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BACTERIAL MICROBIOTA IN AQUATIC ENVIRONMENTS AND THE BIODEGRADATION POTENTIAL OF SUSTAINABLE MATERIALS: INSIGHTS INTO ENVIRONMENTAL FATE - A REVIEW

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Abstract

In recent years, a global strategy to replace petroleum-based polymers has been the development of durable, innovative and sustainable alternatives, namely biodegradable materials. This review provides a narrative synthesis of studies published between 2009 and 2026 investigating the interactions between biodegradable polymers and bacterial microbiota from aquatic environments. It focuses on major classes of biodegradable materials, including PLA, PHA, starch-based polymers and commercial blends and examines their behaviour in freshwater and marine environments. Current literature highlights that environmental conditions strongly influence biodegradation rates and microbial colonization patterns, yet the relationships between biodegradable materials and aquatic microbiomes remain insufficiently characterized. According to published studies, biodegradable polymers generally support more extensive bacterial colonization than conventional plastics, promoting higher microbial diversity and facilitating polymer breakdown into final metabolic products. This review identifies key knowledge gaps regarding the long-term environmental fate of biodegradable materials, synthesizes evidence on microbial drivers of biodegradation, and outlines implications for future research priorities, environmental monitoring strategies and the design of next-generation biomaterials.

Key words*: aquatic ecosystem, bacterial microbiota, biodegradable materials, biodegradation, environmental risk.*

INTRODUCTION

Nowadays, one of the biggest global challenges is represented by plastic pollution with a negative impact on the aquatic environment and on the development of natural biological processes. Waste that reaches the environment interacts with it, leading to the release of harmful substances or altering the composition and structure of existing microbial communities, which can contribute to the reduction of water quality and increase the risk of toxicity for humans and the environment (Zlati et al., 2023). The advantages of petroleum-based plastics are represented by lower costs and better mechanical properties, but the disadvantage is their slow degradation capacity and persistence in the environment, which leads to the accumulation of pollutants (Wang et al., 2026). Specialists' forecasts estimate that by 2050, approximately 12 billion tons of plastic waste will be released into natural environments, having a negative effect on the balance of aquatic ecosystems (Amelia et al., 2025).

The solution that arouses interest and comes to meet this problem of excessive plastic use is represented by its replacement with new biodegradable materials. Materials that can be bio-based, biodegradable or can meet both characteristics at the same time are called bioplastics and are considered to be durable and sustainable substitutes that can replace conventional polymers (Lavagnolo et al., 2024). It is worth noting that the biodegradability of a material is not a universally valid characteristic for all polymers obtained from biological

sources, and not all plastic materials derived from fossil sources are non-biodegradable (Ahsan et al., 2023). For example, recent analyses confirm that bio-based polyethylene (bio-PE) remains chemically identical to conventional polyethylene and therefore non-biodegradable (Burelo et al., 2023), whereas fossil-derived polycaprolactone (PCL) continues to be recognized as a clearly biodegradable polyester in natural environments (Ntrivala et al., 2025).

Biodegradable materials are numerous and among the most commonly used are polylactic acid (PLA), polyhydroxy-alkanoates (PHA/PHB), polybutylene adipate terephthalate (PBAT) and polybutylene succinate (PBS), which are most widely used in the packaging industry due to their remarkable properties (Meyer-Cifuentes et al., 2020; Chen, 2022; Ahsan et al., 2023; Amelia et al., 2025).

However, despite their promise as sustainable alternatives, recent evidence indicates that biodegradable materials may also exhibit incomplete degradation, environmental persistence and ecological risks under natural aquatic conditions.

The biodegradation process of materials that reach the aquatic environment is usually not complete, being influenced by the bacterial communities present and their degradation capacity. An important role is also played by environmental, biological, physical and chemical factors such as water temperature, salinity, pH, dissolved oxygen concentration, ultraviolet radiation and the presence of nutrients, on which the dynamics of material degradation in the aquatic environment depend (Eronen-Rasimus et al., 2022; Jiao et al., 2026; Velayudhan et al., 2026). These environmental parameters not only influence polymer degradation rates but also shape the composition and activity of microbial taxa colonizing biodegradable materials, with certain genera becoming dominant under specific physicochemical conditions.

The microbial community of the aquatic environment has the property of colonizing biodegradable materials from the moment they are released into the aquatic environment (Amaral-Zettler et al., 2020). Microorganisms such as species belonging to the genera *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Variovorax* or the families *Comamonadaceae* and *Xanthobacteraceae* have a remarkable role in the biodegradation process of biodegradable materials through the secretion of extracellular enzymes capable of cleaving polymer chains into low molecular weight compounds (Peng et al., 2022; Ahsan et al., 2023). Recent findings show that the incomplete degradation of biodegradable materials under natural conditions of aquatic ecosystems leads to their prolonged persistence and the potential emergence of unwanted ecological impacts (Zhang et al., 2025).

In this context, understanding the interactions between bacterial microbiota and biodegradable materials becomes essential for assessing the ecological impact and behaviour of these materials in the natural environment. This review synthesizes current information on the impact of aquatic bacterial communities on the degradation of biodegradable materials in both freshwater and marine environments, the dynamics of the plastisphere, a distinct microhabitat, in where bacteria, fungi and other microorganisms adhere to the surface of polymers and actively participate in biodegradation processes. This biofilm provides protection primarily for the microorganisms themselves, offering a stable micro-environment that shields them from environmental stressors while enabling enzymatic activity on the polymer surface (Amaral-Zettler et al., 2020).

The successional colonization pattern of the plastisphere - comprising early, intermediate and advanced stages - has been described in detail by Šerá et al. (2026), and is broadly consistent with observations from other studies reporting shifts from early colonizers consisting of fast-growing, surface-attaching microorganisms, including species of *Pseudomonas*, *Vibrio* and *Alteromonas* to mature biofilms enriched in taxa like *Burkholderiaceae*, *Comamonadaceae* and *Rhodococcus* (Zettler et al., 2013; Danso et al., 2019; Amaral-Zettler et al., 2020).

Although microbial colonization follows a predictable successional trajectory, the extent of biofilm development and the composition of the resulting microbial community depend strongly on the type of polymer. Compared to conventional plastics, biodegradable materials favor higher microbial diversity and biomass and more intense enzymatic activity than that formed on conventional materials such as polyethylene, polypropylene and polystyrene

(PE, PP and PS) due to their hydrophilic properties and the release of low molecular weight organic compounds (Zheng et al., 2025). Studies have shown that the average microbial biofilm biomass on biodegradable materials such as PHA and PLA was consistently, although modestly, higher (1.08-1.26 fold) than that on non-biodegradable plastics (PE, PP and PS), indicating an enhanced potential for microbial colonization and biodegradation (Peng et al., 2022; Zhang et al., 2025).

BIODEGRADABLE MATERIALS IN AQUATIC ENVIRONMENTS

Biodegradability is defined as the ability of a material to be decomposed by microorganisms into CO_2, water and biomass under aerobic conditions, or into CO_2, CH_4 and biomass under anaerobic conditions. The biodegradation process generally involves three sequential stages: biodeterioration, biofragmentation and microbial assimilation, culminating in the mineralization of polymer-derived compounds (Ahsan et al., 2023; Cerbule et al., 2023).

Figure 1 shows the disintegration process of biodegradable materials, under the action of external environmental factors of degradation but also through internal mechanisms such as enzymatic cleavage.

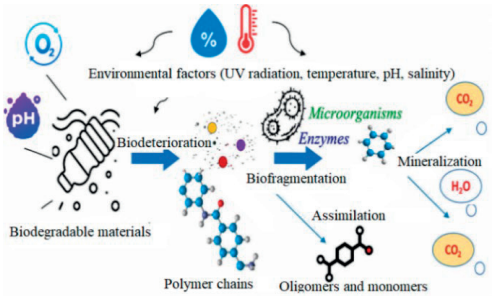


Figure 1. Schematic representation of the biodegradation process of biodegradable polymers, illustrating the sequential stages of biodeterioration, biofragmentation, microbial assimilation and final mineralization (adapted from Amelia et al., 2025)

During the biodeterioration stage, abiotic factors, including UV radiation, oxidation and temperature fluctuations, together with microbial colonization, alter the surface properties of the polymer, facilitating subsequent degradation. In the biofragmentation stage, extracellular enzymes degrade polymer chains into oligomers and monomers that can subsequently be assimilated by microorganisms. Polyesters such as PLA, PBAT and PHA are mainly hydrolysed by esterases, lipases and cutinases, whereas starch-based materials are primarily degraded by amylases. During the assimilation stage, these degradation products are utilized as carbon and energy sources and are ultimately converted into biomass and inorganic products through mineralization (Amelia et al., 2025).

Although the fundamental mechanisms of biodegradation are similar across environments, degradation generally proceeds more slowly in aquatic ecosystems than in terrestrial or industrial composting environments because of lower temperatures, reduced nutrient availability, lower microbial abundance and other environmental constraints that limit microbial activity and enzymatic degradation (Ahsan et al., 2023; Tantawi et al., 2025).

The biodegradability of different polymers therefore depends not only on environmental conditions but also on their chemical composition and physicochemical properties.

Due to their chemical composition, biodegradable materials are more hydrophilic and more susceptible to hydrolysis, which generates oligomers and monomers that can be utilized as carbon and energy sources by microorganisms (Zhang et al., 2025).

Compared with conventional polyolefins such as polyethylene (PE) and polypropylene (PP), biodegradable polyesters including PLA and PBAT exhibit greater biodegradation potential. However, their degradation rates differ substantially depending on environmental conditions, with PLA generally degrading efficiently under industrial composting conditions but much more slowly in natural freshwater and marine environments (Chen, 2022; Ahsan et al., 2023). PHB and PHA are considered among the most biodegradable materials in aquatic environments, both in freshwater and marine systems (Chen, 2022).

Starch-based materials also exhibit high biodegradation potential; however, their degradation rates vary considerably depending on starch content, polymer blending ratio, plasticizer composition, crystallinity and environmental moisture, all of which influence

microbial accessibility and enzymatic hydrolysis (Ahsan et al., 2023).

ENVIRONMENTAL FACTORS INFLUENCING BIODEGRADATION

Biodegradation of materials in aquatic ecosystems is influenced by the complex interaction of physical, chemical and biological factors, which control both the activity of microorganisms and the properties of polymers. Indicators of biodegradation include mass loss, surface erosion, changes in molecular weight and chemical modifications of the polymer. In particular, oxidative processes generate carbonyl-containing functional groups, which increase surface polarity and consequently reduce hydrophobicity, thereby promoting microbial colonization and further biodegradation (Amelia et al., 2025).
Temperature is one of the most important factors, as low temperatures slow down microbial metabolic activity. For this reason, materials such as PLA exhibit efficient degradation under industrial composting conditions, but much slower degradation under natural conditions of aquatic ecosystems (Ahsan et al., 2023).
Oxygen levels also influence aerobic and anaerobic biodegradation processes. Under aerobic conditions, degradation mainly leads to the formation of CO_2, water and biomass, while anaerobic conditions favour fermentative processes and methane production. Aquatic sediments and the water-sediment interface represent areas of intense microbial activity, which favour depolymerization and mineralization processes (Amelia et al., 2025). Ultraviolet radiation promotes surface modification of polymers and increases their susceptibility to microbial colonization. Salinity, pH, and nutrient availability shape the composition of bacterial communities and the microbial succession within the plastisphere, indirectly influencing the efficiency of biodegradation (Eronen-Rasimus et al., 2022). Physico-chemical and biological parameters determine the integrity of the aquatic ecosystem, and an integrated approach to these parameters is essential for managing surface and groundwater used in agriculture, industry, and daily life (Iticescu et al., 2014).
Recent studies suggest that the variability of environmental conditions represents one of the main reasons why the biodegradation of materials labelled as “biodegradable” often remains incomplete in natural ecosystems.

BACTERIAL COMMUNITIES IN BIODEGRADATION PROCESSES

Among the most frequently reported bacterial genera involved in the degradation of biodegradable materials in aquatic environments are *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Variovorax*, *Alcaligenes*, *Comamonas*, *Shewanella*, and *Vibrio*. These microorganisms adhere to polymer surfaces and secrete extracellular enzymes capable of hydrolyzing polymer chains into oligomers and monomers that are subsequently assimilated and mineralized by the microbial community (Danso et al., 2019; Ru et al., 2020; Amelia et al., 2025).
The biodegradability of biodegradable polymers differs considerably according to polymer chemistry and environmental conditions. Polyhydroxyalkanoates (PHA), including polyhydroxybutyrate (PHB), are consistently reported among the most readily biodegradable biopolymers in aquatic environments, whereas materials such as poly(butylene succinate) (PBS) may exhibit very high degradation rates under specific sediment conditions. For example, Amelia et al. (2025) reported degradation rates approaching 100% for PBS and approximately 70% for PHB in aquatic sediments; however, these values should be interpreted as study-specific rather than universal rankings, as biodegradation strongly depends on environmental conditions, exposure time and experimental design.
The degradation of PLA has been associated with shifts in microbial community composition, including the enrichment of denitrifying bacteria that utilize lactic acid released during polymer hydrolysis as a carbon source and electron donor. Changes in the abundance of anammox bacteria have also been reported during PLA degradation, although their role appears to be linked to nitrogen cycling rather than the direct metabolism of lactic acid (Chen, 2022; Nie et al., 2022). According to studies, among bio-based materials, PHB was the most readily biodegradable, both in freshwater and in seawater (Chen, 2022). Biodegradable starch-based materials also

exhibit a significant degree of biodegradation in seawater; however, the process shows high variability, being influenced by factors such as material properties and environmental conditions (Chen, 2022; Ahsan et al., 2023).
Table 1 summarizes the principal biodegradable polymers investigated in aquatic environments, the dominant bacterial taxa associated with their degradation, the enzymes involved and the reported biodegradation outcomes, based on data compiled from the scientific literature.

Table 1. Biodegradable Materials (BM) in Aquatic Systems - Processes and Mechanisms of Their Degradation Under the Influence of the Plastisphere

BM	Plastisphere	Effects	Reference
PLA	*Vibrionaceae* *Actinomycetaceae* *Flavobacteriaceae* *Flavobacteriales* *Planctomycetaceae*	Slow biodegradation; mass loss detected; no consistent % reported.	(Peng et al., 2022; Amelia et al., 2025)
PHA	*Actinomyces* *Acinetobacter* *Arthrobacter* *Aspergillus* *Bacillus* *Clostridium* *Comamonas* *Enterobacter* *Klebsiella* *Variovorax* *Mycobacterium* *Streptomyces* *Pseudomonas,* *Rhodococcus*	Degradation in multiple aquatic conditions, including extreme habitats.	(Du et al., 2022; Amelia et al., 2025)
PHB	*Pseudomonas* *Bacillus* *Rhodococcus* *Variovorax* *Comamonas* *Alcaligenes* *Xanthomonas* *Klebsiella* *Streptomyces*	Very high; up to ~100% in sediments ~8.5% mass loss in 365 days at 25ºC.	(Du et al., 2022; Ahsan et al., 2023; Šerá et al., 2026)
PBS	*Actinomicete* *Proteobacteria* *Maribus* *Neptunibacter* *Bacillus*	Microbial degradation in the aquatic environment.	(Brakstad et al., 2022; Peng et al., 2022)
PHBH	*Acidovorax,* *Undibacterium* *Chitinimonas*	Signs of deterioration are visible after two weeks.	(Peng et al., 2022; Šerá et al., 2026)
Corn starch	*Capitella capitata*	1.5% mass loss in 90 days at 25°C; up to 69% mass loss in 236 days.	(Ahsan et al., 2023)

PLA - polylactic acid, PHA - polyhydroxyalkanoate, PHB - poli-3-hidroxibutirat, PHBV - poly(3-hydroxybutyrate-co-3-hydroxyvalerate), PHBH - poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), PBS - poly (butylene Succinate).

Although numerous bacterial and fungal taxa have been identified on the surface of biodegradable materials, their actual contribution to polymer degradation in natural aquatic environments remains poorly understood. The presence of a microorganism in the plastisphere does not necessarily demonstrate that it actively participates in polymer depolymerization, as many taxa may simply exploit degradation products released by other microorganisms or colonize the biofilm without directly degrading the polymer. Consequently, most studies describe the composition of the microbial community rather than experimentally confirming the biodegradation potential of individual taxa under environmentally relevant conditions. This lack of functional validation represents one of the main knowledge gaps in understanding the fate of biodegradable plastics in aquatic ecosystems and highlights the need for field studies that combine microbial community analyses with measurements of enzymatic activity and polymer degradation (Peng et al., 2022).

ECOLOGICAL LIMITATIONS AND RISKS IN NATURAL BIODEGRADATION

Although biodegradable materials represent promising alternatives to conventional polymers, they may also generate undesirable ecological effects.
Incomplete biodegradation can lead to the formation of biodegradable fragments that persist in aquatic ecosystems and interact with pollutants and living organisms (Amelia et al., 2025). These fragments can adsorb organic pollutants and trace metals from surrounding waters and subsequently release them after ingestion by aquatic organisms, thereby acting as vectors that increase contaminant transport and bioavailability within aquatic food webs (Catarci Carteny et al., 2023; Lu et al., 2024).
The plastisphere developing on biodegradable materials may also provide a favourable habitat for opportunistic and potentially pathogenic microorganisms. The close spatial organization of microbial cells within biofilms facilitates cell-to-cell interactions and horizontal gene transfer, thereby promoting the dissemination of antibiotic resistance genes (ARGs) and other mobile genetic elements.

Several opportunistic and potentially pathogenic bacteria have been reported in plastisphere biofilms associated with biodegradable materials (Amaral-Zettler et al., 2020; Zhang et al., 2023). Their occurrence and ecological significance are discussed in the following section.

These issues demonstrate that the environmental benefits of biodegradable materials cannot be assessed solely based on their biodegradation potential. A comprehensive assessment should also consider the persistence of degradation products, their interactions with contaminants and microorganisms, and their long-term ecological effects under natural environmental conditions. Addressing these knowledge gaps through long-term field studies will be essential for accurately assessing the environmental sustainability of biodegradable polymers in aquatic ecosystems.

SUSTAINABLE WATER PURIFICATION IN AQUACULTURE

Aquaculture systems represent an increasingly important source of plastic and biodegradable polymer inputs into aquatic environments. Operational materials such as nets, ropes, feed bags, and filtration components introduce both conventional plastics and emerging biopolymers into surrounding waters, where they rapidly become colonized by microbial communities. These biofilm-covered surfaces form localized plastisphere niches, influencing nutrient cycling, pathogen proliferation, and antibiotic-resistance dynamics- all central themes of this review.

At the same time, aquaculture wastewater itself contains high nitrogen and phosphorus loads, suspended organic matter, pathogenic bacteria, antibiotic-resistant strains, and mobile resistance genes (Sun et al., 2025). These pollutants interact with plastic debris present in the system, creating complex microbial consortia that affect both water quality and the degradation pathways of plastic and biodegradable materials. For this reason, sustainable purification strategies are increasingly exploring biodegradable materials as filtration media, microbial carriers, or components of circular-economy remediation technologies.

The link between pollutant accumulation and insufficient recycling or reuse practices is well documented, particularly in systems where circular-economy principles are not implemented (Georgescu et al., 2025). As aquaculture expands, untreated wastewater discharge intensifies environmental pressures (Raza et al., 2025), reinforcing the need for purification methods that align with biodegradation processes and reduce plastisphere-associated risks.

To illustrate current directions in sustainable aquaculture remediation - including microbial consortia, advanced material-based treatments, and energy-efficient systems - Table 2 summarizes several high-efficiency purification methods and highlights their relevance for biodegradable-material applications, plastisphere management, and circular-economy integration.

Table 2. Sustainable aquaculture purification solutions with relevance to biodegradable materials and plastisphere dynamics

Solution	Description	Effect	Relevance to biodegradable materials & plastisphere	Reference
Symbiotic bacteria-algae system	Nitrogen-fixing bacteria isolated from *Penaeus albus* used synergistically with *Tetraselmis suecica* microalgae to remove nutrients and suppress pathogens.	Removes >93% ammonia; reduces total N and P by 67-95% in 4 days; suppresses *Vibrio* and *Aeromonas* by 97-99%; reduces ARGs by 57.9%.	Supports microbial consortia similar to plastisphere communities, offering a model for biofilm-mediated degradation on biodegradable polymer surfaces; algae-bacteria systems can be immobilized on biopolymer carriers for circular-economy wastewater treatment.	(Sun et al., 2025)
Ag-ZnO/graphene composite	Photocatalytic and antimicrobial composite designed for antibiotic removal and inactivation of resistant bacteria.	Inactivates 99% *A. baumannii* and 97% *S. aureus* within 24 h; rapid antibiotic degradation and ARG reduction in both ultrapure and real wastewater.	Demonstrates how advanced materials can be integrated with biodegradable polymer matrices to create hybrid purification media; reduces microbial pressures that shape plastisphere biofilms and influence biodegradation kinetics.	(Li et al., 2025)

Solution	Description	Effect	Relevance to biodegradable materials & plastisphere	Reference
Energy-efficient electrochemical system	Floating ecological bed combined with a closed-loop microbial electrochemical system.	Enriches functional taxa (*Aeromonas*, *Stenotrophomonas*, *Dechloromonas*, *Thioalkalivibrio*, *Clostridium*, *Thermodesulfovibrio*, *Desulfobulbus*) supporting carbon and nitrogen removal and electron transfer.	Electroactive microbial communities resemble those colonizing biodegradable plastics, offering insights into electron-transfer-driven polymer degradation; floating beds can incorporate biopolymer substrates to reduce plastic pollution in aquaculture.	(Liao et al., 2025)
Microalgae-based purification	Microalgae added to aquaculture systems for nutrient assimilation and biomass production.	Efficient assimilation of dissolved inorganic carbon, nitrogen, and phosphorus; reduces eutrophication potential.	Microalgal biomass can be used to produce biodegradable bioplastics, linking aquaculture purification to circular-economy material loops; microalgae also colonize plastic surfaces, influencing plastisphere succession.	(Raza et al., 2025)

ANTIBIOTIC EFFECTS ON AQUATIC BACTERIAL COMMUNITIES AND THEIR ROLE IN PLASTISPHERE DYNAMICS

Antibiotics are widely used in aquaculture to manage bacterial infections in fish and shellfish. While they provide short-term health benefits, their excessive or prophylactic use has accelerated the emergence of antibiotic-resistant bacteria, disrupting the ecological balance of aquatic systems (Haque et al., 2024). Multiple antibiotic classes, including sulphonamides, fluoroquinolones, and macrolides, are routinely detected in effluents from livestock farms, medical facilities, and wastewater treatment plants. Their presence in aquatic environments alters the structure of bacterial communities, often promoting shifts toward resistant taxa (Zhang et al., 2023).

Freshwater case studies illustrate the scale of this issue: in the upper Danube River, approximately one-third of microorganisms sampled were resistant to one or two antibiotic classes, and over 10% exhibited multi-resistance. Similarly, Swedish data show that *E. coli* populations in rivers and clinical settings share comparable resistance profiles (Leopold et al., 2024). Although these examples come from European freshwater systems, they reflect broader global patterns observed across marine, estuarine, and freshwater environments, where antibiotic contamination shapes microbial community composition and resistance dynamics.

A critical connection to the present review is the role of antibiotics in plastisphere formation. Both conventional plastics and biodegradable materials rapidly develop biofilms when submerged in aquatic environments. Antibiotic exposure influences these biofilms by selecting for resistant strains, modifying microbial succession, and enhancing horizontal gene transfer. As a result, plastisphere biofilms can act as reservoirs and vectors for ARGs, facilitating their spread across ecosystems. This has direct implications for the environmental safety of biodegradable materials, whose degradation depends on microbial activity that may be altered by antibiotic pressure.

In modern aquaculture, intensive antibiotic use also promotes the formation of persistent biofilms. These three-dimensional microbial structures, embedded in an extracellular matrix, exhibit elevated tolerance to antibiotics, disinfectants, and environmental stressors (Haque et al., 2024).

Because plastics and bioplastics serve as ideal substrates for biofilm attachment, antibiotic-selected communities can colonize polymer surfaces, influencing biodegradation rates, polymer fragmentation, and the ecological behaviour of biodegradable materials.

Certain taxa, such as ε-proteobacteria, are frequently associated with environments experiencing high contaminant pressure. Their correlation with antibiotic resistance arises from metabolic versatility, stress-response pathways, and efficient horizontal gene transfer mechanisms (Barra Caracciolo et al., 2019). These traits also make ε-proteobacteria relevant to plastisphere studies, where biofilm-associated microbes encounter complex mixtures of

pollutants, including antibiotics, microplastics, and biodegradable polymer fragments.

The spread of antibiotic resistance in water bodies is largely driven by anthropogenic pollution-wastewater discharges, agricultural runoff, manure applications, and hospital effluents (Callejas et al., 2024). These same pressures influence plastisphere formation and microbial colonization on biodegradable materials.

Understanding antibiotic impacts is therefore essential for evaluating how biodegradable polymers interact with microbial communities, how ARGs propagate within plastisphere biofilms, and how environmental contamination affects biodegradation efficiency and ecological risk.

PATHOGENIC BACTERIA AND AQUATIC BACTERIAL COMMUNITIES

While previous sections discussed the role of bacterial communities in biodegradation and the ecological risks associated with plastisphere formation, it is equally important to consider the occurrence of pathogenic bacteria within these microbial assemblages. Beyond their contribution to polymer degradation, plastisphere-associated biofilms may provide suitable habitats for opportunistic pathogens, with potential consequences for aquatic ecosystem functioning, aquaculture and public health.

Therefore, this section focuses on representative pathogenic bacteria found in aquatic environments and discusses how their interactions with native bacterial communities and biodegradable-material associated biofilms may influence their persistence and dissemination.

Although bacteria play a major role in maintaining the stability of aquatic environments, the evolution of pathogens has become a threat to the aquatic environment, causing infections if they reach the human body. In aquatic environments, fecal indicator bacteria, particularly *Escherichia coli* and intestinal enterococci, are widely used to assess fecal contamination and associated public health risks. These microorganisms are routinely monitored because their presence reflects recent fecal pollution and the potential occurrence of enteric pathogens. In the context of biodegradable materials, monitoring these indicator bacteria is also relevant for evaluating whether plastisphere biofilms associated with biodegradable polymers provide suitable habitats for fecal-associated microorganisms and other opportunistic pathogens (Li et al., 2021; Schneier et al., 2024).

Besides serving as indicators of fecal contamination, the presence of fecal indicator bacteria on the surfaces of biodegradable materials can give valuable information about the potential of these materials to act as carriers for fecal-associated microorganisms.

Another relevant pathogen is *Salmonella enterica* which can enter aquatic environment through sewage discharges, urban and agricultural runoff and animal waste. Once introduced, it can persist for extended periods in soil and surface water contributing to diseases such as typhoid fever and gastroenteritis. At the same time, these pathogens also interact with the bacterial community, often competing for resources. High bacterial diversity generally inhibits pathogenic species through competitive exclusion, whereas depleted bacterial communities weaken this antagonistic effect, facilitating pathogen spread (Díaz et al., 2024).

Studies have identified various potential pathogens, including *Vibrio*, *Acinetobacter*, *Aeromonas*, *Klebsiella*, *Legionella*, *Arcobacter*, and members of the Campylobacteraceae, colonizing plastisphere biofilms on plastic materials, including biodegradable polymers, in marine and freshwater ecosystems worldwide.

Among these, *Vibrio* species are of particular concern because they can cause diseases in aquatic organisms and humans (Amaral-Zettler et al., 2020; Zhang et al., 2023).

Lactococcosis is caused by *Lactococcus garvieae*, an emerging disease that affects many fish species and causes large economic losses in both marine and freshwater aquaculture particularly in summer, when temperatures above approximately 15-18°C favor bacterial proliferation and disease transmission (Callejas et al., 2024; Khalil et al., 2024; Vendrell et al., 2006). Higher temperatures boost microbial growth and biofilm formation on submerged polymers surfaces showing why it's important to study plastisphere-related microbial communities in conditions that match the

environment. *Bacillus cereus* has a wide spectrum of phenotypic traits, can be a source of contamination in food processing chains, representing a severe risk to human health (Callejas et al., 2024).

As discussed in earlier sections on antibiotic effects and aquaculture wastewater, antibiotic contamination, nutrient loads, and pollutant stressors further shape plastisphere communities, often selecting resistant or opportunistic pathogens. Biodegradable materials, while designed to reduce long-term pollution, also undergo biofilm-mediated degradation, meaning their ecological behavior is tightly coupled to the composition and stability of surrounding microbial communities. Therefore, interactions between pathogens and aquatic bacterial communities highlight the need for approaches that minimize the risks of contaminants in water while preserving the native microbial diversity that supports stability of aquatic ecosystems.

Understanding these relationships is imperative because diverse and functionally balanced microbial communities provide an important ecological barrier against pathogen establishment, whereas disturbances in community structure may facilitate pathogen persistence and the dissemination of antibiotic resistance genes.

In this context, biodegradable materials should not be evaluated solely according to their degradation rates, but also according to their influence on plastisphere development and microbial community assembly. Determining whether plastisphere formation supports native microbial functions or promotes the enrichment of opportunistic and pathogenic microorganisms remains a major research challenge that requires long-term investigations under environmentally relevant conditions.

KNOWLEDGE GAPS AND FUTURE DIRECTIONS

The dynamics of the plastisphere and the succession of microbial communities associated with biodegradable materials remain insufficiently investigated, even though numerous studies have identified dominant bacterial taxa involved in polymer colonization and degradation (Peng et al., 2022). As discussed throughout this review, particularly in the sections addressing microbial colonization, bacterial biodegradation processes and ecological risks, understanding the functional role of these microbial communities under natural environmental conditions remains one of the major challenges for predicting the environmental fate of biodegradable materials.

Methodological gaps

Research efforts are directed toward improving the end-of-life biodegradation capacity of commercially available biomass-derived materials such as polylactic acid, polybutylene succinate, and polyhydroxyalkanoates. Although interest in biodegradable materials is steadily increasing, many aspects of their long-term behaviour remain poorly understood, as most studies are conducted under controlled laboratory conditions, using constant temperatures, simplified microbial communities, and relatively short experimental periods that do not reflect the complexity of natural ecosystems (Amaral-Zettler et al., 2020). This results in biodegradation rates that vary considerably between studies and are difficult to compare.

Climate change and environmental variability

Climate change is expected to modify several environmental drivers that regulate biodegradation processes, including increasing water temperature, altered salinity caused by droughts or extreme precipitation, antibiotic-resistant profile and changes in nutrient availability (Banciu et al., 2021). Rising temperatures speed up microbial metabolism, but they can lower oxygen levels and change how biodegradation happens.

The behaviour and resistance of pollutants, interactions with the biological environment and biodegradation processes are affected by climate change phenomena and the studies carried out must consider these aspects (Georgescu et al., 2025).

Future research priorities

Recent studies demonstrate that the biodegradation of biodegradable materials does not necessarily eliminate ecological risks. Incomplete degradation may result in persistent polymer fragments that interact with contaminants, support plastisphere development and provide suitable habitats for opportunistic microorganisms, including bacteria carrying antibiotic resistance genes. Although biodegradable materials represent a promising alternative to conventional plastics, future research should prioritize the development of formulations with improved biodegradation performance under environmentally relevant conditions while minimizing unintended ecological effects. In parallel, advances in waste management systems and standardized environmental biodegradation assessment protocols will be essential to ensure their sustainable application (Dorofte et al., 2025).

In addition, future studies should focus on prioritize long-term field experiments on natural aquatic environments, standardized biodegradation protocols across freshwater, estuarine and marine ecosystems, and the integration of molecular techniques with measurements of enzymatic activity and polymer mineralization. Attention should be given to identifying the functional roles of dominant plastisphere microorganisms, evaluating their biodegradation potential under natural conditions and assessing the long-term ecological consequences of biodegradable polymer degradation.

These aspects highlight the need to evaluate biodegradability not only from the perspective of physical material breakdown but also in terms of the long-term ecological impact on microbiota and the functioning of aquatic ecosystems.

CONCLUSIONS

Given their increasing use, understanding the biodegradation pathways and environmental fate of biodegradable materials in aquatic systems is essential for developing effective waste-management strategies and minimizing ecological impacts.

Although biodegradable materials represent promising alternatives to petroleum-based polymers, their behaviour in aquatic environments is considerably more complex than their performance under controlled laboratory conditions. Consequently, biodegradability must be evaluated not only through physical disintegration but also through long-term ecological and microbiological effects.

Current evidence indicates that biodegradation efficiency is strongly shaped by microbial community structure and by the physicochemical characteristics of aquatic habitats.

This review highlights that the biodegradation of these materials is primarily governed by the composition, succession and functional activity of plastisphere-associated microbial communities. While most microorganisms contribute to polymer colonization and degradation, plastisphere development may also facilitate the persistence of opportunistic pathogens and antibiotic resistance genes under specific environmental conditions, emphasizing the need to evaluate both biodegradation efficiency and ecological safety.

The succession of plastisphere communities represents one of the key mechanisms controlling the environmental fate of biodegradable materials. Early colonizers initiate biofilm formation, whereas later microbial communities contribute to polymer depolymerization, mineralization and nutrient cycling. Understanding these microbial successions is therefore essential for predicting biodegradation efficiency under natural aquatic conditions.

Furthermore, the increasing leakage of biodegradable materials into natural environments, combined with anthropogenic pollution and antibiotic residues, contributes to shifts in microbial communities and the spread of antibiotic resistance.

Overall, these findings underscore the need for integrated assessments that consider microbial dynamics, environmental conditions, and pollutant interactions to accurately evaluate the real-world biodegradation of these materials in aquatic ecosystems.

In conclusion, biodegradable materials should not be evaluated solely according to their physical disintegration or laboratory-derived biodegradation rates. Their environmental

performance depends on complex interactions between polymer properties, plastisphere succession, microbial community composition and environmental conditions. Consequently, assessing the sustainability of biodegradable materials requires integrating biodegradation efficiency with long-term ecological effects on microbial diversity, ecosystem functioning and the potential development of ecological risks under natural aquatic conditions.

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