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Plastic degradation in aquatic environments: a review of challenges and the need for standardized experimental approaches

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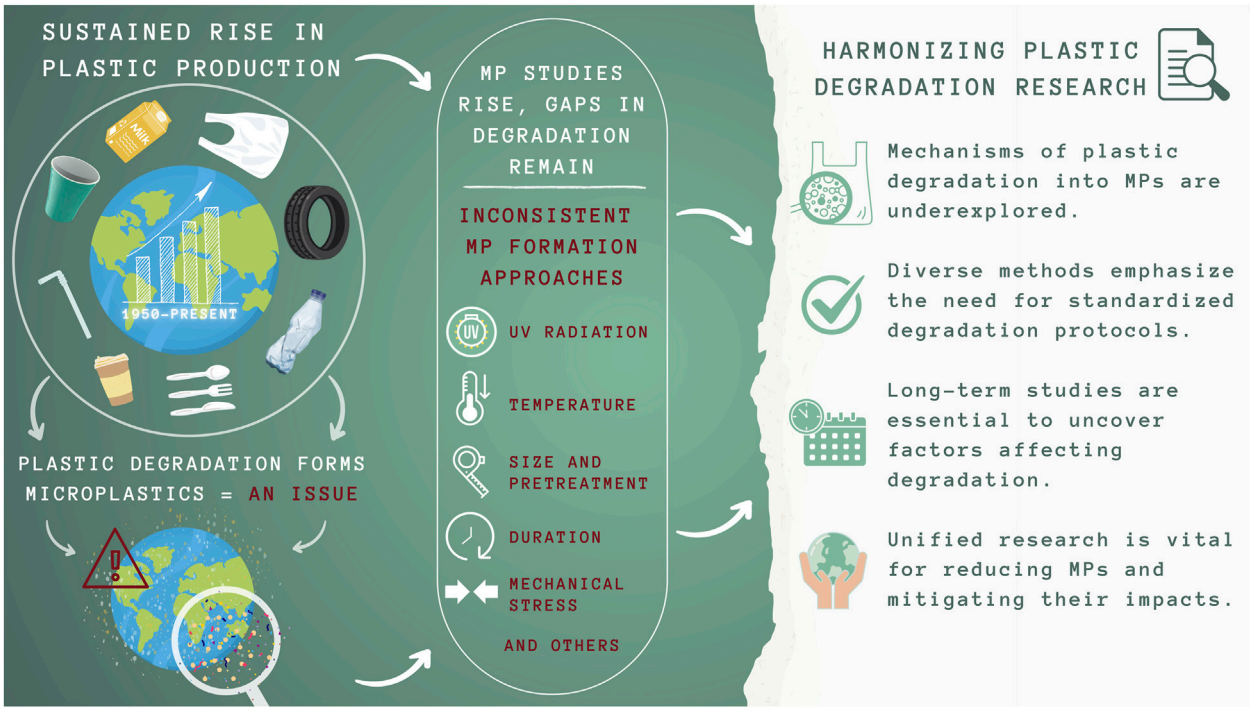
Plastic pollution has a significant impact on ecosystems, primarily due to the formation of microplastics through degradation processes. The degradation of plastic waste in aquatic systems is a key pathway in the formation of microplastics, yet the experimental approaches used to study these processes remain inconsistent and poorly harmonized. This review encompasses over 100 relevant documents, including experimental studies on plastic degradation under laboratory and field aquatic conditions, as well as reviews, standards, and policy reports that contextualize methodological challenges and ongoing standardization efforts. We identify key sources of methodological variation, including material types, particle sizes, exposure durations, environmental settings, and physical–chemical parameters such as UV radiation and mechanical stress. These discrepancies hinder the comparability of results and limit the development of robust, policy–relevant conclusions. Recent progress, including the ISO 24187:2023 standard for microplastic analysis, highlights steps toward harmonization but also underscores remaining gaps for degradation testing. We highlight specific gaps in current practices and propose essential parameters that require harmonization–particularly in long–term degradation testing and the simulation of realistic aquatic conditions. By addressing these methodological inconsistencies, more reproducible results can be achieved, enabling predictive modelling and supporting evidence–based risk assessment. In turn, standardized protocols will provide a stronger foundation for environmental policy and mitigation strategies aimed at reducing microplastic pollution.

KEYWORDS

polymer, fragmentation, laboratory, variability, standardization, toxicity



GRAPHICAL ABSTRACT

Highlights

- This review provides a synthesis of degradation mechanisms in aquatic environments.
- It was found that experimental methodologies vary significantly across studies.
- The review revealed key parameters that require standardization.
- Recommendations for harmonized long–term degradation testing were proposed.
- Findings support science–based policy action to address plastic pollution.

1 Introduction

The massive growth in global plastic production, from 2 million tonnes in 1950 to over 400 million tonnes in 2022, has resulted in widespread environmental contamination (Julie Cohen, 2017; Madhumitha Jaganmohan, 2024; Plastics Europe, 2023; Plastics Europe, 2008). Despite advances in recycling and circular material strategies, most plastic waste is still landfilled, incinerated, or released into the environment, where it contributes to persistent pollution of aquatic ecosystems (Cottom et al., 2024; Geyer et al., 2017; Kapukotuwa et al., 2025; United Nations Environment Programme, 2023).

Once in the environment, plastics undergo physical, chemical, and biological transformations that gradually lead to their fragmentation into microplastics, defined as particles between 1 µm and 5 mm (Arthur et al., 2008; Ellos et al., 2025; Morales Jiménez et al., 2023). These particles are now present in all aquatic environments, including groundwater (Goeppert and Goldscheider, 2021; Gong et al., 2023), wetlands (Amini-Birami et al., 2023), rivers and lakes (Arcadio et al., 2023; Cera et al., 2022), seas and oceans (Fonseca et al., 2024; Zhang et al., 2023), and even glaciers (Stefánsson et al., 2021; Zhang Y. U et al., 2021). Their occurrence has also been reported in mine water up to 700 m below ground (Brožová et al., 2023a).

The presence of microplastics raises concerns due to their persistence, small size, and ability to adsorb and transport toxic compounds (Bradney et al., 2019; Hoang et al., 2025; Joo et al., 2021; Stapleton and Hai, 2023; Xi et al., 2022). The fact that they have been detected in human tissues and fluids–including blood, urine, placenta, and even amniotic fluid–raises concerns about potential systemic exposure pathways (Abbas et al., 2025; Halfar et al., 2023; Massardo et al., 2024; Ragusa et al., 2022; Rotchell et al., 2024). While research has increasingly focused on documenting microplastics and their impacts, less attention has been given to the degradation processes that generate them.

Plastic degradation is a complex process governed by environmental conditions, material characteristics, and time. It involves abiotic mechanisms such as photodegradation, thermo–oxidation, hydrolysis, and mechanical fragmentation, as well as biotic degradation through microbial activity (Dimassi et al., 2022; Oberbeckmann et al., 2014; Schwarz et al., 2023; Sutkar et al., 2023). These processes rarely act in isolation and often operate in sequence or synergy, making it difficult to generalize degradation behavior across environments or plastic types.

The degradation of plastics in aquatic systems has been investigated in both laboratory (*ex situ*) and natural (*in situ*)

settings. However, the available experimental studies differ significantly in their methodological designs. Variables such as polymer type, particle size, UV source and intensity, water chemistry, duration, and mechanical agitation vary widely across experiments (Klein et al., 2021; Lambert and Wagner, 2016; Theobald et al., 2024). This heterogeneity severely limits the comparability and reproducibility of results.

Moreover, although international standards for biodegradation testing exist (e.g., ISO 14855-1, 2012; ISO 17556, 2019; ISO 23977-1, 2020), they are often limited to specific environments and do not account for the full range of degradation pathways relevant to aquatic systems, and also suffer from ambiguous and inconsistent use of terminology (Harrison et al., 2018; Iroegbu et al., 2025; ISO 24187:2023, 2023; Kukkola et al., 2024). Many studies fail to simulate realistic conditions, and few adopt standardized degradation indicators or experimental endpoints. As a result, it remains difficult to assess the actual environmental fate of plastic materials or to compare degradation rates across polymer types.

This review builds on a comprehensive screening of the Web of Science database, complemented by relevant review articles, guidelines, standards, and policy reports. Together, these sources provide the basis for analyzing methodological heterogeneity and identifying parameters requiring harmonization. A detailed description of the search and selection process is provided in the section "Review methodology".

The novelty of this review lies in its explicit focus on methodological inconsistencies across experimental degradation studies, rather than solely summarizing degradation mechanisms or documenting the occurrence of microplastics. By critically evaluating how study design influences outcomes, we identify essential parameters that require harmonization and emphasize the need for standardized, long-term experimental designs that reflect realistic environmental conditions. The review is based on a manual screening of the Web of Science database conducted in April 2024, which included all available publications up to that date. Additional studies and documents published after April 2024 were subsequently integrated during drafting and revision, ensuring that the analysis reflects both the historical development of the field and the most recent advances. This perspective contributes to improving reproducibility, enabling predictive modelling, and supporting evidence-based policymaking and mitigation strategies.

This review is primarily intended for researchers aiming to design and interpret degradation studies, but it also provides guidance relevant for funding agencies, journal editors, and policymakers, who rely on robust and comparable data to inform standardization, regulation, and future research priorities.

2 Plastic pollution

Plastics are among the most widely produced synthetic materials in the modern world (Baztan et al., 2017; Cole et al., 2011; Plastics Europe, 2023; Thompson et al., 2009). Their popularity stems from low production costs, chemical versatility, and durability. However, their widespread use, combined with inefficient waste management and low recycling rates, has led to large–scale accumulation in the environment (Lebreton et al., 2017; Murphy et al., 2016; OECD, 2022; United Nations Environment Programme, 2023). A significant proportion of plastic waste is released into aquatic ecosystems, either directly or via fragmentation from terrestrial sources, contributing to the ongoing formation of microplastics (Brennholt et al., 2018; Brožová et al., 2023b; Sutkar et al., 2023; Tibbetts et al., 2018; Townsend et al., 2019).

Despite growing public awareness and political attention, the majority of plastic waste is not effectively recycled (Prata et al., 2019). In 2019, only 9% of global plastic waste was recycled, while an estimated 22% was mismanaged or directly released into the environment (OECD, 2022). In 2020, more than 51 million tonnes of macroplastic waste entered natural systems globally. Key sources include packaging, construction materials, agricultural films, and consumer products (Cottom et al., 2024; Thanh et al., 2011).

The persistence of plastics in the environment is largely attributed to their resistance to degradation and the presence of various chemical Additives. These additives, such as flame retardants, UV stabilizers, and plasticizers, improve material properties but may also enhance environmental persistence and toxicity (Gallo et al., 2018; Hahladakis et al., 2018). During weathering, plastics release both the polymer matrix and these additives, increasing the chemical complexity of the pollution (Costa A. et al., 2023; Yu et al., 2024).

In the aquatic environment, plastics are subject to various degradation pathways, including photodegradation, thermo–oxidation, mechanical fragmentation, and biodegradation. These processes gradually reduce the size of plastic particles, resulting in the formation of microplastics (Brožová et al., 2023a; Morales Jiménez et al., 2023). Microplastics can originate either as primary particles–deliberately manufactured for use in cosmetics or industrial abrasives–or as secondary particles resulting from environmental degradation of larger plastic debris. Secondary microplastics dominate in natural environments and are continuously generated (Arthur et al., 2008; Halfar et al., 2021).

Microplastics have been detected in all types of aquatic ecosystems, and their transport and fate depend on various factors such as polymer type, particle density and shape, biofouling, and hydrodynamic conditions. While lighter polymers like polyethylene (PE) and polypropylene (PP) tend to float and persist in surface waters, denser materials such as PET and PVC may sink and accumulate in sediments (Costa J. P. et al., 2023; Galindo Montero et al., 2023). Microplastics may act as vectors for the transport of other pollutants, including heavy metals and persistent organic pollutants, due to their high surface area and hydrophobicity (Prajapati et al., 2022; Xi et al., 2022).

From an ecotoxicological perspective, microplastics have been shown to affect a wide range of aquatic organisms, from plankton to fish and mollusks (Mamun et al., 2023; Stapleton and Hai, 2023). Ingestion can lead to physical damage, oxidative stress, altered feeding behavior, or reduced reproduction. Furthermore, microplastics can interact with the microbiome and influence ecological functions such as nutrient cycling and energy transfer within food webs (Dimassi et al., 2022; Rubini et al., 2025).

Although the toxicological aspects of microplastics are not the focus of this review, it is important to note that human exposure has been increasingly documented. Microplastics have been found in blood, urine, placenta, and even amniotic fluid, indicating potential

for systemic bioavailability (Halfar et al., 2023; Massardo et al., 2024; Rotchell et al., 2024). These findings underscore the importance of understanding degradation mechanisms and conditions that influence the formation and fate of microplastics in aquatic environments. Based on the above findings, it is evident that microplastics in the environment are intricately linked to human activity–and to humans themselves.

3 Review methodology

This review is based on a manual screening of the Web of Science database, which was conducted in April 2024. The screening included all available records published up to that date. Different Boolean search strings were applied (e.g., plastic AND degradation AND aquatic, plastic AND degradation AND water), which initially yielded more than 4,000 records in the "Topic" category (title, abstract, keywords). Because these queries also captured many irrelevant works, duplicates, and unrelated records were excluded, and the search was refined by restricting queries to the "Title" field. This reduced the pool to only a few dozen directly relevant experimental studies on plastic degradation under aquatic conditions.

We included primary experimental studies that investigated degradation of plastics under aquatic conditions (laboratory *ex situ* or field *in situ*) and reported at least one degradation indicator (e.g., mass loss, molecular-weight change, chemical signatures, or fragmentation). We excluded studies focused exclusively on non-aquatic environments, papers without experimental degradation under aquatic conditions, and items lacking sufficient methodological detail. Review articles, ISO/ASTM standards, and policy/guideline documents were treated as complementary sources used to contextualize methodological diversity and ongoing harmonization efforts.

Complementary sources encompassed peer-reviewed reviews, ISO/ASTM standards relevant to plastic degradation and microplastic analysis, and policy/guideline reports from recognized organizations (e.g., Plastics Europe, OECD), used to frame methodological gaps and standardization needs.

While the main evidence base of the review comes from studies identified during the April 2024 screening (covering literature from the earliest indexed works up to April 2024), further relevant publications that appeared after this date were incorporated during the drafting, revision, and peer review process. This approach ensures that the review reflects both the historical development of the field and the recent advances.

No artificial intelligence or automated tools were used in this process; the entire screening was performed manually.

4 Plastic degradation

4.1 Plastic to microplastics: degradation transformation processes

Plastic degradation in aquatic environments involves a combination of physical, chemical, and biological mechanisms that gradually fragment polymers into smaller particles, ultimately resulting in microplastics (Cai et al., 2023; Schwarz et al., 2023). To understand how microplastics are formed in aquatic environments, it is essential to examine the specific degradation pathways that govern the transformation of plastic materials. These pathways are generally classified as abiotic or biotic, though they rarely act in isolation. In practice, degradation tends to proceed as a hybrid sequence–abiotic mechanisms such as photodegradation or mechanical stress initiate surface embrittlement and bond cleavage, while microbial colonization and enzymatic activity often follow, further contributing to polymer breakdown (Davidov et al., 2025; Idris et al., 2023; Sutkar et al., 2023).

Five major mechanisms are typically involved: photodegradation, thermo–oxidation, hydrolysis, mechanical fragmentation, and biodegradation. Their activity depends on multiple environmental factors, including UV radiation, temperature, oxygen and salinity levels, water turbulence, and pH (Cai et al., 2023; Lin et al., 2022; Schwarz et al., 2023). These factors often act synergistically; for example, UV exposure can oxidize polymer surfaces, making them more brittle and thus more susceptible to fragmentation and microbial attack (Dey et al., 2024; Niu et al., 2023).

Polymer structure significantly influences degradation behavior. Synthetic polymers generally consist of long, stable chains that resist cleavage under standard environmental conditions. The presence of additives such as UV stabilizers or flame retardants can inhibit degradation, whereas plasticizers may increase surface hydrophilicity and influence biofilm formation (Dimassi et al., 2022; Priya et al., 2022). As a result, two items made from the same polymer may degrade at very different rates depending on their additive content and environmental exposure.

Environmental conditions also determine degradation intensity. A plastic fragment submerged in the photic zone of the ocean can degrade several times faster than one buried in sediment, where oxygen is depleted and UV radiation is absent (Dey et al., 2024; Niu et al., 2023). This variability underscores the importance of material–specific and site–specific approaches when evaluating degradation potential (Roy et al., 2022; Zhang K. et al., 2021).

The transition from macroplastics to microplastics is primarily a process of physical fragmentation rather than complete mineralization. With increasing fragmentation, particle surface area grows, promoting further oxidation and microbial colonization. In favorable conditions, degradation may continue toward the nanoplastic range or even eventual mineral end–products such as CO_2, H_2O, and NH_3 (Chamas et al., 2020; Fava, 2022). However, this process is extremely slow, lasting hundreds to thousands of years for conventional plastics in most aquatic environments (Dimassi et al., 2022; Lin et al., 2022).

Table 1 provides a comparative overview of the main degradation pathways of plastics in aquatic environments, summarizing their underlying mechanisms, key influencing factors, and typical outcomes. This synthesis highlights the complexity of degradation processes and the interplay between abiotic and biotic factors that ultimately govern the formation of microplastics.

Figure 1 outlines a generalized pathway of plastic degradation in aquatic systems. It highlights the key transitions from macro-to microplastic, the environmental interactions that influence

TABLE 1 Degradation pathways of plastics: mechanisms, influencing factors, and typical outcomes.

Degradation pathway	Mechanism	Key influencing factors	Typical outcomes/limitations
Photodegradation	UV radiation breaks polymer bonds, surface oxidation	Light intensity & spectrum, exposure duration, water depth, additives (UV stabilizers)	Surface embrittlement, fragmentation, enhanced microbial colonization; limited in turbid/deep waters
Thermo-oxidation	Heat and oxygen induce chain scission	Temperature, oxygen availability, material type	Accelerated embrittlement under warm, oxygen-rich conditions; limited relevance in cold/deep waters
Hydrolysis	Cleavage of bonds by reaction with water molecules	Polymer chemistry (esters, amides), pH, temperature	Significant for biodegradable polyesters (e.g., PLA, PBAT); negligible for polyolefins
Mechanical fragmentation	Physical abrasion, turbulence, sediment grinding	Wave action, sediment load, flow conditions	Rapid size reduction into microplastics; does not mineralize material
Biodegradation	Microbial enzymes metabolize polymer chains	Polymer chemistry, biofilm formation, nutrient availability, temperature	Effective mainly for biodegradable polymers; slow for conventional plastics

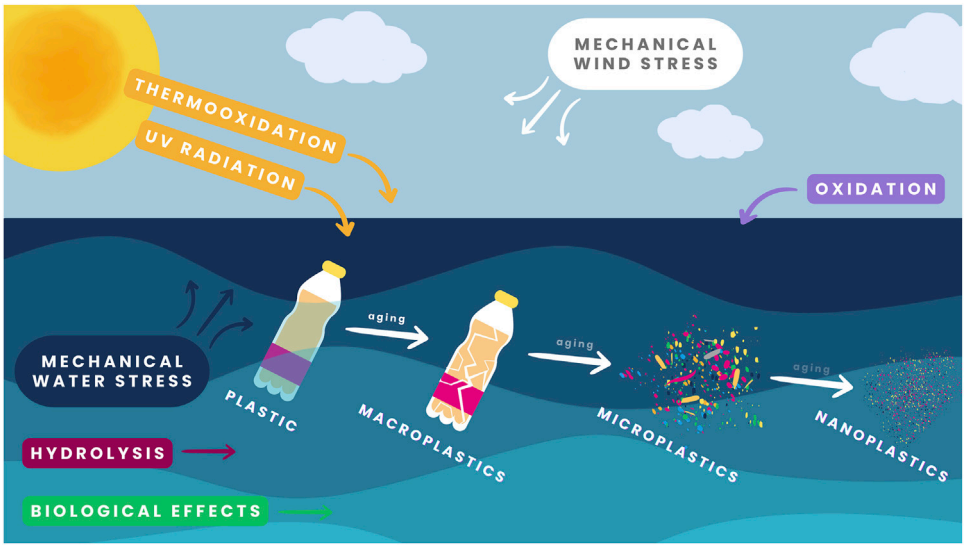


FIGURE 1
Mechanism of degradation of plastics in aqueous environments (created by the authors in Canva).

degradation kinetics, and the eventual colonization by microbial biofilms that may accelerate further breakdown.

4.2 Analytical approaches to microplastic detection and characterization

Understanding plastic degradation and microplastic formation requires accurate and reproducible analytical methods. The identification, quantification, and characterization of microplastic (MP) particles are essential for interpreting their behavior and environmental fate. However, methodological inconsistencies across studies have hindered comparability, which has prompted the recent introduction of harmonization efforts, such as the ISO 24187, 2023 standard (Huang et al., 2023; ISO 24187, 2023).

4.2.1 Sampling strategies

Sampling is the first and most critical step in microplastic analysis. Inadequate sampling or contamination can introduce significant bias (Huang et al., 2023). According to ISO 24187: 2023, 2023 protocols, they must account for the sampling environment–whether water, air, soil, sludge, or biota–and define minimum requirements for volume, frequency, and equipment (ISO 24187:2023, 2023).

- Water samples are typically collected via bulk water extraction (grab sampling) or direct particle capture using nets or pumps (Cutroneo et al., 2020; Jiang et al., 2024).
- Soil and sediment sampling requires manual tools (e.g., trowels, augers) or core samplers for deeper profiles (Qi et al., 2024; Yan and Yang, 2023).
- Airborne microplastics are captured either passively (settling plates or filters) or actively (vacuum pumps), with some studies using filters from HVAC systems or electronics (Fang et al., 2024).
- Sludge and biota sampling depend on moisture content and legal or ethical regulations (Franco et al., 2023; Jo et al., 2022; Sarkar et al., 2023).

4.2.2 Separation of microplastics

Once samples are collected, they must be processed to isolate potential microplastic particles. This step depends on matrix type, expected particle size, and the intended detection method. Most protocols include:

- Drying, preferably below 40 °C, to prevent particle degradation (Adomat and Grischek, 2021).
- Sieving or filtration for particle size separation. Filtration is favored for water samples, while sieving is used for solids to enable granulometric fractioning (ISO 24187, 2023; Rani et al., 2023).
- Density separation with saturated salt solutions (NaCl, NaI, $ZnCl_2$) to remove heavier mineral matter (Nabi et al., 2022; Tirkey and Upadhyay, 2021).
- Chemical digestion (H_2O_2, HNO_3, KOH) or enzymatic treatment to remove organic residues, especially in biotic or complex matrices (Khoshmanesh et al., 2023; Kinigopoulou et al., 2022).
- Flotation methods based on surface hydrophobicity are also applied, e.g., foam flotation (Zhang Y. I. et al., 2021).

Cryogenic grinding may be used if particles must be size–reduced for controlled laboratory testing (e.g., sorption studies), though it is unsuitable for environmental quantification due to particle alteration (McColley et al., 2023; Šunta et al., 2022).

4.2.3 Identification and characterization

MP detection methods vary by research focus and available instrumentation. The ISO 24187, 2023 standard outlines core detection categories: visual, spectroscopic, thermoanalytical, and chemical.

- Visual analysis (microscopy or manual sorting) provides data on particle shape, size, and color, but cannot confirm polymer identity. Although widely used as a screening tool, it is inherently subjective and should be supported by other methods (Huang et al., 2023; Kotar et al., 2022).
- Spectroscopic methods are the most widely adopted, offering non-destructive chemical identification:
  - FTIR, ATR–FTIR, FPA–FTIR,
  - Raman spectroscopy,
  - Near–infrared (NIR) and quantum cascade laser IR (QCL–IR) (Fakayode et al., 2024; Song et al., 2021).

Combining FTIR and Raman is ideal for accurate polymer identification, though cost and technical complexity remain limiting factors.

- Thermoanalytical methods, such as pyrolysis–GC–MS, decompose samples in an inert atmosphere and analyze the resulting gases. These methods are effective for determining polymer composition in complex or heterogeneous mixtures (Dos Santos et al., 2023; Elseblani et al., 2023).
- Chemical techniques like liquid chromatography (LC) detect specific polymer degradation products after hydrolysis and are increasingly used in controlled degradation studies (Chandra et al., 2024; Zhang et al., 2022).

Each technique offers different strengths in terms of sensitivity, resolution, and throughput. Method selection must therefore align with research objectives–whether polymer identification, quantification, or morphological analysis.

4.3 Degradation of plastics in aquatic environments: experimental approaches and limitations

While the detection and characterization of microplastics have received considerable attention, experimental research on plastic degradation in aquatic environments remains limited. A targeted search using the Web of Science database (April 2024) initially yielded more than 4,000 records for "plastic AND degradation AND water." After screening, we identified a focused body of experimental studies that directly investigated degradation under aquatic conditions (both *in situ* and *ex situ*). Alongside post–2020 publications, we also incorporated earlier studies that established the core concepts of photo–oxidation, hydrolysis, and weathering in aquatic matrices.

This review draws on standards, policy reports, and review articles to provide a broader context, altogether reflecting more than 100 relevant documents. The relatively modest number of primary degradation studies, compared to the size of the initial corpus, highlights the methodological inconsistency and lack of focused research in this area.

A central challenge lies in the absence of standardized procedures. Experimental designs across studies vary widely in terms of plastic type, particle size, exposure conditions (UV intensity, temperature, agitation), and environmental matrices. Such inconsistencies complicate result comparison, hinder reproducibility, and limit the development of meaningful degradation metrics.

Numerous ISO and ASTM standards exist for plastic degradation, yet most address only specific processes or environments rather than the full complexity of aquatic systems. ISO standards such as ISO 14855-1, 2012; ISO 17556, 2019; ISO 23977-1, 2020 focus on aerobic biodegradation under composting, soil, or seawater conditions while ISO 14853, 2016; ISO 15985, 2014 target anaerobic biodegradation. Others, ISO 22088-1, 2006 (environmental stress cracking), ISO 10640, 2011 (photo–aging), and ISO 4892-1, 2024 (light exposure), cover single mechanisms but not combined pathways. More recent documents, including ISO 23832 (release of microplastics under marine laboratory conditions) and ISO 24187, 2023(microplastic identification and reporting), represent progress in harmonizing methods but still do not prescribe degradation protocols applicable to natural aquatic environments. ASTM standards (e.g., ASTM D6691, 2024 for aerobic biodegradation in seawater or ASTM D7473/D7473M-21, 2021) face similar limitations. Overall, current standards remain fragmented, heavily focused on biodegradation, and insufficient to capture the interplay of abiotic and biotic processes typical of freshwater, marine, or wastewater systems.

TABLE 2 : Summary of degradation experiments conducted under aquatic conditions with various plastic.

Authors	Type of materials	Size of materials	Type of placement	Type of environment	UV radiation	Mechanical movement	Time allocation
Andrady et al. (2022)	LDPE	Injection molding	*EX SITU*	Chamber – sand + air Chamber – artificial seawater	2xUVB, 313 nm 0.71 W/m^2 (day × night) T = 24 °C–35 °C	no	500 h
Beltrán-Sanahuja et al. (2020)	PA PET PLA1 PLA2	Manually–cut, trim 3.5 × 1.5 cm	*EX SITU*	Cylinder – natural sand Cylinder – natural seawater	A) Micmol Aqua Air 30 lighting B) Darkness T = 16 °C	no	1 year
Briassoulis et al. (2020)	LDPE PHB PBSe PBSeT	Manually–cut, trim 2 × 2 cm	*EX SITU*	Bioreactor – natural sand + natural seawater + NPK	no T = 25 °C ± 1 °C	A) no B) Magnetic stirrer	360 days
			IN SITU	sea	natural	natural	1 year
Gerritse et al. (2020)	PS PP PUR PET latex HDPE LDPE CA Bio–PES PLA	No – objects were in their original size	*EX SITU*	Water chamber – artificial seawater	UVA/B 4 × 30–W (day × night) T = 24 °C ± 1 °C	Water recirculation by pump	427 days
Hu et al. (2024)	PP PLA PSM PPDO PBAT MD blend ST blend	Manually–cut, trim 2 × 3 cm	*IN SITU*	Lake, river, air	natural	natural	1 year
			EX SITU	Dry chamber	no T = ~25 °C	no	1 year
Chubarenko et al. (2020)	PS1 PS2 LDPE PP	Manually–cut, trim 2 × 2 cm	*EX SITU*	Masonry mixer – sediment + drinking water	no	rotation	1 day
Kalogerakis et al. (2017)	HDPE1 HDPE2	Manually–cut, trim 1 × 20 cm	*EX SITU*	Sediment – sand Tank – seawater	A) No UV B) Natural UV C) UVA, 315–400 nm T = ~1 °C–65 °C	rotation	6 months
Klein et al. (2021)	PP PET PS LDPE PVC Bio–PBS SB	Purchased in required pellet size or manually–cut, trim	*EX SITU*	Dry chamber Water chamber – ultrapure water	UVCUVA/B (day × night) T = 23 °C–45 °C	no	2 days
Lambert and Wagner (2016)	PE PP PET PLA PS	Manually–cut, trim 1 × 1 cm	*EX SITU*	Water chamber – demineralized water	UV 320–400 nm T = 30 °C	no	112 days
Menzel et al. (2022)	LDPE	Purchased in required pellet size 125–200 µm fraction	*EX SITU*	Q–SUN XE–3 chamber + deionized water	3 Xe lights + Daylight–Q filtr, irradiation 60 W/m^2, 300–400 nm T = 38 °C	Magnetic stirrer	3,200 h

(Continued on following page)

TABLE 2 (*Continued*) : Summary of degradation experiments conducted under aquatic conditions with various plastic.

Authors	Type of materials	Size of materials	Type of placement	Type of environment	UV radiation	Mechanical movement	Time allocation
Sorasan et al. (2022)	PE PP	Sieved to obtain 1–5 mm fraction	*EX SITU*	Reactor – artificial seawater	A) No irradiation B) Hg lamp 150 W, 297–579 nm T = 24 °C	Magnetic stirrer	360 h
Sørensen et al. (2021)	Wool PET PA	Fibers purchased and cut to ~2 mm length	*EX SITU*	Atlas Suntest CPS + chamber + filtered natural seawater	3 Xe lamps + Daylight–Q filter, irradiation 60 W/m^2, 300–400 nm T = 24 °C ± 3 °C	yes	56 days
Stapleton et al. (2023)	PET PP PLA PC	Production–3D printing 4 × 2 cm ~12 × 2 cm	*EX SITU*	Milli–Q, air, artificial seawater, artificial freshwater	UVA 340 nm, 2 × 10W	no	28 days
Suhrhoff and Scholz-Böttcher (2016)	LDPE PET PS PVC	Manually–cut, trim 5 × 5 cm	*EX SITU*	Deionized water Artificial seawater	A) No irradiation B) UV 300, 15 W T = room	Magnetic stirrer	78 days
Theobald et al. (2024)	PA6 PET LDPE PLA OxoLDPE	Injection molding – twin–screw extruder ~17 × 2 cm ~15 × 5 cm, etc.	*IN SITU*	Sea, WWTP – oxidation tank	natural	natural	1 year
			EX SITU	dry chamber	UVA 340 nm (day × night) T = 50 °C	rotation	~33 days
Wu et al. (2021)	PP1 PP2	Mixture production, 400–500 μm fraction – pressure mixer	*EX SITU*	Thermostatic water bath – artificial seawater Reactor	Reactor XPA Hg lamp 500W, UV365 = 100 w/m^2 T = 25 °C	Magnetic stirrer	12 days

IN SITU, outdoor environment, *EX SITU*, laboratory environment, day × night = combination of light and dark, T = temperature.

This gap underscores the novelty and relevance of our review, which systematically maps methodological heterogeneity and proposes a minimal set of harmonized parameters to guide future aquatic degradation testing. Table 2 summarizes selected studies, comparing parameters such as polymer type, exposure method (*in situ* vs. *ex situ*), presence of UV radiation, and duration. These examples illustrate the diversity of experimental setups, from controlled chambers with artificial seawater to long–term outdoor exposures.

Common experimental trends include the use of *ex situ* setups with artificial media such as deionized or artificial seawater, variability in UV sources ranging from natural sunlight to UVA/B lamps, and marked inconsistencies in sample shapes and sizes, from millimeter–scale fragments to intact objects. Exposure durations also diverge substantially, spanning from as little as 12 days to more than a year. Despite these differences, several conclusions can be drawn. Long–term exposure generally enhances the detection of degradation processes, particularly when combined with UV radiation and mechanical agitation. Nevertheless, in the absence of harmonized standards for exposure intensity, water chemistry, and sampling intervals, the results remain difficult to compare across studies. To advance the field, unified degradation protocols are needed that account for both abiotic and biotic mechanisms, alongside material–specific exposure scenarios reflecting realistic aquatic environments. Replicable designs with standardized degradation metrics, such as mass loss, molecular weight reduction, or chemical signatures, are essential to enable meaningful comparisons. Such efforts are critical for developing a predictive understanding of plastic degradation pathways and for evaluating the environmental performance of emerging materials and additives.

4.4 Bioplastics: degradation potential and environmental considerations

Bioplastics are often presented as environmentally favorable alternatives to conventional polymers. However, their behavior in natural environments–particularly their degradability in aquatic systems–remains insufficiently understood and is frequently overstated in public discourse (Brožová et al., 2023b; Costa A. et al., 2023). While bioplastics are commonly associated with biodegradability, this assumption does not hold universally.

From a chemical perspective, bioplastics encompass a heterogeneous group of materials. These include:

- Bio–based but non–biodegradable plastics (e.g., bio–PE, bio–PET),
- Biodegradable plastics from fossil resources (e.g., PBAT, PCL),
- Biodegradable and bio–based plastics (e.g., PLA, PHAs, starch blends).

Biodegradability depends not only on the polymer type but also on environmental conditions such as temperature, oxygen availability, microbial activity, and exposure to light. For instance, PLA degrades effectively under industrial composting conditions (>58 °C, high humidity), but its degradation in freshwater or marine environments is extremely limited (Briassoulis et al., 2020; Hu et al., 2024).

Several recent studies indicate that bioplastics may exhibit low degradation rates in aquatic environments, comparable to conventional polymers (Beltrán–Sanahuja et al., 2020; Gerritse et al., 2020). Others show that surface biofilm formation can enhance degradation in certain bio–based materials, yet the process is slow and incomplete over typical exposure durations (Menzel et al., 2022).

The potential of bioplastics to serve as a sustainable alternative is further limited by several key factors. First, the presence of additives and composite formulations can significantly alter degradation behavior and introduce additional ecotoxicological risks, particularly when these materials release non–polymeric constituents during weathering. Second, bioplastics currently face economic and technical constraints related to production scalability and high manufacturing costs, which restrict their widespread adoption. Finally, public confusion over labeling–particularly the interchangeable and often misleading use of terms such as "biodegradable" and "compostable"–leads to improper disposal and undermines intended end–of–life strategies (Dimassi et al., 2022; European Bioplastics, 2023; Idris et al., 2023; Roy et al., 2022). These challenges underscore the need for clearer communication, regulatory alignment, and further material optimization to ensure bioplastics fulfill their environmental promise.

To evaluate bioplastics as a viable alternative, degradation studies must go beyond short–term laboratory tests. They should include:

- Standardized test methods (e.g., ISO 14855–1, ISO 17556),
- Long–term field exposures,
- Assessments under realistic freshwater and marine conditions.

Without such rigorous data, claims about the environmental superiority of bioplastics remain speculative. Moreover, the substitution of conventional plastics with bioplastics should not distract from broader systemic changes in plastic production, consumption, and waste management.

5 Conclusion

This review integrates insights from over 100 relevant documents, including experimental studies of plastic degradation under aquatic conditions. By focusing not only on what has been studied, but especially on how it has been studied, the review highlights a critical and underexplored dimension: the methodological heterogeneity that hampers comparability, reproducibility, and the translation of findings into reliable policy advice. The novelty of this review lies in its explicit attention to these methodological inconsistencies and the argument that harmonized protocols are a prerequisite for scientific progress and policy relevance. Unlike previous reviews that primarily summarize degradation mechanisms or the occurrence of microplastics, this work uniquely emphasizes the need for standardized experimental protocols as a prerequisite for advancing both science and regulation. Despite recent progress in analytical methodologies and standardization efforts–such as the ISO 24187, 2023 standard–data remain fragmented, and many detection techniques still lack inter–laboratory comparability.

5.1 Challenges

Despite the breadth of available literature, several persistent challenges remain. A major limitation is methodological inconsistency, as experimental designs differ in polymer types, particle sizes, exposure conditions, and analytical endpoints, which results in poor comparability across studies. Another issue is the limited ecological realism of many experiments, since simplified *ex situ* conditions rarely capture the complexity of natural aquatic systems. Standards provide only fragmented guidance: existing ISO and ASTM documents are restricted to specific environments or processes and do not encompass the diversity of degradation pathways relevant to aquatic contexts. Analytical comparability also continues to be problematic, as many detection techniques lack inter–laboratory harmonization, making cross–study synthesis unreliable. Finally, the misconception surrounding bioplastics complicates the discourse: although often promoted as sustainable alternatives, bioplastics frequently degrade slowly in aquatic environments and may release additives, raising concerns comparable to conventional plastics.

5.2 Future perspectives

To move the field forward, several priorities should be addressed. First, it is essential to develop standardized, environment–specific protocols that realistically reflect freshwater, marine, and wastewater conditions. Long–term *in situ* experiments are needed to capture environmentally relevant degradation rates and interactions, while integration with ecotoxicological and transport research would allow for a more holistic understanding of risks. The environmental behavior of bioplastics also requires critical evaluation under natural aquatic conditions, recognizing them not as straightforward replacements for conventional plastics but as one of several complementary solutions requiring systemic alignment. Embedding standardized protocols into regulatory practice is another priority, ensuring their integration into life–cycle analyses, environmental monitoring, and long–term pollution control strategies. Finally, strengthening the science–policy interface is crucial so that experimental evidence can directly inform regulation, standardization, and mitigation efforts.

Author contributions

KB: Writing – original draft, Investigation, Visualization, Writing – review and editing, Project administration. SH: Supervision, Writing – review and editing. JH: Visualization, Conceptualization, Writing – review and editing, Methodology, Investigation, Writing – original draft. KČ: Validation, Writing – review and editing, Investigation. AV: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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