antibiotic resistance dissemination, biogeochemical cycles, and food web dynamics (Li et al., 2024b; Wang et al., 2024a; Chen et al., 2025). Furthermore, the plastisphere supports high densities of both bacteria and their associated phages, increasing the probability of phage-mediated transfer of ARGs between host cells. It was reported that bacteriophages within the plastisphere can contribute to HGT through transduction, potentially promoting the spread of virulence factors and ARGs (Chen et al., 2021; Xia et al., 2025). Biofilms can provide a protective environment for viruses, shielding them from inactivation by environmental factors compared to free-living viruses in water (Lu et al., 2022b). Given that MP particles and their microbial residents often travel long distances, this can accelerate the spread of pathogens and AMR, and increase viruses-associated disease outbreaks. In addition, bacteriophages in the plastisphere may significantly influence community function through the carriage of auxiliary metabolic genes (AMGs). These viral-encoded genes can expand host metabolic processes, such as nutrient acquisition and energy production, potentially enhancing the resilience and metabolic potential of the plastisphere microbiome under oligotrophic or stressful environmental conditions (Wang et al., 2024a). Further investigations are needed to fully elucidate the specific drivers of plastisphere virome assembly and assess the real-world risks associated with the viral transport of pathogens and AMR.

3 Ecological and human health risks

Besides acting as reservoirs and vectors of ARGs and pathogens, microplastics pose severe and multifaceted ecological risks across aquatic, terrestrial, and atmospheric environments. They can change the microbial composition and function, and threaten the health of plants and animals through direct physical damage, the leaching of toxic additives, or the adsorption of pollutants. Finally, these ecological risks can translate into human health through trophic transfer within food chains (Fig. 1), causing growing public concerns.

Microplastics act as ideal vectors for microbial and chemical contaminants, causing serious ecological risks in aquatic, terrestrial, and atmospheric environments. They disrupt microbial functions, impair the health of plants and animals, and finally threaten human health by direct exposure or trophic transfer within food webs.

3.1 Ecological risks of microplastics

3.1.1 Aquatic ecological risks

Microplastics pose multifaceted threats to aquatic ecosystems by impacting organisms across all trophic levels, from primary producers to higher consumers. As foundational components of aquatic systems, phytoplankton are vulnerable to both physical and chemical stressors induced by microplastics. For example, microplastics have been shown to adhere to algal surfaces, thereby inhibiting photosynthesis and growth (Liu et al., 2020). Furthermore, they can act as carriers for adsorbed pollutants such as copper, which induce oxidative stress and cause severe cellular damage (Fu et al., 2019).

In aquatic animals, microplastics cause both direct physical damage and systemic physiological effects. For instance, zooplankton experience gut blockage, reduced feeding efficiency, impaired reproduction, and elevated mortality, with broader ecological effects such

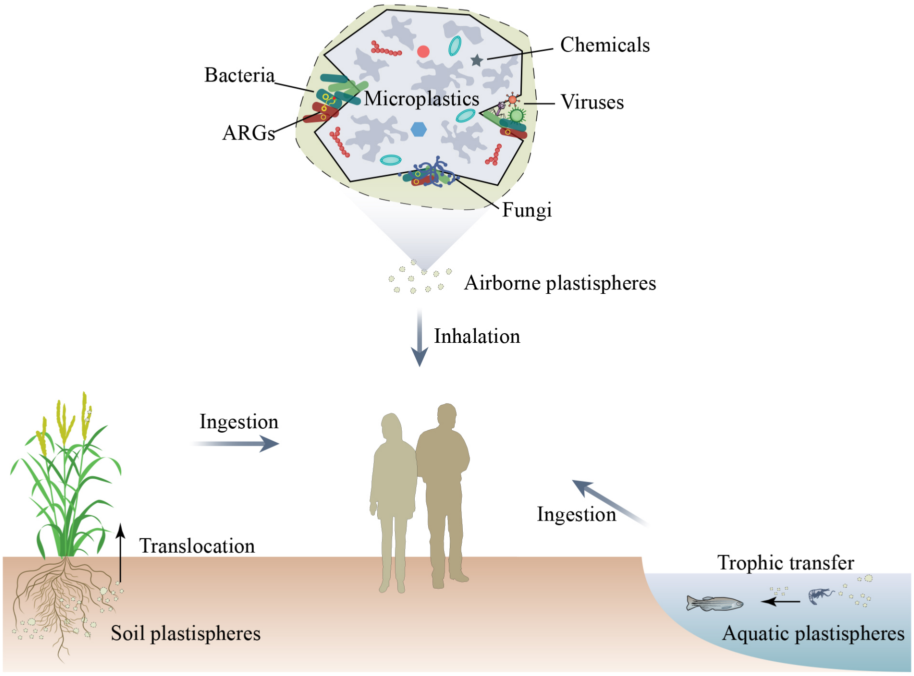

Fig. 1 Ecological and health risks of microplastics in the environment. Microplastics act as ideal vectors for microbial and chemical contaminants, causing serious ecological risks in aquatic, terrestrial, and atmospheric environments. They disrupt microbial functions, impair the health of plants and animals, and finally threaten human health by direct exposure or trophic transfer within food webs.

as the reduction of the populations among filter-feeding species (He et al., 2022). In fish, microplastic ingestion leads to intestinal injury and digestive disorders, which may progress to malnutrition, immune suppression, and diminished growth (Eerkes-Medrano et al., 2015; Ghosh, 2025). In particular, nanoplastics can more easily penetrate cellular membranes than microplastics due to their small size, cause oxidative stress and cellular damage, accumulate in tissues, and transfer through the food chain (Zhao, 2023). Beyond direct physical effects, microplastics act as vectors for chemical contaminants and pathogens. They leach endocrine-disrupting compounds such as phthalates and bisphenol A, which impair gonadal development and reproductive behavior (Oehlmann et al., 2009; Lithner et al., 2011; Banaee et al., 2025). Furthermore, harmful volatile organic compounds (VOCs, e.g., acrolein and benzene) can be formed and released due to oxidative photodegradation of plastic debris (Lomonaco et al., 2020; Ivleva, 2021). Additionally, microplastics can adsorb persistent organic pollutants (POPs) and toxic metals from water bodies, and then transfer these pollutants to feeding organisms, resulting in the rise of pollutant concentrations in organisms (Teuten et al., 2009; Ivleva et al., 2017; Ivleva, 2021). Furthermore, microplastic surfaces provide an environment conducive to the formation of biofilms that harbor pathogenic bacteria, such as *Vibrio cholerae* and *Vibrio alginolyticus*, promoting their dispersal and infection risks in aquatic organisms and humans (Zettler et al., 2013; Oberbeckmann et al., 2014).

Therefore, through integrated mechanisms of physical damage, chemical toxicity, and spread of pathogens, microplastics represent a complex and escalating threat to the stability of aquatic ecosystems and public health. Although existing studies have confirmed that microplastics can be transferred across trophic levels and undergo bioaccumulation (Miller et al., 2020; Ghosh, 2025), their biomagnification potential and the ultimate implications for human health need further research.

3.1.2 Terrestrial ecological risks

Microplastics are a grave danger to terrestrial ecosystems because they destroy the health of soil, interrupt biological functions, and compromise ecological security. Microplastics change soil structure, thereby affecting soil aeration and water retention capacity (Wang et al., 2022a, 2023; Hofmann et al., 2023). Moreover, microplastics have an impact on the composition and functional profiles of soil microbial communities, potentially inhibiting key processes such as nitrification and organic matter decomposition, which interferes with carbon and nitrogen cycling (Büks and Kaupenjohann 2020; Hanif et al., 2024; Wang et al., 2024a).

Microplastics can also be ingested by soil organisms such as earthworms and springtails, leading to their accumulation in tissue and trophic transfer within food webs (Okeke et al., 2022). Earthworms have been shown to experience decreased growth and reproduction due to microplastic exposure, and soil fauna may facilitate the vertical migration of microplastics through their burrowing and feeding activities (Kwak and An, 2021; Thompson et al., 2024). In the rhizosphere of plants, microplastics alter the physical environment around roots, impairing root elongation and the uptake of water and nutrients (Jia et al., 2023). These particles may then be consumed by crops in agricultural systems, raising concerns over crop productivity and food security (Hofmann et al., 2023; Li et al., 2025b).

In higher terrestrial animals like birds and mammals, microplastic exposure occurs primarily through the ingestion of contaminated prey, plants, or plastic debris itself, which can cause gastrointestinal damage, inflammatory responses, and behavior changes (Jeong et al., 2024; Elias and Corbin 2025). Moreover, microplastics in soil readily adsorb heavy metals, organic pollutants, and antibiotics, thus facilitating the transfer of these co-contaminants into the food chain upon consumption (Zhang et al., 2022e; Zheng et al., 2023; Li et al., 2024a). Therefore, further studies are urgently required to clarify the long-term bioaccumulation behavior and synergistic toxic effects of microplastics under realistic conditions.

3.1.3 Atmospheric ecological risks

Atmospheric microplastics represent emerging airborne pollutants that may be transported over long distances. Through air exposure and deposition, they pose health threats to terrestrial organisms and humans. Microplastics in the atmosphere can enter the human body via inhalation, and their harmful mechanisms are size-dependent: large particles tend to deposit in the upper respiratory tract; small particles can enter the alveoli; and nanoplastics may be absorbed by epithelial cells (Prata, 2018; Amato-Lourenço et al., 2020). Microplastics have also been detected in human lung tissues such as bronchoalveolar lavage fluid, potentially triggering inflammation or oxidative stress (Baeza-Martínez et al., 2022; Cao et al., 2023; Liu and You 2023). However, the existing analysis of the effect of atmosphere microplastics on human health remain inconclusive. This is because laboratory studies typically use higher concentrations, which differ significantly from the actual long-term chronic exposure scenarios in humans (Thompson et al., 2024).

Apart from direct inhalation, airborne microplastics can settle on plant surfaces, potentially blocking stomata and impairing photosynthesis (Zhao et al., 2023). It has been confirmed that microplastics can enter edible plant leaves and subsequently be incorporated into the human food chain (Peijnenburg, 2025). Furthermore, upon deposition onto terrestrial and aquatic surfaces, atmospheric microplastics become secondary pollution sources, thereby presenting wider ecological threats. Notably, the biocorona that forms on the surface of microplastics may alter the physio-chemical properties and biological interactions, increasing the complexity of their impacts (Cao et al., 2022). Overall, as ubiquitous pollutants and a final component in the global plastic cycle, atmospheric microplastics and their effects on respiratory health are becoming a critical frontier in environmental health research.

3.2 Human health risks

3.2.1 Multiple exposure routes

As terminal consumers in ecosystem hierarchies, humans are inextricably exposed to this contamination crisis. The pervasive and persistent nature of microplastic in the environment facilitates their transfer into the human body, posing a long-term and multifaceted threat to human health. Human exposure to microplastics-associated risks occurs primarily through ingestion and inhalation (Fig. 1). Ingestion is a main route driven by the consumption of microplastics-contaminated food and drinking water (Yang et al., 2015; Hernandez et al., 2019). For instance, terrestrial crops can absorb micro- and nanoplastics from soil and water, translocating them from roots to edible shoots (Li et al., 2020; Sun et al., 2021a). In aquatic environment, microplastics can easily be ingested by organisms and bioaccumulate into higher trophic levels (Seltenrich, 2015), leading to their trophic transfer to human consumers. Furthermore, inhalation is another significant pathway, particularly in indoor environments where synthetic textile fibers and fragmented plastic particles present in household dust (Zhang et al., 2020b).

3.2.2 Physical damage to biological organisms

Since microplastics were firstly reported in human blood in 2022 (Leslie et al., 2022), they have now been detected in a range of human tissues and organs (Marfella et al., 2024; Nihart et al., 2025), even within immunologically privileged sites including the heart, brain, reproductive organ, and placenta. Upon incorporation into the body, microplastics can inflict direct damage on target organs through established mechanisms including oxidative stress, chronic inflammation, and cytotoxicity (Hoang et al., 2025). Evidence also suggested a correlation between the presence of microplastics and the incidence or severity of certain diseases (Yan et al., 2022). Notably, the ability of microplastics to cross the blood-brain barrier presents a direct threat to neurological integrity (Nihart et al., 2025), and their placental translocation enables intergenerational transfer (Medley et al., 2023), potentially compromising fetal development and the health of future generations. However, scientists also pointed out that the high levels of microplastics detected in human tissue may be attributed to insufficient contamination controls and limitations in current detecting techniques. For example, fat substances can be misidentified as PVC, leading to false positive (Monikh et al., 2025). Additionally, Py-GC-MS may not be suitable for analyzing PE and PVC in human blood due to matrix interferences and the lack of specificity in pyrolysis products (Rauert et al., 2025). Therefore, a more rigorous assessment is needed to determine the true extent of microplastic contamination in the human body and its associated health risks, which would require further investigation and the development of novel analytical technologies.

3.2.3 Combined effects on human health

Beyond their direct physical effects, microplastics act as potent vectors for hazardous chemicals and pathogens in the environment. During aging and degradation, microplastics can leach inherent chemical additives, such as plasticizers (e.g., phthalates, bisphenols) and heavy metals. Furthermore, the surface properties of microplastics facilitate the adsorption and concentration of ambient pollutants, including antibiotics and POPs. The exposure to microplastics may deliver a complex mixture of contaminants to the human body, inducing synergistic effects that need to be investigated.

In addition to chemicals, microplastics also serve as vectors for harmful microbes. Plastisphere are colonized by various pathogenic microbes, viruses and ARB. Through environmental exposure, such as swimming and inhalation, the harmful pathogens may be introduced into human gut. The effects of microplastics ingestion could be compounded by the particle-induced inflammatory responses, severely threatening human health (Hoang et al., 2025). A critical gap of current research is whether ARB and their associated ARGs introduced by microplastics-ingestion can colonize the human gut and implicated with HGT with native microbiome, thereby promoting the spread of antibiotic resistance.

Therefore, a comprehensive and systematic research framework is urgent required to fully assess the environmental risks of microplastics to human health. It is also imperative to develop feasible control technologies to address these risks.

4 Microbial degradation of plastics

Microbial degradation is considered as a promising avenue for mitigating plastic pollution in the environment. By utilizing microorganisms capable of enzymatically breaking down synthetic polymers, sustainable solutions for plastic waste management can be developed. Key areas that require further exploration include the study of microbial plastic degraders in environmental reservoirs and insect gut microbiomes, investigation into their underlying mechanisms and metabolic pathways, and the development of advanced technologies (Fig. 2).

4.1 Environmental sources and key microbial degraders

Earth ecosystems, such as marine ecosystems, terrestrial soils, and engineered systems (e.g., landfill sites), serve as rich environmental reservoirs and sources of plastic-degrading microorganisms. These ecosystems host diverse microbial communities with unique enzymatic capabilities, making them invaluable resources for plastic degradation research.

Marine environments, heavily polluted by microplastics, harbor microbial biofilms that adhere to the surface of floating plastic debris, providing a stable microenvironment, i.e., plastisphere (Amaral-Zettler et al., 2020), for microorganisms, including bacteria and fungi capable of degrading polymers such as low-density polyethylene (LDPE) (Urbanek et al., 2018; Delacuvellerie et al., 2019). For instance, anaerobic marine microbes have been reported to degrade PVC under specific conditions, highlighting the degradation potential in marine habitats (Giacomucci et al., 2020). Similarly, terrestrial soils contaminated by agricultural mulch films and urban waste are home to numerous

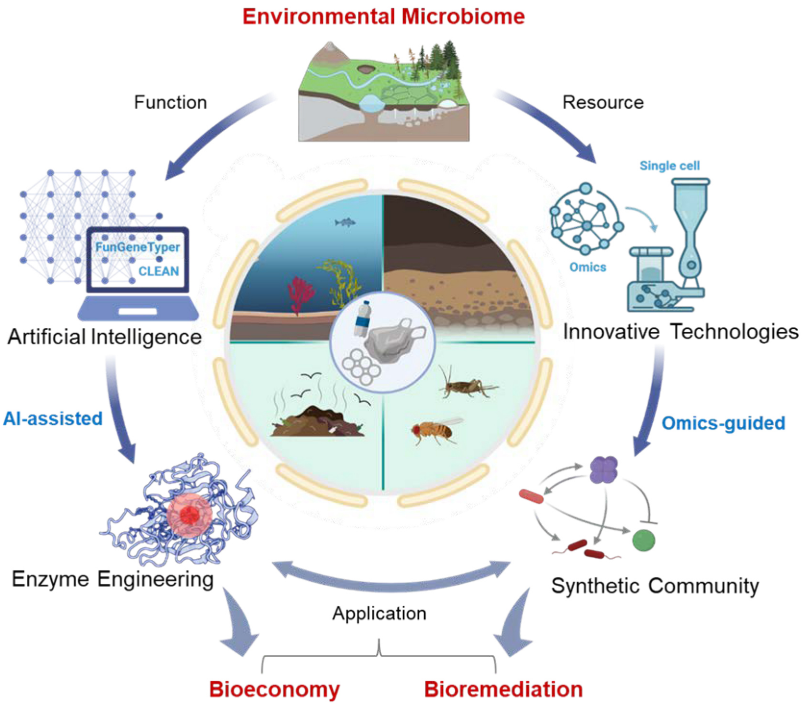

Fig. 2 Biodegradation strategies for mitigating microplastic pollution on Earth. Mitigating plastic waste is a global challenge. Microbial degradation offers a sustainable alternative by harnessing natural microbes, deciphering metabolic pathways through omics technologies, and guiding the construction of synthetic consortia. Cutting-edge tools such as AI, enzyme engineering, and single-cell analysis, are crucial for addressing this pressing issue.

fungi and bacteria, such as *Aspergillus terreus*, *Microbacterium* sp., and *Pseudomonas aeruginosa*, which have demonstrated the ability to degrade PE and PVC through enzymatic activity (Zahra et al., 2010; Muhonja et al., 2018). Landfill sites, where large quantities of plastic waste accumulate, provide another important microbial reservoir. A key example is *Ideonella sakaiensis*, which utilizes PETase and MHETase enzymes to degrade polyethylene terephthalate (PET) into simpler compounds like terephthalic acid (TPA) and ethylene glycol (EG), which can be further metabolized by microbial communities (Yoshida et al., 2016). Advanced meta-omics approaches have also helped uncover functional pathways for plastic degradation and identify enzymatic candidates in landfill environments (Kumar et al., 2020).

In summary, the microbiome diversity of earth ecosystems offers significant potential for plastic degradation, thus offering possibilities for future bioremediation and bioresource recovery applications. By studying these natural reservoirs, researchers can identify and harness microbial candidates with specialized enzymatic functions to tackle plastic pollution effectively.

4.2 Insect gut microbiota as emerging sources of plastic degraders

The gut microbiota of certain insects has emerged as an intriguing source of plastic-degrading microorganisms, offering innovative possibilities for plastic waste management. Insect larvae, such as wax moths (*Galleria mellonella*), Indian meal moths (*Plodia interpunctella*), mealworms (*Tenebrio molitor*), and fall armyworms (*Spodoptera frugiperda*), have demonstrated the ability to consume and partially degrade synthetic plastics like PE, PS, and PVC (Yang et al., 2014; Bombelli et al., 2017; Yang et al., 2020b; Zhang et al., 2020a).

The plastic degradation process by insects involves both mechanical fragmentation of plastics by the insects and enzymatic depolymerization facilitated by their gut microbiota or by enzymes identified in the saliva of *G. mellonella* that enable oxidative depolymerization of PE (Sanluis-Verdes et al., 2022). Microorganisms such as *Enterobacter asburiae* and *Bacillus* sp., isolated from the gut of *P. interpunctella*, play a role in breaking down PE into smaller compounds (Yang et al., 2014). Similarly, the gut microbiota of *S. frugiperda* has been reported to degrade PVC films, with recent findings identifying enzymes capable of dechlorinating PVC polymers (Zhang et al., 2022c; Peng et al., 2025).

Despite these promising observations, the efficiency of plastic degradation within insect systems remains limited. Incomplete mineralization and biosafety concerns regarding large-scale applications pose significant challenges. Investigating the enzymatic mechanisms of insect gut microbiota and enhancing their activity through biotechnological approaches may help unlock the potential of these microorganisms for plastic biodegradation, offering innovative avenues for addressing the challenges posed by synthetic polymers.

4.3 Degradation mechanisms and metabolic pathways

Microbial plastic degradation is a complex process involving adhesion to the plastic surface, enzymatic depolymerization, and metabolic assimilation or mineralization of degradation intermediates. These interconnected steps are central to the microbial breakdown of synthetic polymers.

The degradation process begins with microbial adhesion to the plastic surface, often facilitated by the formation of biofilms which create a stable microenvironment and enhance enzymatic activity, particularly for hydrophobic plastics like PE and PS (Delacuvellerie et al., 2019). This initial step is critical for initiating contact between the microorganisms and the polymer substrate. Next, enzymatic depolymerization occurs at varying degrees based on the plastic’s chemical backbone. Plastics with ester-based C-O backbones, such as PET, are more susceptible to enzymatic hydrolysis due to the presence of ester bonds. Hydrolytic enzymes, such as PETase and cutinase, catalyze the cleavage of these bonds, producing intermediates that are further metabolized (Yoshida et al., 2016; Han et al., 2017). Conversely, plastics with C-C backbones, such as PE, PS, and PVC, are chemically inert and resistant to enzymatic attack (Restrepo-Flórez et al., 2014; Kumar Sen and Raut 2015). Oxidative enzymes, including manganese peroxidase, laccases, and alkane hydroxylase, introduce functional groups into polymer chains, generating reactive intermediates like alcohols and fatty acids. These intermediates are assimilated into microbial metabolic pathways, often converting into central carbon compounds like acetyl-CoA (Iiyoshi et al., 1998; Zhang et al., 2020a).

Despite recent advancements, the efficiency of enzymatic degradation remains a challenge, particularly for highly crystalline plastics and those containing complex additives. Combining microbial strategies with chemical or physical pretreatments and engineering enzymes with improved catalytic properties may help overcome these barriers. Furthermore, the use of stable isotope (^{13}C and deuterium) labeled polymers enable to trace element fluxes from a polymer into microbial biomass, providing a direct proof of (micro)plastic biodegradation in natural systems (Müller et al., 2025). Understanding these mechanisms provides valuable insights into the challenges and opportunities for developing effective solutions to plastic pollution.

4.4 Cutting-edge technologies driving plastic mitigation innovations

4.4.1 AI-assisted microbiome function discovery and enzyme engineering

Artificial intelligence (AI) and protein engineering are revolutionizing the discovery and optimization of microbial plastic-degrading enzymes. These cutting-edge technologies offer transformative approaches to sustainable recycling solutions.

Protein language models (PLMs) are increasingly pivotal for predicting enzymatic functions from genetic sequences, particularly in mining environmental microbiomes and uncultured microbial communities (Zhang et al., 2024; Wu et al., 2025). While tools like AlphaFold enable structural predictions for plastic-degrading proteins (Jumper et al., 2021), other AI-based algorithms such as CLEAN, leverages ESM-based representations to predict enzymatic activities (Lin et al., 2023; Yu et al., 2023). Recently, FunGeneTyper exemplifies the power of PLMs through its high-accuracy framework for functional gene discovery (Zhang et al., 2024). Its deep learning architecture, trained on discriminative semantic features and enhanced by community-shared adapters, specializes in classifying diverse enzymes directly from noisy metagenomic data. This capability bridges the critical gap between DNA sequencing and functional annotation in environmental samples (Zhang et al., 2024), powerfully facilitating the identification of plastic and plasticizer-degrading genes from microbiomes in complex ecosystems.

Following computational discovery, enzyme engineering refines promising candidates to enhance their performance. Tournier et al. (2020) optimized PET hydrolase, achieving rapid PET depolymerization with unprecedented efficiency. Similarly, Lu et al. (2022a) employed structure-guided machine learning to develop FAST-PETase, introducing targeted mutations to expand its catalytic activity across diverse temperature and pH ranges. This robust enzyme successfully degraded untreated post-consumer PET waste within one week and showed strong potential for industrial-scale application. However, the potential of AI in enzyme engineering is currently constrained by a lack of high-quality, experimentally verified plastic-degrading enzymes, compromising model accuracy and generali-zation. Therefore, expanding the database of characterized enzymes is critical to advance AI-driven discovery.

The synergy between computational prediction and experimental optimization is accelerating the development of scalable and efficient enzymatic solutions for plastic recycling. Looking ahead, continued integration of AI and enzyme engineering will play a pivotal role in advancing biodegradation technologies, enabling more sustainable and economically viable plastic waste management strategies at global scale.

4.4.2 Omics and single-cell approaches for environmental resource mining

Omics technologies have become indispensable for prospecting plastic-degrading functional resources directly from environmental microbiomes. Multi-omics approaches, including metagenomics, transcriptomics, proteomics, and metabolomics, have been widely applied to identify plastic-degrading enzymes, their regulatory networks, and associated metabolic intermediates (Farveen Mohamed and Narayanan 2024; Messer et al., 2024).

However, conventional omics approaches often suffer from the "population-averaging effect", which obscures functional heterogeneity within microbial communities (Sarfatis et al., 2025). Single-cell and spatial omics techniques are overcoming this limitation by providing high-resolution and culture-independent insights into microbial activity. In this context, Raman microspectroscopy combined with stable isotope approach can be applied for tracing a deuterium label from plastics into distinct biomolecules (lipids, proteins, DNA, and carotenoids) of microbial biomass at the single-cell level, demonstrating a significant potential to study the fate of (micro)plastics in the environment (Müller et al., 2025). Techniques like bio-orthogonal non-canonical amino acid tagging (BONCAT) integrated with fluorescence-activated cell sorting (FACS), and single-cell sequencing allow precise identification and profiling of metabolically active microorganisms (Lin et al., 2024; Bi et al., 2025; Ge et al., 2025). Meanwhile, integrating Raman spectroscopy with fluorescence *in situ* hybridization (FISH) enables simultaneous determination of taxonomic identity and metabolic function (Huang et al., 2007). Spatial transcriptomics platforms, such as multiplexed error-robust fluorescence *in situ* hybridization (MERFISH), further map the expression of functional genes and ecological niches of microbial populations *in situ* (Qian et al., 2025; Watson et al., 2025).

Although not yet extensively applied to plastic degradation studies, these omics and/or single-cell approaches offer unprecedented capacity to mine uncultured microbial dark matter for discovering novel plastic/plasticizer-degrading genes, pinpoint keystone degraders in environmental samples, and guide bioprospecting of enzymatic resources for bioengineering applications. Their integration promises accelerated discovery of environmentally relevant and applicable degradation resources, transforming waste-impacted ecosystems into reservoirs for plastic waste treatment.

4.4.3 Synthetic microbial consortia for enhanced plastic degradation

Moving beyond single-microbe approaches, contemporary research underscores symbiotic microbial communities' pivotal role in plastic decomposition. Natural and synthetic consortia leverage metabolic interactions and functional complementarity to achieve superior efficiency compared to single-microbe systems (Chen et al., 2021b; Lv et al., 2022).

Natural consortia demonstrate synergistic polymer breakdown, as evidenced in the degradation of PE (Skariyachan et al., 2016) and PET degradation (Gao and Sun, 2021). Computational modeling tools, such as SuperCC, enable the rational design of synthetic consortia by simulating microbiome performance and linking pollutants to biotransformation pathways. Interestingly, when processing five plastic-derived substrates, *Rhodococcus* dominated microbial communities while substrate-specific specialists remained minor components, suggesting a division of labor between generalists and specialists in mixed plastic waste degradation (Schaerer et al., 2023). Artificial consortia further enhance degradation efficiency by integrating complementary metabolic pathways (Ruan et al., 2024). Hybrid bio-abiotic systems, which combine microbial activity with biocompatible chemistry, extend the range of reactions achievable in plastic degradation. For instance, Johnson et al. (2025) demonstrated a phosphate-catalyzed Lossen rearrangement in *E. coli*, facilitating the conversion of PET-derived substrates into pharmaceutical precursors (Johnson et al., 2025). To scale these approaches, advanced bioreactor technologies optimize operational parameters and incorporate recovery systems that support circular economy models (Tournier et al., 2020; Liu et al., 2021). Additionally, the division of labor among microbial populations boosts efficiency, enabling the synthesis of high-value bioproducts.

The integration of synthetic microbial consortia (SynComs) with computational modeling and bioprocess optimization offers a transformative approach to global plastic waste management. By harnessing microbial metabolic diversity and collaboration, these systems enable efficient polymer degradation and resource recovery. Beyond waste management, such approaches pave the way for the development of a sustainable circular bioeconomy, where plastic waste transitions from an environmental burden to a valuable feedstock for producing high-value bioproducts. However, transitioning these technologies from the laboratory to open environments presents significant biosafety challenges, including potential ecological invasion, microbiome disruption, and uncontrolled HGT. Addressing these risks through robust assessment frameworks is therefore essential to ensure the safe and sustainable deployment of SynComs.

5 Dual roles of the plastisphere microorganisms: From ecological risk to sustainable remediation

The plastisphere is the microbial ecosystem that covers the surface of microplastics, which is an interesting environmental paradox. On the one hand, it serves as a highly effective vector for ecological and health threats. Biofilms on these mobile surfaces concentrate pathogens, ARGs, and viruses, facilitating their transport across environmental boundaries and into food webs. On the other hand, plastisphere acts as valuable resources for novel plastic-degrading enzymes, such as hydrolases and oxidases, that can convert inert polymers into more bioavailable intermediates (Wright et al., 2021; Bocci et al., 2024). The coexistence of the risk and remediation functions establishes the plastisphere as the critical nexus between the environmental hazards of microplastics and the potential for their biological mitigation.

5.1 Unresolved questions at the risk–remediation interface

The inherent duality of the plastisphere highlights a crucial gap in current scientific understanding and technological capability. There are still fundamental issues as to whether there is any functional or taxonomy relationship between degradation ability and harboring risk-associated genes. As an example, are the risk and degradation functions usually present within the same microbial taxa? It has been observed, for example, that some of the most effective plastic-degrading isolates, such as members of the genus Pseudomonas, are also known to be opportunistic pathogens and ARG carriers (Gao et al., 2025). The mechanistic links between risk and degradation functions within the plastisphere remain largely unexplored.

Moreover, we lack a robust framework for screening and selecting the safe degraders. Traditional screening protocols focus almost exclusively on degradation efficiency, such as the catalytic activity of PETase (Yoshida et al., 2016). The risk attributes of these microbes, including their potential pathogenicity or ARG carriage, are rarely included in the assessment system. This one-dimensional focus creates a blind spot, where we might inadvertently select for and deploy organisms that solve one problem while creating another.

5.2 A dual-dimensional framework for sustainable biodegradation

To address this methodological limitation, we propose a dual-dimensional evaluation framework for the rational screening and prioritization of plastic-degrading microorganisms (Fig. 3). This framework moves beyond the singular metric of degradation efficiency, incorporating biosafety as a co-equal axis of evaluation to enable a more holistic risk-benefit assessment. By conceptualizing microbial candidates within a plane defined by "Degradation Efficiency" and "Microbial Risk", we categorize them into four distinct functional groups. The most desirable of these are the "Ideal Candidates", which couple high degradation efficiency with low microbial risks, marking them as priority targets for direct environmental application. Strains exhibiting low efficiency but also posing minimal risk, the "Safe but Inefficient", represent potential targets for performance enhancement through bioengineering. In contrast, the "Effective but Risky" group, possessing high degradation potential with considerable biosafety concerns, their application should be restricted to closed systems, such as bioreactors, where function can be harnessed without ecological dissemination. Finally, microorganisms falling into the "Hazardous and Ineffective" quadrant must be excluded from further consideration in any remediation strategy.

Application of this framework also informs the

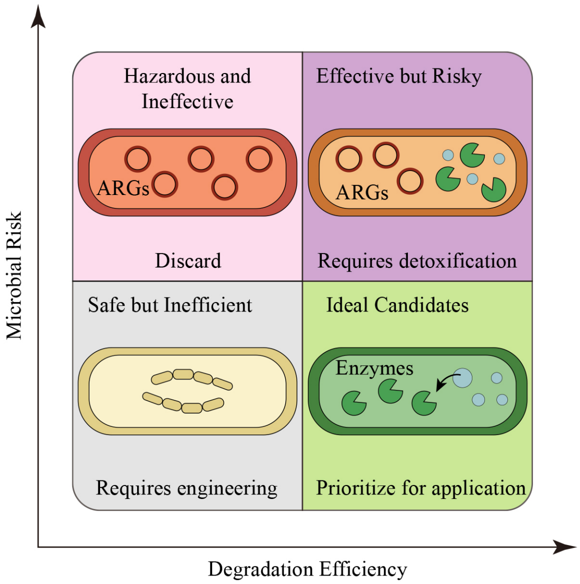

Fig. 3 A dual-dimensional framework for screening safe and efficient plastic-degrading microbes. Four distinct functional groups are categorized in the plastispheres: the "Ideal Candidates" (high efficiency, low risk) that should be prioritized for application; the "Safe but Inefficient" (low efficiency, low risk) that are prime candidates for bioengineering; the "Effective but Risky" (high efficiency, high risk) that may be useful only in contained systems; and the "Hazardous and Ineffective" (low efficiency, high risk) that should be discarded.

strategic choice of microbial chassis. For instance, the use of fungi for bioremediation presents a compelling strategy to circumvent the primary risk of ARG dissemination. As eukaryotes, fungi are not targeted by most antibiotics and do not participate in the HGT networks that drive ARG proliferation among bacteria. This makes them inherently attractive "low-risk" candidates from an AMR perspective. However, a truly comprehensive "Safety by Design" approach necessitates a broader risk appraisal. The evaluation of a fungal candidate must therefore encompass a different suite of risk parameters, including its potential for mycotoxin production, opportunistic pathogenicity, or the indirect selection of resistant bacteria through the secretion of antimicrobial secondary metabolites. This underscores a crucial principle: while the framework itself is universal, the specific parameters defining the "Microbial Risk" axis must be tailored to the unique biology of the chosen organism, whether it be bacterium, fungus, or a multi-kingdom consortium.

5.3 Tackling plastispheres using interdisciplinary strategies

Implementing a chassis-specific risk assessment is an inherently interdisciplinary challenge, demanding the integration of microbiology, environmental chemistry, and synthetic biology. Given that the vast majority of environmental microbes remain unculturable by standard techniques, single-cell technologies that circumvent cultivation are highly needed. For instance, by detecting the metabolic uptake of isotopically labeled plastics, single cell Raman spectroscopy could directly identify functionally active cells from complex communities (Huang et al., 2007; Müller et al., 2025; Yang et al., 2025a). Following identification, these specific cells can be physically sorted for targeted cultivation, and subjected to single-cell genomics. This final genomic assessment is critical for evaluating their application risk by screening for ARGs or known virulence factors. This workflow provides a direct path to mining the microbial dark matter for potent and verifiably safe bioremediation resources.

Beyond the laboratory, the successful deployment of any bioremediation agent requires robust environmental monitoring process. Quantitative molecular tools, including targeted qPCR and metagenomics, will be important to track the fate, activity, and persistence of the introduced microbes. In addition, the monitoring of any off-target effects on native microbial community structure and function, ensuring that the intervention is both effective and eco-friendly.

Ultimately, these scientific and technological advances must be coupled with sound policy and management frameworks. Regulatory pathways are needed for the risk assessment and environmental release of engineered microorganisms intended for bioremediation. Establishing international standards for validating the efficacy and safety of these technologies would further promote responsible innovation. Therefore, building the bridge that connects risk identification with safe remediation design is a responsibility that extends from the single-cell biologist to the environmental manager and policymaker. This holistic approach represents the essential application of the "Safety by Design" principle, ensuring that our collective efforts to solve the plastic pollution crisis are both scientifically robust and environmentally sustainable.

6 Conclusions and future perspectives

The plastispheres act as both vectors for microbial risks like ARGs and reservoirs for novel biodegradation solutions. Although some progress has been made, this duality presents several critical challenges and opportunities that must now be addressed:

(1) Microbial risks of the plastisphere

There is an urgent need to gain a deeper mechanistic understanding of microbial risks in the plastisphere. Critical unresolved questions include how microplastic properties (e.g., the polymer types or hydrophobicity) influence microbial colonization and the profiles of antibiotic resistance and virulence factors. Moreover, systematic studies are lacking on how complex interactions among leached additives, degradation intermediates, and co-pollutants (e.g., metals and antibiotics) collectively shape microbial communities and associated risks. Finally, a comprehensive microbial risk assessment should integrate the microbial phenotypic and genotypic traits, metabolic activity, and interspecies interactions.

(2) Ecological and human health effects

Quantifying the long-term, chronic impacts of micro- and nano-plastics on human health and ecosystems remains challenging. On the individual scale, there is a lack of understanding regarding long-term physiological responses and accumulation patterns across species, due to the predominant use of high-dose, short-term exposure experiments that fail to represent realistic, low-dose chronic exposure conditions. On the ecosystem scale, it is also necessary to investigate the ecological consequences of chronic microplastic pressure, such as disruptions to biogeochemical cycling. In particular, the combined effects of microplastics and co-occurring contaminants cannot be neglected in assessments of human health and ecotoxicological risks.

(3) Future directions in biodegradation solutions

The discovery and engineering of enzymes targeting the ester bonds of plastics such as PET represent a key advance in bioremediation. However, the enzymatic degradation of polymers with inert carbon–carbon backbones (e.g., PE, PS, PVC), remains a significant challenge. Moreover, existing microbial degraders often exhibit poor environmental colonization and low degradation efficacy under real-world conditions. Future study should prioritize applying single-cell techniques to identify *in situ* active degraders and rationally construct SynComs. In particular, a two-dimensional evaluation framework considering both microbial risks and degradation efficiency should be used to identify the most promising candidates and guide the design of the safest and most effective microbiota to address the plastic crisis worldwide.

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Amaral-Zettler L A, Zettler E R, Mincer T J (2020). Ecology of the plastisphere. Nature Reviews Microbiology, 18(3): 139–151

Amato-Lourenço L F, Galvão L D S, De Weger L A, Hiemstra P S, Vijver M G, Mauad T (2020). An emerging class of air pollutants: Potential effects of microplastics to respiratory human health? Science of the Total Environment, 749: 141676

Arias-Andres M, Klümper U, Rojas-Jimenez K, Grossart H P (2018). Microplastic pollution increases gene exchange in aquatic ecosystems. Environmental Pollution, 237: 253–261

Arp H P H, Kühnel D, Rummel C, MacLeod M, Potthoff A, Reichelt S, Rojo-Nieto E, Schmitt-Jansen M, Sonnenberg J, Toorman E, et al. (2021). Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. Environmental Science & Technology, 55(11): 7246–7255

Ashton K, Holmes L, Turner A (2010). Association of metals with plastic production pellets in the marine environment. Marine Pollution Bulletin, 60(11): 2050–2055

Baeza-Martínez C, Olmos S, González-Pleiter M, López-Castellanos J, García-Pachón E, Masiá-Canuto M, Hernández-Blasco L, Bayo J (2022). First evidence of microplastics isolated in European citizens' lower airway. Journal of Hazardous Materials, 438: 129439

Banaee M, Multisanti C R, Impellitteri F, Piccione G, Faggio C (2025). Environmental toxicology of microplastic particles on fish: a review. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 287: 110042

Beloe C J, Browne M A, Johnston E L (2022). Plastic debris as a vector for bacterial disease: an interdisciplinary systematic review. Environmental Science & Technology, 56(5): 2950–2958

Bhagwat G, Zhu Q Y, O'Connor W, Subashchandrabose S, Grainge I, Knight R, Palanisami T (2021). Exploring the composition and functions of plastic microbiome using whole-genome sequencing. Environmental Science & Technology, 55(8): 4899–4913

Bi J Y, Marques R, Wang D Q, Qin L, Close K, Li G Y, Wang Z L, Tooker N B, Srinivasan V, Onnis-Hayden A, et al. (2025). Phenotypic discrimination and characterization of microbial populations in enhanced biological phosphorus removal using single-cell raman spectroscopy-based methods. Water Research, 281: 123577

Bocci V, Galafassi S, Levantesi C, Crognale S, Amalfitano S, Congestri R, Matturro B, Rossetti S, Di Pippo F (2024). Freshwater plastisphere: a review on biodiversity, risks, and biodegradation potential with implications for the aquatic ecosystem health. Frontiers in Microbiology, 15: 1395401

Bombelli P, Howe C J, Bertocchini F (2017). Polyethylene bio-degradation by caterpillars of the wax moth *Galleria mellonella*. Current Biology, 27(8): R292–R293

Büks F, Kaupenjohann M (2020). Global concentrations of microplastics in soils: a review. Soil, 6(2): 649–662

Cao J W, Xu R, Geng Y, Xu S W, Guo M Y (2023). Exposure to polystyrene microplastics triggers lung injury via targeting toll-like receptor 2 and activation of the NF-κB signal in mice. Environmental Pollution, 320: 121068

Cao J Y, Yang Q, Jiang J, Dalu T, Kadushkin A, Singh J, Fakhrullin R, Wang F J, Cai X M, Li R B (2022). Coronas of micro/nano plastics: a key determinant in their risk assessments. Particle and Fibre Toxicology, 19(1): 55

Chen M L, An X L, Liao H, Yang K, Su J Q, Zhu Y G (2021a). Viral community and virus-associated antibiotic resistance genes in soils amended with organic fertilizers. Environmental Science & Technology, 55(20): 13881–13890

Chen Q L, Hu H W, He Z Y, Cui L, Zhu Y G, He J Z (2021b). Potential of indigenous crop microbiomes for sustainable agriculture. Nature Food, 2(4): 233–240

Chen X P, Zhu D, Liu S Y, Sun M M, Ye M, Wang L, Lin D, Zhang T L, Rillig M C, Zhu Y G (2025). Unique plastisphere viromes with habitat-dependent potential for modulating global methane cycle. Nature Communications, 16(1): 8098

Choi S Y, Lee Y, Yu H E, Cho I J, Kang M J, Lee S Y (2023). Sustainable production and degradation of plastics using microbes. Nature Microbiology, 8(12): 2253–2276

Dantas G, Sommer M O. (2012). Context matters: the complex interplay between resistome genotypes and resistance phenotypes. Current Opinion in Microbiology, 15(5): 577–582

Delacuvellerie A, Cyriaque V, Gobert S, Benali S, Wattiez R (2019). The plastisphere in marine ecosystem hosts potential specific microbial degraders including *Alcanivorax borkumensis* as a key player for the low-density polyethylene degradation. Journal of Hazardous Materials, 380: 120899

Eerkes-Medrano D, Thompson R C, Aldridge D C (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Research, 75: 63–82

Elias J M, Corbin C E (2025). Microplastics and terrestrial birds: a review on plastic ingestion in ecological linchpins. Journal of Ornithology, 166(1): 1–8

Farveen Mohamed S, Narayanan R (2024). Omic-driven strategies to unveil microbiome potential for biodegradation of plastics: a review. Archives of Microbiology, 206(11): 441

Flemming H C, Wingender J (2010). The biofilm matrix. Nature Reviews Microbiology, 8(9): 623–633

Fu D D, Zhang Q J, Fan Z Q, Qi H Y, Wang Z Z, Peng L C (2019). Aged microplastics polyvinyl chloride interact with copper and cause oxidative stress towards microalgae *Chlorella vulgaris*. Aquatic Toxicology, 216: 105319

Gao F Z, Jia W L, Li B, Zhang M, He L Y, Bai H, Liu Y S, Ying G G (2025). Contaminant-degrading bacteria are super carriers of antibiotic resistance genes in municipal landfills: a metagenomics-based study. Environment International, 195: 109239

Gao R R, Sun C M (2021). A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. Journal of Hazardous Materials, 416: 125928

Ge S, Sun S Q, Xu H, Cheng Q, Ren Z X (2025). Deep learning in single-cell and spatial transcriptomics data analysis: advances and challenges from a data science perspective. Briefings in Bioinformatics, 26(2): bbaf136

Geyer R, Jambeck J R, Law K L (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7): e1700782

Ghosh T (2025). Microplastics bioaccumulation in fish: Its potential toxic effects on hematology, immune response, neurotoxicity, oxidative stress, growth, and reproductive dysfunction. Toxicology Reports, 14: 101854

Giacomucci L, Raddadi N, Soccio M, Lotti N, Fava F (2020). Biodegradation of polyvinyl chloride plastic films by enriched anaerobic marine consortia. Marine Environmental Research, 158: 104949

Gkoutselis G, Rohrbach S, Harjes J, Brachmann A, Horn M A, Rambold G (2024). Plastiphily is linked to generic virulence traits of important human pathogenic fungi. Communications Earth & Environment, 5(1): 51

Godoy V, Blázquez G, Calero M, Quesada L, Martín-Lara M A (2019). The potential of microplastics as carriers of metals. Environmental Pollution, 255: 113363

Gouin T, Roche N, Lohmann R, Hodges G (2011). A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. Environmental Science & Technology, 45(4): 1466–1472

Gulizia A M, Patel K, Philippa B, Motti C A, Van Herwerden L, Vamvounis G (2023). Understanding plasticiser leaching from polystyrene microplastics. Science of the Total Environment, 857(Pt 1): 159099

Han X, Liu W D, Huang J W, Ma J T, Zheng Y Y, Ko T P, Xu L M, Cheng Y S, Chen C C, Guo R T. (2017). Structural insight into catalytic mechanism of PET hydrolase. Nature Communications, 8(1): 2106

Hanif M N, Aijaz N, Azam K, Akhtar M, Laftah W A, Babur M, Abbood N K, Benitez I B (2024). Impact of microplastics on soil (physical and chemical) properties, soil biological properties/soil biota, and response of plants to it: a review. International Journal of Environmental Science and Technology, 21(16): 10277–10318

He M T, Yan M T, Chen X F, Wang X K, Gong H, Wang W J, Wang J (2022). Bioavailability and toxicity of microplastics to zooplankton. Gondwana Research, 108: 120–126

Hernandez L M, Xu E G, Larsson H C E, Tahara R, Maisuria V B, Tufenkji N (2019). Plastic teabags release billions of microparticles and nanoparticles into tea. Environmental Science & Technology, 53(21): 12300–12310

Hoang H G, Nguyen N S H, Zhang T, Tran H T, Mukherjee S, Naidu R (2025). A review of microplastic pollution and human health risk assessment: current knowledge and future outlook. Frontiers in Environmental Science, 13: 1606332

Hofmann T, Ghoshal S, Tufenkji N, Adamowski J F, Bayen S, Chen Q Q, Demokritou P, Flury M, Hüffer T, Ivleva N P, et al. (2023). Plastics can be used more sustainably in agriculture. Communications Earth & Environment, 4(1): 332

Hu X J, Waigi M G, Yang B, Gao Y Z (2022). Impact of plastic particles on the horizontal transfer of antibiotic resistance genes to bacterium: dependent on particle sizes and antibiotic resistance gene vector replication capacities. Environmental Science & Technology, 56(21): 14948–14959

Huang W E, Stoecker K, Griffiths R, Newbold L, Daims H, Whiteley A S, Wagner M (2007). Raman-FISH: combining stable-isotope Raman spectroscopy and fluorescence *in situ* hybridization for the single cell analysis of identity and function. Environmental Microbiology, 9(8): 1878–1889

Iiyoshi Y, Tsutsumi Y, Nishida T (1998). Polyethylene degradation by lignin-degrading fungi and manganese peroxidase. Journal of Wood Science, 44(3): 222–229

Ivleva N P (2021). Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives. Chemical Reviews, 121(19): 11886–11936

Ivleva N P, Wiesheu A C, Niessner R (2017). Microplastic in aquatic ecosystems. Angewandte Chemie International Edition, 56(7): 1720–1739

Jeong E, Lee J Y, Redwan M (2024). Animal exposure to microplastics and health effects: a review. Emerging Contaminants, 10(4): 100369

Jia L, Liu L N, Zhang Y J, Fu W X, Liu X, Wang Q Q, Tanveer M, Huang L P (2023). Microplastic stress in plants: effects on plant growth and their remediations. Frontiers in Plant Science, 14: 1226484

Joannard B, Sanchez-Cid C (2024). Bacterial dynamics of the plastisphere microbiome exposed to sub-lethal antibiotic pollution. Microbiome, 12(1): 97

Johnson N W, Valenzuela-Ortega M, Thorpe T W, Era Y, Kjeldsen A, Mulholland K, Wallace S (2025). A biocompatible Lossen rearrangement in *Escherichia coli*. Nature Chemistry, 17(7): 1020–1026

Jumper J, Evans R, Pritzel A, Green T, Figurnov M, Ronneberger O, Tunyasuvunakool K, Bates R, Žídek A, Potapenko A, et al. (2021). Highly accurate protein structure prediction with AlphaFold. Nature, 596(7873): 583–589

Kang Y Y, Gao S H, Pan Y S, Gao R, Li T Y, Fan L, Su Y Y, Zhang W Y, Yu Z G, Liang B, et al. (2025). Roles of micro/nanoplastics in the spread of antimicrobial resistance through conjugative gene transfer. Nature Communications, 17(1): 1118

Kumar M, Xiong X N, He M J, Tsang D C W, Gupta J, Khan E, Harrad S, Hou D Y, Ok Y S, Bolan N S (2020). Microplastics as pollutants in agricultural soils. Environmental Pollution, 265: 114980

Kumar Sen S, Raut S (2015). Microbial degradation of low density polyethylene (LDPE): a review. Journal of Environmental Chemical Engineering, 3(1): 462–473

Kwak J I, An Y J (2021). Microplastic digestion generates fragmented nanoplastics in soils and damages earthworm spermatogenesis and coelomocyte viability. Journal of Hazardous Materials, 402: 124034

Leslie H A, Van Velzen M J M, Brandsma S H, Vethaak A D, Garcia-Vallejo J J, Lamoree M H (2022). Discovery and quantification of plastic particle pollution in human blood. Environment International, 163: 107199

Li C C, Jin L N, Bank M S, Fan C L, Gillings M R, Zhao T T, Han Y, Chen T, Gao M, Zhu D, et al. (2025a). Potential planetary health impacts of the airborne plastisphere. One Earth, 8(10): 101446

Li F P, Gong Y F, Yang X Y, Jiang Y C, Cen Y L, Zhang Z M (2024a). Distribution characteristics and integrated ecological risks evaluation modelling of microplastics and heavy metals in geological high background soil. Science of the Total Environment, 944: 173602

Li J, Zhang K N, Zhang H (2018). Adsorption of antibiotics on microplastics. Environmental Pollution, 237: 460–467

Li L Z, Luo Y M, Li R J, Zhou Q, Peijnenburg W J G M, Yin N, Yang J, Tu C, Zhang Y C (2020). Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nature Sustainability, 3(11): 929–937

Li R L, An X L, Wang Y J, Yang Z G, Su J Q, Cooper J, Zhu Y G. (2024b). Viral metagenome reveals microbial hosts and the associated antibiotic resistome on microplastics. Nature Water, 2(6): 553–565

Li R L, Zhu L J, Yang K, Li H Z, Zhu Y G, Cui L (2021). Impact of urbanization on antibiotic resistome in different microplastics: evidence from a large-scale whole river analysis. Environmental Science & Technology, 55(13): 8760–8770

Li Y, Zhang J J, Xu L, Li R Q, Zhang R, Li M X, Ran C M, Rao Z Y, Wei X, Chen M L, et al. (2025b). Leaf absorption contributes to accumulation of microplastics in plants. Nature, 641(8063): 666–673

Lin W F, Cao S H, Wu Q H, Xu F, Li R L, Cui L (2024a). Size effects of microplastics on antibiotic resistome and core microbiome in an urban river. Science of the Total Environment, 919: 170716

Lin W F, Li R L, Cao S H, Li H Z, Yang K, Yang Z G, Su J Q, Zhu Y G, Cui L (2024b). High-throughput single-cell metabolic labeling, sorting, and sequencing of active antibiotic-resistant bacteria in the environment. Environmental Science & Technology, 58(40): 17838–17849

Lin Z M, Akin H, Rao R O S, Hie B, Zhu Z K, Lu W T, Smetanin N, Verkuil R, Kabeli O, Shmueli Y, et al. (2023). Evolutionary-scale prediction of atomic-level protein structure with a language model. Science, 379(6637): 1123–1130

Lithner D, Larsson Å, Dave G (2011). Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Science of the Total Environment, 409(18): 3309–3324

Liu G, Jiang R F, You J, Muir D C G, Zeng E Y (2020). Microplastic impacts on microalgae growth: effects of size and humic acid. Environmental Science & Technology, 54(3): 1782–1789

Liu L, Zhang Q H, Li R T (2023). *In situ* and individual-based analysis of the influence of polystyrene microplastics on *Escherichia coli* conjugative gene transfer at the single-cell level. Environmental Science & Technology, 57(42): 15936–15944

Liu P, Zhang T, Zheng Y, Li Q B, Su T Y, Qi Q S (2021). Potential one-step strategy for PET degradation and PHB biosynthesis through co-cultivation of two engineered microorganisms. Engineering Microbiology, 1: 100003

Liu Z G, You X Y (2023). Recent progress of microplastic toxicity on human exposure base on *in vitro* and *in vivo* studies. Science of the Total Environment, 903: 166766

Lomonaco T, Manco E, Corti A, La Nasa J, Ghimenti S, Biagini D, Di Francesco F, Modugno F, Ceccarini A, Fuoco R, et al. (2020). Release of harmful volatile organic compounds (VOCs) from photo-degraded plastic debris: a neglected source of environmental pollution. Journal of Hazardous Materials, 394: 122596

Lu H Y, Diaz D J, Czarnecki N J, Zhu C Z, Kim W, Shroff R, Acosta D J, Alexander B R, Cole H O, Zhang Y, et al. (2022a). Machine learning-aided engineering of hydrolases for PET depolymerization. Nature, 604(7907): 662–667

Lu J, Yu Z G, Ngiam L, Guo J H (2022b). Microplastics as potential carriers of viruses could prolong virus survival and infectivity. Water Research, 225: 119115

Luo G Y, Liang B, Cui H L, Kang Y Y, Zhou X, Tao Y, Lu L, Fan L, Guo J H, Wang A J, et al. (2023). Determining the contribution of micro/nanoplastics to antimicrobial resistance: challenges and perspectives. Environmental Science & Technology, 57(33): 12137–12152

Lv M J, Jiang B, Xing Y, Ya H B, Zhang T, Wang X (2022). Recent advances in the breakdown of microplastics: strategies and future prospectives. Environmental Science and Pollution Research, 29(44): 65887–65903

Mao R F, Lang M F, Yu X Q, Wu R R, Yang X M, Guo X T (2020). Aging mechanism of microplastics with UV irradiation and its effects on the adsorption of heavy metals. Journal of Hazardous Materials, 393: 122515

Marfella R, Prattichizzo F, Sardu C, Fulgenzi G, Graciotti L, Spadoni T, D’Onofrio N, Scisciola L, La Grotta R, Frigé C, et al. (2024). Microplastics and nanoplastics in atheromas and cardiovascular events. New England Journal of Medicine, 390(10): 900–910

Medley E A, Spratlen M J, Yan B Z, Herbstman J B, Deyssenroth M A (2023). A systematic review of the placental translocation of micro- and nanoplastics. Current Environmental Health Reports, 10(2): 99–111

Messer L F, Lee C E, Wattiez R, Matallana-Surget S (2024). Novel functional insights into the microbiome inhabiting marine plastic debris: critical considerations to counteract the challenges of thin biofilms using multi-omics and comparative metaproteomics. Microbiome, 12(1): 36

Miller M E, Hamann M, Kroon F J (2020). Bioaccumulation and biomagnification of microplastics in marine organisms: a review and meta-analysis of current data. PLoS One, 15(10): e0240792

Monikh F A, Materić D, Valsami-Jones E, Grossart H P, Altmann K, Holzinger R, Lynch I, Stubenrauch J, Peijnenburg W (2025). Challenges in studying microplastics in human brain. Nature Medicine, 31(12): 4034–4035

Muhonja C N, Makonde H, Magoma G, Imbuga M (2018). Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya. PLoS One, 13(7): e0198446

Murray L M, Hayes A, Snape J, Kasprzyk-Hordern B, Gaze W H, Murray A K (2024). Co-selection for antibiotic resistance by environmental contaminants. npj Antimicrobials and Resistance, 2(1): 9

Müller K, Elsner M, Leung A E, Wacklin-Knecht H, Allgaier J, Heiling M, Ivleva N P (2025). Raman microspectroscopy to trace the incorporation of deuterium from labeled (micro)plastics into microbial cells. Analytical Chemistry, 97(8): 4440–4451

Nihart A J, Garcia M A, El Hayek E, Liu R, Olewine M, Kingston J D, Castillo E F, Gullapalli R R, Howard T, Bleske B, et al. (2025). Bioaccumulation of microplastics in decedent human brains. Nature Medicine, 31(4): 1114–1119

Oberbeckmann S, Loeder M G J, Gerdts G, Osborn A M (2014). Spatial and seasonal variation in diversity and structure of microbial biofilms on marine plastics in Northern European waters. Fems Microbiology Ecology, 90(2): 478–492

Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk K O, Wollenberger L, Santos E M, Paull G C, Van Look K J W, et al. (2009). A critical analysis of the biological impacts of plasticizers on wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526): 2047–2062

Okeke E S, Okoye C O, Atakpa E O, Ita R E, Nyaruaba R, Mgbechidinma C L, Akan O D (2022). Microplastics in agroecosystems-impacts on ecosystem functions and food chain. Resources, Conservation and Recycling, 177: 105961

Pang R R, Wang X T, Zhang L M, Lei L, Han Z B, Xie B, Su Y L (2024). Genome-centric metagenomics insights into the plastisphere-driven natural degradation characteristics and mechanism of biodegradable plastics in aquatic environments. Environmental Science & Technology, 58(42): 18915–18927

Peijnenburg W (2025). Airborne microplastics enter plant leaves and end up in our food. Nature, 641(8063): 601–602

Peng C, Zhang X F, Zhang X Y, Liu C G, Chen Z Y, Sun H W, Wang L (2022). Bacterial community under the influence of microplastics in indoor environment and the health hazards associated with antibiotic resistance genes. Environmental Science & Technology, 56(1): 422–432

Peng H R, Zhang Z, Kang X X, Zhang Y H, Zhang H L, Wang Y X, Yang D C, Zhang J L, Wang Y J, Cui L, et al. (2025). Unveiling gut microbiota and metabolic functions contributed to polyvinyl chloride degradation in Spodoptera frugiperda larvae. Journal of Hazardous Materials, 492: 138209

Pham D N, Clark L, Li M Y (2021). Microplastics as hubs enriching antibiotic-resistant bacteria and pathogens in municipal activated sludge. Journal of Hazardous Materials Letters, 2: 100014

Pottinger A S, Geyer R, Biyani N, Martinez C C, Nathan N, Morse M R, Liu C, Hu S Y, De Bruyn M, Boettiger C, et al. (2024). Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050. Science, 386(6726): 1168–1173

Prata J C (2018). Airborne microplastics: consequences to human health?. Environmental Pollution, 234: 115–126

Qian X Y, Coleman K, Jiang S Z, Kriz A J, Marciano J H, Luo C Y, Cai C H, Manam M D, Caglayan E, Lai A, et al. (2025). Spatial transcriptomics reveals human cortical layer and area specification. Nature, 644(8075): 153–163

Rauert C, Charlton N, Bagley A, Dunlop S A, Symeonides C, Thomas K V (2025). Assessing the efficacy of pyrolysis–gas chromatography–mass spectrometry for nanoplastic and microplastic analysis in human blood. Environmental Science & Technology, 59(4): 1984–1994

Restrepo-Flórez J M, Bassi A, Thompson M R (2014). Microbial degradation and deterioration of polyethylene: a review. International Biodeterioration & Biodegradation, 88: 83–90

Rios L M, Moore C, Jones P R (2007). Persistent organic pollutants carried by Synthetic polymers in the ocean environment. Marine Pollution Bulletin, 54(8): 1230–1237

Ruan Z P, Chen K, Cao W M, Meng L, Yang B G, Xu M J, Xing Y W, Li P F, Freilich S, Chen C, et al. (2024). Engineering natural microbiomes toward enhanced bioremediation by microbiome modeling. Nature Communications, 15(1): 4694

Sanluis-Verdes A, Colomer-Vidal P, Rodriguez-Ventura F, Bello-Villarino M, Spinola-Amilibia M, Ruiz-Lopez E, Illanes-Vicioso R, Castroviejo P, Cigliano R A, Montoya M, et al. (2022). Wax worm saliva and the enzymes therein are the key to polyethylene degradation by *Galleria mellonella*. Nature Communications, 13(1): 5568

Sarfatis A, Wang Y Y, Twumasi-Ankrah N, Moffitt J R (2025). Highly multiplexed spatial transcriptomics in bacteria. Science, 387(6732): eadr0932

Sathicq M B, Sabatino R, Corno G, Di Cesare A (2021). Are microplastic particles a hotspot for the spread and the persistence of antibiotic resistance in aquatic systems? Environmental Pollution, 279: 116896

Schaerer L, Putman L, Bigcraft I, Byrne E, Kulas D, Zolghadr A, Aloba S, Ong R, Shonnard D, Techtmann S (2023). Coexistence of specialist and generalist species within mixed plastic derivative-utilizing microbial communities. Microbiome, 11(1): 224

Seltenrich N (2015). New link in the food chain? Marine plastic pollution and seafood safety. Environ Health Perspect, 123(2): A34–A41

Skariyachan S, Manjunatha V, Sultana S, Jois C, Bai V, Vasist K S (2016). Novel bacterial consortia isolated from plastic garbage processing areas demonstrated enhanced degradation for low density polyethylene. Environmental Science and Pollution Research, 23(18): 18307–18319

Skraber S, Ogorzaly L, Helmi K, Maul A, Hoffmann L, Cauchie H M, Gantzer C (2009). Occurrence and persistence of enteroviruses, noroviruses and F-specific RNA phages in natural wastewater biofilms. Water Research, 43(19): 4780–4789

Steffen W, Richardson K, Rockström J, Cornell S E, Fetzer I, Bennett E M, Biggs R, Carpenter S R, De Vries W, De Wit C A, et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223): 1259855

Su Y L, Zhang Z J, Zhu J D, Shi J H, Wei H W, Xie B, Shi H H (2021). Microplastics act as vectors for antibiotic resistance genes in landfill leachate: The enhanced roles of the long-term aging process. Environmental Pollution, 270: 116278

Sun H F, Lei C L, Xu J H, Li R L (2021a). Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants. Journal of Hazardous Materials, 416: 125854

Sun X M, Booth A M, Sui Q, Zhu L, Yu Y X, Xia B, Meng S L, Xing B S (2025). Potential impact of marine-derived plastisphere as a Vibrio carrier on marine ecosystems: current status and future perspectives. Journal of Hazardous Materials, 495: 138927

Sun Y Z, Cao N, Duan C X, Wang Q, Ding C F, Wang J (2021b). Selection of antibiotic resistance genes on biodegradable and non-biodegradable microplastics. Journal of Hazardous Materials, 409: 124979

Teuten E L, Rowland S J, Galloway T S, Thompson R C (2007). Potential for plastics to transport hydrophobic contaminants. Environmental Science & Technology, 41(22): 7759–7764

Teuten E L, Saquing J M, Knappe D R U, Barlaz M A, Jonsson S, Björn A, Rowland S J, Thompson R C, Galloway T S, Yamashita R, et al. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526): 2027–2045

Thompson R C, Courtene-Jones W, Boucher J, Pahl S, Raubenheimer K, Koelmans A A (2024). Twenty years of microplastic pollution research—What have we learned? Science, 386(6720): eadl2746

Thompson R C, Olsen Y, Mitchell R P, Davis A, Rowland S J, John A W G, McGonigle D, Russell A E (2004). Lost at sea: where is all the plastic?. Science, 304(5672): 838

Tournier V, Topham C M, Gilles A, David B, Folgoas C, Moya-Leclair E, Kamionka E, Desrousseaux M L, Texier H, Gavalda S, et al. (2020). An engineered PET depolymerase to break down and recycle plastic bottles. Nature, 580(7802): 216–219

Urbanek A K, Rymowicz W, Mirończuk A M (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. Applied Microbiology and Biotechnology, 102(18): 7669–7678

Van Doremalen N, Bushmaker T, Morris D H, Holbrook M G, Gamble A, Williamson B N, Tamin A, Harcourt J L, Thornburg N J, Gerber S I, et al. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New England Journal of Medicine, 382(16): 1564–1567

Wang F Y, Wang Q L, Adams C A, Sun Y H, Zhang S W (2022a). Effects of microplastics on soil properties: current knowledge and future perspectives. Journal of Hazardous Materials, 424: 127531

Wang L, Lin D, Xiao K Q, Ma L J, Fu Y M, Huo Y X, Liu Y J, Ye M, Sun M M, Zhu D, et al. (2024a). Soil viral–host interactions regulate microplastic-dependent carbon storage. Peedings of the National Academy of Sciences of the United States of America, 121(45): e2413245121

Wang L, Zhang T L, Xiang Q, Fu C X, Qiao M, Ding L J, Zhu D (2024b). Selective enrichment of virulence factor genes in the plastisphere under antibiotic and heavy metal pressures. Journal of Hazardous Materials, 465: 133319

Wang S S, Xue N N, Li W F, Zhang D Y, Pan X L, Luo Y M (2020). Selectively enrichment of antibiotics and ARGs by microplastics in river, estuary and marine waters. Science of the Total Environment, 708: 134594

Wang X X, Li H, Chen Y, Meng X Q, Dieketseng M Y, Wang X M, Yan S, Wang B Z, Zhou L X, Zheng G Y (2022b). A neglected risk of nanoplastics as revealed by the promoted transformation of plasmid-borne ampicillin resistance gene by *Escherichia coli*. Environmental Microbiology, 24(10): 4946–4959

Wang Y, Xiang L L, Amelung W, Elsner M, Gan J, Kueppers S, Christian L, Jiang X, Adu-Gyamfi J, Heng L E, et al. (2023). Micro- and nanoplastics in soil ecosystems: analytical methods, fate, and effects. TrAC Trends in Analytical Chemistry, 169: 117309

Wang Y F, Liu Y J, Fu Y M, Xu J Y, Zhang T L, Cui H L, Qiao M, Rillig M C, Zhu Y G, Zhu D (2024c). Microplastic diversity increases the abundance of antibiotic resistance genes in soil. Nature Communications, 15(1): 9788

Wang Z Q, Gao J F, Zhao Y F, Dai H H, Jia J X, Zhang D (2021). Plastisphere enrich antibiotic resistance genes and potential pathogenic bacteria in sewage with pharmaceuticals. Science of the Total Environment, 768: 144663

Watson B R, Paul B, Rahman R U, Amir-Zilberstein L, Segerstolpe Å, Epstein E T, Murphy S, Geistlinger L, Lee T, Shih A, et al. (2025). Spatial transcriptomics of healthy and fibrotic human liver at single-cell resolution. Nature Communications, 16(1): 319

Witsø I L, Basson A, Vinje H, Llarena A K, Bringas C S, Aspholm M, Wasteson Y, Myrmel M (2023). Freshwater plastispheres as a vector for foodborne bacteria and viruses. Environmental Microbiology, 25(12): 2864–2881

Wright R J, Langille M G I, Walker T R (2021). Food or just a free ride? A meta-analysis reveals the global diversity of the Plastisphere. The ISME Journal, 15(3): 789–806

Wu B H, Zhong B Z T, Zheng L R, Huang R Y, Jiang S F, Li M C, Hong L, Tan P (2025). Harnessing protein language model for structure-based discovery of highly efficient and robust PET hydrolases. Nature Communications, 16(1): 6211

Wu J, Lv Y H, Sun D, Zhou J H, Wu J, He R L, Liu D F, Song H, Li W W (2024). Phthalates boost natural transformation of extracellular antibiotic resistance genes through enhancing bacterial motility and DNA environmental persistence. Environmental Science & Technology, 58(17): 7291–7301

Wu J, Zhou J H, Liu D F, Wu J, He R L, Cheng Z H, Li H H, Li W W (2023). Phthalates promote dissemination of antibiotic resistance genes: an overlooked environmental risk. Environmental Science & Technology, 57(17): 6876–6887

Wu X J, Pan J, Li M, Li Y, Bartlam M, Wang Y Y (2019). Selective enrichment of bacterial pathogens by microplastic biofilm. Water Research, 165: 114979

Xia R, Yin X L, Balcazar J L, Huang D, Liao J Q, Wang D S, Alvarez P J J, Yu P F (2025). Bacterium-phage symbiosis facilitates the enrichment of bacterial pathogens and antibiotic-resistant bacteria in the plastisphere. Environmental Science & Technology, 59(6): 2948–2960

Xu L B, Bai X Y, Li K, Zhang G B, Zhang M J, Hu M, Huang Y (2024). Human exposure to ambient atmospheric microplastics in a megacity: spatiotemporal variation and associated microorganism-related health risk. Environmental Science & Technology, 58(8): 3702–3713

Yan Z H, Liu Y F, Zhang T, Zhang F M, Ren H Q, Zhang Y (2022). Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status. Environmental Science & Technology, 56(1): 414–421

Yang D Q, Shi H H, Li L, Li J N, Jabeen K, Kolandhasamy P (2015). Microplastic pollution in table salts from China. Environmental Science & Technology, 49(22): 13622–13627

Yang J, Yang Y, Wu W M, Zhao J, Jiang L (2014). Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environmental Science & Technology, 48(23): 13776–13784

Yang K, Chen Q L, Chen M L, Li H Z, Liao H, Pu Q, Zhu Y G, Cui L (2020a). Temporal dynamics of antibiotic resistome in the plastisphere during microbial colonization. Environmental Science & Technology, 54(18): 11322–11332

Yang K, Xu F, Xing X Y, Wei J, Chen Q L, Su J Q, Cui L (2025a). Microplastics pose an elevated antimicrobial resistance risk than natural surfaces via a systematic comparative study of surface biofilms in rivers. Environmental Science & Technology, 59(22): 11216–11228

Yang Q E, Lin Z Y, Gan D H, Li M C, Liu X D, Zhou S G, Walsh T R (2025b). Microplastics mediates the spread of antimicrobial resistance plasmids via modulating conjugal gene expression. Environment International, 195: 109261

Yang Y, Wang J L, Xia M L (2020b). Biodegradation and mineralization of polystyrene by plastic-eating superworms *Zophobas atratus*. Science of the Total Environment, 708: 135233

Yang Y Y, Liu G H, Song W J, Ye C, Lin H, Li Z, Liu W Z (2019). Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. Environment International, 123: 79–86

Ye J, Rensing C, Su J Q, Zhu Y G (2017). From chemical mixtures to antibiotic resistance. Journal of Environmental Sciences, 62: 138–144

Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K, Miyamoto K, Kimura Y, Oda K (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). Science, 351(6278): 1196–1199

Yu T H, Cui H Y, Li J C, Luo Y A, Jiang G D, Zhao H M (2023). Enzyme function prediction using contrastive learning. Science, 379(6639): 1358–1363

Zadjelovic V, Wright R J, Borsetto C, Quartey J, Cairns T N, Langille M G I, Wellington E M H, Christie-Oleza J A (2023). Microbial hitchhikers harbouring antimicrobial-resistance genes in the riverine plastisphere. Microbiome, 11(1): 225

Zahra S, Abbas S S, Mahsa M T, Mohsen N (2010). Biodegradation of low-density polyethylene (LDPE) by isolated fungi in solid waste medium. Waste Management, 30(3): 396–401

Zettler E R, Mincer T J, Amaral-Zettler L A (2013). Life in the “plastisphere”: microbial communities on plastic marine debris. Environmental Science & Technology, 47(13): 7137–7146

Zhang A N, Gaston J M, Dai C L, Zhao S J, Poyet M, Groussin M, Yin X L, Li L G, Van Loosdrecht M C M, Topp E, et al. (2021). An omics-based framework for assessing the health risk of antimicrobial resistance genes. Nature Communications, 12(1): 4765

Zhang F, Wang Z, Vijver M G, Peijnenburg W J G M (2022a). Theoretical investigation on the interactions of microplastics with a SARS-CoV-2 RNA fragment and their potential impacts on viral transport and exposure. Science of the Total Environment, 842: 156812

Zhang G Q, Wang H, Zhang Z G, Zhang L, Guo G B, Yang J, Yuan F J, Ju F (2024). Highly accurate classification and discovery of microbial protein-coding gene functions using FunGeneTyper: an extensible deep learning framework. Briefings in Bioinformatics, 25(4): bbae319

Zhang J Q, Gao D L, Li Q H, Zhao Y X, Li L, Lin H F, Bi Q R, Zhao Y C (2020a). Biodegradation of polyethylene microplastic particles by the fungus Aspergillus flavus from the guts of wax moth Galleria mellonella. Science of the Total Environment, 704: 135931

Zhang Q, Zhao Y P, Du F N, Cai H W, Wang G H, Shi H H (2020b). Microplastic fallout in different indoor environments. Environmental Science & Technology, 54(11): 6530–6539

Zhang S J, Zeng Y H, Zhu J M, Cai Z H, Zhou J (2022b). The structure and assembly mechanisms of plastisphere microbial community in natural marine environment. Journal of Hazardous Materials, 421: 126780

Zhang Z, Peng H R, Yang D C, Zhang G Q, Zhang J L, Ju F (2022c). Polyvinyl chloride degradation by a bacterium isolated from the gut of insect larvae. Nature Communications, 13(1): 5360

Zhang Z Q, Zhao S L, Chen L, Duan C J, Zhang X C, Fang L C (2022d). A review of microplastics in soil: Occurrence, analytical methods, combined contamination and risks. Environmental Pollution, 306: 119374

Zhang Z Y, Zhang Q, Wang T Z, Xu N H, Lu T, Hong W J, Penuelas J, Gillings M, Wang M X, Gao W W, et al. (2022e). Assessment of global health risk of antibiotic resistance genes. Nature Communications, 13(1): 1553

Zhao X R, Zhou Y P, Liang C Z, Song J C, Yu S Y, Liao G X, Zou P Y, Tang K H D, Wu C M (2023). Airborne microplastics: occurrence, sources, fate, risks and mitigation. Science of the Total Environment, 858(Pt 2): 159943

Zheng X B, Wu X D, Zheng Q, Mai B X, Qiu R L (2023). Transfer of microplastics in terrestrial and aquatic food webs: the impact of E-waste debris and ecological traits. Environmental Science & Technology, 57(3): 1300–1308

Zhu D, Ma J, Li G, Rillig M C, Zhu Y G (2022). Soil plastispheres as hotspots of antibiotic resistance genes and potential pathogens. The ISME Journal, 16(2): 521–532

Zumstein M T, Schintlmeister A, Nelson T F, Baumgartner R, Woebken D, Wagner M, Kohler H P E, McNeill K, Sander M (2018). Biodegradation of synthetic polymers in soils: tracking carbon into CO_2 and microbial biomass. Science Advances, 4(7): eaas9024