Review

Utilization routes of plastic waste from the marine environment: a review

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ABSTRACT

Plastic pollution in the marine environment has become a global concern due to its ecological impacts, persistence, and difficulty in removal. To address this issue, various routes are being explored, not only to remove plastic waste from marine environments but also to repurpose and recycle it. This review presents a comprehensive overview of the latest research conducted over the past five years in the monitoring, collection, cleaning, recycling, and valorization of marine plastic litter. The attention is given to emerging technologies and strategies for monitoring and recovery from oceans, rivers, and shorelines. Cleaning and pretreatment methods are evaluated for their effectiveness in removing marine origin contaminants without compromising polymer integrity. A detailed comparison of recycling possibilities for marine plastic waste are preseted, including mechanical, chemical, and solvent-based methods, as well as alternative utilization routes such upcycling into art, and conversion to fuels, functional materials or energy recovery. By synthesizing recent findings, we aim to highlight advancements in understanding the pathways of marine plastic litter, the challenges associated with its management, and innovative approaches to its reuse.

1. Introduction

Plastic pollution has emerged as a critical global issue, particularly in the context of marine contamination. This growing environmental threat has been exacerbated by alarming reports of plastic particles being detected inside living organisms. Numerous species, including birds, fish, and turtles, have been significantly affected by plastic pollution (Kühn and van Franeker, 2020; MacLeod et al., 2021). A comparison with the International Union for Conservation of Nature (IUCN) Red List revealed that at least 17% of species impacted by entanglement and ingestion are classified as threatened or near threatened (Gall and Thompson, 2015). Studies reveal plastic fragments in dead marine animals' intestines, showing plastic's harmful impact.

Mistaken for food, plastics accumulate in their bodies, causing lasting health risks. The issue of plastic waste in oceans was first documented in scientific literature in the early 1970s (Carpenter et al., 1972; Carpenter and Smith, 1972). Over the past few decades, awareness and research on marine plastic pollution have surged, as reflected by a sharp rise in publications containing the term "marine plastic debris" since 1975. While general awareness and studies on marine plastic debris have been increasing for several decades, only a few publications specifically addressing marine plastic recycling were recorded before 2014. According to Scopus data (see Fig. 1), this research topic remained niche until around 2019, after which publication rates accelerated, sharply rising from 117 documents in 2021 to 180 in 2024. This trend underscores a recent and growing recognition of recycling as a viable

mitigation strategy for addressing marine plastic pollution.

Research indicates that a significant portion of marine plastic waste originates from land-based sources (Guggisberg, 2024). The majority of plastic pollution enters the ocean via rivers (1.15 - 2.41 million tonnes) (Andrady, 2011; Serra-Gonçalves et al., 2019), primarily between May and October, with just 20 highly polluted rivers responsible for nearly two-thirds of marine debris (Lebreton et al., 2017). Additionally, approximately 18% of marine plastic waste is linked to the fishing industry (Andrady, 2011). More recent study focusing solely on macroplastics estimated that more than 1000 rivers contribute 80% of global riverine plastic emissions, with annual inputs ranging from 0.8 to 2.7 million metric tons and identified small urban rivers as particularly significant sources of pollution (Meijer et al., 2021). For Europe specifically, rivers are estimated to transport between 1656 and 4997 metric tons of macro-litter (>25 mm) into the ocean each year, with plastics comprising over 80% of this total (González-Fernández et al., 2021). The composition of marine debris includes high-density polyethylene (HDPE) and polyethylene terephthalate (PET) from bottles, containers, and packaging straps; polyethylene (PE) and polypropylene (PP) from plastic bags; rubber latex products such as balloons and condoms; expanded polystyrene (EPS) from flotation devices; cellulose acetate (CA) from cigarette filters; nylon and PET fibers originating from the textile industry and domestic laundry; as well as rubber from tires and polyamides (PA) and PE from fishing gear, including buoys, lines, and nets (Peña-Rodriguez et al., 2021). Although points of entry into the oceans appear to be geographically concentrated, marine plastic pollution is a global issue. In fact, ocean currents and the plastic durability facilitate its spread beyond a region and into areas beyond national jurisdiction. Therefore, the EU Single-Use Plastics Directive (European Parliament & Council, 2019), entered into force in July 2021, banned the ten most common single-use plastic products found on EU beaches. This action aimed to reduce the prevalence of items such as cutlery, plates, straws, and expanded polystyrene food containers that frequently contribute to coastal litter. The observed 40 % reduction in single-use plastic items between 2015–2016 and 2020–2021 may already reflect the early effects of national measures adopted in preparation for this EU-wide ban. However, since the Directive was implemented near the end of the monitoring period, its full impact on marine litter composition is expected to become more evident in subsequent assessments (MSFD Technical Group on Marine Litter et al., 2025).

Given the complexity and transboundary nature of marine plastic pollution, there is an urgent need to comprehensively and systematically examine the entire lifecycle of plastic waste in the marine environment,
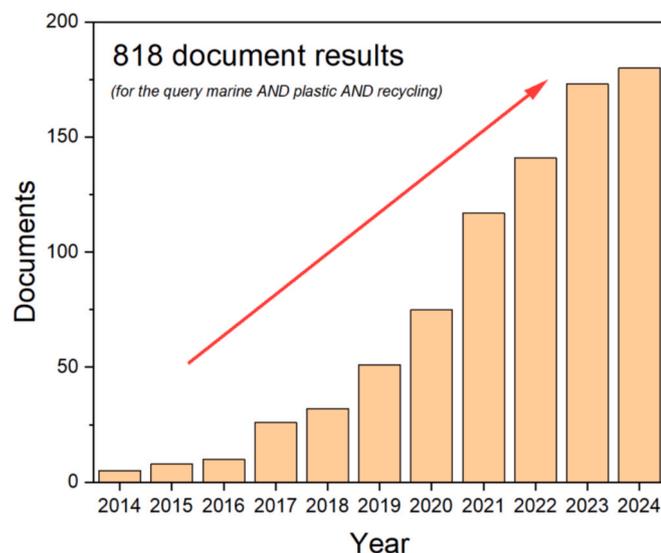
from sources and monitoring to collection, cleanup, recycling, and innovative reuse strategies. While several reviews have addressed aspects of this issue, they often focus on specific stages or approaches. For instance, Fonseca et al. (2024) reviewed the scientific literature to discuss management strategies for marine plastic pollution, adopting a systemic perspective to map current efforts and highlight research gaps that must be addressed to inform effective public policies. In contrast, Râpă et al. (2024) focused specifically on the recovery and treatment of marine plastics, evaluating laboratory-scale methods such as melt reprocessing, pyrolysis, gasification, and hydrothermal carbonization. Meanwhile, Oro et al. assessed plastic waste management using chemical recycling combined with a carbonate/bicarbonate system, offering an innovative route for valorizing marine plastic waste (Oro et al., 2023). Despite these valuable contributions, a comprehensive lifecycle-oriented framework is still lacking. Addressing this gap is crucial to developing effective responses to the marine plastic crisis.

This review aims to systematically examine the entire lifecycle of plastic waste in the marine environment, from pollution and monitoring to collection, cleaning, recycling, and innovative utilization, highlighting current technologies, challenges, and future opportunities for sustainable management and valorization. Each step in this pathway is essential and interconnected: monitoring provides crucial data on pollution levels, guiding the selection of the most appropriate collection methods; the type and condition of the recovered plastic then determine the subsequent cleaning and treatment processes; and these steps collectively influence the feasibility and success of recycling and alternative utilization strategies. Therefore, we prepared a comprehensive review that integrates all these stages, emphasizing their interdependence and importance for enabling effective plastic waste utilization from marine environments.

2. Monitoring Strategies

The monitoring of land-based litter is crucial for understanding and mitigating the impacts of marine plastic pollution. This led to a range of methodologies that have been developed, combining both traditional and advanced technologies for monitoring and removal of litter. These include visual observations (Haarr et al., 2022; Hurley et al., 2023); remote sensing via satellites, aircraft and UAVs (Ma et al., 2023; Salgado-Hernanz et al., 2021; Tikász et al., 2025; Topouzelis et al., 2021; Veettil et al., 2022); machine learning (Jeong et al., 2024; Nunkhaw and Miyamoto, 2024); cleaning technologies (Schmaltz et al., 2020; Sugianto et al., 2023) and active litter collection (Hurley et al., 2023; Molnár et al., 2024). Each method has strengths and limitations, but variations in timing, location, and analysis hinder consistent comparisons and conclusions. While diversity fosters innovation, it also challenges standardization (Aliani et al., 2023). Standardized, long-term monitoring can establish pollution baselines and track changes over time. However, many methods lack clear objectives and are short-term or location-specific, limiting their use in assessing mitigation effectiveness (Ryan et al., 2020) The primary objective of long-term monitoring is to evaluate the effectiveness of mitigation measures in reducing (plastic) pollution in the environment while ensuring the collection of reliable data at an affordable cost (Hanke et al., 2013). Therefore, the cost and effort associated with monitoring methodologies must be carefully balanced against the value of the information they provide for management decisions (González et al., 2016), reinforcing the need for efficiency and reliability in data collection.

This need for a coordinated and standardized approach to marine litter monitoring was recognized early by the European Union (EU). The Marine Strategy Framework Directive (MSFD) (European Parliament & Council, 2008) was adopted in 2008 and remains the most important legal instrument for the conservation and sustainable use of the European marine environment. It mandates measures to reduce marine litter, ensuring that the: 'Properties and quantities of marine litter do not cause harm to the coastal and marine environment' (European Parliament &

Fig. 1. Graph showing the development of research on marine plastic recycling from 2014 to 2024, based on Scopus data.

Council, 2008). To achieve this, the directive calls for the development of monitoring programs to assess, among other things:

i) Trends in the amount of litter washed ashore and/or deposited on coastlines, including analysis of its composition, spatial distribution and, where possible, source (10.1.1) (European Commission, 2010)'

ii) 'Trends in the amount of litter in the water column (including floating at the surface) and deposited on the seafloor, including analysis of its composition, spatial distribution and, where possible, source (10.1.2) (European Commission, 2010) '

To support marine litter monitoring under the MSFD, the Technical group on Marine Litter (TGML) published the 'Guidance on Monitoring of Marine Litter in European Seas' in 2013 (Hanke et al., 2013), with a revised edition in 2023 (Galgani et al., 2023). Additionally, in 2016, the TGML published a report on Options and Recommendations for Riverine Litter Monitoring, providing guidance on methodologies for assessing litter transport from rivers to the marine environment (González et al., 2016). Furthermore, in 2022, the TGML published a State of the Art and Literature Overview focusing on the Monitoring of Floating Marine Macro Litter (Vighi et al., 2022) providing an in-depth assessment of existing methods and emerging technologies. Further emphasis is placed on the recommendations and guidelines of the MSFD TGML, which are especially relevant for EU Member States. The focus is on visual monitoring of macro litter, defined as items larger than 2.5 cm (Galgani et al., 2023; HELCOM, 2015), across key marine compartments:

i) Riverine Floating Macro Litter (RFML);
ii) Floating Marine Macro Litter (FMML);
iii) Beached Macro Litter (BML).

RFML and FMML are defined as litter pieces larger than 2.5 cm that float on the water's surface or within the upper layer of the water column, either in rivers or the marine environment (Hanke et al., 2013). Since RFML and FMML are typically observed rather than collected, their size serves as a key indicator for assessing litter quantities within riverine and marine compartments.

2.1. Floating Litter Monitoring Applications

One of the most important steps to facilitate harmonized monitoring, litter identification, and data collection was the development of the JRC Floating Litter Monitoring Application (App), a tablet-based tool designed for systematic assessments of floating litter (INSPIRE, 2025) The App allows the user to choose between the monitoring of FMML and RFML (Fig. 2) using standardized visual observation techniques based on predefined size categories and litter items harmonized with the EU's 'Joint List of Litter Categories for Marine Macrolitter Monitoring' (J-list) by Fleet et al. (2021). In addition, the connected Online Photo Catalogue of the Joint List of Litter Categories (European Commission, 2025) can help with the identification of litter. Once the observer begins a monitoring session, the J-list for litter classification appears. Selecting a litter item opens a secondary menu for additional details. Each recorded litter item is logged with time and GPS data, and when the session ends, a file is generated containing all metadata and litter records (INSPIRE, 2025).

2.2. Methodology for Remote Floating Marine Litter (RFML)

The most harmonized methodological approach for RFML consists of regular short visual monitoring sessions (30–60 min) in river estuaries, using the JRC App, to evaluate litter inputs to the sea (González-Fernández and Hanke, 2017). To cover the expected high temporal variability of litter loads, weekly or bi-weekly monitoring sessions are recommended. Observations are conducted from elevated points (e.g., bridges, piers, pontoons) to improve visibility of RFML. Alternatively, boats can be used in bigger rivers and estuaries (González et al., 2016). Observation sessions are kept short (0.5 to 1-hour surveys) to minimise observer fatigue and to ensure consistent and efficient data collection. Observers are advised to face upstream for an unobstructed view and choose optimal lighting conditions to reduce reflections and shadows. In tidal regions (e.g., the North East Atlantic Ocean), monitoring is ideally conducted during ebb tide to ensure a downstream flow. Defining the width of the monitoring area allows the litter flux to be estimated in relation to the total width of the river, while considering the speed of the surface water for flux calculations (González-Fernández and Hanke, 2017). This approach was implemented on a large scale by González-Fernández and Hanke (2017) in the RIMMEL Project (Riverine and Marine floating macro litter Monitoring and Modelling of Environmental Loading) initiated by the European Commission Joint Research Centre (EC JRC), engaging 36 institutions to monitor 58 rivers across Europe.
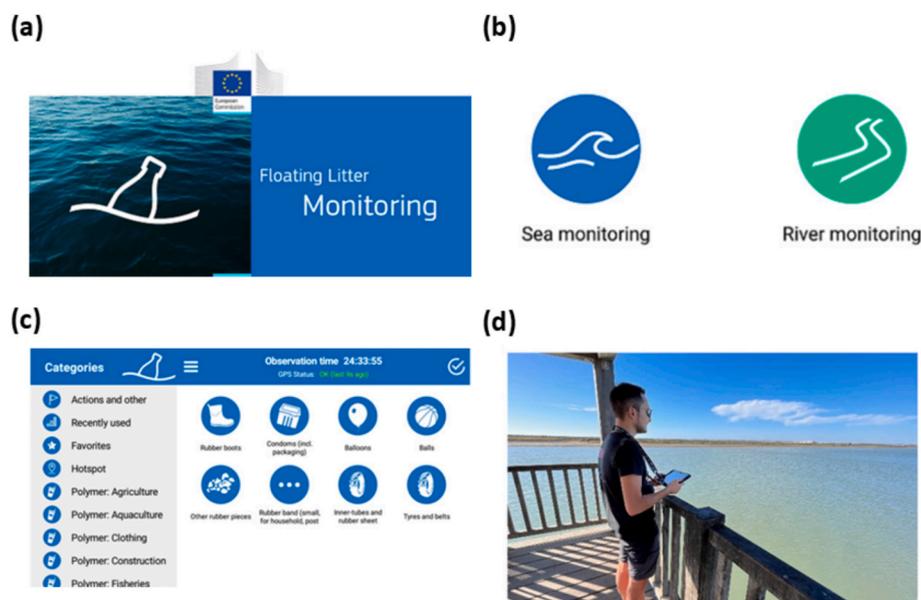

Fig. 2. Screenshots of the JRC Floating Litter Monitoring Application: (a) the registration site; (b) selection whether the monitoring of floating litter is carried out in rivers or the sea; (c) an example of different types of litter items; (d) an example of an observer using the App with a tablet device (INSPIRE, 2025).

2.3. Methodology for Fixed Marine Monitoring Litter (FMML)

The selection of the monitoring site is highly dependent on the purpose and the monitoring method. FMML monitoring is usually performed from platforms by visual observation from large ships, and small or medium-sized vessels (Vighi et al., 2022). The most commonly used and recommended approach, especially in offshore or large-scale areas, is the fixed-width strip transect method (Galgani et al., 2023). The fixed transect widths typically range from 10 to 50 m for large and medium vessels in offshore waters, with observation heights up to 25 m and speeds up to 25 knots. However, FMML detectability is strongly influenced by a combination of operational parameters such as transect width, observation height, observer fatigue, speed of vessel, and angle, and environmental conditions like wind speed, sea state, light, and visibility. Together, these factors determine the detection limit for the smallest identifiable litter size classes. While the goal is to accurately record all items down to the minimum threshold of 2.5 cm, this may not always be feasible under certain conditions. In such cases, a larger minimum size can be selected for monitoring. To ensure consistency and comparability, it is recommended to report FMML using the following standardized size ranges: A. $2.5 \leq x < 5$ cm: B. $5 \leq x < 10$ cm; C. $10 \leq x < 20$ cm: D. $20 \leq x < 30$ cm; E. $30 \leq x < 50$ cm; F ≥ 50 cm (Galgani et al., 2023).

Strip width can be defined using an inclinometer mounted at the bow or side of the vessel. When monitoring from the side, the side with minimal sun glare and best visibility should be chosen. The strip should be clearly marked (e.g., using tape or physical markers) and continuously controlled during the survey to ensure only items within the defined area are recorded (Galgani et al., 2023). For small or medium-sized vessels in coastal areas, transect widths are typically between 3 and 20 m, with observation heights between 1.5 and 9 m and speeds between 2 and 10 knots. This set-up should allow the detection of items ≥ 2.5 cm across the entire strip. If more observers are on board, additional transects (strips on each side of the bow) may be added. For small vessels with limited visibility (e.g. 3 m height), parallel transects are recommended to cover the target area more effectively (Galgani et al., 2023).

To ensure representative data, monitoring should be stratified by pollution source such as urban areas, riverine inputs, or offshore activities or alternatively designed to cover gradients of expected litter density, from low-density areas like the open sea to high-density zones near harbours and marinas (Galgani et al., 2023). Since FMML observations are highly influenced by weather conditions such as sea state and wind speed, seasonal surveys are strongly recommended. Ideally, monitoring should take place after a period of calm seas to avoid biases caused by recent storms or rough conditions (Galgani et al., 2023). To avoid bias from small 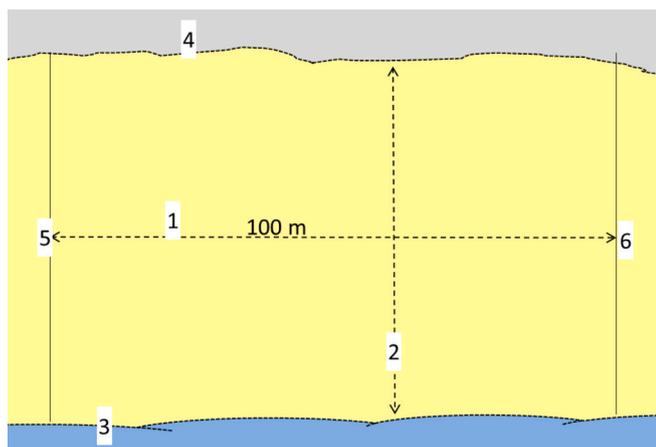sample sizes, a minimum transect length should be defined for each survey. A grid overlay can support spatial analysis, with each cell acting as a statistical unit, but to prevent outliers, there needs to be a minimum sampling effort per cell. Sampling units should be randomly placed. Replicates are recommended, but their ideal number depends on the site and seasonal variability (Galgani et al., 2023). To categorize litter, record geographic coordinates, and enable pollution comparisons across all marine compartments, the above-mentioned Floating Litter Monitoring App should be used. Binoculars may be used to confirm sightings when necessary. To ensure reliable observations, monitoring should be conducted under wind conditions not exceeding Beaufort scale 3, to avoid reduced visibility due to waves and surface mixing. All relevant information, including weather conditions, sea state, and observation parameters, should be documented as metadata (Galgani et al., 2023).

2.4. Methodology for Beach Marine Litter (BML)

Beach Marine Litter is mostly based on the visual collection and identification of litter on the surface of sandy or gravel beach surfaces. Selected beaches should have clear access to the sea and be accessible year-round. Their locations should be spatially stratified to reflect varying pressures and litter exposure such as proximity to river mouths, harbours, marinas, or tourist facilities, and should represent a range of development types, including urban, semi-urban, and remote or natural beaches. Beach litter surveys should be conducted at a minimum of four sites per country-subregion, with four surveys per year (once per season) (Galgani et al., 2023). This approach aligns with the method for assessing beach litter threshold values and ensures over 40 surveys within a three-year period (Van Loon et al., 2020). At selected beaches, a fixed 100 m section, from the waterline to the back of the beach (e.g., dunes, walls), is systematically surveyed four times a year, once each season (Fig. 3). All visible macro-litter collected by hand during each survey is removed from the beach and classified according to the Joint List of Litter Categories for Marine Macrolitter Monitoring (Fleet et al., 2021). To support identification, an Online Photo Catalogue of the Joint List of Litter Categories (European Commission, 2025) has been developed. BML is measured as the number of items per litter category (e.g., plastic, textiles, glass/ceramics) per 100 m of coastline.

Even though the methods presented are among the most harmonized so far, there is still need for improvement. Galgani et al. (2024) point out that MSFD assessments remain underdeveloped for FMML, with Member States citing issues such as the subjective use of protocols, limitations caused by rough sea and poor visibility, and the need for large-scale surveys to improve consistency and comparability. The use of different monitoring, protocols and litter item classification makes it difficult to compare data on a larger scale (Arcangeli et al., 2020; González-Fernández et al., 2022) while the focus is mostly on larger macro-litter (Galgani et al., 2024). In terms of RFML similar issues occur (González et al., 2016). Compared to the methods used for RFML and FMML, BML monitoring is much less demanding in terms of effort and cost (Galgani et al., 2023). Even though slightly different monitoring protocols and litter item lists for BML have been used in the past or are still in use in regions like: the Baltic Sea (HELCOM), the Mediterranean Sea (Barcelona Convention), or the North-East Atlantic (OSPAR) the results remain largely comparable and transferable within the framework of the Joint List of Litter Categories for Marine Macrolitter Monitoring (European Commission and ARCADIS, 2014; Fleet et al., 2021). Nevertheless, emerging monitoring technologies, such as drones, satellites, aircraft, and UAVs, along with cleaning systems, trash capture devices, and active litter collection, offer promising potential to reduce monitoring time and costs across marine compartments, while improving data acquisition and comparability at broader scales.

Fig. 3. Section of the beach for BML monitoring: 1. The 100 m length sampling unit section; 2. The sampling unit width; 3. Waterline; 4. Back of the beach. 5 and 6; Location to take GPS coordinates.

3. Current Methods of Plastic Waste Recovery and Collection

According to (Schmaltz et al., 2020) 38 different technologies exist

for the collection of ocean plastic, of which 31 technologies target macroplastics, 3 technologies target microplastics and 4 technologies target both types. Plastic collection from oceans, rivers and sea shores differs quite drastically.

3.1. Recovery and Collection Techniques from Oceans

Plastic waste recovery from open waters primarily targets macroplastics due to challenges in detecting and capturing smaller particles. Technologies are classified into mechanical, autonomous, and semi-autonomous systems.

Mechanical retrieval utilizes vessels outfitted with booms and nets to capture surface plastics (Lebreton et al., 2017). Booms act as floating barriers, guiding plastic waste toward collection zones. Organisations such as The Ocean Cleanup leverage these barriers across ocean gyres to capture plastics. Studies indicate that these methods can reduce macroplastic concentrations but face limitations in durability, particularly under harsh marine conditions (Spencer et al., 2023). Mechanical cleanup efforts, like those used by The Ocean Cleanup project, could significantly reduce surface plastics but are challenged by plastic fragmentation and drift, which complicates capture and removal (Lebreton et al., 2017).

Autonomous devices, including drones and robots, have emerged as effective tools for localized plastic collection (Rojas, 2018). These autonomous devices demonstrate diverse approaches to collecting ocean plastic, from river interceptors (Fig. 4b) to multi-robot systems. They highlight the growing reliance on AI, autonomous navigation, and sustainable energy sources in tackling marine pollution. Autonomous vehicles, such as the WasteShark, have demonstrated efficacy in collecting floating debris from surface waters near coastlines and harbors (Casoli and Ramkumar, 2020). These technologies provide an adaptable solution but are mostly limited to calm waters and require regular maintenance to sustain functionality. Autonomous devices are already being developed for collecting debris from the sea floor, for example, in the Horizon 2020 funded project SeaClear.

Semi-autonomous devices can function like a floating trash cans in marinas, ports, and calm coastal areas. They use a pump to create a water flow that draws in floating debris, which is collected in a removable bucket. Operators need to empty the device periodically and ensure it's functioning correctly. These floating trash cans, such as the PortBin, developed by the Norwegian company SpillTech, need an electricity connection, which limits the operability to shore areas (Haug, 2024).

Other semi-autonomous technologies are vessels or drones designed to operate in rivers and nearshore environments to collect floating waste. These vehicles can scoop of or trap plastic waste and return it to collection areas. While these technologies are capable of performing some tasks autonomously, they typically require remote control and manual intervention for positioning and emptying the collected debris (Kamarudin et al., 2021).

3.2. Recovery and Collection from Shorelines

Plastic accumulation on shorelines has facilitated the development of both manual and mechanized retrieval methods.

Manual cleanups remain widespread due to their low cost and community engagement benefits (Testa, 2018). These efforts, coordinated by NGOs and government agencies, are highly effective at removing visible macroplastics from shorelines but are time-intensive and limited by human resources. Studies show that while manual cleanups are effective for large debris, they rarely address microplastic particles, which remain embedded in sand (Haseler et al., 2020).

Mechanical beach cleaners use rakes and sieves to remove larger plastic debris efficiently (Zielinski et al., 2019). While these machines can cover extensive shoreline areas in shorter timeframes, they pose risks to coastal ecosystems, potentially disturbing habitats and wildlife. Additionally, mechanical cleaners are limited in effectiveness when dealing with microplastics, which most often evade conventional sieve mechanisms (Ahmed et al., 2022).

Emerging robotics, such as BeBot from Searial Cleaners, have been designed to autonomously patrol and clean shorelines, distinguishing plastic waste from natural materials using sensors and artificial intelligence (Ichimura and Nakajima, 2016). These robots offer promise for reducing human labor requirements and mitigating environmental impact. However, technological limitations in object recognition and high operational costs constrain their widespread adoption and these technologies are currently mainly prototypes.

3.3. Recovery and Collection from Rivers

Rivers contribute significantly to marine plastic pollution by carrying waste from urban and rural areas into oceans. Interception at the river level has proven effective in reducing downstream pollution (Lebreton et al., 2017).

Barge-based interception technologies, such as The Interceptor (The OCEANCLEANUP) or Trash Trawl (SpillTech), utilize floating barriers to funnel plastics toward a centralized collection system (Sugianto et al., 2023). These systems operate effectively in slow-flowing rivers, although rapid flow and debris clogging present significant challenges. Studies show that barriers are effective in intercepting macroplastics but less efficient in handling microplastics or dispersed waste (Schmaltz et al., 2020).

Trash traps and floating booms are widely utilized for intercepting plastic waste in river systems, particularly in urban areas (Vriend et al., 2020) (Fig. 4 a,c). While booms provide a passive solution to guide
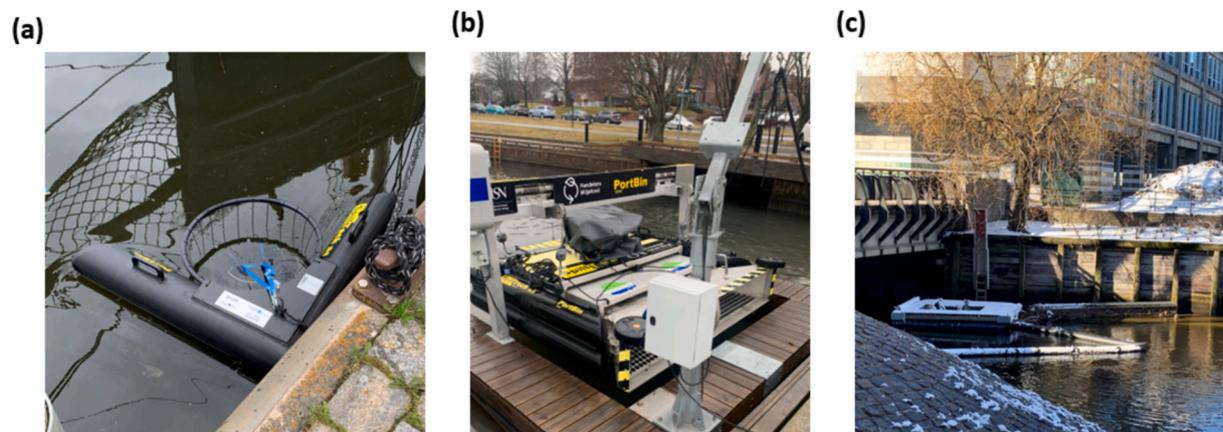

Fig. 4. Images of various riverine litter collection methods: (a) port bin; (b) drone; (c) litter boom. All photos are from a private collection, made by M.-M. Narra.

plastics toward collection points, they require regular cleaning and may be disrupted by adverse weather or water flow changes (Vriend et al., 2020). Floating boom systems are particularly effective in capturing larger plastic items but less efficient at collecting small particles.

Bubble Barriers represent an innovative solution that directs floating debris using a wall of air bubbles (Zhang et al., 2022). Bubble barriers allow plastics to be concentrated for collection while minimizing impacts on fish and other aquatic life. Though effective in calm waters, bubble barriers face difficulties in highly turbulent environments and present challenges related to energy use and deployment costs.

Despite technological advancements, numerous challenges remain that hinder effective marine plastic recovery. Most recovery systems target macroplastics, with significant limitations in capturing smaller microplastic particles. Existing skimming and filtration technologies struggle to effectively retain particles below a certain size (Hartmann et al., 2019). Additionally, limited efficiency in identifying plastics mixed with other materials contributes to operational inefficiencies. Mechanical and automated systems often inadvertently disturb marine life and ecosystems. For example, beach-cleaning machines can alter coastal habitats, impacting nesting sites for birds and marine life (Ahmed et al., 2022). Additionally, ocean-based collection systems risk entangling small marine animals, particularly in high-density collection areas (Galgani et al., 2019). Many collection systems, especially autonomous devices and riverine barriers, incur high operational costs that limit scalability. Maintenance requirements, particularly in high-traffic regions, represent significant logistical and financial burdens (Schmaltz et al., 2020). Furthermore, the frequent need for skilled labor to manage and maintain these systems is a recurring cost that limits long-term sustainability. The dispersal of plastic waste over vast oceanic areas complicates centralized collection efforts (Cózar et al., 2017). In river systems, logistical challenges include hindering ship traffic, accessibility to collection sites, and infrastructure for disposal or recycling (Sugianto et al., 2023).

4. Pre-Treatment and Cleaning of Collected Plastics

It is important to note, that effective cleaning and decontamination are crucial steps in the recycling process, ensuring that recovered plastic waste is suitable for reuse and manufacturing. The cleaning process typically involves several key stages. Collected plastic waste is first sorted to separate different polymer types and remove non-plastic materials (Williams-Wynn and Naidoo, 2020). Large debris, such as metals and glass, is manually or mechanically filtered out (Kurniawan et al., 2021). After that, plastic waste undergoes an initial rinse to remove surface dirt, sand, and loose contaminants. The method, type, and sequence of the pre-treatment steps vary depending on the primary waste treatment process. However, there are only a few scientific reports specifically addressing marine plastic litter clean-up pathways. Most research focuses on plastic litter processing and recycling, occasionally providing methodologies for pretreatment. On the other hand, there are many reports on marine microplastic extraction methods, which deal with plastic contamination in complex matrices like fish tissue, biofilm, and sediment. These methods not only help in effectively removing persistent contaminants but also assess the impact of cleaning processes on plastic integrity, ensuring they do not cause degradation or alter the sample's properties. Thus, we decided to review that information as it can be useful also for bigger plastic samples.

The effectiveness of chemical cleaning depends highly on the type of contamination present on the plastic sample. For marine-based plastic litter, the presence of organic matter is the biggest issue (Iñiguez et al., 2016). One commonly used approach for eliminating organics from microplastics from sludge is oxidation with hydrogen peroxide (H_2O_2) (Sujathan et al., 2017; Avio et al., 2015). However, the effectiveness of H_2O_2 has been questioned. Nuelle et al. (Nuelle et al., 2014) found that using 35% H_2O_2 for a prolonged exposure period of 7 days led to the removal of only 25% of the biological material present. The remaining biogenic material was bleached, which the authors highlighted as a potential issue that could complicate the isolation of microplastics. Additionally, the authors noted that H_2O_2 can degrade certain polymers, such as polyethylene (PE) and polypropylene (PP). They also observed several visible changes in some polymers, including the formation of gas bubbles, indicating a chemical reaction between H_2O_2 and the polymers. A potential alternative to H_2O_2 that can be used for oxidative processes is Fenton's reagent. It is used in chemical oxidation processes to generate hydroxyl radicals ($\bullet OH$), which are highly reactive and capable of degrading organic compounds, including pollutants and contaminants, which are typically recalcitrant in H_2O_2 (Pignatello et al., 2006). Hurley et al. (2018) established organic matter removal efficiencies for the test sludge and soil samples, identifying Fenton's reagent as the most effective protocol. In contrast, all other methods either resulted in particle degradation or were insufficient in reducing organic matter content. Additionally, the reaction proceeds much faster, often requiring

Table 1
Common cleaning agents and their general function

Type	Reagent	General functions	Key benefits	Main drawbacks	Extraction Efficiency	Ref.
Acids	HCl, HNO$_3$	pH regulation, dissolution of inorganic precipitates, acidic hydrolysis of macromolecules	Effective in removing mineral deposits and inorganic scale	Can cause corrosion, hazardous handling requirements	4% - 83%	(Avio et al., 2015; Dehaut et al., 2016; Cole et al., 2014)
Alkalis	NaOH, KOH	pH regulation, alteration of surface charges, alkaline hydrolysis of proteins, catalysing saponification of fats	Efficient in breaking down organic matter, grease, and proteins	Potential polymer degradation, safety hazards	57% - 99%	(Mintenig et al., 2017; Dehaut et al., 2016)
Oxidants	H$_2$O$_2$, Fenton's reagent	oxidation of organics, disinfection	Strong disinfectant, effective in organic matter breakdown	Can degrade certain polymers, requires controlled handling	25% -87%	(Sujathan et al., 2017; Avio et al., 2015)
Surfactants	SDS, Triton X-100, ECOSurf	dispersion/suspension of deposits	Enhances solubilization of hydrophobic substances, reduces fouling	Potential environmental toxicity, residual contamination	nd	(Hänninen et al., 2021)
Organic solvents	Isopropanol, Ethanol, Acetone, Methanol,	Solubilizing hydrophobic compounds, extraction of lipids and organic materials	less destructive cleaning methods over chemical manipulation with acids and strong solvents for green chemistry reasons	Toxicity, environmental hazards, solvent evaporation	nd	(Jung et al., 2018)
Enzymes	Proteases, lipases	catalysing lysis of various substrates	Highly specific, biodegradable, effective at mild conditions	Limited substrate range, costlier than chemical alternatives, requires complex procedure	89% - 97%	(Mintenig et al., 2017; Cole et al., 2014)

less than an hour to treat wastewater samples. Other potential methods for removing organic matter are derived from existing studies on extracting microplastics from biota. Acidic digestion using hydrochloric acid and nitric acid has proven highly effective in breaking down organic material from marine samples, thus facilitating cleaning of plastic particles (Avio et al., 2015; Dehaut et al., 2016). However, this method has also been suggested to partially degrade polymers with a low pH tolerance, such as polyammide and polystyrene, thus, its application is limited (Claessens et al., 2013). In fact, Avio et al. (2015) reported that the acidic extraction of spiked gastrointestinal tracts, caused a marked dissolution of both polyethylene and polystyrene tested particles, resulting in an extraction yield of only 4%. Therefore, this procedure must be carefully tested, with particular emphasis on evaluating the integrity of the plastic structure after the washing process. As an alternative, Cole et al. (2014) proposed the use of low concentration non-oxidizing acid HCl at room temperature, but it turned out to be inconsistent and inefficient for digesting plankton. Another approach is alkaline hydrolysis, which utilizes strong bases (e.g., potassium hydroxide (KOH) and sodium hydroxide (NaOH)). Mintenig et al. (2017) successfully employed a heated 10 M NaOH solution to remove organic material from sewage sludge plastic samples. In addition, Dehaut et al. (2016) proposed a protocol using a 10% KOH solution with incubation at 60°C for 24 hours as an effective method for extracting and characterizing microplastics from seafood tissues. This protocol successfully digested mussel tissues, leaving no visible residues in the digestate, which facilitated efficient filtration. Among the tested methods, this approach appeared the most promising, as it minimized the degradation of plastic polymers, with the exception of cellulose acetate (CA). Notably, CA, a polymer derived from cellulose, exhibits a higher potential for environmental degradation, which may explain its susceptibility to KOH treatment. However, a similar procedure using 10 M NaOH instead of 10% KOH appeared to be less promising, since it led to significant PET degradation and hindered polymer identification.

Surfactants are another important class of cleaning agents used in plastic recycling, effective at removing organic contaminants like oils, grease, and biofilms. By reducing surface tension, they promote the detachment and breakdown of residues, aiding in the preparation of plastics for further processing. Hänninen et al. (2021) found SDS to be an efficient reagent for digesting organic materials without causing decomposition of the microplastics. However, plastics must be immersed in the SDS solution for several weeks to effectively separate them from the waxes on seaweed surfaces. On the downside, surfactants like SDS can interact with eukaryotic cell membranes, potentially causing biological damage, especially at high concentrations (Abu-Ghunmi et al., 2014). Finally, enzymatic digestion has been used in several studies to remove organic matter from plastics. Cole et al. (2014) demonstrated the use of proteinase K for extracting microplastics from seawater. The optimized enzymatic protocol digested 97% (by weight) of organic matter in plankton-rich seawater without damaging microplastics. However, it was limited to small sample sizes (0.2 g dry weight) and depended on proteinase K, a costly enzyme, making it unsuitable for large, high-organic-content samples. Additionally, the complexity of organic compounds likely requires multiple enzymes for complete degradation. Following this, Mintenig et al. (2017) applied an enzymatic-based procedure to extract microplastics from wastewater samples, using protease, lipase, and cellulase, enzymes that are less expensive than proteinase K. While the use of less expensive enzymes is advantageous, the method's duration of over six days represents a significant drawback for large-scale or time-sensitive applications. Prolonged treatment times may also increase the likelihood of microplastic degradation or loss, raising concerns about the integrity of recovered particles.

Based on the literature study, we summarized cleaning agents into six main types, as outlined in Table 1. The broad range of extraction efficiencies observed in this study can be attributed to several critical factors, primarily the variability in reagent concentration, temperature, plastic type, and the composition of the organic material targeted for removal. Firstly, reagent concentration plays a significant role in influencing extraction outcomes. Higher concentrations of acids, alkalis, or oxidants typically promote more aggressive chemical interactions, enhancing hydrolysis, oxidation, or solubilization processes. However, overly concentrated reagents may also lead to undesirable effects such as polymer degradation or non-selective reactions, thereby impacting the specificity and reproducibility of extraction. Secondly, different polymers possess varying chemical resistance, surface energy, and porosity, all of which influence how readily contaminants are desorbed or degraded. Finally, organic contaminants can range from relatively labile substances like proteins and lipids to more recalcitrant compounds such as humic acids or biofilm matrices. The chemical nature of these substances determines their susceptibility to specific treatments.

Extraction efficiency varied due to differences in reagent concentration, temperature, plastic type, and organic contaminant composition. Higher reagent concentrations enhance removal but may damage polymers. Secondly, different polymers possess varying chemical resistance, surface energy, and porosity, all of which influence how readily contaminants are desorbed or degraded. Finally, organic contaminants can range from relatively labile substances like proteins and lipids to more recalcitrant compounds such as humic acids or biofilm matrices. The chemical nature of these substances determines their susceptibility to specific treatments.

5. Recycling and reprocessing pathways for ocean-bound plastics

From the waste management perspective, the following options can be proposed for marine plastic waste: upcycling, reuse, mechanical recycling, solvent-based extraction, chemical recycling, energy recovery and the emerging option of biodegradation (including enzymatic or photodegradation). These approaches are consistent with the waste hierarchy proposed in the Waste Framework Directive, which outlines the preferred order of waste treatment: (1) prevention, (2) reuse, (3) recycling, (4) other recoveries, and (5) disposal. Fig. 5 illustrates the main recycling types that are proposed for marine plastic waste. Table 2 provides a summary of different recycling options proposed in the literature for marine waste. However, possible degradation must be taken into account as it influences the type of recycling process the materials can undergo.

5.1. Degradation of ocean-bound plastic waste

Degradation occurs when the plastic items remain in the water for longer periods and are subjected to mechanical forces from waves or wind, UV radiation, oxidation, and biofouling. Additionally, the leaching of chemical additives such as plasticizers, flame retardants from the polymeric chains is influenced by external factors, which modify the material properties (Ibrahim et al., 2024; Râpă et al., 2024). Usually, photooxidation initiated by UV-B radiation (280-390 nm) degrades plastic, beginning on the outer surface. Chemical weathering alters polymers by reducing molecular weight, introducing oxygen-rich groups, breaking bonds, and causing chemical changes (Manzoor et al., 2022). PE and PP from the Great Pacific Garbage Patch showed crosslinking, oxidation, and chain scission; some oxidized samples also had microbial adhesion, potentially aiding biodegradation (Pelegrini et al., 2019). Artificial marine weathering studies report weakened mechanical and thermal properties, increased rigidity, and visible surface damage such as cracks, flakes, and oxidation (Iñiguez et al., 2018). Such degradation limits mechanical recycling, as the recycled material often lacks the quality to replace virgin plastics. When appearance matters, processing becomes even harder. Chemical recycling or energy recovery may be more suitable.

To assess degradation level of plastics, various techniques evaluating chemical composition, appearance, physicochemical, and mechanical properties are being used (Chamas et al., 2020; Zhang et al., 2021).
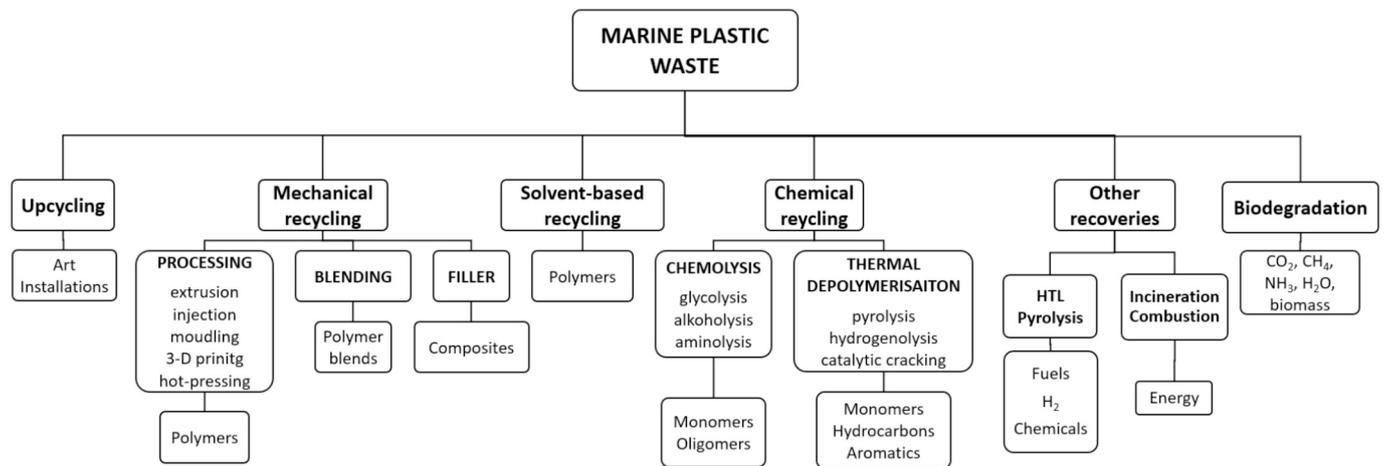
Fig. 5. Options for the management of marine plastic waste

Degradation causes a reduction of average molecular weight, commonly measured via gel permeation chromatography (GPC), viscometry, or light scattering (Ojeda et al., 2011). However, GPC requires the polymer to be dissolved in a carrier solvent, which for polyolefins requires high temperatures, which brings concern about their further degradation. Chemical changes are often assessed by infrared (IR), Raman, and nuclear magnetic resonance (NMR) spectroscopy, which can detect the presence and concentration of various functional groups in polymers (Hoshino et al., 2002). Oxidation of plastic leads to changes in the surface density of polar functional groups and surface energy, measured by the contact angle with liquids (Fotopoulou and Karapanagioti, 2015). Furthermore, degradation modifies color, surface texture, and creates cracks, pits, and grooves that can be examined using optical, scanning electron, or atomic force microscopy (Bläsing and Amelung, 2018). Another good indicator of plastic degradation is its crystallinity, influencing rigidity and melting temperature, which are determined by X-Ray diffraction (XRD) or differential scanning calorimetry (DSC) (Bläsing and Amelung, 2018). Recently, Ronkay et al. (2025) proposed an analytical approach based on DSC to evaluate the extent of riverine PET degradation and to determine suitable recycling pathways. They established a correlation between the melting temperature of subpeak no. 5 and the estimated molecular weight, thereby enabling quantitative assessment of the material's degradation level. Thermogravimetric analysis measures mass changes that occur during heating. When combined with product analysis, it provides insights into the nature of decomposition processes, such as oxidation or the loss of volatile compounds, during thermal degradation (Peñalver et al., 2020). Surface cracking and pore formation as well as reductions in molecular weight directly affect the mechanical properties of material. Tensile, shear, and elastic properties, critical for application, are measured using standard stress-strain methods (Arhant et al., 2019). Finally, mass loss, measured directly or via total organic carbon, reflects degradation but may include additive leaching (Oberbeckmann and Labrenz, 2025). However, conventional plastics degrade slowly, requiring long-term studies.

5.2. Reuse approaches

Reuse is an ideal waste management strategy because it consumes less energy and fewer resources. After the cleaning process, the product should ideally be returned to its primary application. This method is often applicable for glass bottles, but they are typically collected after use and are not contaminated like plastics floating in the rivers, which may absorb pollutants. However, the concept of reuse is most effective at the point of use, eg, refilling the same soap bottles instead of discarding them (Datta and Kopczyńska, 2016). Nevertheless, such situations are rare, specifically for collected marine waste, as many products are

broken, crashed, or defective in some ways. Therefore, alternative management strategies should be considered.

5.3. Upcycling options

Upcycling is a creative approach of repurposing waste materials into entirely new products, very often done by artists, architects, fashion makers and scientists. The main goal of upcycling is not necessarily practicality or durability but rather to be an interesting form, catching the eye or transferring an important message (Fig. 6). For instance, the Kenya Marine Conservation Organization-Ocean Sole (Oceansole, 2025), promotes beach environmental protection by encouraging local people to recycle used slippers, by processing them into toys and handicrafts (Luo and Deng, 2021). Various artists such as Aurora Robson, Marina DeBris, Cindy Pease Roe, or Christine Lew (founder of NPO "UpSculpt"), working as environmental artist, transform plastic litter into installations, paintings, collages or clothes and accessories (referred to as "trashion"). Similarly, brands like ORSKA, in cooperation with the MARE foundation, upcycle ghost nets collected from the sea into commercially available pins or earrings (ORSKA, 2025). While these initiatives are innovative and impactful in raising awareness, they cannot address the vast amount of plastic waste generated each year. However, it conveys a clear message to the society.

5.4. Mechanical recycling methods

Mechanical recycling, the preferred option for marine waste, reprocesses materials into pellets, composites, or products through physical methods like grinding, drying, and mixing, without altering polymer structure. Common techniques include injection molding, extrusion, hot pressing, and 3D printing (Ragaert et al., 2017). This process is suitable for a single type of plastic or when waste is separated by type, mostly applicable for thermoplastics such as polyolefins, PET, etc. Particularly, "ghost" nets have the potential for mechanical recycling, since they are homogeneous polymers. Nylon (PA 6) was successfully recovered via extrusion from waste nets collected from the Basque Country ports. The recovered polymer exhibited mechanical properties similar to the commercial variant, although viscosity and molar mass were slightly decreased (Mondragon et al., 2020). Similar findings were reported by Ferrari et al. (2020), who observed that 3-D printed objects from sea-collected PET bottles exhibited lower thermal and mechanical properties after several reprocessing cycles. In the work of Ronkay et al. (2021) PE and PET recovered from simulated marine conditions were successfully reprocessed into 3D-printed objects, though PET exhibited reduced transparency and mechanical properties. On the other hand, Pelegrini et al. (2019) assessed the degradation levels of ocean-collected PE and

Table 2
Recycling processes of marine plastic reported in the literature.

Product waste/ Plastic type	Origin	Pprocess, reaction	Operations and conditions	Resulting Product/ monomer	Ref.
			MECHANICAL RECYCLING PROCESSES		
PE, PET	Modelled a marine environment for 3-4 years in ocean	Extrusion, injection moulding, 3D printing and thermoforming	Drying → extrusion (PET: 240–270°C) or 3D printing (300°C) or injection moulding (260–275°C) orthermoforming (100°C)	PE products with good properties,;PET products with reduced mechanical properties and transparency	(Ronkay et al., 2021)
PA66/ Nets	Ports along the Atlantic coast	3D printing	Cleaning → shredding → drying → extrusion → pelletizing → drying → filamentation → drying → 3D printing	3D printed PA66 objects	(Cañado et al., 2022)
PET/ Bottles	Italian Ionian coast	3D printng	Washing → milling → drying at 70°C → extrusion (220–280°C, 10 rpm) → 3D printing (250°C)	3D-printed PET objects	(Ferrari et al., 2020)
PE, PP/ Plastic fragments	Great Pacific Garbage Patch	Injection moulding	Cleaning (water + detergent) → drying at 60°C (48 h) → grinding → density separation (alcohol solution, 0.91 g/cm^3) → drying at 60°C → extrusion (170–180°C) → injection moulding (180–170°C)	Test samples from PE and PP	(Pelegrini et al., 2019)
PET, EPS/ Microplastics	Model environment	Reuse as a filler	Washing → grinding → drying → sol-gel addition → crosslinking → freeze-drying	Filler forthermal and acoustic insulating foams	(Caniato et al., 2021)
PA,PET,PP,PE,PVC/ Nets, rope, household items	Coastal area in Busan, Korea	Pulverizing	Collection → sorting → shredding → grinding → freezing → low-temp pulverizing (223 K) → dechlorination	Pulverized particles of 2-4 mm size	(Lee et al., 2021)
PA6/ Nets	Hokkaido, Japan	Reinforcing fibres	Cutting (20–40 mm) → washing → drying → mixing with mortar → curing (28 days)	Composites with cement and sand for mortar	(Orasutthikul et al., 2017)
PA6/ Fishing nets	Ports of Basque Country, Spain	Extrusion	Washing → cutting into pellets → drying (80°C) → extrusion (250–265°C) → cutting to yarn	Pellet and granules of PA	(Mondragon et al., 2020)
PE/ Fishing Net	Nets collected from the ocean by Plastix	Filler in composite	Pre-washing → mechanical cutting into short fibres	Filler reinforcement in gypsum-based material, composite (up to 2%)	(Bertelsen and Ottosen, 2022)
PE, PP/ Plastic objects	Coast of the Latium Region, Italy	Blending by injection moulding	Washing → drying at 65°C (12 h) → grinding → injection moulding (160–170°C)	Polymer blends samples, mixed waste or waste with HDPE	(Pietrelli et al., 2017)
PA 66/ Nets	Naples Port, Italy	Filler in composite	Grinding → cold mixing (RT, EPS/ABS in acetone) → drying → pelletizing → compression moulding (200°C, 5 min, 50 bar) or cutting → dissolving EPS/ABS → layering → compression moulding (200°C, 5 min, 50 bar)	Filler (40-80 wt.%) in composite with EPS or ABS matrices	(Liotta et al., 2023)
HDPE, PP/ prepared pellet	Provided by Oceanworks	Compounding Polymer blending	Mixing with virgin polymers (200–240°C) → pelletizing → 3D printing (270°C)	Polymer blends or copolymers; LDPE (33%)-HDPE (33%)-PP (33%); LDPE (30%)-PP (30%)-HDPE (30%)-clay (10%); LDPE-PP-HDPE-EPR (25%)	(Martey et al., 2022)
HDPE, LDPE,PP, PET/ Marine plastic	Cávado River, Portugal	Simulated compounding Polymer blending	Cleaning of plastic→drying→grounding→extrusion (180-260°C)→compresion moulding (270°C, 7.7MPa, 5 min)	Polymer blends: HDPE (42%)-LDPE (13%)-PET (25%)-PP (20%)-MA (2-10%)	(Piedade Cestari et al., 2024)
PE/ Fishing nets	Dalpo Port, Ulsan, Republic of Korea	Filler in composites	Cleaning → drying → cutting → mixing with cement/silica/quartz → add plasticizer → add fibres → curing	Fiber reinforcement in cementitious composites	(Pae et al., 2022)
PA/Ffishng nets	Port of Ribadesella, Spian	Filler in asphalt binder	Grounding→ incorporation into asphalt binder	Reinforced asphalt	(Movilla-Quesada et al., 2025)
PP, PE/ Fishing ropes	Magdalen Islands, Canda	Blending	Sorting →shredding→extrusion →pelletization→second extrusion (180-190°C), →injection molding(450 bar)	Wall cladding panels	(Belmokhtar et al., 2024)
PA	Quebec, Canada	Mixing, injection molding	Cutting→extrustion→pelletization→second extrusion→→injection molding (450 bar)	Composite PA with 20% of switchgrass	(Belmokhtar et al., 2025)
			SOLVENT-BASED RECYCLING		
PE, PP/ Pellets	Teluk Batik, Perak, Malaysia	Solvent extraction	Dissolution in acetone-toluene (HDPE: 75°C, 20 min; PP: 90°C, 30 min) → reprecipitation in acetone → drying (100°C, 20 h)	Clean PE, PP	(Ibrahim et al., 2023)
PA	Artifical seawater, model	Dissolution	Dissolution in formic acid and cosolvent (e.g. dichloromethane) (RT, 0.1-1h)	Clean PA	(Tanks and Tamura, 2025)
			CHEMICAL RECYCLING		
PE, PP, PET/ Packaging, bags, utensils, straws	Singapore seashore	Pyrolysis	Sorting → drying → shredding → pyrolysis (600°C, N$_2$) → CVD (Ni-Ca catalyst, 600°C)	Pyrolysis oil, Multi-walled carbon nanotubes	(Veksha et al., 2022)

Table 2 (*continued*)

Product waste/ Plastic type	Origin	Pprocess, reaction	Operations and conditions	Resulting Product/ monomer	Ref.
PET/ Bottles	Coast of the Basque Country, Spain	Glybolysis	Glycolysis with EG (220°C, 3 bar, 1000–1200 rpm, PET/EG = 1/3, 1% zinc acetate catalyst)	BHET, ogliomers	(Mendiburu-Valor et al., 2022)
PA	Model	Solvolysis	Acidolysis with HCL (100°C, 4h, PA:HCL=1:11)→ neutralization with NaOH→centrigfugantion→washing with water and supernatant with t-butanol→drying	Monomers (aminocaproic acid, caprolactam), oligomers, PA with 10% of recycled content	(Gama et al., 2024)
Mixed; plastic containers, bottles, nets,	Venice Lagoon and North Adriatic Sea	Pyrolysis	Reaction (400°C, 4 h, autogenic pressure) → distillation (180°C: light, 320°C: MGO, >320°C resuidal)	2,4-dimethyl-1-heptene, hexane, BTX, alkenes, cycloalkenes, MGO	(Faussone and Cecchi, 2022)
PA6/ Fishing nets	Beach near Buan County, Korea.	Thermocatalytic conversion	Cutting (20–25 mm) → thermocatalytic conversion (500°C, 1 min, N₂ and CO₂, seashell catalyst)	Monomer - caprolactam	(Kim et al., 2022)
PET, PP, HPDE, PS , PUR/ 3D plastics, nets	Sylt and Norderney, North Sea, Germany	Pyrolysis	Pyrolysis (700°C, 30 min) → condensation	Pyrolysis condensate	(Hee et al., 2021)
PP, PE/ Caps, bottles, nets, ropes, containers, toothbrushes	North Pacific Garage Patch	HTL	HTL (450–480°C, 250–275 bar, 45–60% plastic loading)	Synthetic crude oil:70 % paraffis and 10 % olefins, with 20 % of diverse aromatics	(dos Passos et al., 2024)
PA6/ Fishing net	nd	Cyclodepolymerization	Reaction (240°C, 30 -180 min, 0.2-1 mol% catalyst loading : yttrium ansa-metallocene)	ε-caprolactam	(Fieser and Knight, 2024)
OTHER RECOVERY TECHNIQUES					
PP, PE	Model marine plastic feedstock	HTL	HTL(400°C, 250–300 bar, 60 min)	85% oil No solid by-products	(Belden et al., 2021)
HDPE	OPW, Envision Plastics	HTL	HTL (450–475°C, 2–4 h)	78% oil of energy 41.4–43.2 MJ/kg Composition: 60% aromatic hydrocarbons , 20-25% parraffins, 5-10% olefins, 5-10% cyclic hydrocarbons	(Lu et al., 2022)
PS	Artificial seawater, model	Pyrolysis	Pryolysis (500-700°C; p:1-4 MPa, N₂)	Oil 70-97%,; calorific value 31.8 - 42.1 MJ/kg	(Gao et al., 2024)
HDPE, PP/ Mixed marine plastic waste	Venice Lagoon, Italy	Pryolysis	Pyrolysis (400°C) → CaO additive → distillation →steaming (820-880°C)	Hydrocarbons C₄ ~61.5-66.0%; C₅₋₉ ~27.5-31.9; BTX ~15.7-17.9%	(Kusenberg et al., 2022)
Mixed marine plastic waste	North Adriatic Sea, Italy	Pyrolysis	Pyrolysis (450°C, 4 h) → CaO additive → distillation (170°C: light, 320°C: MGO)	MGO compliant with ISO8217 DMA (51.5%); Intermediate Fuel Oil (5.9%); VN (23.5%)	(Faussone et al., 2021)
Polyolefins, PA/ Mixed marine plastic waste	Venice Lagoon, Italy	Pyrolysis	Pyrolysis (400°C, 4 h) → CaO additive → distillation (180°C: light, 320°C: MGO)	MGO compliant with ISO 8217, viring naptha rich in BTX	(Faussone and Cecchi, 2022)
Marine waste (nets, buoys, ropes)	Wando County, South Korea	Pryolysis, combustion	Pyrolysis (500°C, 30 min) →liquid collection → fixed bed co-combustion (wood pellet)	RPR : 62.75% oil, 27.34% gas, and ~10% solid residues	(Park et al., 2023)
PE, PA/ Fishing gear	nd	Pyrolysis	Cleaning→drying →Pyrolysis (300°C, 320-345 min) →liquid collection	Pyroltic oil for addition to biodiesel (up to 10%)	(Nugroho et al., 2024)
Onboard waste collected	South Korea	Gasification	Pulverizing→microwave-assisted plasma gasification with Cu-Zn-Al catalyst →separaion and purification	H₂ of 99.99%, CO and CO₂	(Woo et al., 2024)
BIODEGRADATION					
HDPE	Coastal area of Gulf of Mannar, India	Biodegradation	Incubation (12 weeks, 30°C, 150 rpm) →-isolation by spread plate technique	Cracked surface of PE	(Sangeetha Devi et al., 2015)
PS	Coast of Xiamen Island, Thailand	Biodegradation	Incubation (45 days, 28°C, 150 rpm)→-centrifugation of supernatant	Weight loss by 18.9%	(Wang et al., 2025)

PP and found that, despite signs of degradation, the recycled materials still exhibited mechanical and rheological properties comparable to those of virgin materials. Similarly, recycled discarded fishing ropes, despite evident signs of photodegradation, could be repurposed into new products such as cladding panels (Belmokhtar et al., 2024). In another study, they (Belmokhtar et al., 2025) prepared composites from fishing nets (nylon 6) and switchgrass with potential application for the automotive sector. The preparation of such composites can help address the decline in mechanical and thermal properties that occurs when materials degrade in the marine environment. However, the recycling of these materials remains challenging; therefore, the targeted applications should have a longer service life. Interestingly, the LCA of nylon fishing

nets collected from the sea and processed via 3-D printing into new products showed that recycling of such marine waste is environmentally preferred over the use of virgin biobased plastic, such as bio-PA, PLA or PHB, by a factor of 3.7 fold (Cañado et al., 2022). As shown in Table 3 recycled polymers, recovered from marine sources, generally retain comparable tensile strength and elasticity to virgin materials, though parameters such as transparency, viscosity, and crystallinity tend to decline. Overall, this demonstrates that mechanical recycling remains a technically feasible and environmentally advantageous strategy for valorizing homogeneous marine plastic waste. However, mechanical recycling is not recommended when materials exhibit chemical aging, contamination with undesirable substances, or the presence of pigments. Also, it is important to note that each recycling cycle diminishes the mechanical and thermal properties; therefore, when the next recycling cycle is not possible, other management options should be considered.

Material recycling also includes blending and compounding, where plastics are mixed or used as fillers in composites. Blending helps preserve material quality despite the lower quality of marine litter, though most polymers are immiscible when melted, often resulting in altered morphology and weaker mechanical properties. Pietrelli et al. (2017) managed to obtain polymer blends of coastal PE and PP via injection molding, although with somewhat diminished mechanical performance. To counteract this issue, compatibilizers such as block or graft copolymers, polymers with polar groups like PCL, or functionalized polymers (e.g., PP grafted with maleic anhydride) are used (Dorigato, 2021; Rodrigues et al., 2025). Such a solution was applied by Piedade Cestari et al. (2024) which used maleic anhydride to improve miscibility between PET and PP. Martey et al. (2022) developed blends of improved elasticity from virgin PP with ocean-bound PP and HDPE by using ethylene-propylene rubber (EPR) as stabilizer.

Recycled PE from fishing nets, in the form of fibers, was used as a filler in gypsum-based materials up to 2 wt.%, significantly improving the post-crack performance, although some reduction was observed (Bertelsen and Ottosen, 2022). Another study demonstrated that polyamide-based fibrous filler at 60% content improved the mechanical properties of expanded polystyrene (EPS). In laminates, good adhesion between fibers and the matrix is crucial for overall performance (Liotta et al., 2023) In the work of Orasutthikul et al. (2017), different fiber types were evaluated, and straight nylon fibers improved flexural

Fig. 6. Examples of upcycled ocean-bound plastics: (a) Fish- art installation/ sculpture made from ocean plastic by Cindy Pease Roe (Reproduced with - permission of Cindy Pease Roe (Cindy Pease Roe, 2025); (b) Round pin with amber from the Baltica collection made by ORSKA with MARE foundation. Reproduced with permission of ORSKA (ORSKA, 2025); (c) Turtle- Flip Flop Sculpture made by Kenyan artists (Oceansole, reproduced with permission of Oceansole (Oceansole, 2025).

strength by up to 41% compared to knotted R-Nylon, recycled PET, and PVA fibers. An interesting approach was proposed by Caniato et al. (2021) in which microplastics were used as a filler in biobased foams, resulting in enhanced acoustic and thermal properties. This demonstrates a simple utilization route for microplastics, which are typically composed of mixed polymer types and collected in small quantities, factors that often limit their suitability for large scale solutions such as mechanical recycling.
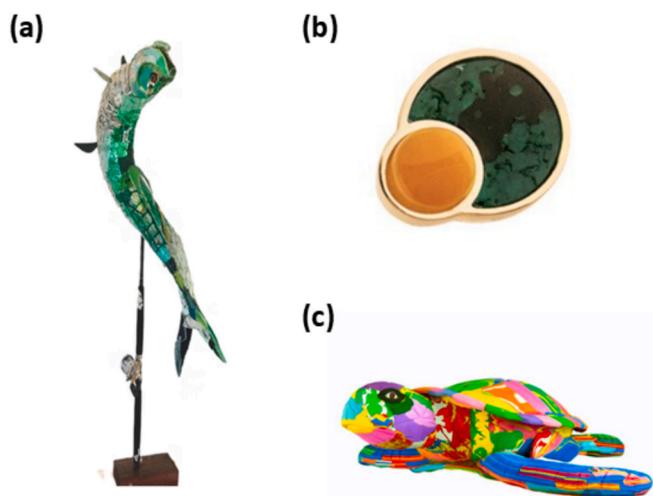
5.5. Solvent-based recycling

For homogeneous and single types of waste, an interesting approach is a semi-chemical one, namely, solvent-based recycling. This method requires the use of solvents in which the collected materials are soluble, allowing the polymer to be separated from additives, dyes, and contaminants through purification steps such as centrifugation, filtration, or phase extraction. Subsequently, selective crystallization may occur and clean polymer is recovered (Sherwood, 2020). This method is usually applied to PVC, PS, and polyolefins. Also, it can be applied to some extent to mixed plastic waste, using a sequence of different types of solvents (Zhao et al., 2018). Increasing dissolution time and temperature significantly improves polymer recovery rates. However, this also depends on the specific polymer type. For example, high recovery rates for HDPE were achieved at 75 °C for 20 minutes, whereas PP required 90 °C. This variation is related to the polymer structure as well as the microstructure of crystalline and amorphous phases (Ibrahim et al., 2023). To ensure high recovery rates while minimizing thermal degradation, the dissolution–reprecipitation process must be carefully controlled. When degradation is avoided, recycled marine plastics can retain properties comparable to those of virgin resins. For instance, Tanks and Tamura (2025) studied PA dissolutions in formic acid and cosolvent (eg, dichloromethane) under ambient conditions, achieving dissolution in less than one hour.

5.6. Chemical recycling technologies

When marine plastic is too degraded for reprocessing, chemical recycling offers a complementary option. It breaks down polymers into monomers or petrochemical fractions, altering their chemical structure (Vollmer et al., 2020). The recovered chemicals can be used to synthesize high-quality polymers (Datta et al., 2018; Jutrzenka Trzebiatowska et al., 2019) or intermediates used in other chemical processes (Karam et al., 2021; Saito et al., 2020).

The thermochemical recycling processes include pyrolysis, gasification, hydrogenolysis, and catalytic cracking, where the material is converted at high temperatures (>300°C) in an inert atmosphere or reactive gases (e.g. hydrogenolysis using H_2), often with high pressure and the presence of catalysts. These methods are suitable for polyolefins, PMMA, PTFE, acrylates, etc. (Hou et al., 2021; Jubinville et al., 2020). In contrast, solvolysis (chemolysis) reactions usually refer to depolymerization of polycondensation and polyaddition polymers such as PET, PC, PA, PU, PLC etc. (Ragaert et al., 2017). These reactions are performed under milder conditions but require specific cleaving agents (e.g., water, alcohol, acids, or amines) and often co-solvents for polymer dissolution, alongside catalysts. Methods include alcoholysis, hydrolysis, aminolysis, glycolysis, and other related techniques, named after their respective reagents (Jutrzenka Trzebiatowska, 2022; Ellis et al., 2021). For example, glycolysis of marine plastic bottles yielded bis(2-hydroxyethyl) terephthalate (BHET), comparable to virgin PET monomers. Interestingly, pre-existing PET degradation enhanced BHET monomer yield in glycolyzed samples (Mendiburu-Valor et al., 2022). Gama et al. (2024) carried out acidolysis of PA to obtain a mixture of monomers and oligomers, which was further processed to obtain PA with 10% recycled content. The chemical recycling approach enables repeated recycling of plastics since new polymers can be produced after each depolymerization cycle. In the literature, many papers focus on feedstock recycling

because the waste fraction is often composed of polyolefins (mainly PE or PP). Among various techniques, pyrolysis is the most widely used, typically yielding a C_4–C_{10} hydrocarbon fraction (Lopez et al., 2017). Hee et al. (2021) used thermochemical recycling, pyrolysis, and gasification, for treating heterogeneous and weathered marine plastic waste (including PET, PP, PE, PS, PUR) and obtained condensate which can be further processed to obtain valuable chemicals. An interesting approach involved chemical vapor deposition (CVD) of pyrolytic oil to obtain multi-walled carbon nanotubes (Veksha et al., 2022). In another work, thermocatalytic conversion yielded approx. 80% of the PA6 monomer caprolactam when a base catalyst derived from sea shells was used, whereas non-catalytic reactions yielded only 45% (Kim et al., 2022). The use of yttrium ansa-metallocene catalyst in solventless cyclo-depolymerization of nylon from fishing net allowed for over 90% recovery of caprolactam (Fieser and Knight, 2024).

5.7. Other recovery options

Innovative technologies such as pyrolysis and HTL allow efficient conversion of marine plastics waste into fuels and energy sources (Arena et al., 2023). HTL operates at temperatures ranging from 250–400 °C under high pressure (10–25 MPa) in the presence of water as a reaction medium. This process produces oil (crude), which can be further refined into transport fuels, as well as gas and char. Belden et al. (2021) proposed a conceptual solution based on HTL of PE:PP, integrated directly into a marine vessel, which yielded approximately 85% oil without solid by-products. The system became energy self-sufficient at above 12% plastic concentration (by volume). Lu et al. (2022) demonstrated that HTL of marine-based HDPE achieved oil yields exceeding 78 wt%, with negligible solid residue, with a high energy content (41.4–43.2 MJ/kg). Other studies confirmed HTL's effectiveness in converting HDPE and PP collected from the North Pacific into C_{10}–C_{20} paraffins, suitable for fuel use (dos Passos et al., 2024).

Although HTL is particularly well-suited for moist and heterogeneous feedstock such as directly recovered plastic waste from the sea, pyrolysis offers an alternative, especially when targeting the production of liquid fuels or intermediates. A pyrolytic oil obtained from fishing gear (PE, PA) can be added up to 10% to biodiesel with good engine performance (Nugroho et al., 2024). Faussone et al. (2021) obtained a condensate from medium-to-heavy pyrolysis products from seabed

plastic waste, which aligned with ISO 8217:2017 marine fuel standards, while a lighter fraction, rich in BTEX, styrene, and α-olefins, can be used as a potential petrochemical feedstock or fuel additive after purification (Faussone and Cecchi, 2022). Calorific value of pyrolysis oil depends on feedstock composition (Gao et al., 2024). Particularly, PET and PVC reduces oil quality, PET introduces acidic oxygenates like benzoic acid, and PVC forms harmful halogenated compounds; therefore, prior separation of collected materials is recommended to enhance the stability and purity of the pyrolytic oil (Kusenberg et al., 2022). The second major product of the pyrolysis process, is the gas fraction (Faussone et al., 2021; Faussone and Cecchi, 2022; Gao et al., 2024), rich in methane, pentane, and CO, with a high calorific value and can power micro-turbines or shipboard generators.

Beyond thermochemical methods, marine plastic waste is also being explored as a solid fuel in the form of Refuse Plastic Fuel (RPF) for energy recovery. Park et al. (2023) evaluated RPF pellets made from marine debris (nets, buoys, ropes), which produced ~63% oil, 27% gas, and 10% solids in a fixed-grate reactor. While standalone combustion led to airflow blockage due to melting, co-combustion with at least 20% biomass (e.g., wood pellets) stabilized the process. An interesting concept was presented by Woo et al. (2024), who proposed an integrated system for converting plastic waste into clean hydrogen with a purity of 99.99%, for use in fuel cells powering a vessel. Tashima et al. (2023) in turn, converted marine PET waste into an activated carbon with a very high specific surface area (2389 m^2/g) and high capacitance (201 F/g), suitable for use in supercapacitor electrodes for energy storage. It represents an innovative example of utilizing plastic waste in technologies supporting the energy transition.

5.8. Biodegradation

An environmentally friendly option is biodegradation, which would be particularly beneficial for waste already dispersed in marine environments, requiring minimal intervention. The material degradation is caused by environmental factors and biological agents, mainly enzymes produced by various microorganisms. Depending on the conditions, degradation should result in CO_2, H_2O, mineral salts, biomass, or CO_2, CH_4, inorganic salts, and biomass. Unfortunately, biodegradation usually applies only to a few petrochemical-based and naturally derived plastics (e.g., PLA, PHB, PCL) (Lee and Liew, 2021), while for polyolefins

Table 3

Comparison of physicochemical and mechanical properties of virgin and recycled polymers recovered from marine sources.

Polymer	Property	Virgin	Recycled	Ref.
PET	Transparency (%)	89±3	43±2	(Ronkay et al., 2025)
	TS (MPa)	52.2±0.8	51.9±1.6	
	IS (kJ/m^2)	4.4±0.5	2.8±0.5	
PA6	[η] (dL/g)	2.34±0.02	2.17±0.00	(Mondragon et al., 2020)
	M_w (g/mol)	41 511±460	36 731±118	
	χ (%)*	32	28	
	TS (MPa)	~68	~69	
PET	T_g (°C)	81	71	(Ferrari et al., 2020)
	$T_{95\%}$ loss (°C)	596.96	584.08	
	TS (MPa)	59.6±2.9	40.9±6.2	
PE	E (MPa)	740.0	698.3±94.3	(Pelegrini et al., 2019)
	ε (%)	7.2	7.2	
	MFI (g/10 min)	5.0	6.5±1.2	
PP	E (MPa)	1300.0	1036.9±34.3	
	ε (%)	10.0	6.9	
	MFI (g/10 min)	24.0	25.9±0.9	
mixed waste (41% PE, 37% PP)	E (MPa)	1316±131	694±189	(Pietrelli et al., 2017)
	TS (MPa)	20.5±1.5	17.3±1.7	
	ε (%)	622±206	480±245	
PET	TS (MPa)	58.6±3.5	54.5±4.2	(Ronkay et al., 2025)
	ε (%)	48±9	4±1	

*Calculated from DSC. Abbreviations: TS- tensile strength, IS- impact strength, [η] - Intrinsic viscosity, M_w – molecular weight, χ- crystallization degree, T_g- glass transition temperature; E- Young's modulus, ε- elongation at break, MFI- melt flow index.

the biodegradation is marginal (Oliveira et al., 2020). However, Wang et al. (2025) demonstrated that ocean-bound polystyrene (PS) underwent biodegradation, marked by the formation of new functional groups, surface erosion, and a weight loss of up to 18.9% over 45 days, when exposed to biofilms. These findings indicate early steps toward effective microbial biodegradation of marine plastics.

5.9. Industrial and commercial recycling applications

Besides the academic research, several industrial initiatives are already recycling marine plastic waste, primarily PET and PA from fishing nets. For instance, Plastix from Denmark reclaims end-of-life maritime gear, made of PPC, PE, PP and transforms them into new recyclates (Plastix, 2025). Seaqual® Yarns by Antex (Spain) are recycled PET from marine waste (Seaqual, 2025). Tide Ocean (Switzerland) mechanically recycles ocean-bound plastic, mostly PET, PE and PP, collected from the coastline in Thailand, Indonesia, and the Philippines converting them into pellets, yarns, and filaments for new products like reusable mugs (Tide Ocean, 2025). Ocean Parely Material is another recycled material derived from marine debris collected in the Maldives, the Dominican Republic, and Sri Lanka (Ocean Parley, 2025). Meanwhile, Aquafil developed ECONYL® Regeneration System, a chemical recycling process, to recycle nylon (polyamide 6) from marine plastic waste, fishing nets and textile fabric waste primarily for use in clothing and textiles (Econyl, 2025).

6. Conclusions and perspectives

Marine plastic pollution represents a persistent and complex environmental challenge, demanding a multidisciplinary approaches. This review examined the entire lifecycle of ocean-bound plastic waste, from its sources and environmental monitoring to advanced collection methods, cleaning, and recycling techniques.

The monitoring of marine litter is essential for understanding pollution sources, assessing the quantities, and evaluating mitigation efforts to prevent plastic from entering the sea. In addition, it provides a rough estimate of the types of waste that can be collected and potentially recycled later. The collection methods are still being developed, from manual clean-up to semi- or automated solutions. Significant development has been made for riverine systems through the use of booms, barges, or bubble barriers that block a large portion of plastics before they reach the sea. The valorization of marine plastic waste is possible through tailored methods, depending on the polymer type, its condition, and local capabilities. Mechanical recycling is widely used for polyolefins and polyamides, especially when the waste is homogenous and relatively clean, with successful applications in 3D printing, injection molding, and production of composite materials intended for construction applications. There is also significant interest in composite materials, where recycled plastic is used as reinforcement or filler in construction materials like mortar, cement, gypsum, or insulation foams. This approach enables the utilization of mixed or contaminated waste streams that are less suitable for chemical recycling. However, when plastics are degraded, contaminated, or highly heterogeneous, chemical recycling methods such as glycolysis, pyrolysis, or hydrothermal liquefaction offer better efficiency by producing valuable monomers or petrochemical fractions that can be further processed into chemicals or fuels. Notably, pyrolysis and HTL processes allow for real-time waste processing and the direct production of marine fuels and synthetic crude oil on board, making plastic waste collection vessels self-sufficient. Successful industrial recycling efforts, such as processing PA from fishing nets and PET bottles retrieved from oceans, demonstrate the feasibility of these approaches. Moreover, using marine plastic waste as feedstock, for example in 3D printing, is an effective way to reduce emissions and environmental impact.

While significant progress has been made in understanding and addressing plastic pollution in the marine environment, several gaps and challenges remain. First, the lack of standardized and globally harmonized methodologies for monitoring marine litter limits cross-comparability and long-term trend analysis. Moreover, most current collection technologies are optimized for macroplastics, leaving microplastic recovery unresolved. Despite extensive research on plastic litter processing and recycling, there is a notable lack of scientific studies specifically focused on marine plastic litter clean-up pathways. Existing methodologies for pretreatment are often basic and limited, primarily involving simple water cleaning to remove water-soluble contaminants, which may be insufficient for effective marine plastic waste management. There is a significant knowledge gap in the fate and transformation pathways of collected plastic waste, particularly the degradation effects during long-term marine exposure and their impact on recycling outcomes. Further interdisciplinary research is also required to explore the feasibility and scalability of chemical recycling methods for heterogeneous, degraded plastic waste streams. Additionally, emerging pathways such as converting plastic waste into hydrogen, activated carbon, or energy storage materials remain underexplored and warrant deeper investigation.

CRediT authorship contribution statement

Emilia Gontarek-Castro: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Mirco Haseler:** Writing – review & editing, Writing – original draft, Project administration. **Mona-Maria Narra:** Writing – review & editing, Writing – original draft, Project administration. **Anna Gołąbiewska:** Writing – review & editing, Writing – original draft. **Patrycja Jutrzenka Trzebiatowska:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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