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MORALITY BEFORE KNOWLEDGE

The hidden costs of biodegradable plastics: Environmental persistence, microplastic toxicity, and implications for sustainable development

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ABSTRACT

Background: Biodegradable plastics are widely promoted as environmentally friendly alternatives to conventional plastics, yet their real-world environmental benefits are often overstated relative to performance under standard certification conditions. This narrative review examines the gap between biodegradability certification standards and degradation under real-world conditions, the formation of microplastics and nanoplastics from biodegradable polymers, their toxicological effects, and the implications for sustainability policy. **Methods:** Literature was retrieved from PubMed, Scopus, Web of Science, and Google Scholar and synthesised narratively across four themes: polymer chemistry and certification, micro- and nanoplastic generation, ecotoxicological evidence, and policy implications. **Findings:** Common bioplastics, including polylactic acid, polyhydroxyalkanoates, and starch-based polymers, frequently degrade slowly in natural environments and can fragment into persistent microplastics and nanoplastics; these particles have been associated with oxidative stress, inflammation, endocrine disruption, and ecological harm across multiple biological levels of organisation. **Conclusion:** Biodegradable plastics can contribute to reducing plastic pollution, but their benefits are conditional on effective waste management, stronger regulatory oversight, and informed use; a systems-based approach combining material certification, infrastructure, and governance is required for genuine environmental sustainability. **Novelty/Originality of this article:** This review integrates evidence from polymer chemistry, environmental toxicology, and sustainability policy into a three-layer systems framework (material certification, waste infrastructure, and governance) for evaluating the genuine environmental benefit of biodegradable plastics, an integrative perspective that is largely absent from single-discipline treatments of the topic.

KEYWORDS: biodegradation standards; ecotoxicology; environmental persistence; microplastics; sustainability policy.

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1. Introduction

A global plastic pollution problem has emerged that requires timely action based on scientific evidence. Less than 10% of the global annual plastic production is recycled, with less than 8–12 million metric tonnes of plastic entering the marine ecosystems each year (Geyer et al., 2017; Lau et al., 2020). In this context, biodegradable plastics have become a key technological approach to sustainability issues and are included in national environmental policies, corporate sustainability commitments, and international climate policies as a potential solution to the plastic problem.

The concept of biodegradable plastics is very simple. Conventional polymers such as polyethylenes, polypropylenes, and polystyrenes are essentially biologically unreactive on human-relevant timescales, whereas polymeric materials that are biodegradable are designed to break down through enzymatic or hydrolytic processes into water, carbon dioxide, and biomass. This chemical property has been the reason such materials have been considered harmless and allowed for their rapid commercialisation in packaging, agriculture, food service, and biomedical applications. According to Grand View Research, the global biodegradable plastics market was estimated at USD 5.3 billion in 2022 and is forecast to expand to USD 11.8 billion by 2030 (Grand View Research, 2023).

A growing body of scientific literature has, however, begun to challenge these assumptions in a more rigorous manner. Multiple lines of evidence now question the equivalence between certified biodegradability and benign environmental fate. First, international standards for biodegradability certification (most notably ISO 14855, ASTM D6400, and EN 13432) define conditions of elevated temperature, humidity, and microbial activity typical of industrial composting facilities, conditions that differ substantially from those found in the diverse and often thermodynamically less favourable natural environments in which discarded plastics actually persist (Haider et al., 2019). Second, many biodegradable polymers can fragment into microplastics and nanoplastics and undergo abiotic degradation at rates that result in long-term accumulation before mineralisation occurs, a process that may be as environmentally complex, and in some respects more concerning, than fragmentation from conventional plastics (Lambert & Wagner, 2017). Third, growing evidence from ecotoxicological studies indicates that biodegradable polymers generate particles that are not environmentally neutral, as they have been associated with oxidative stress, endocrine effects, reproductive impairment, and altered microbial community structure across taxonomic levels (Ding et al., 2021; Shruti & Kutralam-Muniasamy, 2019).

This emerging evidence carries implications beyond academic interest. In many jurisdictions, waste legislation does not provide differentiated treatment for biodegradable plastics, as illustrated by the European Union Single-Use Plastics Directive and aspects of extended producer responsibility regulations in several countries. The policy architecture designed to incentivise biodegradable polymer use may therefore be exacerbating the underlying problem by systematically understating the ecological risks associated with these materials. A vital and largely overlooked question follows: how effective are the environmental benefits of biodegradable plastics, and what are the actual ecological consequences of their extensive use? Biodegradable plastics are not condemned outright in this review; rather, the review argues against treating them as an unqualified solution without subjecting them to the same level of critical analysis that sustainable development decision-making requires. Evidence from polymer chemistry, environmental science, toxicology, and policy analysis is brought together here to define the conditions under which biodegradable plastics can provide a genuine ecological benefit, the conditions under which they create a false ecological benefit, and the regulatory and industrial changes needed to resolve this dichotomy.

2. Methods

The aim of this narrative review was to critically integrate the scientific evidence regarding the environmental fate, ecotoxicological risks, and implications for sustainable development of biodegradable plastics. Narrative reviews are more appropriate for synthesising heterogeneous evidence across disciplines and for identifying concepts that span study-level results (Greenhalgh et al., 2018). As this topic is interdisciplinary, involving polymer chemistry, environmental microbiology, ecotoxicology, waste policy, and development economics, a narrative approach is both suitable and necessary.

Literature was retrieved by searching appropriate databases (PubMed, Scopus, Web of Science, Google Scholar) using combinations of the terms biodegradable plastics, bioplastics, polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based polymers, poly (butylene adipate-co-terephthalate) (PBAT), microplastics, nanoplastics, environmental persistence, biodegradation standards, ecotoxicology, soil toxicity, marine toxicity, endocrine disruption, and circular economy. Research articles published between 2010 and 2026, together with systematic reviews and authoritative technical reports, were given priority, although a small number of seminal earlier studies were included where appropriate. Grey literature from the Ellen MacArthur Foundation, the United Nations Environment Programme, the European Chemicals Agency, and the Organisation for Economic Co-operation and Development was included to provide context on policy dimensions. The review is organised around four themes: the chemistry and certification of biodegradable polymers and the mismatch between laboratory and field degradation; micro-and nanoplastic generation mechanisms and the analytical challenges associated with bioplastic-derived micro- and nanoparticles; ecotoxicological evidence at the cellular, organism, and ecosystem levels; and policy, regulatory, and sustainable development implications. In each section, points of consensus, areas of controversy, methodological limitations, and priority knowledge gaps are identified.

3. Results and Discussion

3.1 Biodegradation: Polymer chemistry, certification standards, and the field reality gap

3.1 Chemistry of biodegradable polymers

Biodegradable plastics comprise a diverse group of materials that are all prone to microbial enzymatic degradation and/or hydrolysis under certain conditions. Polylactic acid (PLA), thermoplastic starch (TPS) and its blends, polyhydroxyalkanoates (PHAs, such as PHB, PHBV, and PHBH), poly (butylene adipate-co-terephthalate) (PBAT), polycaprolactone (PCL), and poly(butylene succinate) (PBS) are the main commercial categories. The degradation mechanisms, rate-limiting steps, and environmental sensitivity differ considerably across these polymers. PLA, synthesised from lactic acid derived from fermentable sugars, undergoes primary abiotic hydrolysis of the ester backbone that is temperature- and water-activity-dependent. Hydrolytic degradation proceeds efficiently under composting conditions above 55°C and can be largely completed within 90 days (Emadian et al., 2017). At temperatures below 40°C, however, the hydrolysis rate of PLA is very low on decadal time scales: PLA films showed no significant mass loss after 12 months under simulated marine conditions at 25°C (Bagheri et al., 2017). This temperature dependence is not a secondary phenomenon but a thermodynamic limit that renders extrapolation from industrial composting data to ambient environmental behaviour unreliable. PHAs, synthesised by microbial fermentation, are the only class of bioplastic directly biodegradable by a wide range of environmental microbes.

Table 1. Comparative properties, degradation mechanisms, and environmental performance of major commercial biodegradable polymer types

Polymer	Primary feedstock	Common applications	Main degradation mechanism	Real-world environmental performance	Key limitation
Polylactic acid (PLA)	Corn starch, sugarcane	Packaging, food serviceware, biomedical devices	Hydrolysis followed by microbial degradation	Rapid degradation under industrial composting (>55°C); negligible degradation in marine/ ambient soil environments	Requires temperatures >55°C; ineffective in most natural environments
Polyhydroxyalkanoates (PHAs, e.g., PHB, PHBV)	Microbial fermentation substrates	Packaging, agriculture, medical applications	Direct enzymatic depolymerization by microbial PHA-depolymerases	Broader environmental biodegradability than PLA; rate highly dependent on microbial community and temperature	High production cost; very slow degradation in deep sediments or arid soils
Poly(butylene adipate-co-terephthalate) (PBAT)	Petrochemical-derived biodegradable polyester	Agricultural mulch films, compostable bags	Hydrolysis of aliphatic units; aromatic terephthalate units poorly biodegradable	Moderate soil degradation; fragmentation documented before complete mineralization; microplastic residues reported after 1–3 seasons	Aromatic fraction resists biodegradation; microplastic accumulation risk in agricultural soil
Thermoplastic starch (TPS) and blends	Corn, potato, cassava starch	Packaging films, disposable cutlery, agricultural films	Direct microbial hydrolysis of starch matrix	Generally biodegradable under adequate moisture; blended components may persist	Poor water resistance; mechanical properties often require synthetic blend partners that reduce biodegradability
Polycaprolactone (PCL)	Synthetic biodegradable polyester (ε-caprolactone)	Medical implants, drug delivery, specialty packaging	Hydrolytic and enzymatic degradation	Biodegradable in multiple environments but relatively slow (years in soil)	Slow degradation limits packaging utility; primarily used in medical/controlled-release contexts

Note. Degradation rates described reflect performance documented in peer-reviewed field and laboratory studies. Industrial composting data based on ISO 14855/ASTM D6400 conditions (58°C, high humidity). Real-world performance represents ambient environmental conditions. PLA = polylactic acid; PHA = polyhydroxyalkanoates; PBAT = poly(butylene adipate-co-terephthalate); TPS = thermoplastic starch; PCL = polycaprolactone; PBS = poly(butylene succinate).

Enzymatic depolymerisation of PHB by extracellular PHA depolymerases secreted by soil and marine bacteria has been demonstrated (Jendrossek & Handrick, 2002); however, PHA degradation rates depend strongly on microbial community composition and are markedly reduced in environments such as deep ocean sediments and arid soils, where relevant degraders are absent or inactive (Mergaert et al., 1995; Khandare & Bhatt, 2021). PBAT, used as a flexible film for agricultural mulching, contains both aliphatic and aromatic monomers. The aliphatic fraction is biodegradable, but the aromatic (terephthalate) fraction is much less readily biodegradable, and PBAT film has been shown to leave behind microplastic residues in agricultural soils over periods of several years (Weng et al., 2021), a finding with important implications for large-scale agricultural deployment. Regarding Table 1, it shows that real-world environmental performance diverges consistently from performance under industrial composting conditions across all major commercial biodegradable polymer classes.

3.2 Limitations of biodegradable plastic certification standards

A distinction should be drawn between what is tested as part of certification processes and what is not. The most widely accepted certification standards are ISO 14855 (aerobic biodegradation in controlled composting conditions), ASTM D6400 and EN 13432 (compostability for packaging), and ISO 14851/14852 (aquatic biodegradation). These standards require candidate materials to reach 90% mineralisation within 180 days in a controlled environment, typically 58°C with high humidity and an abundant microbial population characteristic of mature compost. A critical synthesis of certification data identifies several basic problems.

Table 2. Comparison of conditions specified in major biodegradability certification standards versus conditions encountered in real-world natural environments

Standard	Testing environment	Temperature	Key criteria	Critical limitation for real-world applicability
ASTM D6400 (USA)	Industrial composting	58°C	≥90% mineralization within 180 days; disintegration under composting conditions; no ecotoxicity to plant growth	Conditions do not reflect marine, freshwater, soil, or home composting environments; inapplicable where industrial composting is unavailable
EN 13432 (European Union)	Industrial composting	58°C	≥90% biodegradation within 6 months; ≥90% disintegration within 3 months; no heavy metal thresholds exceeded	Same as ASTM D6400; excludes multi-layered or additive-containing packaging from testing
ISO 14855 (International)	Controlled aerobic composting	58°C	Measures CO2 evolution as proxy for mineralization under controlled composting conditions	Does not assess degradation in ambient soil, freshwater, or marine environments; CO2 metric cannot distinguish complete mineralization from oligomer accumulation
ISO 14851/ ISO 14852	Aquatic biodegradation (aerobic)	Room temperature (~25°C)	Aerobic biodegradation in aqueous media; measures oxygen demand or CO2 evolution	Does not represent open ocean, beach, or sediment environments; lacks standardized protocol for marine conditions

OK Compost Home (TÜV Austria)	Home composting simulation	25–30°C	≥90% biodegradation within 12 months at ambient temperature	Lower threshold than industrial standards; limited global regulatory recognition; few commercial products certified to this level

Note. Certification conditions reflect internationally recognized standards as of 2024. Real-world performance data synthesized from peer-reviewed field studies. ASTM = American Society for Testing and Materials; EN = European Standard; ISO = International Organization for Standardization. Temperature ranges for natural environments reflect global variation; degradation rates for specific polymers under natural conditions vary with climate, microbial community composition, and exposure history.

First, test conditions do not reflect industrial composting availability and are not predictive of performance in home composting, soil burial, freshwater, or marine environments; under typical soil conditions in Switzerland, PLA films certified as industrially compostable exhibited no degradation after 12 months (Zumstein et al., 2018). Second, the mineralisation metric used in certification (CO_2 evolution relative to theoretical maximum) does not differentiate between complete mineralisation and partial degradation with accumulation of oligomers or monomers that may carry their own ecological implications. Third, certification evaluates bulk material samples under optimal mixing conditions, whereas actual packaging products may be multi-layered, coated, or combined with inks and additives that can alter degradation pathways. Most tellingly, certification requirements do not address the behaviour of material that escapes managed waste streams, which constitutes the majority of consumer plastics sold in many regions and an overwhelming majority in low- and middle-income countries (LMICs) where formal composting facilities may not exist. Use of biodegradable terminology on products without supporting infrastructure can reduce consumer motivation to dispose of waste responsibly, potentially contributing to increased litter despite the material itself being biodegradable under appropriate conditions (Schnurr et al., 2018). Regarding Table 2, it shows that every major certification standard is validated under industrial composting or comparable controlled conditions that are frequently unavailable in the settings where biodegradable plastics are actually discarded.

3.3 Real-world degradation: Evidence from field studies

Evidence from field studies on the fate of biodegradable plastics in natural environments differs markedly from certification data. Synthesis of available field studies reveals several consistent patterns. Under marine conditions, PLA, PHA, and PLA/PHA blends exhibit a range of degradation rates, with most studies reporting negligible mass loss but extensive surface fragmentation after 6–12 months of immersion at ambient ocean temperatures (Bagheri et al., 2017; Patrício Silva et al., 2021). Even PHAs may persist for many years, or effectively indefinitely, in deep ocean sediments, where cold temperatures, high pressure, and low microbial activity prevail (Haider et al., 2019).

Table 3. Certification testing conditions compared with real-world environmental conditions for major biodegradable polymers

Parameter	Industrial composting (certification conditions)	Real-world natural environments
Temperature	>55°C (controlled)	0–30°C (soil, ocean, freshwater — highly variable)
Humidity/water activity	Controlled high humidity	Seasonal variation; frequently sub-optimal for hydrolysis
Microbial community	Rich, active mature compost microbiome	Variable; degradation-competent microbes often absent or sparse
Oxygen availability	Aerobic throughout	Often limited (sediments, landfill, waterlogged soil)

Timeframe for certification	90–180 days	Years to decades for most polymers outside industrial composting
Degradation rate of PLA	~90% mineralization in 12 weeks	Negligible mass loss over 12 months at 25°C (Zumstein et al., 2018)
Degradation rate of PBAT	~85% in 180 days (compost)	Residues detected after 3 growing seasons in agricultural soil
Additive/coating assessment	Not required under current standards	No assessment; additives persist and may leach independently
Infrastructure requirement	Industrial composting facility required	No specific requirement — but without it, biodegradation does not occur
Key implication	Standards validate performance under optimal, managed conditions only	Without matching infrastructure, 'biodegradable' products behave similarly to conventional plastics

Comparison of certification testing conditions (industrial composting) versus real-world environmental conditions for major biodegradable polymers. Blue columns represent parameters under which certification testing is conducted; orange columns represent corresponding conditions in natural environments where most discarded plastics are deposited. The systematic divergence between these conditions explains why certified biodegradability does not reliably predict environmental fate outside managed industrial composting systems. Data synthesized from ISO 14855, ASTM D6400, EN 13432, Zumstein et al. (2018), Bagheri et al. (2017), and Weng et al. (2021). Regarding Figure 1, it shows that certification conditions and real-world environmental conditions diverge across every parameter relevant to biodegradation, from temperature and microbial activity to infrastructure requirements.

3.4 Microplastic and nanoplastic generation from biodegradable polymers

3.4.1 Fragmentation pathways

Microplastics (particles between 1 μm and 5 mm) and nanoplastics (< 1 μm) arise through secondary abiotic and biotic processes that transform an intact polymer article into micro- or nanoplastic fragments. Abiotic pathways include ultraviolet photodegradation, thermal oxidation, mechanical abrasion, and hydrolysis, while biotic pathways involve surface colonisation, enzymatic attack, and partial mineralisation. These processes act synergistically rather than independently; for ester-based biodegradables, for example, hydrolytic weakening can increase susceptibility to mechanical fragmentation.

Evidence indicates that biodegradable plastics can undergo substantial fragmentation without complete breakdown. Environmental weathering processes such as ultraviolet radiation, mechanical abrasion, precipitation, and tillage degrade biodegradable polymers and generate microplastic particles at the surface. In agriculture, for instance, fragmentation of PBAT-based biodegradable mulch films in agricultural soils was found to increase significantly with ultraviolet exposure and tillage abrasion, generating substantial quantities of microplastic particles (Zhang et al., 2026). Similarly, several biodegradable polymers were found to produce measurable microplastic particles during degradation, with microplastic formation reported as an intermediate step in polymer mineralisation (Sun et al., 2026). These findings raise the question of whether fragmentation and biodegradation occur simultaneously, potentially resulting in the release of microplastics into the environment (Zhang et al., 2026; Sun et al., 2026). Considerable uncertainty remains regarding the generation of nanoplastics from biodegradable polymers. Existing analytical techniques are not yet sufficiently sensitive, matrix-independent, or supported by reference materials for characterising particles smaller than approximately 100 nm. Laboratory ageing experiments using nanoparticle tracking analysis and asymmetric field-flow fractionation have provided preliminary evidence of nanoscale PLA and PHA particles, but it remains uncertain whether these findings can be replicated in natural environments or what the long-term nanoplastic load from biodegradable polymer use would be.

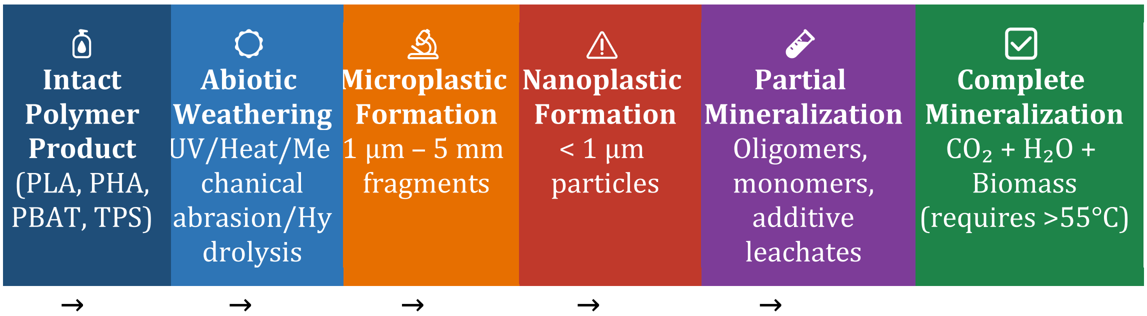

Fig. 1. Schematic degradation pathway of biodegradable polymers from intact polymer article to complete mineralization

The pathway illustrates the generation of microplastic (1 µm–5 mm) and nanoplastic (< 1 µm) particles as intermediate stages of degradation rather than direct transitions to complete mineralization. Complete mineralization to CO_2, H_2O, and biomass requires temperatures exceeding 55°C and is reliably achieved only under industrial composting conditions. At ambient environmental temperatures, degradation frequently stalls at the microplastic or partial mineralization stage, with accumulation of oligomers, monomers, and additive leachates. Colors indicate increasing environmental risk of intermediate degradation products (blue = low risk; red = elevated risk; amber = uncertain risk with active toxicological investigation). Pathway based on Haider et al. (2019), Lambert & Wagner (2017), Zhang et al. (2026), and Sun et al. (2026).

3.5 Ecotoxicological evidence: From molecules to ecosystems

3.5.1 Cellular and molecular mechanisms

Oxidative stress is the cellular response most consistently reported following exposure to microplastics, including those composed of biodegradable polymer. Experimental research has demonstrated that biodegradable microplastics can induce the generation of reactive oxygen species, impair antioxidant defence mechanisms, and alter cellular redox status both in vitro and in vivo. Comparative investigations show oxidative stress responses to polylactic acid microplastics that are broadly similar to those induced by conventional petroleum-based microplastics, indicating that biodegradability does not necessarily imply reduced biological toxicity. These results contradict the common perception that microplastics derived from biodegradable polymers are inherently less harmful than those derived from conventional polymers (Mahmud et al., 2024).

Beyond oxidative stress, exposure to biodegradable microplastics has been linked to inflammatory responses in experimental models. Available evidence indicates that biodegradable polymer particles can induce release of pro-inflammatory mediators and activation of immune regulatory signalling pathways, although this remains considerably less studied than for conventional microplastics. These inflammatory effects may be relevant to pulmonary or gastrointestinal health following environmental exposure (Hu & Palić, 2020).

Chemicals reported in biodegradable plastic formulations have also demonstrated potential endocrine-disrupting effects. Biodegradable polymers such as PLA are frequently promoted as safe alternatives to conventional plastics, although some additives and processing agents used in these formulations have shown estrogenic activity in bioassays. The biological safety of biodegradable plastics therefore depends not only on the polymer itself but also on the chemical additives introduced during manufacturing (Thin et al., 2025).

Table 4. Summary of ecotoxicological evidence for biodegradable microplastics and nanoplastics acrossk biological levels of organization, with comparison to conventional microplastics and identification of key knowledge gaps

Biological level	Organism/ system	Polymer/ particle type	Reported effect	Comparison with conventional microplastics	Key knowledge gap
Cellular/ molecular	Human HepG2 hepatocytes; in vitro cell lines	PLA microplastics	Reactive oxygen species (ROS) generation; antioxidant defense impairment; apoptosis induction; altered cellular redox status	Comparable oxidative stress responses to petroleum-based microplastics; biodegradability does not reduce cellular toxicity	Long-term sub-lethal exposure; dose-response curves in primary cells; nanoplastic-specific cellular mechanisms
Cellular/ molecular	Mammalian cell lines; yeast bioassay systems	PLA additives and plasticizers	Estrogenic activity detected in bioassays; potential endocrine disruption via additive leachates independent of polymer backbone	Additive-driven effects may match or exceed those of conventional plastic additives; polymer alone is not a reliable safety proxy	Comprehensive additive profiling for commercial biodegradable products; in vivo endocrine disruption studies
Organism-level (aquatic)	Zebrafish (Danio rerio); marine invertebrates; freshwater crustaceans	PLA, PBAT, PHA microplastics	Reduced feeding and growth; reproductive impairment; oxidative stress; developmental abnormalities; behavioral changes; gut microbiome disruption	Multi-level ecotoxicity broadly similar to conventional MP; effect magnitudes are polymer- and particle-size specific	Chronic multigenerational studies; combined effects of microplastics with co-contaminants (pesticides, heavy metals)
Organism-level (terrestrial)	Earthworms (Eisenia fetida, Lumbricus terrestris); soil meso-fauna	PLA, PBAT microplastics in agricultural soil	Oxidative stress; gut microbiome alteration; physiological performance impairment; reduced burrowing activity; altered soil enzyme activity	Effects comparable to conventional PE microplastics in similar exposure conditions; specific sensitivities differ by polymer type	Multi-season field accumulation studies; impacts on soil food webs and nutrient cycling at realistic field concentrations
Organism-level (vertebrate)	Rodent models; zebrafish developmental models	PLA, PBAT biodegradable microplastics	Gut microbiota composition shifts; inflammatory responses; metabolic homeostasis disruption; developmental	Limited direct comparisons with conventional microplastics at equivalent doses; biodegradable MP show similar	Human epidemiological data entirely lacking; biomonitoring studies in populations with high bioplastic exposure

			abnormalities at high doses	inflammatory pathways	
Ecosystem-level	Soil microbial communities; agricultural mesocosms	PLA, PHA microplastics from mulch film residues	Reduced bacterial alpha-diversity; altered fungal community composition; impaired soil respiration; disrupted litter decomposition rates	Both conventional and biodegradable microplastics alter soil microbial community structure; functional impacts differ by polymer type	Threshold concentrations for ecosystem-level functional impairment; recovery trajectories after microplastic removal; field-scale validation
Ecosystem-level (Plastisphere)	Marine and freshwater biofilm communities	Biodegradable polymer surfaces (PLA, PHA, PBAT)	Distinct microbial biofilm communities ('plastisphere') enriched in biodegradation-related functional genes; potential hotspot for mobile genetic elements	Biodegradable plastisphere enriches different taxa compared to PE/PP; conventional plastisphere more frequently harbors opportunistic pathogens and antibiotic resistance genes	Horizontal gene transfer potential; long-term ecological consequences of functional gene enrichment; field-scale metagenomic studies

Note. Effects reported represent findings from peer-reviewed experimental studies published predominantly between 2018 and 2026

Comparison with conventional microplastics reflects evidence from studies using equivalent exposure concentrations and particle size ranges. 'Comparable' effect magnitudes do not imply identical mechanisms; polymer-specific differences in surface chemistry, additive content, and degradation products may produce distinct biological responses. PLA = polylactic acid; PBAT = poly(butylene adipate-co-terephthalate); PHA = polyhydroxyalkanoate; PE = polyethylene; PP = polypropylene; ROS = reactive oxygen species; MP = microplastics. Regarding Table 4, it shows that biodegradable microplastics produce measurable adverse effects at every biological level examined, from cellular oxidative stress to ecosystem-level shifts in microbial community structure, with effect magnitudes broadly comparable to those of conventional microplastics.

3.5.2 Organism-level effects

Organism-level toxicity studies indicate that biodegradable microplastics can affect several life-history traits and physiological systems in aquatic and terrestrial organisms. Exposure of aquatic organisms to biodegradable microplastics has been associated with decreased feeding, growth, and reproduction, as well as oxidative stress and mortality. Biodegradability does not necessarily reduce the ecological risk of biodegradable microplastics, as several comparative studies report biological effects similar to those induced by conventional petroleum-based microplastics (Cao et al., 2025).

Soil ecosystems are similarly affected, with microplastics from polylactic acid and poly(butylene adipate-co-terephthalate) associated with oxidative stress, altered gut microbial communities, and impaired physiological performance in earthworms and other soil fauna. These findings suggest that biodegradable plastic waste could pose a risk to long-term agricultural soil productivity through the accumulation of residues and their effects on soil ecosystem functions (Kang et al., 2025).

Further research indicates that biodegradable microplastics can disrupt normal development, metabolism, and immune function in vertebrates. Zebrafish studies have reported developmental abnormalities, oxidative stress, behavioural changes, and inflammation following exposure to biodegradable plastic particles. Biodegradable microplastics have similarly been shown to shift gut microbiota composition, trigger inflammatory responses, and disrupt metabolic homeostasis in rodents, suggesting potential relevance to human health and environmental risk assessment (Zhi et al., 2024).

3.5.3 Ecosystem-level effects and the plastisphere

At the ecosystem level, biodegradable plastic surfaces can support the formation of distinct microbial biofilm communities, termed the plastisphere, that differ from both the surrounding environmental microbiota and the biofilms that form on conventional petroleum-based plastics. These differences arise primarily from polymer chemistry, environmental factors, and the presence of biodegradable carbon substrates that selectively enrich microorganisms capable of polymer degradation. The biodegradable plastisphere appears to support taxa with biodegradation potential, although the ecological consequences of these community shifts have not been studied in detail, whereas the conventional plastic plastisphere has been reported to harbour opportunistic pathogens and antibiotic resistance genes. Emerging metagenomic evidence suggests that biodegradable plastispheres may act as hotspots for biodegradation-related functional genes and mobile genetic elements, warranting further study of their potential role in microbial adaptation and ecosystem functioning (Amaral-Zettler et al., 2020).

Effects of microplastics on soil microbial community diversity have been demonstrated for both conventional and biodegradable plastics. Mesocosm experiments have shown that PLA and PHA microplastics introduced at concentrations achieved after multiple applications of mulch film significantly affected soil bacterial alpha-diversity and altered fungal community composition, with downstream effects on soil respiration and litter decomposition (Huang et al., 2021). Such ecosystem-level functional disruptions are not captured by current regulatory toxicity testing paradigms and represent a systemic gap in regulatory risk assessment approaches. The ecotoxicological evidence reviewed here indicates that biodegradable microplastics are not inherently harmless; effects are dose-dependent, highly particle- and polymer-specific, and often comparable in magnitude to those of conventional microplastics in similar test systems. Replacement of conventional plastics with biodegradable plastics will not remove the toxicological risk associated with microplastics unless accompanied by a proportionate improvement in waste management capable of preventing environmental release.

3.5.4 Life cycle assessment: Comparative environmental burdens

Life cycle assessment (LCA) provides a tool for evaluating and comparing the total environmental impact of biodegradable and conventional plastics across the full life cycle, from production through use to end-of-life. The available LCA literature presents a complex picture. On a mass basis, PLA production from corn starch results in 30% to 70% lower greenhouse gas emissions compared with PET production, representing a genuine climate benefit (Hottle et al., 2013). Consumption of agrochemicals, land, and water resources is, however, considerably higher for bio-based polymer production than for petrochemical polymer production; fertiliser nitrogen run-off, pesticide use, and land-use-change emissions can offset the climate benefit substantially, or in some cases entirely, depending on feedstock origin and agricultural system (Vink et al., 2010).

The most consequential factor in the LCA profile of biodegradables is, however, the end-of-life scenario. Industrial composting produces beneficial outcomes across most impact categories for PLA and PHA relative to disposal options such as landfill or incineration. The theoretical biodegradability of these materials becomes irrelevant under landfill conditions, the most common disposal method for plastic waste worldwide, and the greenhouse gas effects of anaerobic methane generated during partial breakdown of the organic material may impose a climate cost greater than that of conventional plastic landfilling (Levis &

Barlaz, 2011). Available evidence indicates that under ocean-fate scenarios, biodegradable plastics degrade at rates equal to or lower than those of conventional plastics within the first decade in the environment, with microplastic generation occurring through fragmentation.

Although life cycle assessment provides a valuable framework for comparing biodegradable and conventional plastics, its conclusions remain highly sensitive to methodological assumptions. Differences in functional units, allocation methods, feedstock origin, electricity mix, transportation distances, and end-of-life scenarios can substantially alter estimated environmental impacts. Consequently, studies evaluating the same polymer frequently report contrasting environmental rankings. These methodological differences underscore the importance of interpreting LCA findings within their specific analytical context rather than treating individual studies as universally applicable. Future assessments would benefit from harmonized methodological frameworks that incorporate realistic disposal pathways, regional waste management infrastructure, and long-term environmental persistence to improve comparability across studies.

3.6 Implications for lmics

Biodegradable plastics, as a proposed solution for sustainable development, pose specific risks in low- and middle-income countries (LMICs). The entire biodegradability value proposition depends on the availability of industrial composting infrastructure capable of transforming these materials into harmless end products. In most African, Southeast Asian, and Latin American countries, such facilities are lacking or serve only a small proportion of the urban population. In this context, biodegradable plastics that are not collected within formal waste streams share the same environmental fate as conventional plastics, with the added burden of a false safety message that may reduce environmental and behavioural motivation for proper disposal.

In addition, the price of biodegradable plastics remains higher than that of conventional plastics, raising distributional equity concerns. Environmental burden displacement is also likely within sustainable packaging trade flows, as high prices for premium packaging in high-income countries can push plastic waste into LMICs through informal recycling processes, in a manner similar to conventional plastic packaging flows since the 2018 Chinese National Sword policy.

Economic factors are not the only constraints to the effective use of biodegradable plastics in many LMICs, however; implementation challenges also exist. However, industrial composting plants are still limited, municipal waste collection is less than 100% and significant amount of plastic waste is collected informally, dumped or burned without control. In such cases, biodegradable plastics can often become part of the same waste stream as conventional plastics, thereby preventing conditions that would allow for biodegradation to be efficient. As the number of "biodegradable" claims grow without investments in waste management equipment, there also may be unintentional greenwashing, giving the impression that waste disposal is less important since it will "biodegrade" naturally. These misunderstandings can lead to more waste being thrown away and reduce public involvement in the correct separation of waste. To overcome these barriers, there is a need for coordinated investments in waste collection, composting facilities, public education and regulation to enable biodegradable plastics to provide the environmental benefits expected from laboratory certification.

Certain LMIC applications nonetheless offer legitimate and relevant advantages for biodegradable materials. In smallholder agriculture, PHA-based mulch films that completely break down in soil may reduce the labour required for manual removal of conventional polyethylene mulch and avoid soil microplastic accumulation. PHA-based packaging can also contribute to reduced plastic waste in humanitarian and emergency settings where formal waste management is unavailable. Rather than positioning biodegradables as a universal solution, these benefits are best realised through context-specific deployment strategies.

3.7. Policy and regulatory landscape: gaps, inconsistencies and reform pathways

3.7.1 Current regulatory frameworks

Regulatory treatment of biodegradable plastics is highly fragmented and inconsistent, and in some cases exceeds the current evidence base in the level of support provided. The European Union Single-Use Plastics Directive (2019/904/EU) excludes certain requirements for conventional plastic single-use items on the basis that they are environmentally harmless, an assumption that is not well supported by the rapidly growing toxicological literature. This has not yet been reflected in an updated regulatory framework by the European Chemicals Agency.

The United States Federal Trade Commission Green Guides (2012) provide guidance on marketing claims for biodegradable products, requiring that degradation claims be accompanied by specific conditions and time frames. Certification data from laboratory tests are, however, not applied uniformly in consumer communications, and the conditions underlying certified biodegradation are not always disclosed. Internationally, the ongoing negotiation of a Global Plastics Treaty under the framework of the United Nations Environment Assembly offers an important opportunity to define performance-based requirements for biodegradability labelling that more meaningfully reflect environmental impact.

3.7.2 Regulatory reforms and research priorities

The evidence synthesised in this review indicates that current regulatory approaches to biodegradable plastics are not adequately aligned with their demonstrated environmental performance. Several targeted reforms are therefore warranted. A major limitation of existing certification frameworks is their reliance on testing conditions that do not reflect the diversity of real-world environments in which plastics are discarded. Most certification schemes continue to emphasise industrial composting conditions, despite substantial evidence showing that degradation rates in marine, freshwater, and soil environments are often considerably slower and more variable. Future certification standards should therefore incorporate environment-specific testing protocols conducted under realistic temperature, moisture, and ecological conditions. Recent efforts by the European Chemicals Agency to develop marine biodegradability criteria represent an important step in this direction, although broader international harmonisation remains necessary.

Findings from this review also point to a need for greater transparency in product labelling. Widespread use of unqualified biodegradable claims can create the impression that materials will degrade rapidly and completely regardless of disposal conditions. In reality, biodegradation is highly dependent on environmental context and often requires specific conditions unavailable in most natural environments. Regulatory frameworks should therefore require labels to communicate clearly the conditions under which biodegradation has been demonstrated, including whether degradation occurs only under industrial composting conditions. Such measures would improve consumer understanding and reduce the risk of inappropriate disposal practices.

Similarly, incorporation of biodegradable plastics into extended producer responsibility (EPR) schemes should not rely solely on certification status or biodegradability claims. The evidence reviewed here indicates that environmental outcomes vary substantially across disposal contexts and polymer types. Linking producer obligations to demonstrated environmental performance would create stronger incentives for manufacturers to develop materials that perform effectively under realistic end-of-life scenarios rather than idealised laboratory conditions.

Public procurement policies also warrant reassessment. In several jurisdictions, biodegradable plastics are increasingly promoted as environmentally preferable alternatives to conventional polymers. The evidence presented in this review demonstrates, however, that biodegradability alone is not a reliable indicator of environmental sustainability. Procurement frameworks should therefore incorporate life cycle assessment evidence and consider potential impacts associated with environmental persistence, microplastic generation, resource use, and waste management requirements, helping to ensure that material selection is based on overall environmental performance rather than a single material attribute.

3.8. From material substitution to systems redesign

The evidence synthesised throughout this review points to a broader conclusion that extends beyond biodegradable plastics themselves. It challenges the assumption that environmental sustainability can be achieved primarily through the replacement of one material with another while maintaining existing patterns of production, consumption, and waste generation. Biodegradable plastics illustrate both the potential and the limitations of this substitution-based approach. Under carefully managed conditions, certain biodegradable materials can contribute to waste reduction and support circular resource management strategies. When deployed without appropriate waste management infrastructure, regulatory oversight, or consumer awareness, however, these same materials may persist in the environment, generate microplastic and nanoplastic particles, and produce ecological impacts similar to those associated with conventional plastics.

These findings suggest that the central question should not simply be which material is most sustainable, but rather which system of production, use, collection, treatment, and recovery is most capable of delivering the desired environmental outcome. From this perspective, material selection should be guided by the availability of appropriate end-of-life management pathways rather than by material properties alone. In some applications, recyclable conventional plastics may represent the more sustainable option where efficient recycling systems already exist; in others, biodegradable materials may offer advantages when integrated into established composting systems or agricultural applications where degradation has been demonstrated under realistic conditions.

This systems perspective also highlights the importance of infrastructure development. The environmental benefits of biodegradable plastics cannot be fully realised in the absence of effective collection and treatment systems capable of managing them appropriately, a challenge that is particularly relevant in LMICs, where waste management infrastructure often remains limited. Investment in composting facilities, waste collection networks, and technology transfer may therefore generate greater environmental benefits than reliance on material substitution alone.

Ultimately, the principles of reduction and reuse must remain central to efforts aimed at addressing plastic pollution. Evidence from life cycle assessment studies consistently demonstrates that reducing material consumption and increasing product reuse generally provide greater environmental benefits than replacing one form of single-use packaging with another. Biodegradable plastics may play an important role within a broader sustainability strategy, but they should not be viewed as a standalone solution to the global plastic pollution crisis. Long-term progress will depend on systemic changes that address the entire lifecycle of materials rather than focusing exclusively on the properties of individual products. Figure 2 presents this systems framework and makes explicit the constraint that is most consistently overlooked in current policy discourse: without all three layers functioning simultaneously and in coordination, biodegradable plastics cannot deliver on their environmental promise regardless of the sophistication of the material science underlying them.

LAYER 1: MATERIAL SELECTION & CERTIFICATION		
Context-Specific Polymer Choice Match polymer type to available end-of-life infrastructure (e.g., PHAs for soil applications; PLA only where industrial composting exists)	**Environment-Specific Certification** Require testing under marine, soil, and freshwater conditions — not only industrial composting	**Full-Formulation Safety Assessment** Evaluate additive and plasticizer toxicity, not only the polymer backbone

▼ ▼ ▼

LAYER 2: WASTE MANAGEMENT INFRASTRUCTURE		
Industrial Composting Facilities Expand access globally; essential prerequisite for PLA and PBAT biodegradability claims to be realized	**Separate Collection Systems** Prevent contamination of recyclable plastic streams; dedicated collection for certified compostables	**LMIC-Adapted Solutions** Community-scale composting, PHA-specific agricultural take-back schemes, appropriate end-of-life in low-income settings

▼ ▼ ▼

LAYER 3: POLICY, REGULATION & CONSUMER GOVERNANCE		
Qualified Biodegradability Labeling Mandate disclosure of specific conditions required for degradation; prohibit unqualified 'biodegradable' claims	**Lifecycle-Linked EPR Schemes** Link producer obligations to demonstrated real-world environmental performance, not certification status alone	**Procurement & Investment Standards** Require LCA evidence before preferential procurement; invest in infrastructure equally with material substitution

⚠ CRITICAL CONSTRAINT: Without all three layers functioning simultaneously, biodegradable plastics cannot deliver genuine environmental benefit ⚠

Fig. 2. Three-layer systems framework for realizing genuine environmental benefit from biodegradable plastics

The framework illustrates that ecological benefit requires the simultaneous functioning of all three layers: context-specific material selection supported by environment-representative certification; adequate waste management infrastructure to deliver the end-of-life conditions required for biodegradation; and policy and governance frameworks that align producer incentives and consumer information with demonstrated environmental performance. Absence of any single layer compromises the entire system. Framework developed from synthesis of evidence in Lambert & Wagner (2017), Haider et al. (2019), Levis & Barlaz (2011), and Schnurr et al. (2018).

3.9 Future research priorities

Despite significant advances in recent years, important knowledge gaps continue to limit understanding of the long-term environmental implications of biodegradable plastics. One of the most pressing research priorities concerns the formation, persistence, and toxicity of biodegradable nanoplastics. Although several studies have demonstrated fragmentation of biodegradable polymers into microplastic particles, considerably less is known about the generation of nanoscale particles under environmental conditions. Current analytical methods remain insufficient for accurately detecting and characterising sub-100 nm particles in complex environmental matrices. Advances in analytical techniques, development of standardised reference materials, and establishment of nanoplastic-specific toxicological testing frameworks are therefore urgently needed.

Long-term field studies also remain scarce. Most available investigations have monitored degradation over periods of six to twelve months and have been conducted primarily in temperate regions of Europe and North America, limiting understanding of how biodegradable polymers behave under tropical, arid, or monsoonal climatic conditions where temperature, moisture, and microbial activity differ substantially. Multi-year studies across diverse environmental settings are needed to establish realistic estimates of degradation rates and environmental persistence.

A further knowledge gap concerns the cumulative effects of biodegradable microplastic accumulation in agricultural soils. Residues from biodegradable mulch films can persist beyond a single growing season, raising concerns regarding long-term impacts on soil health and ecosystem functioning. Future research should prioritise multi-year mesocosm and field experiments examining relationships between biodegradable plastic accumulation and key indicators such as microbial diversity, soil respiration, earthworm abundance, nutrient cycling, and crop productivity, in order to establish ecologically relevant exposure thresholds and inform sustainable agricultural practices.

The environmental significance of additive packages incorporated into biodegradable plastics also remains poorly understood. While considerable attention has focused on polymer degradation, comparatively little research has evaluated the ecotoxicological effects of stabilisers, plasticisers, pigments, nucleating agents, and other additives released during weathering. Comprehensive environmental risk assessments should therefore evaluate the entire polymer formulation rather than focusing exclusively on the polymer backbone.

Finally, further research is needed to understand how biodegradable plastic labelling influences consumer behaviour and disposal decisions. Misinterpretation of biodegradability claims may contribute to inappropriate disposal practices and unintended environmental consequences. Comparative studies across different cultural, regulatory, and socioeconomic contexts would provide valuable evidence for improving communication strategies, product labelling, and public education initiatives.

4. Conclusion

Biodegradable plastics represent a technology with real potential to contribute to the reduction of plastic pollution under specific and well-managed conditions, but one that has been promoted more rapidly than the research required to verify its safety and effectiveness for widespread use has been established. This review shows that many certified biodegradable polymers persist in the natural environment for far longer than their labelling suggests and can generate microplastic and nanoplastic particles with demonstrated toxicity at the cellular, organism, and ecosystem level. The evidence presented here does not support the general assumption that biodegradable plastics are harmless to the environment, nor that regulations excluding these materials from oversight on the basis of biodegradability alone remain valid. The central argument of this review is that the safety of biodegradable plastics cannot be assessed on the basis of material chemistry alone. Environmental fate results from the interaction of material properties, disposal pathway, receiving environment, microbial community, and time scale. A sustainable system for biodegradable plastics therefore requires the coordinated functioning of certified material performance, adequate waste infrastructure, consumer awareness, and regulation; none of these elements is sufficient on its own. This review conveys a specific message for the global sustainable development investment community: investment in biodegradable plastics technology needs to be matched by proportional investment in the waste management infrastructure required to realise the benefits of biodegradable plastics, alongside honest communication about the conditions under which those benefits are achieved. For regulators, the review points to reforms including environment-specific certification protocols, qualified labelling requirements, lifecycle-linked EPR schemes, and procurement standards that would strengthen policy alignment with the existing evidence base. For researchers, it identifies priority investigations in nanoplastic characterisation, long-term field degradation monitoring, ecosystem-level toxicity assessment, and behavioural science. Biodegradable plastics can be part of the solution to plastic pollution; they are not, however, the complete solution they are sometimes presented as. Treating them as such risks displacing the more difficult and systemic efforts required to limit unnecessary plastic production, establish effective waste management systems, and redesign industrial supply chains that currently shift the environmental costs of plastics onto society. Realising the genuine ecological potential of biodegradable plastics will depend on applying the same systems-thinking approach that the plastic pollution crisis as a whole requires.

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Declaration of Generative AI Use
Generative artificial intelligence (AI) tools were used during the preparation of this manuscript to assist with language refinement, improve clarity of expression, enhance the organization of ideas, and provide editorial support. No AI-generated content was used as scientific evidence, and no AI tool was used to generate, interpret, or validate the scientific findings, analyses, or conclusions presented in this review. All literature selection, critical appraisal, interpretation of evidence, and final editorial decisions were performed by the authors. The authors carefully reviewed, verified, and edited all AI-assisted output and accept full responsibility for the accuracy, originality, and integrity of the final manuscript.

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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. https://doi.org/10.1038/s41579-019-0308-0

Bagheri, A. R., Laforsch, C., Greiner, A., & Agarwal, S. (2017). Fate of so-called biodegradable polymers in seawater and freshwater. *Global Challenges, 1*(4), 1700048. https://doi.org/10.1002/gch2.201700048

Cao, Z., Nik Mut, N. N., Kim, C., An, G., Li, Z., & Jung, J. (2025). Multi-level ecotoxicity of biodegradable microplastic to aquatic organisms: A meta-analysis. *Environmental Research, 286*, 122894. https://doi.org/10.1016/j.envres.2025.122894

Ding, L., Ouyang, Z., Liu, Q., Zhang, S., Wang, Y., & Shen, M. (2021). Polylactic acid microplastics cause cytotoxicity and apoptosis in human HepG2 cells by inducing oxidative stress. *Environmental Pollution, 283*, 117075. https://doi.org/10.1016/j.envpol.2021.117075

Emadian, S. M., Onay, T. T., & Demirel, B. (2017). Biodegradation of bioplastics in natural environments. *Waste Management, 59*, 526–536. https://doi.org/10.1016/j.wasman.2016.10.006

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Grand View Research. (2023). *Biodegradable plastics market size, share & trends analysis report by product, by application, by region, and segment forecasts, 2023–2030*. Grand View Research, Inc.

Greenhalgh, T., Thorne, S., & Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? European Journal of Clinical Investigation, 48(6), e12931. https://doi.org/10.1111/eci.12931

Haider, T. P., Völker, C., Kramm, J., Landfester, K., & Wurm, F. R. (2019). Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angewandte Chemie International Edition, 58*(1), 50–62. https://doi.org/10.1002/anie.201805766

Hottle, T. A., Bilec, M. M., & Landis, A. E. (2013). Sustainability assessments of bio-based polymers. *Polymer Degradation and Stability, 98*(9), 1898–1907. https://doi.org/10.1016/j.polymdegradstab.2013.06.016

Hu, M., & Palić, D. (2020). Micro- and nano-plastics activation of oxidative and inflammatory adverse outcome pathways. *Redox Biology, 37*, 101620. https://doi.org/10.1016/j.redox.2020.101620

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2021). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution, 260, 114096. https://doi.org/10.1016/j.envpol.2020.114096

Jendrossek, D., & Handrick, R. (2002). Microbial degradation of polyhydroxyalkanoates. *Annual Review of Microbiology, 56*, 403–432. https://doi.org/10.1146/annurev.micro.56.012302.160838

Khandare, S. D., & Bhatt, P. (2021). Novel approaches for degradation of bioplastics under natural environmental conditions. *Journal of Environmental Management, 294*, 113059. https://doi.org/10.1016/j.jenvman.2021.113059

Lambert, S., & Wagner, M. (2017). Environmental performance of bio-based and biodegradable single-use plastics: The end matters. Green Chemistry, 19(16), 3740–3753. https://doi.org/10.1039/C7GC01394C

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science, 369*(6510), 1455–1461. https://doi.org/10.1126/science.aba9475

Levis, J. W., & Barlaz, M. A. (2011). Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. *Environmental Science & Technology, 45*(13), 5470–5476. https://doi.org/10.1021/es200721s

Mahmud, F., Sarker, D. B., Jocelyn, J. A., & Sang, Q.-X. A. (2024). Molecular and cellular effects of microplastics and nanoplastics: Focus on inflammation and senescence. *Cells, 13*(21), 1788. https://doi.org/10.3390/cells13211788

Mergaert, J., Anderson, C., Wouters, A., Swings, J., & Bernaerts, K. (1995). Biodegradation of polyhydroxyalkanoates. *FEMS Microbiology Reviews, 15*(2–3), 153–158. https://doi.org/10.1111/j.1574-6976.1994.tb00130.x

Patrício Silva, A. L., Prata, J. C., Walker, T. R., Duarte, A. C., Ouyang, W., Barcelo, D., & Rocha-Santos, T. (2021). Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. *Science of the Total Environment, 742*, 140565. https://doi.org/10.1016/j.scitotenv.2020.140565

Schnurr, R. E. J., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., et al. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. *Marine Pollution Bulletin, 137*, 157–171. https://doi.org/10.1016/j.marpolbul.2018.10.001

Shruti, V. C., & Kutralam-Muniasamy, G. (2019). Bioplastics: Missing link in the era of microplastics. *Science of the Total Environment, 697*, 134139. https://doi.org/10.1016/j.scitotenv.2019.134139

Thin, Z. S., Raja Ali, R. A., & Gew, L. T. (2025). Ecotoxicity of microplastics and nanoplastics in endocrine systems: A systematic review. *Toxicology and Environmental Health Sciences, 17*(4), 461–479. https://doi.org/10.1007/s13530-025-00269-5

Vink, E. T. H., Rábago, K. R., Glassner, D. A., Springs, B., O'Brien, R., Kolstad, J., & Gruber, P. R. (2010). The sustainability of NatureWorks™ polylactide polymers and Ingeo™ polylactide fibers: An update of the future. *Macromolecular Bioscience, 10*(6), 580–588. https://doi.org/10.1002/mabi.200400023

Weng, Y. X., Jin, Y. J., Meng, Q. Y., Wang, L., Zhang, M., & Wang, Y. Z. (2021). Biodegradation behavior of poly(butylene adipate-co-terephthalate) (PBAT), poly(lactic acid) (PLA), and their blend under soil conditions. *Polymer Testing, 32*(5), 918–926. https://doi.org/10.1016/j.polymertesting.2013.05.001

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. https://doi.org/10.1021/es401288x

Zhang, H., Tang, D. W. S., Gooren, H., Wang, K., Liu, X., Geissen, V., & Yang, X. (2026). UV and tillage abrasion facilitate macro- and micro-plastic fragmentation in agricultural soils. *Ecotoxicology and Environmental Safety, 314*, 120065. https://doi.org/10.1016/j.ecoenv.2026.120065

Zhi, L., Li, Z., Su, Z., & Wang, J. (2024). Immunotoxicity of microplastics: Carrying pathogens and destroying the immune system. *TrAC Trends in Analytical Chemistry, 177*, 117817. https://doi.org/10.1016/j.trac.2024.117817

Zumstein, M. T., Narayan, R., Kohler, H. P. E., McNeill, K., & Sander, M. (2018). Biodegradable plastic in soil: Degradability under ambient conditions. Environmental Science & Technology Letters, 4(9), 382–386. https://doi.org/10.1021/acs.estlett.7b00222

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