

Catalytic Degradation of Microplastics: From Apparent Removal to True Destruction and Carbon Valorization

Qixin Zhou ¹, Xinghao Qi ^{2,3}, Yonghang Yue ⁴, Yan Guo ^{2,*} and Chuyang Y. Tang ^{5,*}

¹ Department of Materials Science and Engineering, City University of Hong Kong, Hong Kong SAR, China

² School of Environment, University of Science and Technology of China, Hefei 230052, China

³ Key Laboratory of Interface Science and Engineering in Advanced Materials, Ministry of Education, Taiyuan University of Technology, Taiyuan 030024, China

⁴ School of Materials and Metallurgy, University of Science and Technology Liaoning, Anshan 114051, China

⁵ Department of Civil and Environmental Engineering, College of Design and Engineering, National University of Singapore, Singapore 119077, Singapore

* Correspondence: yanguo@ustc.edu.cn (Y.G.); cy_tang@nus.edu.sg (C.Y.T.)

How To Cite: Zhou, Q.; Qi, X.; Yue, Y.; et al. Catalytic Degradation of Microplastics: From Apparent Removal to True Destruction and Carbon Valorization. *Science for Energy and Environment* **2026**, 3(2), 10. <https://doi.org/10.53941/see.2026.100010>

Received: 3 May 2026

Revised: 22 July 2026

Accepted: 16 August 2026

Published: 18 August 2026

Abstract: Microplastic control often removes particles from water without destroying polymer carbon and transfers this carbon to sludge or other residual streams. Catalytic treatment can deconstruct the polymer, yet surface oxidation, particle loss, chain scission, and mineralization are frequently reported as equivalent outcomes. This Review defines an evidence hierarchy that distinguishes interfacial ageing, backbone scission, product-resolved deconstruction, and terminal carbon conversion. Degradation denotes measurable chemical change of the polymer. Destruction denotes irreversible elimination of the polymeric particulate phase. Mineralization denotes conversion to CO₂ or inorganic carbon. Valorization denotes formation of chemically defined, recoverable products. Microplastics with carbon-carbon backbones are limited by hydrophobicity and inert C-C bonds, whereas hydrolysable polyesters permit depolymerization and subsequent conversion. Representative studies are evaluated by the analytical evidence supporting each claim. Required measurements include carbon balance closure, identification of dissolved and volatile products, detection of secondary nanofragments, and separate toxicity assessment of residual solids and aqueous products. Selective valorization is environmentally credible mainly for concentrated, polymer-defined streams that permit product recovery. Dilute or mixed environmental microplastics require verified polymer deconstruction, reduced toxicity, and a traceable terminal carbon fate.

Keywords: microplastics; catalytic deconstruction; carbon balance; evidence hierarchy; treatment realism

1. Introduction

Microplastics are a pervasive and poorly reversible form of plastic pollution. They arise from direct release of manufactured particles and progressive fragmentation of larger plastic articles during environmental exposure [1,2]. Their persistence in aquatic environments reveals a central limitation of capture-based management. Wastewater treatment plants remove much of the suspended particulate load from the aqueous phase, yet residual discharges remain environmentally relevant at plant scale and retained particles are transferred to sewage sludge or other concentrated residues [3,4]. Physical



separation therefore redistributes polymer carbon among effluent, sludge, and solid waste. It neither cleaves the polymer backbone nor resolves its long-term fate.

Catalytic degradation has emerged as a distinct remediation objective because it seeks chemical deconstruction of the polymer itself. A growing literature now demonstrates photocatalytic mineralization of selected microplastics, tandem microplastic oxidation with hydrogen generation, and polymer-dependent routes to defined oxygenates [5–7]. At the same time, the terminology of the field remains inconsistent. Many studies assign degradation on the basis of particle shrinkage, surface oxidation, roughening, or mass loss, yet these observations describe analytically different states of matter transformation [5,8]. They do not necessarily imply backbone cleavage, dissolved-phase product formation, complete mineralization, or selective carbon valorization. Fragmentation can also generate secondary micro- and nanoplastics and dissolved organic products with independent environmental behaviour [8].

This Review examines four aspects of catalytic microplastic treatment. These are the evidence needed to distinguish chemically resolved polymer degradation from apparent particle removal, polymer-dependent reaction pathways and accessible terminal fates, realistic feedstocks and treatment sequences, and boundary-based comparison of chemical conversion with established treatment options. The analysis focuses on catalytic reactions in aqueous media and slurries, with emphasis on carbon fate, mechanistic evidence, toxicity evolution, and practical applicability. Figure 1 compares carbon routing after physical capture with chemical conversion after particle interception. The graphical abstract presents the progression from apparent removal to a defensible endpoint [1–8].

Environmental microplastic remediation differs from bulk-plastic upcycling. Product-directed valorization is rarely the primary objective for dilute, heterogeneous, and environmentally dispersed microplastics because polymer loading and product concentrations are low and product separation is demanding. Catalytic treatment is justified when it achieves verified polymer deconstruction, lowers secondary risk, or provides a traceable and environmentally preferable carbon fate. Selective product formation is therefore a boundary case for concentrated, polymer-defined streams and is not a universal endpoint for microplastic remediation.

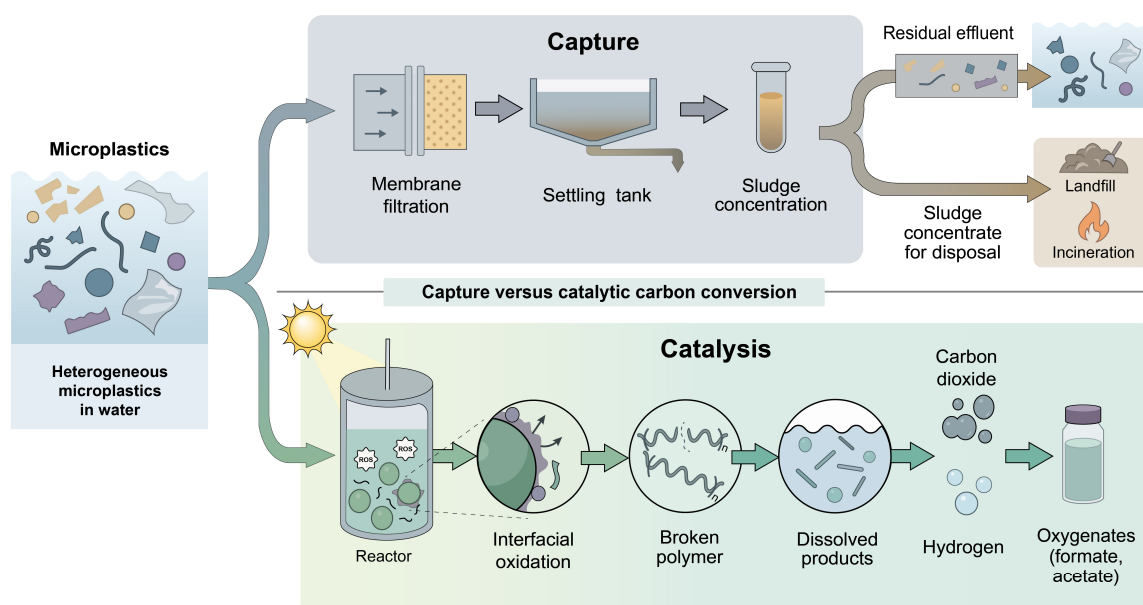


Figure 1. Carbon routing in capture-based management and catalytic treatment of environmental microplastics. Capture can reduce particle abundance in the water phase while transferring polymer carbon to residual effluent, sludge, landfill, or incineration. Catalytic treatment is shown as a chemical sequence from interfacial oxidation and backbone scission to quantified dissolved products and, only after carbon accounting, mineralization or recovery of chemically defined products.

2. Criteria for Verified Catalytic Deconstruction

2.1. Operational Definitions and an Evidence Hierarchy

The terms used in this Review refer to different measurable outcomes. Degradation is a broad descriptor for chemical alteration of the polymer and is therefore qualified by the demonstrated event.

Chain scission is cleavage of the polymer backbone. Deconstruction is conversion of the parent polymer into lower-molecular-weight polymer-derived species. Destruction is reserved for irreversible loss of the original polymeric particulate phase within a stated detection limit and particle-size range, together with evidence that particle disappearance did not simply produce secondary micro- and nanoplastics. Mineralization is restricted to conversion of polymer-derived carbon into CO₂ or dissolved inorganic carbon. Valorization requires chemically defined, quantified, and practically recoverable products derived from polymer carbon. Terminal carbon conversion denotes assignment of the major polymer-derived carbon pools to inorganic carbon or defined products within the analytical uncertainty of a carbon balance. A safe terminal fate cannot be inferred from carbon conversion alone and additionally requires evaluation of toxicity and the fate of additives, heteroatoms, metals, and secondary particles.

On this basis, Figure 2 organizes the evidence into four levels. Level I is interfacial ageing. Oxygenated surface functionalities, carbonyl growth, roughening, cracking, and embrittlement establish chemical attack at or near the interface, but they do not show that polymer carbon has left the particulate phase [8,9]. Level II is chain scission and requires direct evidence that the parent backbone has been cleaved, such as a molecular-weight decrease or scission-specific fragments that cannot be explained by abrasion or physical attrition [10,11].

Level III is product-resolved deconstruction. Polymer-derived oligomers or low-molecular-weight products must be identified and quantified in dissolved or volatile fractions so that solubilization is distinguished from fragmentation. Level IV is terminal carbon conversion. A mineralization claim requires quantitative recovery of polymer-derived carbon as gaseous CO₂ and dissolved inorganic carbon. A valorization claim requires chemically defined, quantified, and recoverable polymer-derived products. In both cases, the major carbon pools must be included in a carbon balance with stated analytical uncertainty [6,7,12,13].

This hierarchy ranks the completeness of carbon-fate evidence and does not rank environmental safety. Level I documents interfacial ageing. Level II demonstrates polymer-backbone cleavage. Level III establishes product-resolved deconstruction and supports a claim of particulate-phase destruction only when residual polymer and secondary micro- and nanoplastics are excluded within stated analytical limits. Level IV establishes terminal carbon conversion by accounting for the major polymer-derived carbon pools as inorganic carbon or chemically defined products. Mineralization and valorization are distinct Level IV endpoints. Toxicity reduction, energy demand, and catalyst durability remain independent criteria and do not increase the assigned evidence level. Each study receives the highest level demonstrated for the stated polymer, particle size, matrix, and reaction condition. Table 1 summarizes the minimum evidence for each claim [8–13].

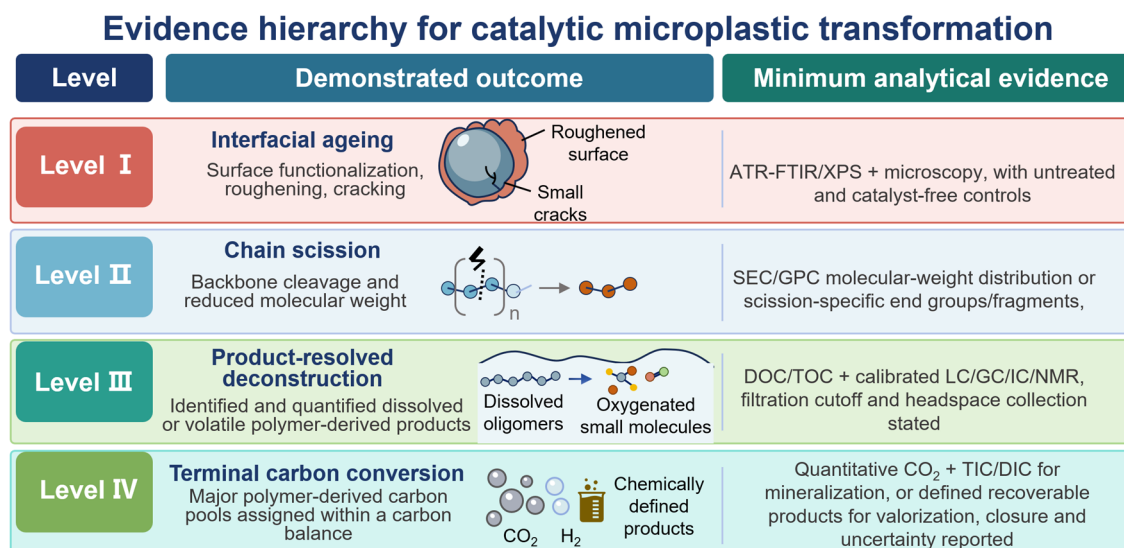


Figure 2. Evidence hierarchy for catalytic transformation of microplastics. Levels I-IV distinguish interfacial ageing, chain scission, product-resolved deconstruction, and terminal carbon conversion. The analytical-evidence panel lists measurements used to assign the highest demonstrated level. Environmental endpoints, including compartment-resolved toxicity, secondary-particle formation, and additive or heteroatom fate, and process endpoints, including energy demand and catalyst durability or recovery, are evaluated independently and do not elevate the evidence level. Mineralization and valorization are distinguished as alternative Level IV carbon endpoints, whereas H₂ generated in a coupled reduction reaction is a non-carbon co-product.

Table 1. Minimum evidence required for common claims in catalytic microplastic treatment.

Claim	Operational Criterion	Minimum Direct Evidence	Evidence Insufficient Alone	Classification Consequence
Surface oxidation	Oxidative functionalization at or enriched near the particle interface.	Quantitative surface-sensitive spectroscopy (for example, ATR-FTIR carbonyl indices or XPS O/C and functional groups) against untreated, catalyst-free, and dark controls, microscopy as support.	Roughening, cracking, colour change, particle-count decrease, or mass loss.	Level I.
Chain scission	Covalent backbone cleavage and decreased chain length.	SEC/GPC molecular-weight distribution and dispersity, or polymer-specific end-group or scission-fragment evidence, controls exclude abrasion.	Surface oxidation, embrittlement, smaller particles, or mass loss.	Level II.
Dissolved-product formation	Transfer of polymer carbon into identified dissolved or volatile species.	DOC/TOC plus calibrated LC, GC, IC, NMR, or MS, stated filtration cutoff and headspace collection, controls for additives, donors, solvents, and matrix carbon.	DOC increase without attribution, uncalibrated MS peaks, or particle disappearance.	Level III when products are identified and quantified.
Verified particulate-phase destruction	Irreversible loss of the original particulate phase without transfer into smaller fragments.	Polymer-specific residual-particle analysis across a stated size range, secondary micro- and nanoplastic evaluation, and quantified carbon transferred to other pools.	No particles visible by one microscopy method or loss from one operational size fraction.	Usually Level III plus fragment exclusion, Level IV only with terminal-fate closure.
Mineralization	Conversion of polymer-derived carbon into CO ₂ or dissolved inorganic carbon.	Quantitative gaseous CO ₂ and TIC/DIC with blanks, normalized yield, time course, uncertainty, and carbon closure.	TOC decline, oxygen consumption, carbonyl growth, or mass loss.	Level IV-mineralization.
Detoxification	Reduced hazard under a defined and comparable exposure.	Separate tests of residual solids and aqueous products, whole mixture when relevant, catalyst, oxidant, matrix, and quenching or separation controls.	Reduced particle mass, one phase, one organism, or greater oxidation.	Independent environmental endpoint, does not alter Level I–IV.
Valorization	Formation of defined, quantified, and practically recoverable polymer-derived products.	Calibrated identity, yield, carbon selectivity, provenance, product concentration and recovery, and overall carbon balance, non-polymer inputs accounted separately.	Trace detection, additive- or reagent-derived products, or H ₂ without resolving polymer carbon.	Level III if products are resolved but fate is incomplete, Level IV-valorization when major pools close.

Note: Minimum evidence denotes the required analytical outcome and does not prescribe an exclusive instrument list. Validated orthogonal methods may be substituted. NR denotes not reported. Evidence levels describe chemical resolution and are not performance scores.

2.2. Evidence-Based Reassessment of Representative Studies

We reassessed representative studies of reactive-oxygen-species-mediated oxidation, polyester depolymerization, coupled photoreforming, and combined separation and catalytic conversion using the proposed hierarchy. Table 2 assigns the highest level supported by the reported measurements, independent of the terminology used by the authors. Unreported measurements are designated NR and do not constitute evidence of absence. The level reflects the chemical resolution of polymer-carbon transformation. Toxicity, catalyst durability, and environmental applicability are evaluated separately. Bulk-plastic studies are included as boundary cases and do not constitute direct evidence for environmental microplastic remediation.

The comparison shows why apparent removal and terminal conversion cannot be treated as equivalent. Microscopy, mass loss, and carbonyl-index changes establish interfacial ageing unless accompanied by direct molecular-weight or backbone-scission evidence. Quantified polymer-derived soluble products support product-resolved deconstruction, whereas Level IV requires direct accounting of polymer carbon as CO₂ or dissolved inorganic carbon, or as chemically defined products within a stated carbon balance. None of the selected studies met this strict Level IV criterion because no study closed all major polymer-carbon pools. Hydrogen evolution confirms a productive reduction reaction but does not resolve the fate of polymer carbon. The frequent absence of compartment-resolved toxicity measurements and post-reaction catalyst characterization also prevents a chemical evidence level from being interpreted as proof of environmentally safe or durable treatment.

Table 2. Conservative evidence-level reassessment of representative catalytic microplastic and boundary-case studies.

Ref.	Feed/Applicability	Polymer and Particle Size	Catalyst, Mode, and Conditions	Direct Analytical Evidence	Carbon Balance and CO ₂ /TIC	Toxicity Evaluation	Catalyst Stability/Recovery	Highest Level and Rationale
[14]	Direct microplastic treatment, dilute continuous flow.	PP, 155 ± 1.4 µm, PVC, 73 ± 0.5 µm, 19 particles L ⁻¹ .	Immobilized ZnO nanorods/SnOx/FeO photo-Fenton with H ₂ O ₂ , visible 120 W tungsten-halogen lamp, about 60 mW cm ⁻² , 7 d.	FTIR, optical microscopy/ImageJ, SEM/EDX, 94% PVC and 96% PP volume reduction, authors state complete mineralization was not achieved.	No carbon balance, CO ₂ NR.	Separate A. fischeri, P. subcapitata, and D. magna assays, generally less than 10% effects.	NR.	Level I, based on surface and particle-volume changes without molecular-weight, quantified-product, or carbon-closure evidence.
[15]	Direct model-microplastic treatment.	Commercial HDPE microbeads, 725 ± 108 µm.	C,N-TiO ₂ , 200 mg catalyst in 50 mL with 0.4% w/v HDPE, pH 3, 0 ± 2 °C, 50 W visible LED, 57.2 W m ⁻² , 50 h.	Gravimetry, ATR-FTIR/carbonyl index, optical microscopy, SEM/EDS, 71.77% mass decrease.	No carbon balance, CO ₂ NR.	NR.	NR.	Level I, based on oxidation and mass loss. Chain scission was proposed but not measured directly.
[16]	Direct model-microplastic treatment.	PE microspheres, 234 ± 12 µm initially.	TiO ₂ P25/UV, 8 h, catalyst-to-microplastic mass ratio 1 to 1.	34.0 ± 1.4% mass loss, 58.5% carbonyl-index increase, particle size, DOC, formic/acetic acids, and gaseous CO ₂ monitored.	CO ₂ detected, but no quantitative closure across all carbon pools.	Phytotoxicity/water-matrix assessment, treated water reported as irrigation-compatible.	Repeated treatment discussed, catalyst reuse or stability not established.	Level II, assigned conservatively because fragments were detected but product-carbon allocation was not quantified.
[17]	Direct model-microplastic treatment.	PS microplastics, size NR in the verified report.	FeB/TiO ₂ photocatalysis, 12 h.	92.3% particle-size reduction, benzaldehyde, benzoic acid, and pathway products identified, 103.5 µmol H ₂ .	No carbon balance, CO ₂ NR.	NR.	NR.	Level II, based on identified scission products without quantified closure of polymer-derived product carbon.
[18]	Direct PET/PLA microplastic photoreforming.	PET and PLA microplastics, size NR.	TiO ₂ and g-C ₃ N ₄ , 254 nm UV, water and NaOH media.	Gas formation, mainly H ₂ with CO/CH ₄ , plus polymer and catalyst characterization, PLA more accessible than PET.	No carbon balance, CO ₂ not shown as the terminal carbon sink.	NR.	g-C ₃ N ₄ instability in alkaline medium noted, reuse NR.	Level II, based on polymer conversion and gas evolution without quantitative resolution of polymer-derived carbon products.
[7]	Direct model-microplastic conversion, product-oriented coupled reaction.	UHMWPE powder, molecular weight 3–6 million, size NR, 1 g L ⁻¹ .	Single-atom Fe on hierarchical carbon nitride, 1 g L ⁻¹ catalyst, 100 mM H ₂ O ₂ , pH neutral, 140 °C for 18 h.	92.0 ± 4.8% gravimetric loss, TOC/IC, GC-MS C3-C20 products, carboxylic acids at 64% selectivity, gas GC.	Trace CO ₂ /H ₂ measured, but no full carbon balance.	ECOSAR in-silico estimates only, no separate solid and aqueous bioassays.	Six cycles, XRD/FTIR/XANES stable, Fe leaching 0.1 ppm.	Level III, based on chemically resolved dissolved products and TOC without closure of all carbon pools.
[13]	Direct model-particle oxidation, MP and nanoplastic subsets require separate classification.	PET, PE, PVC, PP, and EPS MPs, 150–250 µm, PS nanoplastics, 140 nm.	Homogeneous Fenton, 80 °C, pH 3, H ₂ O ₂ 1000 mg L ⁻¹ and Fe ³⁺ 10 mg L ⁻¹ dosed over 7.5 h.	MPs showed about 10% mass loss with surface changes. The PS-NP subset showed about 70% TOC-based ‘mineralization’.	No direct CO ₂ quantification or carbon closure.	Dissolved leachates tested for bacterial growth/biodegradability, not a phase-resolved toxicity battery.	Homogeneous Fe, recovery/reuse NR.	Level I for 150–250 µm MPs, Level III for the PS-NP subset based on extensive TOC removal, but not terminal closure.

Table 2. Cont.

Ref.	Feed/Applicability	Polymer and Particle Size	Catalyst, Mode, and Conditions	Direct Analytical Evidence	Carbon Balance and CO ₂ /TIC	Toxicity Evaluation	Catalyst Stability/Recovery	Highest Level and Rationale
[6]	Direct model-microplastic treatment.	PS, 400 nm, larger PS and PE also examined.	TiO ₂ nanoparticle film, 365 nm UV for 400 nm PS, 12 h, 254 nm used for larger PS/PE.	FE-SEM, Raman, GC, in-situ DRIFTS, HPPI-TOFMS, intermediates and CO ₂ monitored. Headline 98.40% derives from particle diameter/volume.	CO ₂ measured by GC, no complete allocation among residual solids, dissolved/volatile organics, and CO ₂ .	NR.	Post-reaction morphology/oxidation state reported, reuse cycling NR.	Level III, based on product, intermediate, and CO ₂ evidence without carbon closure. The reported mineralization does not establish Level IV.
[19]	Direct nanoplastic oxidation.	PS nanospheres, 140–1100 nm.	Photo-Fenton at 25 °C, Fe/H ₂ O ₂ /pH values NR in the verified abstract.	TOC, turbidity, TEM, Py-GC/MS, and ion chromatography, all sizes reported as fully ‘mineralized’.	TOC-based endpoint, direct CO ₂ measurement and full carbon closure NR.	NR.	Homogeneous catalyst, reuse NR.	Level III, based on extensive TOC removal and reaction-pathway analysis without terminal-carbon accounting.
[20]	Direct microplastic treatment in several water matrices.	ABS, PET, PC, and PS also tested in seawater, river water, and tap water, size NR.	Crystalline supramolecular naphthalimide photocatalyst, AM 1.5G, ABS, 12 h.	92.2% removal and greater than 85% reported ‘mineralization’, multiscale interfacial characterization.	Full carbon pools, direct CO ₂ quantification, and carbon closure NR in the official report.	NR.	Activity retention attributed to a self-healing network, cycle count NR.	Level III provisionally, because the reported mineralization percentage alone does not establish Level IV.
[21]	Bulk/waste-PET upcycling boundary case, not direct environmental-microplastic remediation.	PET plastic waste, size/form NR.	Aerobic iron-salt photocatalysis, detailed conditions NR in the publisher summary.	Terephthalic acid identified and product selectivity reported.	No whole-polymer carbon balance, fate of the second PET carbon pool and CO ₂ NR.	NR.	NR.	Level III boundary case, based on a chemically defined product with incomplete carbon fate in a bulk-plastic feed.
[22]	Real-world PLA photoreforming boundary case, not dilute environmental-microplastic remediation.	Real-world PLA plastic, size/form NR.	Pd-decorated CdS under visible light.	Pyruvic acid reported as a highly selective product, H ₂ also formed.	No full carbon balance, CO ₂ NR.	NR.	NR in the verified publisher summary.	Level III boundary case, based on a selective defined product with incomplete carbon fate in a concentrated plastic feed.

Note: Evidence levels were assigned conservatively from reported measurements, independent of author-assigned labels. A mineralization claim based only on particle-volume loss or TOC removal did not receive Level IV unless initial polymer carbon was quantitatively recovered across residual solids, detached micro- and nanofragments, dissolved and volatile organics, and CO₂ or TIC. NR denotes not reported and was not interpreted further.

2.3. Carbon Balance, Product Analysis, and Toxicity Evolution

Carbon balance should comprise a reactor-wide inventory of mutually exclusive pools and must not be inferred from polymer mass loss. The initial polymer-carbon input, $C_{\text{polymer},0}$, is calculated from the dry polymer mass and its carbon fraction. After reaction, polymer-derived carbon should be recovered from residual particles, secondary micro- and nanoplastic size fractions, material retained on the catalyst, vessel walls, and filters, dissolved organic products, volatile organic products, gaseous CO_2 , and dissolved inorganic carbon. Carbon closure is expressed as $100 \times \sum(C_i)/C_{\text{polymer},0}$, and the unresolved fraction and propagated analytical uncertainty should be reported. The pools must be mutually exclusive. Carbon assigned to quantified soluble products, for example, should be subtracted from the unassigned dissolved-organic-carbon pool to avoid double counting. Carbon introduced by solvents, buffers, natural organic matter, sacrificial donors, carbonaceous catalysts, or additives must be quantified independently or removed through matched blanks [8,12,13].

Each carbon pool requires methods appropriate to its physical state. Residual solids should be separated from the catalyst and identified by polymer-specific chemical analysis. Sequential filtration or ultrafiltration can define operational particle-size fractions, but light scattering or particle counting alone does not establish polymer identity. Dissolved organic carbon should be combined with calibrated chromatographic or spectrometric product quantification, while headspace sampling and volatile traps are required for volatile organics. Mineralization claims require direct measurement of gaseous CO_2 and dissolved bicarbonate or carbonate in a sealed or quantitatively purged reactor, with corrections for atmospheric CO_2 , inorganic carbon already present in the matrix, and adsorption on the catalyst. Time-resolved sampling is important because dissolved products can accumulate transiently and then undergo further oxidation. Carbon retained on sampling lines and filters should also be included when these losses are non-negligible [8,12,13].

Carbon-13-labelled polymers provide a strong provenance control when the matrix, catalyst, or reagents contain background carbon. Isotope-ratio mass spectrometry, GC-MS, or compound-specific isotope analysis can distinguish polymer-derived CO_2 and products from unlabelled carbon sources. The label, however, does not replace mass closure or molecular speciation. A carbon-13 signal establishes origin but not product identity, recovery, or toxicity. Labelled model particles may also differ from environmental microplastics in crystallinity, molecular weight, size, additives, and ageing history. Isotopic dilution, exchange with dissolved inorganic carbon, natural-abundance corrections, and re-dissolution of carbon-13-labelled CO_2 must also be considered. Isotope tracing is therefore most persuasive when combined with phase-resolved carbon quantification and validation using unlabelled, environmentally relevant particles [23,24].

Molecular speciation is required in addition to phase-resolved carbon accounting. Surface spectroscopy and microscopy define the initial oxidation state of the polymer surface, but they cannot distinguish polymer-derived oligomers from additive release or non-intentionally added substances. Dissolved organic carbon or total organic carbon should therefore be combined with calibrated targeted or non-target chromatographic and mass-spectrometric analysis of released organics [14,25,26]. This distinction has direct environmental significance because ultraviolet-aged microplastics can release dissolved organic matter that acts as a precursor for chlorinated and brominated disinfection by-products, with composition that depends on polymer type and exposure history [25,26]. Additives and non-intentionally added substances add a further layer of compositional uncertainty [14].

Degradation efficiency and toxicity evolution should be treated as independent response variables. More extensive oxidation may decrease residual particle mass while increasing dissolved organic matter, mobilizing additives or metals, and producing secondary micro- and nanoplastics with greater mobility or bioavailability. A reduction in particle count or mass therefore cannot be interpreted as detoxification. After treatment, residual solids and the aqueous fraction should be separated at a stated cutoff and tested independently. Where exposure to the unfractionated mixture is plausible, the whole treated suspension should also be evaluated. Comparisons should include untreated-polymer, catalyst-only, oxidant-only, matrix, and quenching or separation controls so that residual catalyst or oxidant toxicity is not attributed to polymer-derived products [27–31].

Detoxification should be claimed only when relevant hazard endpoints decrease under comparable exposure conditions. Particle-phase tests should report particle mass, number, size distribution, and the original polymer dose, whereas aqueous-phase tests should report phase volume, dissolved carbon, and concentrations of identified products or additives. Acute and sublethal endpoints may both be required because residual particles, dissolved oxidation products, and released additives act through different exposure

pathways. A negative result in one organism or one phase cannot establish overall safety. Toxicity, additive release, and secondary-particle formation should therefore be reported alongside, but not embedded within, the Level I-IV assignment. The contrasting outcomes summarized in Refs [27–31] illustrate that oxidation extent has no universal monotonic relation with hazard reduction.

2.4. Measurements beyond Degradation Efficiency

A single degradation efficiency cannot support comparison across catalytic studies because it conflates particle disappearance, carbon conversion, energy demand, and catalyst durability. Plastic-transformation chemistry requires separate reporting of conversion, product yield, and mass balance [32]. Catalytic microplastic treatment requires four groups of measurements. Carbon-fate measurements include mineralization degree and carbon-normalized product yield. Resource inputs include photon flux, electrical energy, oxidant use, and reaction time. Catalyst productivity and stability require an explicit normalization basis. Reactor throughput establishes whether the chemistry remains informative at a stated plastic loading and residence time [15,33–36].

Energy and efficiency measurements must be separated by catalytic mode. Photocatalytic studies should report the irradiation spectrum and wavelength, incident irradiance, illuminated area, incident and, where measurable, absorbed photon flux, apparent or internal quantum yield, and electrical energy consumption normalized to polymer carbon converted or mineralized. Electrocatalytic studies should report current density, geometric electrode area, full-cell voltage, Faradaic efficiency for each gaseous and liquid product, electrode-area-normalized productivity, and specific electrical energy consumption. Photoelectrocatalytic studies should additionally specify the applied bias and reference electrode, light intensity and spectrum, photocurrent, Faradaic selectivity, and solar-to-product or photon-to-product efficiency under clearly defined conditions. These mode-specific data should be reported together with catalyst loading, polymer-to-catalyst ratio, reaction time, temperature, oxidant or electrolyte use, and carbon balance. For ultraviolet advanced oxidation processes, electrical energy per order provides complementary information but does not replace carbon conversion and photon accounting [15,32–36].

These considerations lead to a minimum reporting checklist. Each study should identify polymer composition, source, pretreatment, ageing history, particle size distribution, and shape descriptors. Catalyst identity, phase purity, loading, immobilization state, and the chosen activity normalization basis should be stated explicitly. Reaction conditions should specify irradiation wavelength, photon flux or radiant power, temperature, oxidant dosage, hydrodynamic configuration, and sampling protocol. Carbon accounting should combine residual-solid analysis with dissolved-phase carbon measurements and direct carbon dioxide quantification when mineralization is claimed. Durability should be supported by recycling or time-on-stream data together with post-reaction catalyst characterization. Figure 2 integrates these reporting elements with the evidence hierarchy so that mechanistic claims and performance claims are evaluated on the same basis [15,35,36].

3. Catalytic Pathways toward Microplastic Deconstruction

3.1. Oxidation of Microplastics with Carbon-Carbon Backbones by Reactive Oxygen Species

For microplastics with carbon-carbon backbones, including polyethylene (PE), polypropylene (PP), and polystyrene (PS), catalytic activation is intrinsically difficult because few labile sites are available under aqueous, near-ambient conditions. Reactive oxygen species (ROS) therefore provide the principal oxidation route. Figure 3 summarizes this reaction sequence. The catalyst must generate oxidizing equivalents at a hydrophobic solid surface and maintain productive interfacial contact long enough for initial radical attack to produce measurable chain scission. Reviews of plastic upcycling and recent catalytic studies identify a common mechanistic constraint. Redox potential alone does not determine activity. Interfacial encounter frequency, local charge transfer, and polymer-surface accessibility govern whether oxidizing equivalents react with the polymer or are quenched in water [16,17,19–21,37].

Initiation chemistry begins with hydrogen abstraction or direct oxidative activation of accessible surface sites. A simplified representation is



followed by oxygen capture.



These elementary steps generate carbon-centred and peroxy radicals that evolve into hydroperoxides, alcohols, ketones, aldehydes, and other oxygenated motifs. Once oxygen insertion has weakened the local backbone, β -scission and allied radical pathways release smaller fragments into the dissolved phase. In practice, amorphous domains, pre-existing defects, weathered regions, and catalyst-contact points are attacked first [19,37,38]. This sequence explains why carbonyl growth and surface roughening are often observed well before substantial mineralization.

Several ROS can participate, although hydroxyl radicals dominate many aqueous reactions. Hydroxy-rich bismuth oxychloride accelerates PE oxidation by increasing hydroxyl-radical generation at the catalyst surface. C,N-doped titanium dioxide powders degrade high-density polyethylene microplastics through hydroxyl radicals, photogenerated holes, superoxide-derived species, and electrons that sustain further radical generation [19,37]. Hydroxyl radicals also dominate PS oxidation over FeB/titanium dioxide and during photo-Fenton treatment. Benzaldehyde and benzoic acid occur among the dissolved products [22,39]. Interfacial control remains decisive. Our group showed that a photogenerated outer electric field enriches organic nanocrystals at the microplastic surface through electrophoresis and accelerates solid-solid photocatalysis [21]. A crystalline supramolecular naphthalimide photocatalyst strengthened weak interfacial interactions and promoted visible-light transformation of microplastics [20].

Apparent particle removal frequently outpaces mineralization because ROS-driven treatment proceeds through a sequence of chemically distinct stages. Surface oxidation and embrittlement develop early. Dissolved intermediates appear next. Complete oxidation of those intermediates to carbon dioxide requires additional reaction time, sustained oxidant delivery, and continued catalyst access to newly formed products [13,22,38,39]. Particle size, crystallinity, and hydrophobicity all intensify this gap. Smaller particles expose more accessible area per unit mass and generally degrade faster, whereas highly crystalline and poorly wetted materials resist sustained attack [38]. Level IV remains uncommon. Titanium dioxide films have generated product and CO₂ evidence from selected microplastics, hierarchical carbon nitride-supported single-atom iron catalysts have coupled polymer conversion with hydrogen evolution, and supramolecular photocatalysts have promoted visible-light transformation through enhanced interfacial contact [6,7,20]. As Table 2 shows, however, these studies do not meet the strict Level IV threshold without closure of all major polymer-carbon pools.

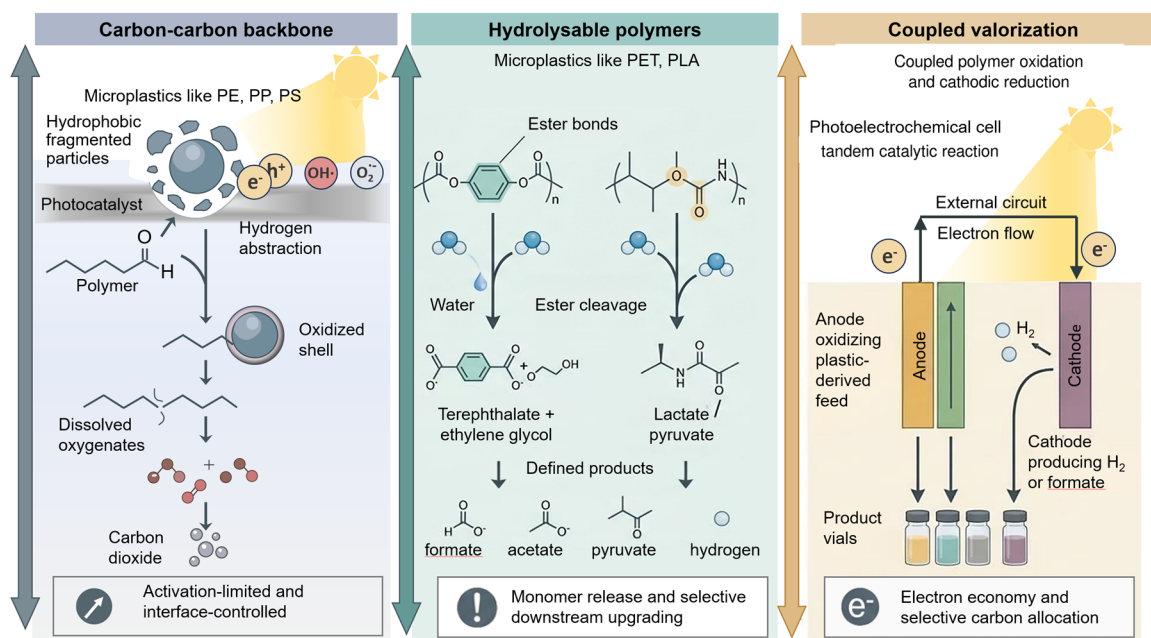
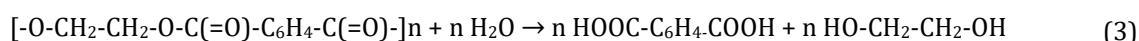


Figure 3. Polymer-dependent catalytic pathways and staged product formation. Polymers with carbon-carbon backbones are activated mainly through interfacial oxidation by reactive oxygen species, followed by chain scission and either mineralization or product-resolved oxidation. For hydrolysable polymers, bond cleavage first yields primary depolymerization products, including terephthalic acid and ethylene glycol from polyethylene terephthalate and lactic acid or lactate from polylactic acid. Subsequent catalytic oxidation or reduction generates secondary upgrading products such as formate, acetate, pyruvate, and other low-molecular-weight oxygenates. Coupled oxidation-reduction reactions should report the fate of polymer carbon separately from hydrogen or products formed at the reduction site.

3.2. Selective Depolymerization of Hydrolysable Microplastics

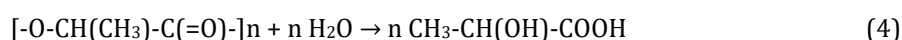
Hydrolysable microplastics follow a distinct reaction regime. Polyethylene terephthalate (PET) and polylactic acid (PLA) contain ester linkages that provide chemically accessible sites for bond cleavage, although their accessibility differs substantially. PLA is generally more susceptible to hydrolysis under mild aqueous or alkaline conditions. The aromatic and often semicrystalline PET matrix commonly requires alkaline pretreatment, elevated temperature, enzymes, or specific catalytic activation for appreciable depolymerization. Ester functionality alone therefore does not imply comparable reactivity. Catalytic treatment begins with depolymerization chemistry, supplemented where needed by oxidation of an inert hydrocarbon surface. Figure 3 separates this route from ROS-dominated oxidation of PE, PP, and PS. Catalytic selectivity in PET and PLA can arise during depolymerization and can be refined during oxidation or reduction of released monomers and intermediates [18,40–45]. The significance extends beyond value-added products. These hydrolysable polymers enable direct analysis of depolymerization, soluble-product accumulation, subsequent conversion, and carbon fate after collection or concentration.

For PET, hydrolysis of the repeating unit can be represented as



Terephthalic acid and ethylene glycol are the primary depolymerization products and should be reported separately from formate and other C1 and C2 oxygenates produced during subsequent conversion of ethylene glycol-derived carbon. These products establish a branch point for catalytic selectivity. Iron-salt photocatalysts drive aerobic PET depolymerization with high selectivity to terephthalic acid [41]. Partially oxidized copper indium sulfide nanosheets continue the reaction to small oxygenates while coupling PET conversion to hydrogen evolution [42]. A photoelectrochemical cell couples pretreated PET oxidation with carbon dioxide reduction, yielding formate at both electrodes [44]. For dilute environmental microplastics, chemically assigned PET-derived carbon pools can provide greater analytical value than the low product concentration can provide economic value. Such assignment distinguishes polymer deconstruction from particle disappearance.

For PLA, hydrolysis of the repeating unit can be written as



This reaction releases lactic acid or lactate as the primary depolymerization product. Pyruvic acid and acetate are secondary upgrading products generated by subsequent oxidation of this soluble carbon pool. Visible-light photoreforming of real-world PLA on palladium-decorated cadmium sulfide produces pyruvic acid with high liquid-phase selectivity [18]. Isolated nickel atoms on cadmium sulfide extend this logic to alkali-free outdoor photoreforming of waste PLA at square-meter scale [43]. Electrocatalytic oxidation over nickel selenide can direct PLA-derived lactate further toward acetate at high current density [45]. Direct microplastic studies reinforce the same mechanistic boundary. PET and PLA microplastics both support photocatalytic hydrogen production, but PLA shows more accessible depolymerization and faster downstream oxidation in simple ultraviolet photoreforming experiments [40]. These examples demonstrate product control for polymer-defined feedstocks while providing mechanistic reference cases for tracing hydrolysable microplastics in environmentally representative studies.

Polymer chemistry determines the relevant measurements. Hydrolysable microplastics require monomer recovery, intermediate selectivity, and carbon yield during subsequent conversion. Polyolefin-rich feeds require direct evidence for activation of the solid hydrocarbon matrix, interfacial oxidation, and chain scission. Treating these polymer classes as a single degradation category obscures their distinct reaction coordinates. Hydrolysable polymers test control of depolymerization and product selectivity. Carbon-carbon backbones test control of interfacial oxidation and chain scission [16–18,40–45]. The acceptable endpoint depends on whether catalytic conversion gives a more defensible carbon fate than separation, recycling, or mineralization for the stated microplastic feed.

3.3. Heteroatom-Containing and Compositionally Complex Microplastics

The contrast between polymers with carbon-carbon backbones and hydrolysable polyesters is mechanistically useful but not exhaustive. Polyamides, commonly termed nylons, polyurethanes, polycarbonates, elastomers, coated fibres, and additive-rich particles contain different scissile bonds, heteroatoms, and composite phases. Amide cleavage in polyamides can release lactams, amino acids, diamines, or dicarboxylic acids, so nitrogen fate accompanies carbon fate. Carbonate-bond scission in

bisphenol A-based polycarbonate can release bisphenol A and oligomers before further oxidation. Polyurethane reactivity depends on polyol, isocyanate, ester or ether content, and crosslink density, and treatment can generate polyols, diacids, diamines, or toxicologically relevant aromatic amines. Coated textile fibres can release fragments from both the base fibre and polyurethane or acrylic coatings, together with dyes and finishing agents. These feeds cannot be assigned to a catalytic pathway from the nominal polymer name alone [10,11,14,46,47].

Polyvinyl chloride and other halogen-containing plastics form a separate risk category. Polyvinyl chloride activation can promote dehydrochlorination before extensive carbon-backbone cleavage, producing hydrogen chloride or aqueous chloride, conjugated polyenes, and potentially chlorinated organic intermediates. Released chloride may also deactivate or restructure the catalyst. Carbon conversion, product yield, or particle disappearance is therefore insufficient to establish safe treatment. A defensible study should close both carbon and chlorine balances across residual particles, dissolved chloride, gaseous hydrogen chloride, volatile and nonvolatile organochlorine products, and chlorine retained on the catalyst. Dechlorination efficiency, catalyst stability, corrosion control, and toxicity of aqueous and volatile fractions should also be reported. The same principle applies to brominated flame-retardant plastics, for which bromine fate requires explicit tracking [14,26,48].

Rubber and tire-wear particles are crosslinked multicomponent particles. They combine natural and synthetic elastomers with sulfur crosslinks, carbon black or silica, zinc and other metals, oils, vulcanization agents, antioxidants, and their transformation products. Pigment-rich plastics can likewise release metals such as lead and chromium. For these particles, polymer-carbon conversion must be accompanied by balances for relevant heteroatoms and metals, non-target analysis of leachates, and separate toxicity testing of treated solids and liquids. This class-specific assessment prevents results obtained for polyethylene or polyethylene terephthalate from being generalized to chemically complex environmental particles [28,49,50].

3.4. Coupled Degradation and Valorization as a Boundary Case

Coupled degradation and valorization extend catalytic microplastic treatment into productive redox chemistry, but remain boundary cases for remediation. High product selectivity has limited relevance to dilute, compositionally mixed environmental microplastics unless the particles are concentrated and polymer identity is constrained. Plastic oxidation supplies electrons for hydrogen evolution or reductive synthesis at the counter electrode. This coupling can decrease the required electrical or photochemical input while forming useful products in the coupled half-reactions shown in Figure 3 [51–54].

Initial demonstrations arose from plastic upcycling. Solar photoreforming showed that nonrecyclable plastic waste can replace oxygen evolution as the electron source for hydrogen production [51,52]. Chemoenzymatic photoreforming extended this reaction sequence to polyester feedstocks under mild conditions by coupling depolymerization with photoredox conversion [53]. These studies define relevant reaction chemistry, but do not resolve dilute feed concentration, mixed-polymer identification, or product recovery for environmental microplastics. Titanium dioxide and graphitic carbon nitride photocatalysts now support hydrogen evolution from PET and PLA microplastics. Seawater electrocatalysis has also coupled microplastic oxidation to hydrogen and formic acid generation over nitride-based nanostructures [40,54]. Hydrogen co-production confirms productive charge extraction from plastic oxidation, but does not resolve carbon fate in the oxidation half-reaction.

Selective carbon reallocation represents a more chemically resolved endpoint. PET is the clearest example because terephthalate and ethylene glycol form separable carbon pools after depolymerization. Copper indium sulfide, bismuth vanadate-molybdenum oxide, and tandem photoelectrochemical cells convert PET-derived carbon into formate or related oxygenates while producing hydrogen or reducing carbon dioxide [42,44,55]. Selective oxygenate formation also extends to polyolefins. Floatable hybrid titanium dioxide photocatalysts convert PE, PP, and PVC in neutral solution, with ethanol as a major product [56]. These results establish defined product formation as an accessible endpoint for selected polymer classes and reaction configurations, in addition to mineralization.

Coupled reactions should be evaluated by carbon selectivity among oxidation products, electron economy in the reduction half-reaction, product separability, and extent of polymer deconstruction. Partial oxidation into dilute unresolved mixtures does not meet the evidential standard achieved by carbon balance closure around polymer-derived oxidation products with separate accounting of hydrogen and other reduction products [44,51–56]. Valorization is therefore credible for concentrated, polymer-defined

streams that permit product recovery. Verified deconstruction and risk reduction remain more defensible goals for dispersed environmental microplastics.

4. From Model Suspensions to Treatable Feedstocks

4.1. Identification, Separation, and Concentration before Catalytic Treatment

Environmental microplastics usually occur as dilute, compositionally mixed particles with incompletely resolved polymer identity, size distribution, ageing state, and additive composition. Direct catalyst addition to open water is difficult to justify because it introduces catalyst into a low-substrate environment without resolving particle identification, catalyst recovery, or product collection. Catalytic treatment becomes more plausible after interception, classification, and concentration into a treatable side stream.

After particle interception, catalysis can be applied to concentrated side streams from wastewater effluents, laundry and textile discharges, membrane concentrates, stormwater retention units, or sludge-derived fractions. The first objective is conversion of a dispersed contaminant into a localized, chemically characterized feedstock. Membrane separation, nanofiltration, flotation, sedimentation, magnetic collection, or surface-affinity capture can be coupled to photocatalysis or electrocatalysis. Reported membrane-photocatalytic and nanofiltration-photocatalytic treatments demonstrate this concentration-before-conversion sequence [57,58].

Feed identity and concentration determine the appropriate catalytic pathway. A polyester-rich stream can be examined for depolymerization, dissolved product tracing, and potential product recovery. A polyolefin-rich stream requires evaluation of interfacial oxidation, chain scission, mineralization, and toxicity reduction. PVC-rich or additive-rich streams also require analysis of halogenated or metal-containing products. Polymer identification and feed definition are therefore integral to catalytic chemistry.

The treatment sequence comprises six linked steps. Representative sampling and polymer or additive identification are followed by separation and concentration into a manageable side stream, polymer-class-specific catalytic conversion, recovery or containment of the catalyst and any chemically defined products, carbon-fate and toxicity assessment of residual solids, aqueous products, gases, and volatile species, and comparison with conventional separation, recycling, or disposal. Selective valorization is appropriate only when the first two steps establish a concentrated, polymer-defined feed and product recovery is realistic. All other feeds require verified destruction and risk reduction [57,58].

4.2. Feedstock Realism—Ageing, Additives, Size, and Morphology

Environmental feedstocks seldom resemble pristine commercial polymer particles. Ageing history controls surface oxidation state, roughness, crack density, hydrophilicity, and the accessibility of catalyst contact points. In situ observations from coastal wetlands show that environmental exposure rapidly introduces oxygenated functionalities and heterogeneous surface damage [59]. These changes are not uniform across different polymer classes or exposure conditions. They depend on light dose, salinity, mechanical abrasion, temperature, and biological conditioning. Pristine standards therefore provide a useful baseline but not a sufficient surrogate for environmentally encountered materials.

Additives introduce a second layer of heterogeneity. Accelerated ageing of pigmented microplastics can release chromium- and lead-containing species and substantially change leachate toxicity [49]. Other ageing regimes generate dissolved organic carbon, nanoplastics, and polymer-specific dissolved organic matter with distinct molecular signatures [60–62]. Catalytic studies that focus only on the parent polymer matrix can therefore miss parallel chemistry involving additives, residual monomers, processing aids, and non-intentionally added substances. Those species can compete for oxidants, alter toxicity, and complicate product analysis.

Particle size and morphology add a third constraint. Photocatalytic experiments on high-density polyethylene and low-density polyethylene show explicit size and shape effects. Smaller particles expose more interfacial area and more readily sustain catalyst contact and oxidative turnover [63]. Visible-light degradation studies also show that catalyst performance depends on the morphology of the microplastic substrate and on the distribution of accessible surface defects [64]. A realistic feed descriptor therefore needs polymer identity, primary or secondary origin, pretreatment and ageing history, size distribution, and shape class. Crystallinity and additive formulation should be reported whenever available. Figure 4 begins with this feedstock layer because it determines the chemical substrate that every downstream reactor will actually encounter [49,59–64].

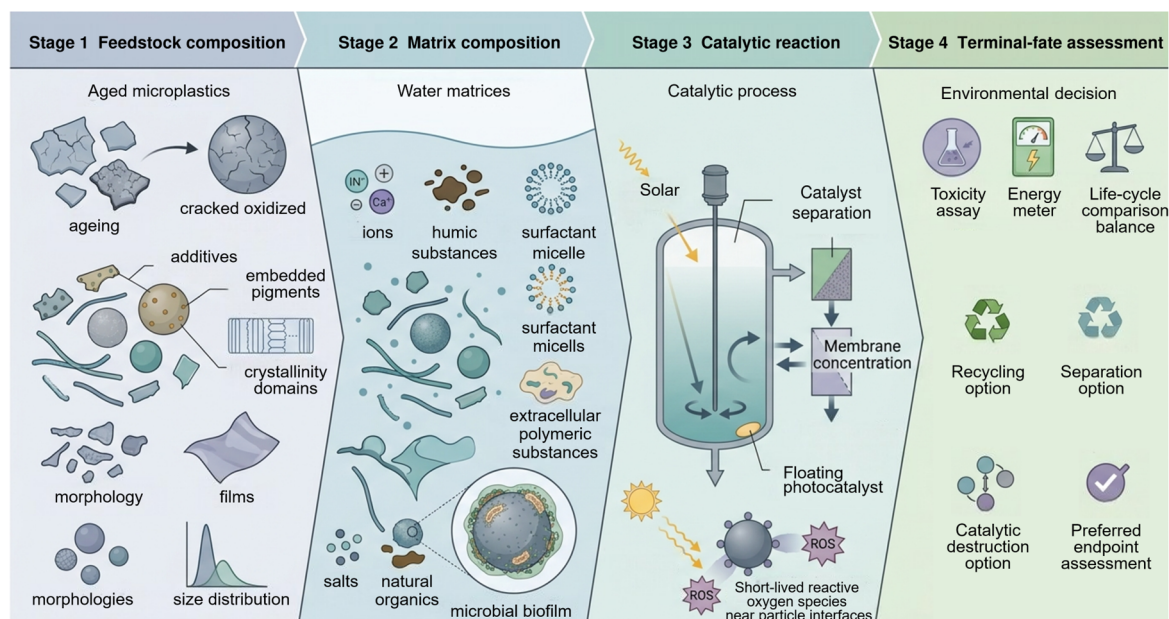


Figure 4. Treatment sequence and experimental criteria for catalytic microplastic management. Representative sampling and identification are followed by separation and concentration, polymer-class-specific catalytic conversion, catalyst and product recovery, carbon-fate and toxicity assessment, and comparison with separation, recycling, disposal, or other relevant options. Feedstock composition, matrix chemistry, reaction conditions, and treatment boundaries are evaluated throughout the sequence.

4.3. Matrix Realism—Salts, Natural Organic Matter, Surfactants, and Biofilms

Complex water matrices alter catalytic behavior through optical attenuation, interfacial adsorption, and changes in reactive-intermediate concentrations. Nitrate, bicarbonate, and halides can accelerate photo-ageing through carbonate radicals, halogen radicals, or other secondary oxidants. Dissolved organic matter can attenuate light and quench short-lived radicals [65,66]. These effects depend on matrix composition. Humic acid can promote PS oxidation under ultraviolet irradiation by increasing local reactive-species generation and altering soluble-product distributions [67]. In seawater, elevated salinity strengthens this effect through increased humic-acid adsorption and interfacial radical production [68].

Surfactants exert an additional control on dispersion, wettability, and mass transfer. Electrochemical degradation of PET microplastics is strongly affected by the identity of the surfactant present, and sodium dodecyl sulfate-assisted electrochemical advanced oxidation accelerates PS degradation and changes the released product spectrum [69,70]. These observations matter beyond specialized laboratory formulations because detergents, natural amphiphiles, and residual treatment chemicals can all change the effective microenvironment of the particle surface.

Biofilms introduce the highest level of matrix complexity. Natural organic matter conditioning and microbial colonization reduce the hydrophobicity of microplastic surfaces and alter their interfacial charge, but the extracellular polymeric substances matrix can also shield the substrate from photons and reactive species [71,72]. Recent freshwater and photoaging studies show that biofilm growth can suppress subsequent photochemical ageing by optical filtering and by limiting generation of singlet oxygen and hydroxyl radicals near the polymer surface [72]. Catalytic performance measured in ultrapure water therefore cannot be assumed to translate directly to freshwater, seawater, stormwater, or wastewater treatment scenarios. Figure 4 captures this matrix layer as the second realism filter between laboratory activity and field relevance [65–72].

4.4. Reaction Conditions—Light, Mass Transfer, Catalyst Recovery, and Larger Reaction Volumes

Feedstock heterogeneity and matrix composition converge at the reactor scale. In suspended catalysts, photon delivery, catalyst loading, plastic concentration, and radical transport are coupled variables. Titanium dioxide-mediated polyethylene oxidation exhibits a maximum at a defined catalyst-to-polymer mass ratio. Excess catalyst lowers activity by increasing optical attenuation and decreasing productive use of photons and oxidants at the polymer surface [38]. Effective reaction conditions must balance interfacial

area, light attenuation, solids loading, and hydrodynamic mixing. A catalyst-rich slurry may show low optical efficiency when photons and oxidants are consumed away from the polymer surface.

Catalyst recovery presents a second limitation. Powder photocatalysts add a separation requirement to an already dilute plastic suspension. Concentration and catalytic conversion can therefore be combined. Membrane-photocatalytic treatments have completely recovered polyester micro- and nanoplastics from textile-derived streams while concentrating the particles for catalytic degradation [57]. Nanofiltration has also preconcentrated PS nanoplastics before titanium dioxide photocatalysis, decreasing treatment volume and strengthening the interpretation of subsequent mineralization measurements [58]. Catalytic conversion becomes more tractable after substrate localization.

Interfacial control offers a complementary means of increasing conversion. Floatable hybrid titanium dioxide photocatalysts localize the reaction at the plastic-water-air boundary and enhance photoreforming in neutral water [56]. This arrangement improves mass transfer and catalyst recovery. Outdoor photoreforming of real-world PLA over isolated nickel atoms on cadmium sulfide has also been demonstrated at square-metre scale [43]. These studies show that light distribution, interfacial contact, substrate concentration, and catalyst recovery determine whether promising reaction chemistry can support practical treatment [38,43,56–58].

4.5. Environmental Relevance—Secondary Risks, Energy Input, and Treatment Boundaries

Environmental relevance begins with secondary risk. Catalytic treatment is justified only if it produces an endpoint preferable to the starting material within the relevant exposure context. Oxidative processing can change size, surface charge, dispersibility, and dissolved-phase composition in ways that alter hazard. Simulated Fenton oxidation of PS nanoplastics in urban wastewater treatment conditions increased intracellular reactive oxygen species responses and worsened developmental phenotypes in *Caenorhabditis elegans* [30]. By contrast, ozone and ozone/hydrogen peroxide treatment of PE microplastics in real up-flow anaerobic sludge blanket effluent produced physicochemical ageing without acute *Artemia salina* toxicity under the reported conditions [31]. No universal monotonic relation exists between oxidation extent and hazard reduction.

Energy input is the second test. Because the relevant quantities differ among photocatalytic, electrocatalytic, and photoelectrocatalytic treatments, comparisons should use the mode-specific reporting set defined in Section 2.4. Lamp rating, half-cell potential, or product concentration alone cannot establish energy performance. Electrical energy per order remains useful for ultraviolet advanced oxidation used in contaminant removal and should be reported alongside carbon-normalized conversion and photon or electron accounting [34,73].

Treatment boundaries provide the third test. Life-cycle and techno-economic assessments of enzymatic PET recycling, catalytic fast pyrolysis, chemoselective PET upcycling, and PET-to-Kevlar conversion show that resource use, greenhouse-gas emissions, solvent demand, utilities, and product allocation can reverse an apparent environmental benefit [74–77]. Comparisons across common plastics further show that mechanical recycling and established chemical recycling remain favorable for relatively clean, recoverable streams [78]. Catalytic destruction is most defensible for dilute, contaminated, compositionally mixed, or environmentally dispersed fractions that are poorly suited to recovery and recycling. Catalytic valorization is credible only after concentration and chemical narrowing permit realistic product recovery. Figure 4 summarizes these boundary conditions. The relevant criterion is whether catalytic conversion gives a safer and more traceable endpoint than separation, concentration, or recycling for the specific waste stream [30,31,73–78].

5. Conclusions and Outlook

Two treatment regimes should be distinguished. Catalytic valorization is environmentally meaningful for sufficiently concentrated, polymer-defined streams that permit recovery of chemically defined products. Dilute, mixed, or environmentally dispersed microplastics require representative identification, separation and concentration, polymer-class-specific conversion, verified destruction through carbon closure, separate toxicity assessment of residual solids and dissolved products, and an environmentally defensible terminal fate. Figure 5 summarizes these criteria.

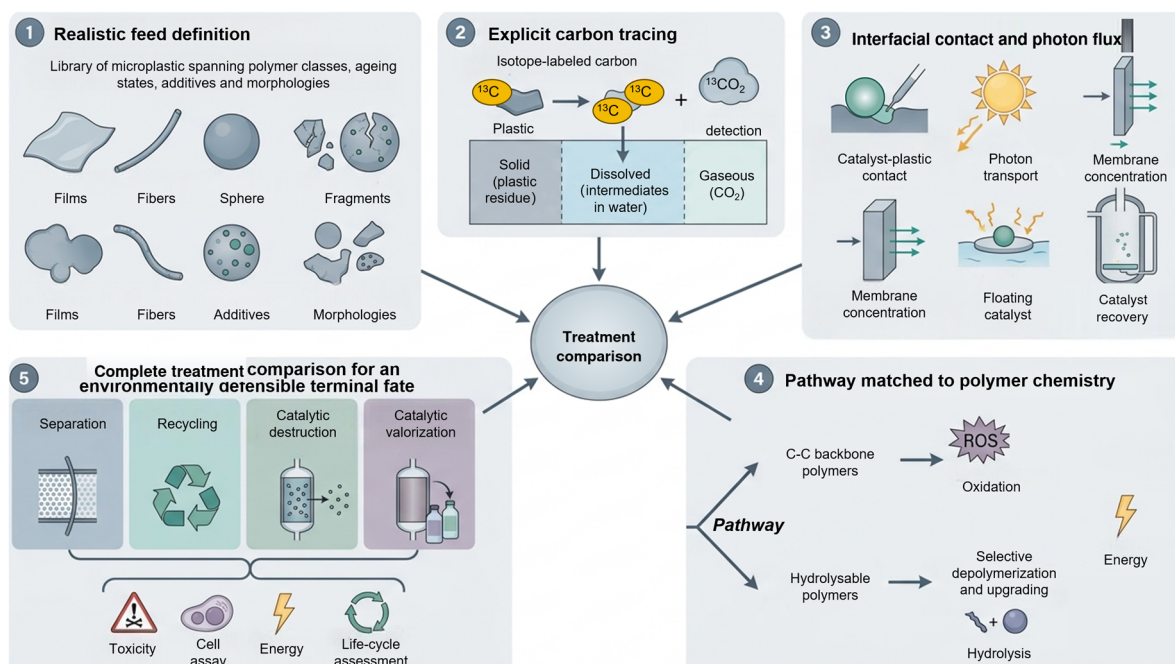


Figure 5. Chemical and environmental criteria for catalytic microplastic treatment. The sequence includes identification and concentration of mixed particles, realistic feed definition, explicit carbon and heteroatom tracing, control of interfacial contact and reaction conditions, polymer-class-specific pathway selection, compartment-resolved toxicity testing, and comparison with separation, recycling, and safe disposal.

Realistic feed definition is the first requirement. For environmental microplastics, the description should include polymer identity, ageing history, and methods used for particle identification, separation, and concentration before catalysis. Published procedures for ultraviolet-induced photoageing and reproducible preparation of reference materials now provide environmentally relevant substrates [79,80]. Such materials extend beyond pristine commercial particles while retaining experimental reproducibility.

Explicit carbon tracing is the second requirement. Stable-isotope-labelled nanoplastics and mineralization assays with carbon-13-labelled polyethylene enable assignment of polymer-derived carbon in complex matrices, including its conversion to carbon dioxide [23,24]. Isotope attribution complements but does not replace phase-resolved carbon closure, molecular product identification, or tests with environmentally representative particles.

Productive interfacial contact and recoverable catalyst structures constitute the third requirement. Visible-light supramolecular photocatalysis, electrophoretic enrichment of organic nanocrystals at polymer surfaces, floatable photocatalysts, and outdoor photoreforming show that interfacial contact can determine catalytic activity [20,21,43,56].

Polymer-specific reaction selection is the fourth requirement. Microplastics with carbon-carbon backbones require efficient interfacial oxidation. Hydrolysable polymers permit control of depolymerization and subsequent carbon fate. Halogenated, nitrogen-containing, crosslinked, and additive-rich particles require parallel tracing of heteroatoms, additives, metals, and potentially hazardous products. Product selectivity is relevant only when feed concentration, polymer identity, and product recovery support valorization [16–18,40–48,50].

Direct comparison with separation, concentration, recycling, and disposal is a final requirement. Life-cycle and techno-economic assessments identify conditions under which destruction is justified and valorization gives a genuine environmental benefit [74–78]. A rigorous catalytic microplastic study should define the feed, close carbon and relevant heteroatom balances, report photon flux, electrical input, energy consumption, and catalyst durability as appropriate, evaluate aqueous products and residual solids separately, and compare the terminal fate with separation, recycling, or disposal. Detection of a valuable molecule does not support valorization when the feed is dilute or compositionally unresolved, or when product recovery is implausible. Success requires verified polymer deconstruction, demonstrable risk reduction, and a terminal fate safer than transfer of polymer carbon and additives to another environmental compartment [23,24,46–48,50,79,80].

Author Contributions

Q.Z.: Writing, original draft preparation, and visualization; X.Q.: Writing and visualization; Y.Y.: Supervision, review, and editing; Y.G. and C.Y.T.: Supervision, review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by National Key Research and Development Project of China 2020YFA0710304.

Data Availability Statement

The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Thompson, R.C.; Courteney-Jones, W.; Boucher, J.; et al. Twenty Years of Microplastic Pollution Research and What We Have Learned. *Science* **2024**, *386*, eadl2746. <https://doi.org/10.1126/science.adl2746>.
2. MacLeod, M.; Arp, H.P.H.; Tekman, M.B.; et al. The Global Threat from Plastic Pollution. *Science* **2021**, *373*, 61–65. <https://doi.org/10.1126/science.abg5433>.
3. Murphy, F.; Ewins, C.; Carbonnier, F.; et al. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environ. Sci. Technol.* **2016**, *50*, 5800–5808. <https://doi.org/10.1021/acs.est.5b05416>.
4. Iyare, P.U.; Ouki, S.K.; Bond, T. Microplastics Removal in Wastewater Treatment Plants: A Critical Review. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 2664–2675. <https://doi.org/10.1039/D0EW00397B>.
5. Zandieh, M.; Griffiths, E.; Waldie, A.; et al. Catalytic and Biocatalytic Degradation of Microplastics. *Exploration* **2024**, *4*, 20230018. <https://doi.org/10.1002/EXP.20230018>.
6. Nabi, I.; Bacha, A.-U.-R.; Li, K.; et al. Complete Photocatalytic Mineralization of Microplastic on TiO₂ Nanoparticle Film. *iScience* **2020**, *23*, 101326. <https://doi.org/10.1016/j.isci.2020.101326>.
7. Lin, J.; Hu, K.; Wang, Y.; et al. Tandem Microplastic Degradation and Hydrogen Production by Hierarchical Carbon Nitride-Supported Single-Atom Iron Catalysts. *Nat. Commun.* **2024**, *15*, 8769. <https://doi.org/10.1038/s41467-024-53055-1>.
8. Pfohl, P.; Wagner, M.; Meyer, L.; et al. Environmental Degradation of Microplastics: How to Measure Fragmentation Rates to Secondary Micro- and Nanoplastic Fragments and Dissociation into Dissolved Organics. *Environ. Sci. Technol.* **2022**, *56*, 11323–11334. <https://doi.org/10.1021/acs.est.2c01228>.
9. Gewert, B.; Plassmann, M.M.; MacLeod, M. Pathways for Degradation of Plastic Polymers Floating in the Marine Environment. *Environ. Sci. Process. Impacts* **2015**, *17*, 1513–1521. <https://doi.org/10.1039/C5EM00207A>.
10. Shi, Y.; Liu, P.; Wu, X.; et al. Insight into Chain Scission and Release Profiles from Photodegradation of Polycarbonate Microplastics. *Water Res.* **2021**, *195*, 116980. <https://doi.org/10.1016/j.watres.2021.116980>.
11. Shi, Y.; Zheng, L.; Huang, H.; et al. Formation of Nano- and Microplastics and Dissolved Chemicals during Photodegradation of Polyester Base Fabrics with Polyurethane Coating. *Environ. Sci. Technol.* **2023**, *57*, 1894–1906. <https://doi.org/10.1021/acs.est.2c05063>.
12. Bertier, G.; Martel, A.; George, M.; et al. Where Polymer Carbon Goes under Solar Exposure: A Carbon-Balance Method for Assessing Plastic Fate. *PLoS ONE* **2025**, *20*, e0333021. <https://doi.org/10.1371/journal.pone.0333021>.
13. Ortiz, D.; Muñoz, M.; Nieto-Sandoval, J.; et al. Insights into the Degradation of Microplastics by Fenton Oxidation: From Surface Modification to Mineralization. *Chemosphere* **2022**, *309*, 136809. <https://doi.org/10.1016/j.chemosphere.2022.136809>.
14. Bridson, J.H.; Abbel, R.; Smith, D.A.; et al. Release of Additives and Non-Intentionally Added Substances from Microplastics under Environmentally Relevant Conditions. *Environ. Adv.* **2023**, *12*, 100359. <https://doi.org/10.1016/j.envadv.2023.100359>.
15. Caudillo-Flores, U.; Munoz-Batista, M.J.; Fernandez-Garcia, M.; et al. Recent Progress in the Quantitative Assessment and Interpretation of Photoactivity. *Catal. Rev. Sci. Eng.* **2024**, *66*, 531–585. <https://doi.org/10.1080/01614940.2022.2075535>.

16. Ran, H.; Zhang, S.; Ni, W.; et al. Precise Activation of C–C Bonds for Recycling and Upcycling of Plastics. *Chem. Sci.* **2024**, *15*, 795–831. <https://doi.org/10.1039/D3SC05701A>.
17. Chan, W.X.; Kong, X.Y.; Choo, S.R.; et al. Photocatalytic Upcycling of Plastics Containing Aliphatic C–C Bonds into Versatile Chemicals. *Chem Catal.* **2024**, *4*, 101044. <https://doi.org/10.1016/j.checat.2024.101044>.
18. Miao, Y.; Zhao, Y.; Gao, J.; et al. Direct Photoreforming of Real-World Polylactic Acid Plastics into Highly Selective Value-Added Pyruvic Acid under Visible Light. *J. Am. Chem. Soc.* **2024**, *146*, 4842–4850. <https://doi.org/10.1021/jacs.3c13000>.
19. Jiang, R.; Lu, G.; Yan, Z.; et al. Microplastic Degradation by Hydroxy-Rich Bismuth Oxychloride. *J. Hazard. Mater.* **2021**, *405*, 124247. <https://doi.org/10.1016/j.jhazmat.2020.124247>.
20. Qi, X.; Zhou, Q.; Wang, C.; et al. Crystalline Supramolecular Naphthalimide Photocatalyst for Visible-Light Microplastic Mineralization via Enhanced Interfacial Interactions. *Adv. Funct. Mater.* **2026**, *36*, e27581. <https://doi.org/10.1002/adfm.202527581>.
21. Guo, Y.; Zhu, B.; Tang, C.Y.; et al. Photogenerated Outer Electric Field Induced Electrophoresis of Organic Nanocrystals for Effective Solid-Solid Photocatalysis. *Nat. Commun.* **2024**, *15*, 428. <https://doi.org/10.1038/s41467-024-44700-w>.
22. He, J.; Han, L.; Ma, W.; et al. Efficient Photodegradation of Polystyrene Microplastics Integrated with Hydrogen Evolution: Uncovering Degradation Pathways. *iScience* **2023**, *26*, 106833. <https://doi.org/10.1016/j.isci.2023.106833>.
23. Danquigny, R.; Grassl, B.; Jiménez-Lamana, J.; et al. ¹³C-Labeled Nanoplastic Model Materials: Synthesis and Evaluation of Their Use in Ecotoxicology through Bioaccumulation Studies in Aquatic Crustaceans. *J. Hazard. Mater.* **2025**, *495*, 138810. <https://doi.org/10.1016/j.jhazmat.2025.138810>.
24. Bajo, K.; Kolvenbach, B.; Corvini, P.F.-X.; et al. Mineralization of ¹³C-Labeled Polyethylene by Marine *Bacillus velezensis* MT9. *Int. Biodeterior. Biodegrad.* **2026**, *209*, 106294. <https://doi.org/10.1016/j.ibiod.2026.106294>.
25. Lee, Y.K.; Romera-Castillo, C.; Hong, S.; et al. Characteristics of Microplastic Polymer-Derived Dissolved Organic Matter and Its Potential as a Disinfection Byproduct Precursor. *Water Res.* **2020**, *175*, 115678. <https://doi.org/10.1016/j.watres.2020.115678>.
26. Ateia, M.; Kanan, A.; Karanfil, T. Microplastics Release Precursors of Chlorinated and Brominated Disinfection Byproducts in Water. *Chemosphere* **2020**, *251*, 126452. <https://doi.org/10.1016/j.chemosphere.2020.126452>.
27. Piazza, V.; Uheida, A.; Gambardella, C.; et al. Ecosafety Screening of Photo-Fenton Process for the Degradation of Microplastics in Water. *Front. Mar. Sci.* **2022**, *8*, 791431. <https://doi.org/10.3389/fmars.2021.791431>.
28. Capolupo, M.; Sorensen, L.; Jayasena, K.D.R.; et al. Chemical Composition and Ecotoxicity of Plastic and Car Tire Rubber Leachates to Aquatic Organisms. *Water Res.* **2020**, *169*, 115270. <https://doi.org/10.1016/j.watres.2019.115270>.
29. Xu, Y.; Huang, D.; Liu, P.; et al. The Characteristics of Dissolved Organic Matter Release from UV-Aged Microplastics and Its Cytotoxicity on Human Colonic Adenocarcinoma Cells. *Sci. Total Environ.* **2022**, *826*, 154177. <https://doi.org/10.1016/j.scitotenv.2022.154177>.
30. Zhu, X.; Bu, C.; Zhang, Q.; et al. Dose-Dependent Proteomic Profiling Uncovers Toxicity Transformation of Nanoplastics Induced by Simulated Fenton Oxidation in Urban Wastewater Treatment. *Ecotoxicol. Environ. Saf.* **2025**, *306*, 119299. <https://doi.org/10.1016/j.ecoenv.2025.119299>.
31. Brito, D.A.S.; Silva, T.F.; Cavalheri, P.S.; et al. Aging and Transformation of Polyethylene Microplastics in UASB Effluents Treated with O₃ and O₃/H₂O₂: Physicochemical Changes and Toxicity Assessment. *ACS EST Water* **2025**, *5*, 6830–6841. <https://doi.org/10.1021/acsestwater.5c00773>.
32. Wang, M.; Wang, M.; Ma, D. Key Terms in Plastic Waste Transformation Reactions. *J. Phys. Chem. C* **2024**, *128*, 16302–16307. <https://doi.org/10.1021/acs.jpcc.4c05685>.
33. Haghshenas, Y.; Wong, W.P.; Gunawan, D.; et al. Predicting the Rates of Photocatalytic Hydrogen Evolution over Cocatalyst-Deposited TiO₂ Using Machine Learning with Active Photon Flux as a Unifying Feature. *EES Catal.* **2024**, *2*, 612–623. <https://doi.org/10.1039/D3EY00246B>.
34. Keen, O.; Bolton, J.; Litter, M.; et al. Standard Reporting of Electrical Energy per Order (EEO) for UV/H₂O₂ Reactors (IUPAC Technical Report). *Pure Appl. Chem.* **2018**, *90*, 1487–1499. <https://doi.org/10.1515/pac-2017-0603>.
35. Buriak, J.M.; Kamat, P.V.; Schanze, K.S. Best Practices for Reporting on Heterogeneous Photocatalysis. *ACS Appl. Mater. Interfaces* **2014**, *6*, 11815–11816. <https://doi.org/10.1021/am504389z>.
36. Quintavalla, A.; Carboni, D.; Lombardo, M. Green Metrics and Sustainability in Photocatalysis. *ChemCatChem* **2024**, *16*, e202301225. <https://doi.org/10.1002/cctc.202301225>.
37. Vital-Grappin, A.D.; Ariza-Tarazona, M.C.; Luna-Hernandez, V.M.; et al. The Role of the Reactive Species Involved in the Photocatalytic Degradation of HDPE Microplastics Using C,N-TiO₂ Powders. *Polymers* **2021**, *13*, 999. <https://doi.org/10.3390/polym13070999>.

38. Aragon, D.; Barquin, C.; Bringas, E.; et al. Unravelling the Photocatalytic Degradation of Polyethylene Microplastics with TiO₂ under UV Light: Evidence from Kinetic Studies. *Chem. Eng. J.* **2025**, *522*, 166672. <https://doi.org/10.1016/j.cej.2025.166672>.
39. Garcia, J.; di Luca, C.; Abarkan, A.; et al. Kinetic and Mechanistic Insights into the Photo-Fenton Oxidation of Polystyrene Nanoplastics in Water. *J. Water Process Eng.* **2025**, *78*, 108838. <https://doi.org/10.1016/j.jwpe.2025.108838>.
40. Praus, P.; Rehackova, L.; Filip-Edelmanova, M.; et al. Photoreforming of PET and PLA Microplastics for Sustainable Hydrogen Production Using TiO₂ and g-C₃N₄ Photocatalysts. *J. Environ. Chem. Eng.* **2025**, *13*, 116998. <https://doi.org/10.1016/j.jece.2025.116998>.
41. Jiang, S.; Wang, M.; Huang, Y.; et al. Selective Degradation of Polyethylene Terephthalate Plastic Waste Using Iron Salt Photocatalysts. *ChemSusChem* **2025**, *18*, e202401920. <https://doi.org/10.1002/cssc.202401920>.
42. Du, M.; Xing, M.; Yuan, W.; et al. Upgrading Polyethylene Terephthalate Plastic into Commodity Chemicals Paired with Hydrogen Evolution over a Partially Oxidized CuIn₅S₈ Nanosheet Photocatalyst. *Green Chem.* **2023**, *25*, 9818–9825. <https://doi.org/10.1039/D3GC03156J>.
43. Hu, M.; Feng, C.; Alharbi, J.; et al. Isolated Ni Atoms Enable Alkali-Free Photoreforming of Waste Polylactic Acid Plastic. *Nat. Commun.* **2026**, *17*, 347. <https://doi.org/10.1038/s41467-025-67050-7>.
44. Liu, Y.; Yeung, C.W.S.; Reisner, E. Photoelectrochemical Comproportionation of Pre-Treated PET Plastics and CO₂ to Formate. *Energy Environ. Sci.* **2025**, *18*, 7023–7033. <https://doi.org/10.1039/D5EE00689A>.
45. Lan, B.; Chen, Y.; Xiao, N.; et al. Efficient and Selective Upcycling of Waste Polylactic Acid into Acetate Using Nickel Selenide. *J. Energy Chem.* **2024**, *97*, 575–584. <https://doi.org/10.1016/j.jechem.2024.05.057>.
46. Schmidt, P.M.; Tantawi, O.; Santizo, K.; et al. Abiotic Hydrolysis of Microplastics: Influence of Polymer Chain Scission on Particle Fragmentation and Dissolved Organic Carbon Release. *Environ. Sci. Technol.* **2026**, *60*, 13109–13122. <https://doi.org/10.1021/acs.est.5c17195>.
47. Trhlíková, O.; Vlčková, V.; Abbrent, S.; et al. Microbial and Abiotic Degradation of Fully Aliphatic Polyurethane Foam Suitable for Biotechnologies. *Polym. Degrad. Stab.* **2021**, *194*, 109764. <https://doi.org/10.1016/j.polymdegradstab.2021.109764>.
48. Han, H.; Yan, P.; Li, Q.; et al. Photothermal Upcycling of Waste Polyvinyl Chloride Plastics. *Environ. Sci. Technol.* **2024**, *58*, 21861–21870. <https://doi.org/10.1021/acs.est.4c07350>.
49. Luo, H.; Li, Y.; Zhao, Y.; et al. Effects of Accelerated Aging on Characteristics, Leaching, and Toxicity of Commercial Lead Chromate Pigmented Microplastics. *Environ. Pollut.* **2020**, *257*, 113475. <https://doi.org/10.1016/j.envpol.2019.113475>.
50. Tian, Z.; Zhao, H.; Peter, K.T.; et al. A Ubiquitous Tire Rubber-Derived Chemical Induces Acute Mortality in Coho Salmon. *Science* **2021**, *371*, 185–189. <https://doi.org/10.1126/science.abd6951>.
51. Uekert, T.; Kuehnel, M.F.; Wakerley, D.W.; et al. Plastic Waste as a Feedstock for Solar-Driven H₂ Generation. *Energy Environ. Sci.* **2018**, *11*, 2853–2857. <https://doi.org/10.1039/C8EE01408F>.
52. Uekert, T.; Kasap, H.; Reisner, E. Photoreforming of Nonrecyclable Plastic Waste over a Carbon Nitride/Nickel Phosphide Catalyst. *J. Am. Chem. Soc.* **2019**, *141*, 15201–15210. <https://doi.org/10.1021/jacs.9b06872>.
53. Bhattacharjee, S.; Guo, C.; Lam, E.; et al. Chemoenzymatic Photoreforming: A Sustainable Approach for Solar Fuel Generation from Plastic Feedstocks. *J. Am. Chem. Soc.* **2023**, *145*, 20355–20364. <https://doi.org/10.1021/jacs.3c05486>.
54. Ma, F.; Wang, S.; Gong, X.; et al. Highly Efficient Electrocatalytic Hydrogen Evolution Coupled with Upcycling of Microplastics in Seawater Enabled via Ni₃N/W₅N₄ Janus Nanostructures. *Appl. Catal. B Environ. Energy* **2022**, *307*, 121198. <https://doi.org/10.1016/j.apcatb.2022.121198>.
55. Liang, X.; Gao, T.; Cui, Y.; et al. Photoreforming of Poly(Ethylene Terephthalate) Plastic into Valuable Chemicals and Hydrogen over BiVO₄/MoO_x: Synergistic Promotion of Oxidation and Reduction Processes. *Appl. Catal. B Environ. Energy* **2024**, *357*, 124326. <https://doi.org/10.1016/j.apcatb.2024.124326>.
56. Jiang, M.; Li, J.; Wan, X.; et al. Floatable Organic-Inorganic Hybrid-TiO₂ Generates Superoxide Radicals for Plastic Photoreforming in Neutral Solution. *Nat. Commun.* **2025**, *16*, 4136. <https://doi.org/10.1038/s41467-025-59467-x>.
57. Poerio, T.; Lavorato, C.; Severino, A.; et al. Combined Membrane Separation and Photocatalysis Process for the Recovery and Decomposition of Micro/Nanoplastics from Polyester Fabrics. *J. Environ. Chem. Eng.* **2024**, *12*, 113310. <https://doi.org/10.1016/j.jece.2024.113310>.
58. Severino, A.; Russo, B.; Lavorato, C.; et al. Integrated Nanofiltration and Photocatalytic Processes for the Removal of Polystyrene Nanoplastics Waste in Water. *Sep. Purif. Technol.* **2025**, *360*, 131232. <https://doi.org/10.1016/j.seppur.2024.131232>.
59. Su, X.; Liu, M.; Dai, H.; et al. Novel Insight into the Aging Process of Microplastics: An In-Situ Study in Coastal Wetlands. *Water Res.* **2024**, *248*, 120871. <https://doi.org/10.1016/j.watres.2023.120871>.

60. Ren, X.; Han, Y.; Zhao, H.; et al. Elucidating the Characteristic of Leachates Released from Microplastics under Different Aging Conditions: Perspectives of Dissolved Organic Carbon Fingerprints and Nano-Plastics. *Water Res.* **2023**, *233*, 119786. <https://doi.org/10.1016/j.watres.2023.119786>.
61. Chen, C.; Du, R.; Tang, J.; et al. Characterization of Microplastic-Derived Dissolved Organic Matter in Freshwater: Effects of Light Irradiation and Polymer Types. *Environ. Int.* **2024**, *185*, 108536. <https://doi.org/10.1016/j.envint.2024.108536>.
62. Wang, Q.; Gu, W.; Chen, H.; et al. Molecular Properties of Dissolved Organic Matter Leached from Microplastics during Photoaging Process. *J. Hazard. Mater.* **2024**, *480*, 136154. <https://doi.org/10.1016/j.jhazmat.2024.136154>.
63. Llorente-Garcia, B.E.; Hernandez-Lopez, J.M.; Zaldivar-Cadena, A.A.; et al. First Insights into Photocatalytic Degradation of HDPE and LDPE Microplastics by a Mesoporous N-TiO₂ Coating: Effect of Size and Shape of Microplastics. *Coatings* **2020**, *10*, 658. <https://doi.org/10.3390/coatings10070658>.
64. Jiang, S.; Yin, M.; Ren, H.; et al. Novel CuMgAlTi-LDH Photocatalyst for Efficient Degradation of Microplastics under Visible Light Irradiation. *Polymers* **2023**, *15*, 2347. <https://doi.org/10.3390/polym15102347>.
65. Zhu, K.; Sun, Y.; Jiang, W.; et al. Inorganic Anions Influenced the Photoaging Kinetics and Mechanism of Polystyrene Microplastic under the Simulated Sunlight: Role of Reactive Radical Species. *Water Res.* **2022**, *216*, 118294. <https://doi.org/10.1016/j.watres.2022.118294>.
66. Wu, X.; Liu, P.; Gong, Z.; et al. Humic Acid and Fulvic Acid Hinder Long-Term Weathering of Microplastics in Lake Water. *Environ. Sci. Technol.* **2021**, *55*, 15810–15820. <https://doi.org/10.1021/acs.est.1c04501>.
67. Wang, X.; Muhmood, A.; Ren, D.; et al. Exploring the Mechanisms of Humic Acid Mediated Degradation of Polystyrene Microplastics under Ultraviolet Light Conditions. *Chemosphere* **2023**, *327*, 138544. <https://doi.org/10.1016/j.chemosphere.2023.138544>.
68. Wen, Q.; Liu, N.; Qu, R.; et al. High Salinity Promotes the Photoaging of Polystyrene Microplastics with Humic Acid in Seawater. *Sci. Total Environ.* **2023**, *901*, 165741. <https://doi.org/10.1016/j.scitotenv.2023.165741>.
69. Chen, R.; Deng, Y.; Wang, J.; et al. The Effects of Different Types of Surfactants on the Electrochemical Degradation of PET Microplastics. *J. Water Process Eng.* **2025**, *74*, 107779. <https://doi.org/10.1016/j.jwpe.2025.107779>.
70. Lu, J.; Hou, R.; Wang, Y.; et al. Surfactant-Sodium Dodecyl Sulfate Enhanced Degradation of Polystyrene Microplastics with an Energy-Saving Electrochemical Advanced Oxidation Process (EAOP) Strategy. *Water Res.* **2022**, *226*, 119277. <https://doi.org/10.1016/j.watres.2022.119277>.
71. Gao, J.; Ju, Z.; Yang, Q.; et al. Exploring Different Effects of Biofilm Formation and Natural Organic Matter Adsorption on the Properties of Three Typical Microplastics in Freshwater. *Sci. Total Environ.* **2025**, *958*, 178156. <https://doi.org/10.1016/j.scitotenv.2024.178156>.
72. Zhang, H.; Liu, P.; Zhang, J.; et al. Unveiling the Protective Role of Biofilm Formation on the Photoaging of Microplastics. *Sci. China Technol. Sci.* **2024**, *67*, 3067–3078. <https://doi.org/10.1007/s11431-024-2721-5>.
73. Li, M.; Lou, F.; Huang, Y.; et al. Electrical Energy Consumption of Multiscale UV-AOP Reactors for Micropollutant Removal in Drinking Water: Facilitated Prediction by Reaction Rate Constants Measured on a Mini-Fluidic Photoreactor. *Environ. Sci. Technol.* **2023**, *57*, 18960–18969. <https://doi.org/10.1021/acs.est.3c00888>.
74. Uekert, T.; DesVeaux, J.S.; Singh, A.; et al. Life Cycle Assessment of Enzymatic Poly(Ethylene Terephthalate) Recycling. *Green Chem.* **2022**, *24*, 6531–6543. <https://doi.org/10.1039/D2GC02162E>.
75. Yadav, G.; Singh, A.; Dutta, A.; et al. Techno-Economic Analysis and Life Cycle Assessment for Catalytic Fast Pyrolysis of Mixed Plastic Waste. *Energy Environ. Sci.* **2023**, *16*, 3638–3653. <https://doi.org/10.1039/D3EE00749A>.
76. Iturrondobeitia, M.; Alonso, L.; Lizundia, E. Prospective Life Cycle Assessment of Poly(Ethylene Terephthalate) Upcycling via Chemoselective Depolymerization. *Resour. Conserv. Recycl.* **2023**, *198*, 107182. <https://doi.org/10.1016/j.resconrec.2023.107182>.
77. Han, J.; Nain, P.; Peterson, R.-J.L.; et al. Life Cycle Assessment of Chemical Upcycling of Postconsumer Polyethylene Terephthalate to Kevlar Polymer. *ACS Sustain. Chem. Eng.* **2025**, *13*, 18924–18937. <https://doi.org/10.1021/acssuschemeng.5c04073>.
78. Uekert, T.; Singh, A.; DesVeaux, J.S.; et al. Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965–978. <https://doi.org/10.1021/acssuschemeng.2c05497>.
79. Ducoli, S.; Marchesi, C.; Rigo, M.; et al. Developing Environmentally Relevant Test Materials for Microplastic Research through UV-Induced Photoaging. *J. Hazard. Mater. Adv.* **2025**, *20*, 100905. <https://doi.org/10.1016/j.jhazadv.2025.100905>.
80. Altmann, K.; Wimmer, L.; Alcolea-Rodriguez, V.; et al. Quality-by-Design and Current Good Practices for the Production of Test and Reference Materials for Micro- and Nano-Plastic Research. *J. Hazard. Mater.* **2025**, *497*, 139595. <https://doi.org/10.1016/j.jhazmat.2025.139595>.