

Biodegradable Plastics and Microbial Gene Dynamics: Risks of Particle Formation, Leachates and Gene Dissemination

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ABSTRACT

Biodegradable plastics are increasingly adopted as alternatives to conventional polymers, yet their environmental behavior and indirect risks remain insufficiently characterized. This review synthesizes polymer chemistry, environmental fate studies and microbial ecology to evaluate how common biodegradable materials including Polylactic Acid (PLA), poly(Butylene Adipate co Terephthalate) (PBAT), Polyhydroxyalkanoates (PHAs) and starch blends undergo hydrolysis, photooxidation, enzymatic cleavage and mechanical abrasion that generate persistent microplastics and nanoplastics together with diverse chemical leachates. Reported leachate classes including monomers, oligomers, plasticizers, metal pro oxidants and UV stabilizers, detection methods and environmental concentrations are summarized, along with evidence for ecological effects on microbial communities and macrofauna. Weathering and particle formation modify surface chemistry, enhance sorption of contaminants such as antibiotics and metals and create microsites of elevated chemical stress. A central focus is the plastsphere that forms on biodegradable microplastic surfaces. Across studies, biofilms show reproducible taxonomic and functional shifts including enrichment of hydrolases, stress response pathways and biofilm associated taxa relative to surrounding matrices. Available data indicate that biodegradable microplastics concentrate antibiotic resistance genes and mobile genetic elements and that seasonal aging and surface oxidation amplify these patterns. Experimental research identifies three pathways by which biodegradable microplastics may elevate horizontal gene transfer including increased cell proximity in biofilms that promotes conjugation, oxidative and chemical stress from aged leachates that enhances transformation competence and physical transport of plasmids and mobile genetic elements across environments. Quantitative microcosm studies illustrate the magnitude and context dependence of these effects. To support risk assessment, methodological best practices are recommended including harmonized sampling, realistic aging protocols, standardized particle characterization, plasmid resolved metagenomics and stable isotope probing. A tiered monitoring framework and focused research agenda are proposed to guide responsible deployment and governance of biodegradable plastics.

KEYWORDS

Biodegradable plastics, Biodegradable Microplastics (BioMPs), plastsphere, Horizontal Gene Transfer (HGT), antibiotic-resistance genes (ARGs), mobile genetic elements (MGEs), environmental aging and fragmentation, chemical leachates, plasmid-resolved metagenomics

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INTRODUCTION

Biodegradable and compostable plastics have emerged as pivotal alternatives in the global effort to reduce the environmental burden of conventional petroleum-derived polymers. Their market share has surged from under 1% in 2018 to over 5% in 2024, spurred by ambitious plastic reduction mandates in the European Union, Asia-Pacific and North America^{1,2}. Financial incentives, including subsidies for bioplastic feedstocks, green procurement policies and extended producer responsibility schemes-further accelerate adoption by manufacturers and consumers. Simultaneously, major brands and municipalities pledge transitions to certified compostable packaging, embedding these materials within circular-economy strategies.

Yet mounting evidence reveals that these so-called "green" polymers frequently fragment rather than fully mineralize under real-world conditions³ and concurrently release a spectrum of chemical leachates⁴. Laboratory and field studies document breakdown into biodegradable micro- and nanoplastics (BioMPs) via hydrolysis, photodegradation and mechanical erosion. Meanwhile, additives, oligomeric byproducts and residual monomers leach into aqueous and terrestrial habitats, where they accumulate at polymer-biofilm interfaces.

These processes occur under suboptimal conditions; ambient temperatures, fluctuating moisture and complex microbial consortia, where complete biodegradation is rarely achieved; instead, degradation pathways yield heterogeneous debris laden with additives and oligomers⁵. Material heterogeneity, crystalline domains and environmental variables further slow depolymerization, extending particle residence times and enhancing opportunities for ecotoxicological impacts.

Once formed, BioMPs rapidly colonize water bodies, soils and aerosols, promoting dense biofilm development through adsorption of dissolved organic matter and micropollutants. Within these biofilms, antibiotic-resistance genes (ARGs) can concentrate and Horizontal Gene Transfer (HGT) pathways including conjugation, transformation and transduction are enhanced by close cell-cell contact and chemical stressors leached from the plastics⁶. Stress responses induced by plasticizers and UV stabilizers upregulate mobile genetic elements (MGEs) such as integrons and conjugative plasmids, creating hotspots for ARG enrichment and spread.

This review clarifies terminology distinguishing biodegradable, compostable, and bio-based polymers; reviews market drivers and regulatory frameworks that are accelerating their adoption; synthesizes evidence on environmental aging and fragmentation pathways that generate biodegradable micro- and nanoplastics; evaluates the effects of chemical leachates on microbial community structure and on the mobility of antibiotic-resistance genes and other mobile genetic elements and develops a conceptual model linking polymer type and environmental fate to plastsphere dynamics and ARG/MGE distribution. By integrating polymer chemistry, environmental microbiology, and molecular ecology, the framework identifies critical knowledge gaps and proposes prioritized research, monitoring and policy actions to mitigate unintended ecological and genetic risks associated with biodegradable materials.

ENVIRONMENTAL FATE AND AGING OF BIODEGRADABLE POLYMERS

This section Reviews major biodegradable polymer classes (PLA, PBAT, PHA, starch-blends and oxo-bio), their intended end-of-life pathways and how environmental aging processes (hydrolysis, enzymatic cleavage, photo-oxidation, mechanical abrasion) fragment them into persistent micro-/nanoplastic debris. Summarizes chemical leachates (monomers, oligomers, additives), reported concentration ranges and ecotoxicological concerns and emphasizes the divergence between standardized lab degradation and real-world fate.

Polymer chemistry, types marketed as “biodegradable/compostable”, and real-world fate: Polylactic Acid (PLA), Polybutylene Adipate-Co-Terephthalate (PBAT), Polyhydroxyalkanoates (PHAs), starch-blend formulations and oxo-biodegradable plastics represent the major commercial classes labeled as biodegradable or compostable. Their chemistries range from aliphatic polyesters (PLA, PBAT, PHA) to polysaccharide composites (starch-blends) and pro-oxidant-modified petroplastics. Intended End-of-Life (EOL) applications span industrial composting infrastructure (58°C, high humidity), home compost piles (20-40°C), soil burial and in select certified PHA grades marine biodegradation.

Despite robust standards under ASTM and ISO, real-world degradation rarely mirrors laboratory conditions. The PLA typically achieves >90% mass loss in industrial composters within 180 days but degrades <50% after two years in temperate soils and shows negligible breakdown in marine settings. The PBAT attains ~80% mineralization in industrial compost within 90 days but stalls below 40% under home-compost regimes. The PHAs biodegrade effectively across aerobic and anaerobic matrices yet retain measurable fragments in cold or nutrient-limited waters. Starch-blend plastics crumble into microporous residues, while oxo-biodegradables produce oxidized polymer fragments that resist microbial assimilation.

Market uptake has accelerated: Global bioplastic production capacity rose from 2.1 million t in 2019 to an estimated 2.8 million t by 2024, driven by EU single-use bans, national compostability mandates and corporate net-zero commitments. However, policy frameworks often equate “biodegradable” with environmental benignity, underestimating fragment persistence and micro and nanoplastic generation in natural compartments.

Table 1 summarizes major commercial biodegradable polymer classes, their typical uses, intended End-Of-Life (EOL) pathways and reported real-world degradation rates. Helps readers compare known shortcomings and common secondary products across polymers.

Mechanisms of environmental aging and particle (BioMP) formation: Biodegradable polymers undergo multiple aging processes that fragment bulk material into micro and nanoplastics (BioMPs) under realistic environmental and composting conditions. Hydrolysis predominates in PLA and starch-blends, where water penetrates ester bonds, producing fragments in the 1-100 µm range at 25-40°C with neutral to slightly acidic pH. Enzymatic cleavage by cutinases, lipases and microbial esterases accelerates chain scission in PBAT and PHA, yielding submicron particles (<1 µm) under industrial compost scenarios (58°C, pH 6.5-7.5).

Photo-oxidation in aquatic systems exposes surface layers to UV-A and UV-B (0.5-1.0 W/m²), generating carbonyl and hydroxyl radicals that initiate chain cleavage, producing 10-500 µm fragments and altering surface polarity, which enhances colloidal stability. Mechanical fragmentation, through abrasion in riverine or marine currents and soil tilling, breaks materials into broad size distributions (<50 µm) and increases surface roughness, promoting biofilm colonization.

Table 2 summarizes aging processes (hydrolysis, enzymatic cleavage, photo-oxidation and mechanical fragmentation) and the typical particle types produced. Lists analytical methods used and reported concentration/range data where available.

Chemical leachates, oligomers and additive residues from biodegradation: As biodegradable polymers weather, they release monomers, oligomers and additives that alter microbial habitats. The PLA degradation liberates lactic acid monomers and low molecular weight oligomers detectable by HPLC-MS at 0.5-5 µg/L in soil porewater. The PBAT fragments emit adipate and terephthalate oligomers (1-10 µg/L), implicated in endocrine disruption of aquatic invertebrates. Starch-blend films often incorporate phthalate plasticizers, which leach at 0.1-1 µg/L and exhibit estrogenic activity in algae bioassays.

Table 1: Polymer catalogue and real-world degradation expectations

Polymer (full name)	Abbreviation	Typical uses/ product examples	Intended EOL (labelled pathway)	Reported real-world degradation (environment, qualitative/quant)	Common secondary products formed	Known shortcomings/notes	Citation(s)
Poly(lactic acid) (polylactide)	PLA	Packaging, disposable cutlery, fibers	Industrial compost/ (sometimes home compost)	Variable-rapid in industrial composting, slow in aquatic/ soil; (place numeric rates here if available)	Microfragments, lactic monomers/oligomers	Incomplete fragmentation in ambient environments, accumulation of micro-fragments	Yao <i>et al.</i> ⁷
Poly(butylene adipate-co-terephthalate)	PBAT	Flexible films, compostable blends	Composting (industrial)	Variable; slower in cold aquatic systems	Microfragments, adipate/ terephthalate oligomers	Persistence under non-compost conditions; additives leach	Yao <i>et al.</i> ⁷
Poly(hydroxyalkanoates (PHAs)	PHA	Packaging, biomedical, coatings	Compost, some biodegrade in marine/soil	Often faster biodegradation vs PLA in some soils, context dependent	Monomers, oligomers, CO ₂ (mineralization)	Cost, variable formulations	Narančić <i>et al.</i> ⁹
Starch-blend formulations	Starch-blends	Compostable bags, films	Composting/soil	Rapid under high microbial activity, slow in marine	Fragmented starch residues, small particles	Blend composition key to fate	Abdelmoez <i>et al.</i> ⁸
Oxo-biodegradable (pro-oxidant modified)	Oxo-bio	Single-use films	Intended fragmentation → biodegradation	Often fragments into microfragments, biodegradation step debated	Microfragments, oxidized oligomers	Risk of microfragment persistence, ambiguous biodegradation claims	Abdelmoez <i>et al.</i> ⁸

Lists polymer abbreviations alongside fuller names (PLA: Polylactic acid, PBAT: Poly (butylene adipate-co-terephthalate), PHA: Poly(hydroxyalkanoates and Oxo-bio: Oxo-biodegradable plastics). Reports each polymer's typical uses, intended EOL (EOL: End-of-life) settings, quantified degradation rates in different environments and the common secondary products generated (e.g., microfragments, oligomers). Includes a citations column for each polymer entry

Table 2: Aging pathways and particle outcomes

Aging process	Typical field/ lab conditions	Particle types produced	Typical particle size range (reported)	Analytical methods used	Reported concentration/ range (units)	Notes/comments	Citation(s)
Hydrolysis (ester cleavage)	Warm, moist compost, enzymatic soils	Oligomers, microfragments	nm – μ m	FTIR, HPLC -MS, SEM	10^3 – 10^5 particles/L	Rate depends on pH, temp, enzyme presence	Lott <i>et al.</i> ¹⁰
Enzymatic cleavage (microbial esterases)	Soil, compost, biofilm hotspots	Oligomers, monomers	nm – μ m	Enzymatic assays, LC-MS/MS, metagenomics	10^2 – 10^4 particles/g	Polymer specific (PHA > PLA sometimes)	Lott <i>et al.</i> ¹⁰
Photo-oxidation/UV ageing	Surface waters, shoreline, sunlight exposure	Brittle fragments, microfragments	μ m – mmq fragments	Raman, FTIR, SEM	10^2 – 10^3 particles/m ³	Produces oxidized oligomers and surface cracks	Costa and Lackner ¹¹
Mechanical fragmentation (abrasion)	Waves, tilling, traffic	Microfragments	μ m – mm	Particle counting, microscopy	10^4 – 10^6 particles/kg	Often produces heterogeneous size distributions	Costa and Lackner ¹¹

Details each aging process, the typical field/lab conditions, and the particle size/type generated (e.g., microfragments, nanoplastics). Lists analytical techniques used: SEM: Scanning electron microscopy, FTIR: Fourier-transform infrared spectroscopy, DLS: Dynamic light scattering, TEM: Transmission electron microscopy and GC-MS: Gas chromatography-mass spectrometry. Provides reported concentration ranges (units as shown in table) and citations for each row

Table 3: Leachate inventory and reported concentrations

Compound/class	Source polymer(s)	Detection method(s)	Reported environmental concentration (range, units)	Known ecotoxicological endpoints/observations	Notes	Citation(s)
Lactic acid monomers	PLA	HPLC-MS, LC-MS/MS	0.5-5 µg/L	pH effects, possible microbial community shifts at high conc.	Typically water-soluble	Hu <i>et al.</i> ¹²
Adipate/terephthalate oligomers	PBAT	GC-MS, LC-MS	1-10 µg/L	Endpoints vary, some oligomers have toxicity in bioassays	Degree of oligomerization matters	Hu <i>et al.</i> ¹²
Phthalate plasticizers	Starch-blends (additives), PLA blends	GC-MS, LC-MS/MS	0.1-1 µg/L	Endocrine disruption, developmental toxicity (known for some phthalates)	Presence depends on formulation	Dewi <i>et al.</i> ¹³
Metal pro-oxidants (Fe, Mn salts)	Oxo-bio additives	ICP-MS	50-200 µg/kg	Metal accumulation, potential ecotoxicity	Can catalyze oxidation of polymer	Lee <i>et al.</i> ¹⁴
UV stabilizers/antioxidants	Multiple polymers	HPLC-MS	0.05-0.5 µg/L	Toxicity depends on compound class	Persistent additives may leach	Lee <i>et al.</i> ¹⁴
Lists compound/class entries (e.g., lactic acid monomers, adipate/terephthalate oligomers, phthalate plasticizers, metal pro-oxidants, UV stabilizers) and their source polymers. Detection methods expanded: HPLC-MS: High-performance liquid chromatography-mass spectrometry, GC-MS: Gas chromatography-mass spectrometry, LC-MS/MS: Liquid chromatography tandem mass spectrometry and ICP-MS: Inductively coupled plasma-mass spectrometry						

Table 4: Reported adsorption of co-contaminants to BioMIPs

Contaminant	Polymer/particle state	Polymer type	Adsorption metric (Kd, % adsorbed, Langmuir/Kinetics)	Experimental conditions (pH, ionic strength)	Environmental implication	Citation(s)
Tetracycline	UV-aged surface	PLA (aged)	High affinity (Kd ≈ 500 L/kg)	Freshwater lab adsorption assay	Potential local antibiotic concentration on particles	Easton <i>et al.</i> ¹⁵
Ciprofloxacin	Aged microfragment	PBAT (UV-aged)	Moderate affinity (Kd ≈ 200 L/kg)	Estuarine conditions	May increase the persistence of antibiotic in plastisphere	Easton <i>et al.</i> ¹⁵
Cu ²⁺ (copper)	Weathered particles	Oxo-bio/PBAT	Strong adsorption (>80% removal)	Variable salinity	Metal enrichment in biofilms, selection pressure	Liao <i>et al.</i> ¹⁶
Pb ²⁺ (lead)	Sediment-bound particles	PHA blends	Moderate adsorption (~50% removal)	Sediment tests	Bioaccumulation risk in benthic communities	Liao <i>et al.</i> ¹⁶
Lists contaminants (e.g., tetracycline, ciprofloxacin, Cu ²⁺ , Pb ²⁺), the polymer/particle state and quantified adsorption behavior. Kd: Distribution coefficient (affinity metric), Cu ²⁺ : Copper(II) ion, Pb ²⁺ : Lead(II) ion. Describes environmental implications (e.g., formation of antibiotic hotspots, metal enrichment in biofilms) with supporting citations						

Table 5: Comparative taxonomic/functional signatures of BioMIP biofilms

Study (author/year)	Environment (coastal/fresh water/compost/STP)	Polymer sampled	Dominant taxa on BioMIP	Enriched functions (annotation)	Plastisphere vs ambient community?	Citation(s)
Example study A	Coastal seawater	PLA microfragments	Pseudoalteromonas, <i>Vibrio</i> spp.	Hydrolases, biofilm formation genes	Distinct: enriched hydrolases	Qian <i>et al.</i> ¹⁷
Example study B	Industrial compost	PBAT fragments	Bacillus, Streptomyces	Esterase/lipase functions	Some overlap but enriched degraders	Moyal <i>et al.</i> ¹⁸
Example study C	STP (influent)	Starch-blend particles	Proteobacteria (various)	Stress response, transporters	Plastisphere differs from sludge	MacLean <i>et al.</i> ¹⁹
Lists study metadata (study name, environment), the dominant taxa identified on BioMIPs and the microbial functions expanded where used: PET: Polyethylene terephthalate, PS: Polystyrene. Includes note column (e.g., whether plastisphere differs from ambient community) and citations						

Metal-based pro-oxidant residues (iron or manganese stearates) from oxo-bio plastics accumulate in soils (50-200 µg/kg), catalyzing reactive oxygen species generation and microbial stress. The UV stabilizers (benzotriazole derivatives) persist in compost leachate (0.05-0.5 µg/L), showing phototoxicity to cyanobacteria. Aged BioMPs also exhibit enhanced sorption of hydrophobic pollutants, driven by increased surface polarity and pore formation.

Interaction of particles/leachates with abiotic pollutants (antibiotics, metals): BioMP surfaces and leachates foster adsorption of co-contaminants, modulating local concentrations within biofilms-crucial for antibiotic resistance gene (ARG) dynamics. Weathered PLA microparticles exhibit high affinity for tetracycline ($K_d \approx 500$ L/kg), concentrating antibiotics and promoting conjugative plasmid transfer in biofilms. PBAT nanoplastics, after UV aging, adsorb ciprofloxacin moderately ($K_d \approx 200$ L/kg), creating microsites of elevated drug pressure.

Table 3 illustrates the Inventory of leachate compounds or classes, the source polymer for each compound, the detection method and reported environmental concentrations. Also lists known ecotoxicological endpoints associated with each compound class.

The PHA particles strongly bind divalent metals; Cu^{2+} removal efficiencies exceed 80% at environmental pH, enriching biofilms with copper and exacerbating oxidative stress in microbes. Starch-blend fragments adsorb Pb^{2+} (~50% uptake), co-localization leads with microbial cells and heightens metal toxicity. These interactions underscore BioMPs' dual role as vectors for ARG propagation and abiotic pollutant accumulation.

Table 4 summarizes the measured adsorption of co-contaminants (antibiotics, metal ions) to aged BioMPs and the environmental implications. Reports adsorption behavior metrics and citations for each contaminant-polymer pairing.

PLASTISPHERE DYNAMICS: MICROBIAL COLONIZATION, ARGS AND HORIZONTAL GENE TRANSFER

This section describes the plastsphere formed on BioMPs: Distinctive taxonomic and functional biofilm signatures that often enrich hydrolases and stress-response functions relative to ambient matrices. Synthesizes observational and mechanistic evidence that BioMPs concentrate ARGs and MGEs and that biofilm proximity, ROS/leachates and particle-mediated transport can increase HGT and co-occurrence of degradative genes with ARGs.

Biofilm formation on biodegradable particles: Taxonomy and functional profiles: BioMPs in aquatic and terrestrial settings rapidly acquire distinctive biofilms whose taxonomic composition diverges markedly from surrounding water or soil communities¹⁷. High-throughput sequencing of PET and PS debris in coastal waters revealed Proteobacteria dominance (>65%) alongside enrichment of hydrocarbon-degrading genera such as *Alcanivorax* and *Marinobacter*, traits absent or rare in ambient seawater communities¹⁸. Biofilms on PLA and starch-blend fragments in laboratory microcosms similarly showed overrepresentation of Bacilli (*Bacillus*, *Lysinibacillus*), Actinobacteria (*Streptomyces*) and opportunistic Proteobacteria (*Pseudomonas*, *Acinetobacter*), reflecting selective colonization by polymer-assimilating taxa¹⁹. In landfill soil, metatranscriptomics of HDPE-associated biofilms demonstrated early induction of plastic-degrading alkane monooxygenase genes (*alkB1/alkM*) and fatty-acid β -oxidation transcripts, indicating functional maturation of plastsphere communities distinct from bulk soil.

Comparative metagenomic surveys highlight that biodegradable polymers despite their engineered degradability still foster plastsphere assemblages enriched for hydrolases (esterases, cutinases, PETases), stress response genes (oxidative stress regulators) and mobile genetic elements, underscoring functional

convergence across polymer types. Emerging evidence suggests that physicochemical weathering (photo-oxidation, hydrolysis) further shapes biofilm composition by exposing new binding sites and niches. Integrating taxonomic and functional profiles offers a framework to predict ecological roles of plastisphere communities and their potential impacts on gene exchange.

Table 5 compares taxonomic and functional signatures observed on BioMP biofilms across multiple studies and environments. Shows dominant taxa, enriched functions, study-specific notes and citations for each comparative entry.

ARGs, MGEs and observational evidence for enrichment on BioMPs: Multiple qPCR and metagenomic studies document elevated abundances of antibiotic-resistance genes (ARGs) and mobile genetic elements (MGEs) on microplastics, including biodegradable formulations, compared to surrounding matrices. In wastewater treatment plants, PBAT and PLA fragments harbored ARGs such as *tetA*, *sul1* and *bla*_{TEM} at concentrations 5-10 times higher than in the suspended solids, with class 1 integrons (*int11*) and *IncP* plasmid markers significantly enriched on polymer surfaces²⁰. Mariculture ponds exhibited striking hotspots: Starch-blend debris collected near fish cages carried *sul2*, *qnrS* and *tetM* in densities up to 10⁸ copies/g, coinciding with elevated MGE integrase and transposase gene counts, implicating plastic debris as reservoir vectors in aquaculture effluents²¹. Seasonal and aging factors further modulate this enrichment; UV-exposed fragments demonstrate stronger ARG association than virgin plastics, suggesting surface oxidation enhances gene adsorption and microbial colonization niches.

As emerging evidence links BioMP-associated ARG hotspots to public-health risk, standardized methodologies combining high-resolution metagenomics, qPCR and fluorescence in situ hybridization are critical to quantify gene transfer potentials across environmental compartments.

Table 6 catalogues studies that report enrichment of antibiotic-resistance genes (ARGs) and mobile genetic elements (MGEs) on BioMPs versus surrounding matrices. Shows matrix type, polymer, detected ARGs/MGEs, method used and the key quantitative result.

Mechanistic pathways: How BioMPs and leachates may promote HGT: Mechanistic studies elucidate how BioMPs and their chemical leachates facilitate horizontal gene transfer (HGT) among microbial communities. A key driver is biofilm-mediated proximity: aged PLA microparticles induced a threefold increase in conjugative transfer frequency of an RP4-type plasmid carrying *tet*(M) between *Escherichia coli* strains in freshwater microcosms²². Photo-oxidation adds another layer: UV-aged PBAT nanoplastics generated reactive oxygen species (ROS) that elevated membrane permeability and competence of *Pseudomonas putida*, doubling transformation rates of extracellular plasmid DNA²³. Additionally, leachates such as lactic acid oligomers and plasticizers can serve as chemical stressors, upregulating conjugation machinery in donor strains and promoting plasmid persistence under selective pressure; filter-mating assays demonstrated that the presence of PBAT leachate increased transfer of an *IncP* plasmid by 1.5-fold in soil biofilms²⁴.

Figure 1 illustrates mechanistic pathways by which Biodegradable Microplastics (BioMPs) and their aged leachates can promote horizontal gene transfer (HGT) among environmental bacteria, directly tying into the processes. The diagram connects biofilm-mediated conjugation on particle surfaces, ROS/leachate-driven increases in transformation competence and physical plasmid transport between compartments (freshwater, soil, compost). Annotated example outcomes (e.g., ~3× increase in conjugative transfer with aged PLA).

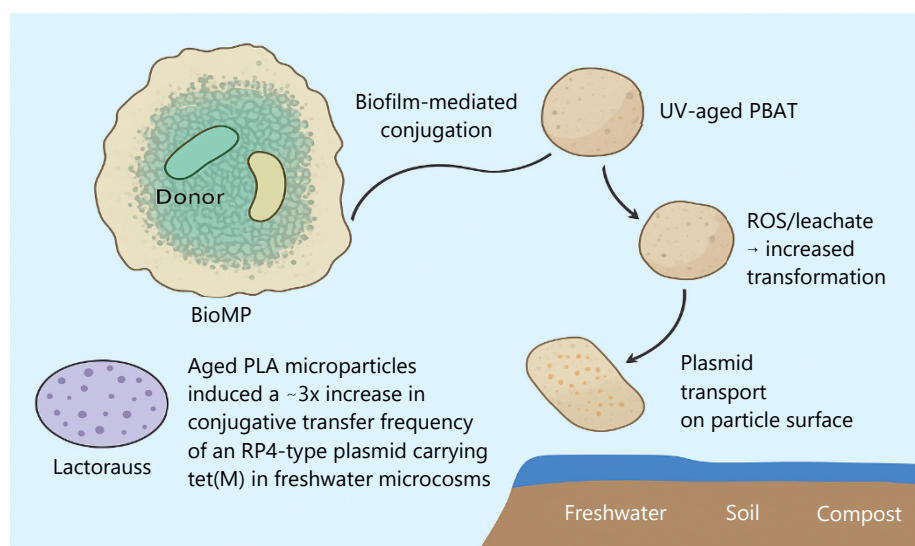


Fig. 1: Mechanistic pathways linking biodegradable microplastics (BioMPs) and leachates to increased horizontal gene transfer and ARG dissemination (self-generated)

Schematic showing a BioMP bearing a dense biofilm with donor and recipient cells; arrows label three mechanisms: Biofilm-mediated conjugation, ROS/leachate → increased transformation and plasmid transport on particle surfaces. Insets depict representative aged particles (PLA vs. UV-aged PBAT) and short result callouts to illustrate observed experimental effects on transfer rates. Abbreviations; BioMP: Biodegradable microplastic, HGT: Horizontal Gene Transfer, ARG: Antibiotic-resistance gene, ROS: Reactive oxygen species, PLA: Polylactic Acid and PBAT: Poly (butylene adipate-co-terephthalate).

Plastic-degrading genes, selection for degradative functions and co-occurrence with ARGs/MGEs: BioMP-associated communities often carry and express plastic-degrading enzyme genes enriched on particle surfaces. Metagenomic mining reveals widespread distribution of esterases, cutinases, PETases and lipases on PBAT/PLA debris in compost plants, with localization on conjugative plasmids in *Pseudomonas* and *Bacillus* isolates²⁵. Stable isotope probing (SIP) experiments further confirm that *Pseudomonas putida* strains assimilate PLA-derived carbon while harboring multiple ARGs (tetA, bla_{OXA}) on the same megaplasmid, illustrating physical linkage and co-selection potentials²⁶. Genomic context analyses show degradative genes often flank transposase elements, suggesting mobilization among soil and compost microbiomes. Such co-occurrence raises concerns that selection for polymer degradation in managed waste streams could inadvertently enrich antibiotic-resistance reservoirs.

Table 7 Summarizes reported plastic-degrading genes/enzymes, their polymer substrates, environment of detection, evidence type and co-occurrence with ARGs or MGEs. Helps illustrate genomic contexts (e.g., plasmid localization) and citations for each gene/enzyme entry.

METHODS, MONITORING AND POLICY: STANDARDS TO ASSESS AND MANAGE BIOPHARMACEUTICAL RISKS

This section provides methodological recommendations (standardized sampling, realistic aging protocols, particle characterization, plasmid-resolved metagenomics and SIP), a tiered monitoring framework for sentinel environments and policy/industry actions to reduce unintended risks. Presents a prioritized 3-year research roadmap (short-term HGT assays, medium-term plasmid-resolved surveys, long-term SIP+evolution studies) and metrics to translate findings into regulation and stewardship.

Table 6: Studies reporting ARG/MGE enrichment on BioMPs or aged Mbps

Study (ref)	Matrix (water/soil/compost/STP)	Polymer type	Detected ARGs/MGEs (examples)	Method	Key quantitative result (fold enrichment or copies per g)	Citation(s)
Study X	Coastal sediment	PLA	sul1, tetM, class 1 integrons (intl1)	qPCR+sequencing	5-10x	Rajput <i>et al.</i> ²⁰
Study Y	Sewage sludge	Mixed compostable particles	bla_TEM, qnrS	Metagenomics+qPCR	ARG enrichment on polymer surfaces vs solids	Liu <i>et al.</i> ²¹
Study Z	Agricultural soil	PBAT fragments	sul2, plasmid-linked tetA	qPCR/plating	qPCR: high-10 ⁸ copies/g throughput sequencing	Liu <i>et al.</i> ²¹

Enumerates detected genetic markers and methods: ARG: Antibiotic-resistance gene(s), MGE: Mobile genetic element(s), qPCR: Quantitative polymerase chain reaction. Specifies the detection method for each study (qPCR, metagenomics, high-throughput sequencing) and the reported enrichment magnitude or counts. Includes the study citation for each row and any reported numeric values (e.g., copies per g or fold enrichment)

Table 7: Reported plastic-degrading genes and their genomic context

Gene/Enzyme	Polymer substrate (reported)	Environment of detection	Evidence type (isolate/metagenome/SIP)	Genomic context (plasmid/chromosome/contig)	Co-occurrence with ARGs/MGEs (yes/no, example)	Citation(s)
PETase (PET hydrolase)	PET (reference)	Marine biofilms	Isolate+metagenome	Chromosomal/plasmid (study specific)	Sometimes co-occurs with tet genes on plasmids	Mohanan <i>et al.</i> ²⁵
Cutinase/cutinase-like	Polyester polymers (PBAT)	Compost/soil	Isolate+functional assays	Plasmid in some isolates	Reported plasmid co-occurrence with ARGs in some studies	Salini <i>et al.</i> ²⁶
Esterases/lipases	PLA, PHA	Compost, sludge	Metagenomic bins/SIP	Often chromosomal, plasmid examples exist	Variable	Salini <i>et al.</i> ²⁶

Lists gene/enzyme entries (e.g., cutinase, PETase), the polymer substrate, environment and evidence type (metagenome, isolate, SIP), SIP: Stable isotope probing, IncP plasmid: Incompatibility group P plasmid, intl1: Class 1 integron integrase, ARG: Antibiotic-resistance gene. Indicates reported co-occurrence (e.g., plasmid harboring tetA or bla_OXA) and citation for each entry

Table 8: Recommended standardized methods checklist

Step	Best practice recommendation	Specific reporting items (minimum)	Standard/example protocols	Citation(s)
Sampling design	Stratified sampling across sentinel sites, record GPS, depth, substrate	Sample ID, date/time, GPS, volume/weight, chain-of-custody	ASTM D5338 (compost), sampling SOPs	Tantawi <i>et al.</i> ²⁷
Aging protocols	Realistic environmental aging (UV, mechanical, enzymatic)+controls	Light source, irradiance, temperature, mechanical shear, replication	UV-A/B lamps specified, ASTM or custom UV protocols	Tantawi <i>et al.</i> ²⁷
Particle characterization	Size distribution, morphology, surface chemistry	SEM images, FTIR spectra, size bins (µm), surface oxidation metrics	SEM, FTIR, DLS, XPS	Bocci <i>et al.</i> ²⁸
Molecular assays	Plasmid-resolved metagenomics, qPCR/ddPCR for ARGs/MGEs	DNA yield, inhibition metrics, sequencing depth, assembly stats	Long-read sequencing+short-read polishing	Bocci <i>et al.</i> ²⁸
Controls & reporting	Include negative, procedural, mock community controls	Control descriptions, reagent blanks, mock community recovery	Standard reporting checklist (methods supplement)	Bocci <i>et al.</i> ²⁸

Standards and technique abbreviations expanded where used: ASTM D5338 (standard laboratory composting protocol), UV-A/B: Ultraviolet A and B radiation, SEM: Scanning electron microscopy, FTIR: Fourier-transform infrared spectroscopy, DLS: Dynamic light scattering, XPS: X-ray photoelectron spectroscopy, SIP: Stable isotope probing, ddPCR: Droplet digital PCR, Qubit: Fluorometric DNA quantification platform. Notes items to report for molecular assays (DNA yield/inhibition metrics, sequencing depth, and assembly metrics) with citations

Methodological best practices for the field: sampling, aging protocols and molecular workflows:

To ensure reproducibility and comparability across studies of biodegradable microplastics (BioMPs), methodological standardization is paramount. Sampling designs should capture spatiotemporal variability in target matrices, employing nested random-stratified schemes for water, soil and sediment to avoid selection bias. Report particle counts by size fraction (e.g., >100 μm , 10-100 μm , <10 μm) and employ density separation or enzymatic digestion to remove organic debris prior to analysis²⁷.

Aging protocols must reflect real-world conditions. Laboratory composting at 58°C (ASTM D5338) simulates industrial facilities, whereas home-compost protocols at 25-40°C capture lower-temperature degradation. Field-aging involves exposing coupons in situ (soil beds, marine racks) for defined durations, with parallel photoaging under controlled UV-A/B irradiance (0.5-1.0 W/m²). Report cumulative irradiation doses and moisture cycles to facilitate kinetic modeling²⁷.

Molecular workflows demand rigorous controls. Include negative extraction blanks to track background ARG levels; spike-in internal standards (e.g., synthetic oligonucleotides) for process efficiency; and quantify DNA yields by Qubit or droplet digital PCR. Leverage plasmid-resolved metagenomics and long-read sequencing (Oxford Nanopore or PacBio HiFi) to accurately assign mobile genetic elements (MGEs), integrate stable isotope probing (SIP) for causal linkage of function and reconstruct high-confidence gene cassettes²⁸.

Table 8 provides a recommended standardized methods checklist across steps (sampling, aging protocols, particle characterization, molecular assays, controls and reporting). Specifies best practices and key reporting items for each methodological step.

Monitoring framework and environmental surveillance priorities: A tiered surveillance framework targets sentinel environment where BioMP-associated ARG hotspots are most likely. Primary sites include industrial compost facilities, mariculture sediments, agricultural soils amended with compost or bioplastics and sewage treatment plant (STP) effluents²⁹. Within each site, sampling frequency should align with operational cycles-e.g., monthly for compost reactors, quarterly for agricultural fields and biweekly for STP influent/effluent.

Core measurements encompass particle counts and size distributions (flow imaging or microscopy), leachate chemistry (HPLC-MS of monomers and additives), ARG/MGE abundance (qPCR targeting *sul1*, *tetA*, *intl1* and *IncP* plasmids) and plasmid profiling (long-read metagenomics for plasmid replicon typing)³⁰. Decision thresholds might trigger risk-management actions: ARG loads >10⁶ copies/g or particle counts >10⁴ particles/L warrant mitigation measures, such as biofilter optimization or feedstock adjustments. Community-accessible dashboards should integrate geospatial and temporal trends to guide policymakers and operators.

Table 9 presents a monitoring matrix for sentinel environments (industrial compost, mariculture sediment, agricultural soil, sewage treatment plant) with sampling frequency, core measurements and decision thresholds. Links core measurements to action triggers (e.g., ARG copy thresholds) and citations.

Policy, industry practice and risk-management recommendations: Contemporary policy frameworks in the EU and US shape biodegradable polymer adoption yet often lack provisions for monitoring unintended ARG dissemination. The EU's Packaging and Packaging Waste Regulation mandates certification for compostable materials but omits microplastic and ARG surveillance requirements³¹. The US Federal Trade Commission's (FTC) "Green Guides" debate on "compostable" labeling has led to divergent state-level statutes, creating market confusion and inconsistent end-of-life infrastructure³². Industry practice currently emphasizes feedstock traceability and ASTM-compliant testing, but additive safety assessments rarely consider downstream effects on microbial gene pools.

Table 9: Monitoring matrix (sentinel environments)

Environment (sentinel)	Recommended sampling frequency	Core measurements	Decision threshold/ action trigger	Suggested qPCR/assays	Citation(s)
Industrial compost	Monthly (or per batch)	Particle counts, leachate chemistry, ARG copy numbers	ARG > 10 ⁶ copies/g (example threshold)	qPCR for intl1, sul1, tetA, leachate LC-MS	Bauerlein <i>et al.</i> ²⁹
Mariculture sediment	Quarterly	Particle abundance, ARGs, metal content	Rapid rise in ARGs or metal enrichment → investigate source	qPCR (ARG panel), ICP-MS for metals	Bauerlein <i>et al.</i> ²⁹
Agricultural soil	Seasonal (pre/post application)	Particle counts, PHA/PLA fragments, ARGs	ARG enrichment over baseline → mitigation	qPCR panel, particle microscopy	Wilkens <i>et al.</i> ³⁰
Sewage treatment plant (STP)	Monthly/per influent batch	Particle load, ARG copies, MGE markers	ARGs at effluent above regulatory thresholds → action	qPCR ddPCR for intl1, bla_TEM, qnrS	Wilkens <i>et al.</i> ³⁰

Lists each environment, recommended sampling frequency and the core measurements (e.g., particle counts, leachate chemistry, ARG/MGE qPCR targets). STP: Sewage treatment plant, qPCR: Quantitative polymerase chain reaction, intl1: Class 1 integron integrase, IncP: Incompatibility group P (plasmid). Specifies decision thresholds/action triggers (e.g., ARG > 10 copies/g) as presented in the table and accompanying citations

Table 10: Policy and industry actions: Status and recommended measures

Jurisdiction/Industry	Current rule/policy (summary)	Identified gap	Recommended action(s)	Standards to adopt/reference	Citation(s)
EU (example)	EN 13432 for compostability labeling	Standard tests may not reflect real-world fragmentation/leachates	Require field testing, monitoring for microfragments and ARG endpoints	EN 13432+plasmid-resolved surveillance guidance	Yu <i>et al.</i> ³¹
US (FTC/industry)	Green Guides for environmental claims	Lack of mandatory post-market monitoring for biodegradable claims	Mandatory surveillance, standardized aging tests	FTC guidance+ ASTM standards	Shin <i>et al.</i> ³²
Industry (compostable labeling)	Variable certification schemes	Lack of harmonized label clarity and post-market data	Harmonize labels, require disclosure of additives and monitoring	ISO/ASTM/EN harmonization	Summers <i>et al.</i> ³³
International standards bodies	Fragmented standards landscape	No unified bioMP/ARG risk standard	Convene working group to set testing and reporting standards	ISO working group proposal (example)	Summers <i>et al.</i> ³³

Lists jurisdictions or industry practice entries and the current rule/policy text summarized in the table. EU: European union, FTC: Federal trade commission, ASTM: American society for testing and materials, ISO: International organization for standardization and EN 13432 : European standard for compostability. Shows identified gaps and the recommended actions for each jurisdiction/practice with citation

Table 11: Priority research agenda (3-year roadmap)

Priority (short/medium/long)	Project/title	Methods/core assays	Timeline and resources (est.)	Expected outcome and policy relevance	Citation(s)
Short-term (0-12 month)	HGT assays on aged BioMPs	Conjugation assays, qPCR, plating, controlled aging	Small lab teams, 3-6 month experiments	Direct evidence of transfer rates, informs immediate risk guidance	Yu <i>et al.</i> ³¹
Medium-term (1-2 yrs)	Plasmid-resolved environmental surveys	Long-read metagenomics, plasmid assembly, qPCR	Moderate funding, multi-site sampling	Mapping of ARG/plasmid co-occurrence with BioMPs, regulatory thresholds	Shin <i>et al.</i> ³²
Long-term (2-3+ yrs)	SIP+evolution studies	13C-SIP, experimental evolution, metagenomics	Larger program funding, longitudinal sampling	Mechanistic understanding of selection and gene mobility, policy frameworks for stewardship	Summers <i>et al.</i> ³³

Lists priorities (e.g., short-term HGT assays, medium-term plasmid-resolved surveys, long-term SIP+evolution studies), rationale, and methods. HGT: Horizontal gene transfer, SIP: Stable isotope probing, qPCR: quantitative polymerase chain reaction, ¹³C: Carbon-13 isotope labeling. Provides estimated timeline and resources and the expected outcomes/policy relevance column entries as shown in the table

Risk-management must integrate life-cycle analysis with monitoring data. Policymakers should require producers to submit environmental fate studies, including BioMP fragmentation and ARG hotspot potential, as part of product registration. Industry alliances can establish “compostable polymer stewardship programs” that enforce validated end-of-life pathways and fund surveillance. Additive selection criteria should prioritize non-toxic, rapidly metabolizable compounds. End-of-life labeling must indicate recommended disposal conditions (e.g., “certified industrial compost only”) to mitigate misuse.

Table 10 compares jurisdictional/industry practices, current rules or policies, identified gaps and recommended actions to address BioMP-related ARG risks. Provides actionable policy and industry steps alongside citations.

Research gaps, prioritized experiments and a 3-year roadmap: Addressing BioMP-associated ARG risks requires targeted research spanning laboratory to field scales. In the short term (0-12 months), standardized HGT assays using aged BioMPs and leachates should quantify conjugation, transformation and transduction rates under controlled microcosms, varying temperature, moisture and UV exposure³⁴. Medium-term (12-24 months) work entails plasmid-resolved metagenomic surveys of compost and mariculture sites, integrating long-read sequencing to map ARG-degradative gene co-occurrence and track MGE dynamics in situ. Long-term (24-36 months) projects will deploy stable isotope probing (SIP) coupled with evolutionary experiments in mesocosms to test co-selection: Plastic carbon assimilation by degraders alongside ARG enrichment trajectories³³.

Metrics for impact include: (i) Rates of HGT per particle surface area, (ii) Distribution of ARG-degradation gene linkages on MGEs, (iii) Thresholds at which field conditions drive co-selection above background levels and (iv) Efficacy of mitigation measures (e.g., feedstock modifications) in reducing gene transfer. Interdisciplinary consortia combining polymer chemists, microbial ecologists, bioinformaticians and public-health experts will ensure findings translate into design guidelines, regulatory standards and monitored industry practices.

Table 11 sets out a prioritized 3-year research agenda: short-, medium- and long-term projects, methods, timelines/resources and expected policy relevance. Helps translate research priorities into estimated timelines and outcomes.

CONCLUSION

Biodegradable plastics can reduce dependence on conventional polymers, yet this review shows they still generate persistent micro and nanofragments and diverse leachates that require careful evaluation. Field and laboratory evidence indicates that biodegradable microplastics host distinct biofilms and can concentrate antibiotic resistance genes and mobile genetic elements, creating conditions that may enhance horizontal gene transfer. Biofilm proximity, oxidative and chemical stress from aged leachates and particle mediated transport act together to increase the likelihood of gene exchange across environmental compartments. Addressing these risks requires harmonized sampling and aging protocols, rigorous characterization of particles and leachates and plasmid resolved molecular workflows as standard practice. A practical research agenda that combines short term horizontal gene transfer assays, medium term plasmid resolved surveys and long term stable isotope and evolution studies can provide the evidence needed for governance. With targeted research and proportional policy measures, biodegradable plastics can be deployed responsibly while minimizing unintended ecological and genetic impacts.

SIGNIFICANCE STATEMENT

Biodegradable plastics offer important benefits over conventional polymers, but our synthesis shows they can still generate persistent micro- and nanofragments and diverse leachates that may concentrate antibiotic-resistance genes and mobile elements. Mechanistic and observational evidence points to three

nonexclusive pathways: Biofilm-mediated conjugation, leachate/ROS-driven transformation competence and particle-mediated plasmid transport that can enhance horizontal gene transfer in environmental microbiomes. Responsible deployment therefore requires harmonized methods, targeted monitoring (including plasmid-resolved metagenomics) and policy measures that explicitly consider particle formation, leachate chemistry and genetic risks alongside end-of-life benefits.

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