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*Review*

# An Overview of the Current Trends in Marine Plastic Litter Management for a Sustainable Development

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**Abstract:** This review summarizes recent data related to the management of marine plastic litter to promote sustainable development. It discusses the distribution and identification of marine plastic litter, assesses the potential socio-economic and environmental impacts of these pollutants, and explores their recovery strategies, from a circular economy perspective. The main findings indicate that the majority of marine plastic litter originates from land-based sources. Current technologies and approaches for valorizing marine plastic litter include mechanical and chemical recycling, blockchain technologies by providing traceability, verification, efficiency and transparency throughout the recycling process, and public awareness programs and education. The developed policies to prevent marine plastic litter emphasize regulations and initiatives focused toward reducing plastic use and improving plastic waste management. By adopting a holistic and sustainable approach, it is possible to mitigate the environmental impact of marine plastic debris while simultaneously creating economic opportunities.

**Keywords:** marine plastic litter; environmental impact; valorization; policy; circular economy

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**Citation:** Râpă, M.; Cârstea, E.M.; Șăulean, A.A.; Popa, C.L.; Matei, E.; Predescu, A.M.; Predescu, C.; Donțu, S.I.; Dincă, A.G. An Overview of the Current Trends in Marine Plastic Litter Management for a Sustainable Development. *Recycling* **2024**, *9*, 30. https://doi.org/10.3390/recycling9020030

Academic Editor: Giovanni De Feo

Received: 4 March 2024
Revised: 29 March 2024
Accepted: 6 April 2024
Published: 9 April 2024



## 1. Introduction

According to the United Nations Environment Program (UNEP), approximately 400 million tons of plastic waste are produced globally every year [1]. For instance, in 2018, plastic products generation was reported to be 35.7 million tons.

The most important events illustrating the European efforts aimed to mitigate plastic pollution refer to those which implement the Single-Use Plastics Directive, reducing plastic waste through improved recycling, as well as tackling plastic pollution in oceans and waterways.

An estimated 330 billion single-use plastic items are manufactured annually and they can persist in the Earth's deepest ocean trench [2]. The majority of plastics are non-biodegradable, suggesting that they do not break down naturally over time, leading to long-term environmental impacts. Only 10% of the world's plastic landfill waste undergoes recycling, while 12% is subjected to incineration, and a significant 79% finds its way into oceans [3]. In the year 2021, just 5.5 million tons of post-consumer recycled plastics were reintegrated into the European economy [4], which means only one-tenth of total plastic debris [5].

Also, regarding plastic waste generated from healthcare activities, of the total waste, about 85% was non-hazardous waste, while the remaining 15% was hazardous material, which may include infectious, toxic, or radioactive waste [6]. The World Health Organization (WHO) recognizes that plastic waste including packaging materials, single-use medical devices, and other disposable items are a significant concern in healthcare settings due to their environmental impact and potential health hazards.

A significant amount of plastic waste (3,090,000 tons) was reported from a total of 69.1 million tons of total municipal solid waste (MSW) recycled in 2018 [7].

The intensity of ocean pollution has reached a critical level, prompting the United Nations to allocate, within the Sustainable Development Goals, a specific target (14.1) on addressing this issue. The objective of target 14.1 is to "prevent, and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution" by the year 2025 [8]. The United Nations Environmental Program (UNEP) characterizes marine litter as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment". Frequently encountered marine litter items include cigarette butts, bags, remnants of fishing gear, and food containers [9]. It was reported that 60–99% of the total marine debris found on shorelines, sea surface, and sea floor is composed of plastics [10–14]. Due to their abundance in both number of items and quantity, it is estimated that plastics are the most common components of marine litter. Annually, a global influx of plastic waste into the marine environment ranges from 4.8 to 12.7 million tons [10,15,16]. Marine plastic litter or debris can be found deposited on the beach [15,17–19], as well as floating [13,15,20–23], or submerged in marine environments [19–21].

Marine plastic litter can be categorized based on its size into different categories, megaplastics (>1.0 m), macroplastics (25–1000 mm), mesoplastics (MeP) (5–25 mm), and microplastics (1–5000 µm) [22–25]. Globally, it is estimated that 51 trillion of microplastics (MPs) are floating on the ocean's surface [2], since 70% of marine litter sinks to the sea bottom with unknown consequences [26]. Nanoplastics (NPs) (<1 µm) [27] are even smaller plastic particles, which often result from the breakdown of larger plastic particles. Due to their extremely small size, NPs can potentially enter cells and tissues, raising concerns about their impact on ecosystems and human health. Significant studies have been conducted and reported on the removal methods of MPs and NPs from aqueous media [28–31]. The accumulation of plastic litter in the ocean is primarily attributed to the rising demand for disposable products, including the absence of incentives for plastic manufacturers to reduce production, heightened fishing activities, insufficient waste management, and urban stormwater. Without coordinated intervention, it is expected that the annual flow of plastics into the ocean will reach 29 million metric tons by 2040 [32].

Marine plastic pollution has substantial economic, environmental, and health impacts, especially on "fisheries, aquaculture, recreation, and heritage values" [32]. Due to their high surface area to volume ratio, plastic debris can potentially adsorb a wide range of other toxic chemical pollutants, such as pharmaceutical and personal care products [33,34], pesticides [35,36], polycyclic aromatic hydrocarbons (PAH) [37], polychlorinated biphenyl (PCB) [38], trace heavy metals [39,40], ultraviolet filters (UV-filters), organo-phosphorus flame retardants (OPFR) [17], and penta-, octa-, and de-ca-(poly)bromodiphenyl ethers (PBDEs) [41]. Also, these small plastic particles could leach their additives such as bisphenol A (BPA), bis(2-ethylhexyl) phthalate (DEHP), and dibutyl phthalate (DBP) [42] in the environment increasing the potential risk to aquatic organisms as well as human health. Organisms interact with marine litter through entanglement in discarded fishing nets, ingestion of litter mistaken as food by marine species, and attachment of smaller organisms like algae or invertebrates to floating marine debris. The significant threat posed by marine plastic litter to sea biodiversity can lead to detrimental effects on marine ecosystems and the species within them, including contamination of food chains and pollution of beaches.

This underscores the urgent need for actions to address the plastic pollution that re-quire concerted efforts from governments, industries, and individuals to mitigate its effects. When macroplastics break down into micro-sized particles, the task of recovering and recycling them becomes exceedingly challenging. However, few studies have reviewed the valorization of marine plastic litter, which is essential for the circular economy concept [43,44]. Therefore, there is need for comprehensive and systematic research on marine plastic litter to gain insights into their origin, distribution, impacts, and recycling strategies aiming to encourage the adoption of sustainable alternatives to traditional plastics. Based on our knowledge, standardized treatment processes for marine litter are lacking due to the absence of comprehensive recovery and recycling strategies. The sole viable approach, aside from preventing waste from entering water bodies, is to retrieve macroplastics before they undergo fragmentation or, at least, to reduce them to a great extent. This study represents a comprehensive report analyzing mechanical and thermochemical treatment processes applied to marine plastic litter, comparing methods such as melt reprocessing, pyrolysis, gasification, and hydrothermal carbonization at the laboratory scale. Additionally, it explores policy support in reducing marine plastic litter.

## 2. Methodology

### 2.1. Sources, Impact and Valorization

The impact of marine plastic litter was discussed, examining both socio-economic and environmental effects. Given that the small plastic particles (MPs and NPs) serve as a food source for aquatic organisms, the potential impact on the health of humans, aquatic birds, and fish is a topic currently under discussion.

Subsequently, the valorization of marine plastic litter was assessed, focusing on mechanical and chemical recycling, as well as hydrothermal carbonization, and their main advantages and limitations. A limited number of studies have been dedicated to investigating the recycling of marine plastic litter.

### 2.2. Marine Plastic Litter Actions

Finally, this paper outlines policies and actions related to marine plastic litter that aim to reduce marine plastic pollution from land-based or sea-based sources. These were identified through generic search engines, artificial intelligence (AI), references in research papers, and G20 and UNEP reports. A total of 310 actions have been identified, which were implemented at national, regional and global levels. The actions include: laws (N = 128), strategies (N = 23), plans (N = 34), initiatives (N = 68), programs (N = 22) and campaigns (N = 14). The list also includes coalitions (N = 9) and conventions (N = 12). Actions were analyzed based on implementation (such as, clean-up, recycling or circular economy) and spatial coverage. However, the list of actions is far from being exhaustive as the analysis was limited to the information accessible in the English language. This excludes several potentially important actions taken, by the authorities, researchers or civil societies, in countries where English is not the main language and websites are not translated. It may also exclude several civil societies' actions on marine plastic litter that were not easily provided by search engines. Thus, an analysis on the level of involvement per country or even continent could not be properly assessed. Also, for countries members of the European Union (EU), we have taken into consideration only the EU actions, addressing plastic pollution, and not individual country actions, because these usually align to the EU's legislation. Nevertheless, the selected number of actions can provide an overview of the current trends and the support of stakeholders in promoting plastic reduction, reuse and recycling. For the analysis, only the initial year of adoption has been taken into account, although many authorities have later made amendments with regard to plastic pollution (micro- or macroplastics).

## 3. Sources, Monitoring and Detection of Marine Plastic Litter in the Aquatic Ecosystem

Marine plastic litter can originate from land-based [13,15,17,18,45–47] and sea-based sources [19–21,26,48,49] (Table 1) and their release into the aquatic environment can be intentional or unintentional.

**Table 1.** Characteristics of collected marine plastic litter.

| Location of Marine Plastic Litter | Sampling Period | Plastic Marine Litter Assessment | Characteristics of Marine Plastic Litter | Estimated Amounts of Collected Plastic Waste | Ref. |
|---|---|---|---|---|---|
| | | | Land-based sources | | |
| Twenty beaches, Cyprus | January, March, June, and September 2021 | Marine Strategy Framework Directive (MSFD) and Ocean Conservancy protocols | 86.3% plastics (with size > 2.5 cm), from which 61.6% were single-use plastics (SUP) | 36,676 plastic items | [15] |
| Thirteen beaches in Solomon Islands and Vanuatu, the South Pacific region | November 2018 and January 2019 | OSPAR guidelines | SUP, fishing related items, and polystyrene (PS) pieces, represent 75% of the recorded items | Solomon Islands: 1053 ± 1017 items of litter per 100 m Vanuatu: 974 ± 745 items of litter per 100 m | [50] |
| Four beaches in the Canary Islands, Spain | 2016 and 2017 | Fourier-transform infrared (FT-IR) and Differential scanning calorimetry (DSC) analyses | 95% poly(ethylene) (PE) and 5% poly(propylene) (PP); fragments were the most predominant shape, then pellets; fragments were categorized into 78.3% PE, 17.4% PP, and 4.3% thermoplastic elastomer | - | [17] |
| Fourteen beaches, Vietnamese coast | September 2020 to January 2021 | Counting and weighing of marine plastic litters in accordance with the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) guideline | 83.4–99.05% plastics from all marine litter; 60% SUP; 31% fishing-related items; Clean Coast Index (CCI) of 92.6 | 20,744 items of marine plastic litter, who weighed 100,371.2 g | [13] |
| Sylt and Norderney, North Sea, Norderney Germany | 22 April–15 May 2020 17 April 2020 | Near-infrared spectroscopy (NIR) | Sylt: 55% nets made of PP and high-density poly(ethylene) (HDPE), and 15 wt% 3D plastics such as fragments of boxes, caps and canisters made of PS, PP, poly(vinyl chloride) (PVC), and acrylonitrile butadiene styrene (ABS); 8 wt% rubber and elastomers; 6 wt% films consisting of PP, PVC, poly(amide) (PA), HDPE, and PS; 5 wt% foamed plastics including poly(ethylene terephthalate) (PET), PS, HDPE, and poly(urethane) (PUR) foams Norderney: 88 wt% PET, PP, HPDE, PS, and PUR from plastic bottles; 10 wt% films including PVC, HDPE, PS, PP, and ABS | Sylt: 5478 g Norderney: 4522 g | [11] |
| Two marine protected areas (MPAs), Peru | January to May of 2022 | FT-IR spectroscopy | The MeP had the distribution: PP 24.1%, low-density poly(ethylene) (LDPE) 20.7%, PS 13.8%, PE 10.3%, PET, PVC, alkyd resin, and cellophane 3.4% each; MPs composition: cellulose 53.3%, PET 17.8%, alkyd resin 6.7%, poly(ether urethane) (PEU) 4.4%, PP, PA, PS, and polyacrylic 2.2% each | The Ballestas Islands: 4.19 ± 2.23 MPs/L | [18] |

**Table 1.** *Cont.*

| Location of Marine Plastic Litter | Sampling Period | Plastic Marine Litter Assessment | Characteristics of Marine Plastic Litter | Estimated Amounts of Collected Plastic Waste | Ref. |
|---|---|---|---|---|---|
| Rhodos sandy beach, Greek island | Summer 2015 | Analytical balance with density kit | 91.8% PP, 3.9% PE-LD, 3.9%, PE-HD, 0.3% PVC, and 0.1% PET | - | [42] |
| Seabird breeding islands located on Lord Howe Island, Australia | 2018–2020 | µ-FT-IR | 99.85% fragments; Chromatic: 70.60% white, 13.26% green, and 10.84% blue | 3265 pieces of plastic weighing a total of 783.45 g | [46] |
| One seabird and two shorebird species, Yongxing Island of South China Sea | 2017 | µ-FT-IR | 92.9% MPs from the total marine plastic litter<br>Chromatic: 91.1% blue, 5.4% dark, and 3.6% white;<br>Morphology: 89.2% filament, 8.9% sheet, and 1.8% foam;<br>Identification: poly(propylene)-poly(ethylene) (PP-PE) copolymer, PE, PP, PET, from which 83.9% were PP-PE | 56 items of plastic debris | [47] |
| | | | Sea-based sources | | |
| Fifty fishing operations during surf-zone trammel nets, Southern Brazil | | | 98.4% plastics, from which 94.5% were SUP | 1384 fragments of marine litter | [51] |
| Proyecto Manta Pacific Mexico | May 2016 to April 2018 | µ-FT-IR-ATR | 79% from the floating plastic were MPs: 45% PP and 43% PE;<br>1–2 mm was the most representative class of MPs;<br>44% from MPs were white, 29% were colorless, and 11% were blue | 0.3 plastic items/m$^3$ | [48] |
| Lake Tahoe, Nevada by scuba divers | Six dive days from water depth $< 7.6$ m | ATR FT-IR | PVC, PS/EPS, PET/PEST, PE, PP, and PA6/PA66 | $83 \pm 49$ plastics/km | [21] |
| Tide sediment, water and submerged sediment zones, Tenerife, Spain | July 2016 and June 2017 | ATR FT-IR | Tide sediment: 66% plastics;<br>Water: 23% plastics;<br>White and transparent plastic fragments with sizes > 1 mm; PE, PP, PS, poly(tetrafluoroethylene) (PTFE), and PVC types;<br>Submerged sediment: 11% plastics; yellow and blue fibers with sizes < 1 mm; PP, PA and rayon types | High tide sediment: 130.64 items/L<br>Water samples: 23.10 items/L<br>Low tide sediment: 6.50 items/L | [19] |

### *3.1. Sources of Marine Plastic Litter*

The initial step in preventing additional plastic debris from entering the marine environment and implementing effective solutions for plastic reduction is to identify their primary sources of input in the environment.

#### 3.1.1. Land-Based Sources

More than 75% of the marine plastic debris originates from land-based sources [52], including river transport inputs [47,53–56], and various human activities such as: (i) improper waste disposal, (ii) sewage and wastewater discharge, (iii) plastic items such as bags, bottles, and packaging materials, which are often discarded irresponsibly and can be carried by wind or water into the sea, (iv) recreational and tourism activities, (v) industrial and construction activities, and (vi) harbor activities [32,52].

The presence of (single-use plastics) SUP and plastic packaging on beaches and coastal zones were identified as potential contributors of marine plastic litter. The COVID-19 pandemic has contributed to the quantity of marine plastic litter due to the use of SUP such as personal protective equipment, including masks, gloves, and clothing, along with the packaging of food and consumer products for home and office delivery [13,57]. For instance, SUP, such as bottles and caps, straws, cutlery and crockery, plastic bags, food containers and wrappers, and cigarette butts, accounted for 61.6% from all plastic items collected from around the Cyprus island [15]. Additionally, 94.5% of the registered marine litter collected in the surf-zone in Southern Brazil was considered as SUP waste [51]. The average density of collected marine litter was found 0.19 items/$m^2$ for island of Cyprus [15] and ranging from 0.14 to 0.58 items/$m^2$ for the Bengal coast of Bangladesh [58].

Recently, McGoran et al. [54] reported that in the Thames Estuary, 40% from the total litter consisted of plastic packaging. Floating plastics were observed with an average catch per unit effort of $0.57 \pm 0.42$ items per minute, while the plastics settling on the riverbed had an average catch per unit effort of $2.75 \pm 2.44$ items per minute.

Pontoons, buoys, and floats, predominantly manufactured from expanded poly(styrene) (EPS), and referred to as "white spill", have a tendency to degrade into smaller pieces over time, becoming other significant sources of macro- and MPs litter [13,59]. Wastewater treatments [60–62], and plant recycling facilities (PRFs), could also serve as potential contributors of MPs to receiving water bodies such as rivers or the sewer network [63]. MPs debris was detected in seabirds [46,47], which can serve as vectors for floating plastic litter, while their breeding colonies can serve as sinks. During 2018–2020, the seabirds from the Tasman Sea ingested 3265 pieces of plastic [46].

Environmental factors that might contribute to the introduction and accumulation rate of land-based plastic litter into the marine ecosystem encompass wave currents, wind patterns, river hydrodynamics, as well as natural disasters like storms, hurricanes, floods, earthquakes, and tsunamis [2,52]. In the hurricane season, there was a significant rise in the quantity of floating plastics compared to the dry season, suggesting that rainfall may play a significant role in the runoff of plastics from land-based sources into the bay [48].

The distribution and composition of marine plastic debris can vary significantly depending on the location and sampling time—see Table 1. For example, it was stated that the predominant entry point for plastic waste into oceans is through rivers from May to October [64]. In another study conducted on the beaches of the Niterói Oceanic Region in Rio De Janeiro, Brazil, it was observed that 85% of MPs were collected during winter, compared to 73% in the summer [65]. In popular tourist destinations, the summer season contributes to 75% of the annual waste production, with tourists typically generating 10% to 15% more waste compared to the local residents [2]. Implementing seasonal monitoring in areas with seasonally variable rainfall is important to avoid the underestimation of marine plastic debris during the dry season or overestimation during the wet season. The results of the cross-correlation analysis conducted as part of the investigation into seasonality in floating plastic level in the Banderas Bay basin, revealed a strong and statistically significant correlation (~0.50) between precipitation and the time series of plastic abundance [48]. This correlation was observed with a lag of +1 month, indicating that the elevated densities of plastic particles become apparent one month after the initial peak in precipitation.

However, there is no systematic evaluation regarding the contribution of river sources and land-based activities to the generation of plastic litter [32,66]. The explanation is that the Water Framework Directive (WFD) (Directive 2006/06/EC), primarily focuses on water quality and ecological aspects, and does not specifically address litter, including plastic litter, in freshwater bodies. By enhancing the alignment and cooperation between the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC) and the WFD, policymakers can take a more integrated approach to managing water resources and ecosystems [66].

Therefore, there is an urgent need for effective actions to reduce, recycle, or properly dispose of these plastic items in order to mitigate their environmental impact.

#### 3.1.2. Sea-Based Sources

Sea-based sources encompass fishing operations, the marine tourism sector, shipping, abandoned fishing gear, aquaculture, and offshore oil and gas platforms. Moreover, 32% of marine plastic litter comes from discarded fishing gear such as nets, lines, and traps, which could be abandoned, lost or otherwise discarded fishing gear (ALDFG) [13,26,52,67]. These are often referred to as "ghost fishing". In most regions, shipping and fishing activities are responsible for 95% of marine debris, often manifesting as abandoned fishing nets [2]. Only in the deep seafloor (30 m–300 m depth), fishing gear represents the dominant part of debris (89%) [26]. Fishing nets are predominantly made from poly(amide) (PA) [52] and poly(ethylene) (PE) [68]. Also, small plastic debris identified in areas where artisanal fishing takes place, is composed of poly(propylene) (PP), low-density poly(ethylene) (LDPE), and poly(ethylene terephthalate) (PET) [11,18]. These items can persist in the marine environment for a long time, posing threats to marine life and the ecosystem.

Recently Kaandorp et al. [69] estimated, using a hybrid Lagrangian–Eulerian model, that the input of ocean plastic for the year 2020 ranged between 470 and 540 kilotons per year (95% confidence interval). This estimation was lower than other reported data. The previously observed increase in the number of plastic particles could be explained by the plastic fragmentation into small particles, potential overestimation of input, and degradation. The numerical model developed by the authors indicated that the plastic inputs into the ocean from fishing activities, coastlines, and rivers fell within the ranges of 220–260 kilotons/year, 190–220 kilotons/year, and 57–69 kilotons/year, respectively [69].

Among the oceans and seas worldwide, the North Pacific and Mediterranean Sea exhibited the highest concentration of floating marine plastic litter [70]. It was reported that the Mediterranean Sea is the most polluted sea in Europe, with an accumulated amount estimated at 1.2 million tons of plastic debris and with an additional amount of 229,000 tons of plastic litter flowing into the sea every year [15].

### *3.2. Monitoring and Detection Methods*

#### 3.2.1. Analytical Methods

The MSFD and Ocean Conservancy have established protocols for monitoring the type and quantities of marine plastic litter present in the marine environment. The most used laboratory methods for marine plastic litter identification based on mass determination consist of: Fourier-transform infrared (FT-IR) spectroscopy [18,19,21,48], thermogravimetry [71], differential scanning calorimetry (DSC) [17], and density measurement [45]. These methods enable the identification of the most abundant marine plastic litter, such as PP-PE copolymer, PE, PP, PET, PVC and PS [11,17,19,21,45,65]. The thermoplastic polymers debris is characterized by melting points ranging from 120 °C to 140 °C, degradation temperatures within 300 °C and 500 °C, and a high heating value of 43.9 MJ $kg^{-1}$, similar to other natural gases [71].

The evaluation of floating macroplastics commonly depends on human visual surveys, which are often associated with a high cost, are time-consuming, and have limited coverage.

#### 3.2.2. Machine Learning

Machine learning tools facilitate the detection, classification, and monitoring of marine debris [72–75]. A total of 66,000 plastic articles, weighing ~1000 kg, and varying in length from 10 to 30 cm, were identified on six beaches in Cyprus using the OpenCV Contours image processing tool [75]. In alternative studies, the categorization of marine plastic litter into floating objects such as bottles, buckets, and straws demonstrated a success rate of ~86% [74], while the identification of a broader range of items including plastic bags, bottles, buckets, food wrappings, straws, derelict nets, fish, and other objects was achieved with a 90% success rate [72], when machine learning was applied. The validation of MAP-Mapper, an automated tool involving machine learning, demonstrated an attainment of 95% precision and precision-recall pairs ranging from 87% to 88% when it identified marine debris and suspected plastic in diverse locations, including the Gulf of Honduras, Manila in the Philippines, Mumbai in India, Hong Kong, the Cornish coastline in the UK, and Chubut in Patagonia, Argentina [73].

The growth in this sector is provided by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) research organization, who developed a semi-automated method using hyperspectral imaging in the near-infrared and short-wavelength infrared ranges to identify sizes and materials of MPs smaller than 300 μm. Additionally, they applied machine learning techniques to automatically and rapidly classify each microplastic feature in the images [76].

The innovative initiative in contributing significantly to tracking marine plastic pollution ensuring the health of our oceans is also offered by the Plastic-i company [77].

#### 3.2.3. Internet of Things

Recent progress in software and hardware technologies, particularly in the fields of the Internet of Things (IoT), opens up possibilities to explore innovative methods for monitoring marine plastic litter. They integrate drones, sensors, and station pad technologies into a unified cloud-based platform, which offers services to both public authorities and residents of coastal areas [78,79]. Through gamification, the platform seeks to actively engage citizens, motivating them to participate in efforts to combat the issue of marine litter [78].

A comprehensive waste-tracking system to tackle the worldwide challenge of marine littering, particularly focusing on plastic bottle waste, was successfully developed in the TRACKPLAST project which leverages IoT technologies, particularly LoRaWAN (Long Range Wide Area Network) and Cloud [80].

#### 3.2.4. Citizen Science

Engaging citizen science is a valuable approach for monitoring plastic litter [13]. For instance, in a survey conducted by local volunteers across fourteen beaches along the Vietnamese coasts involving activities such as cleaning, identification, counting and weighing, a high Clean Coast Index (CCI) value was observed suggesting extremely dirty beaches with plastic litter [13]. This highly polluted state was attributed to poor waste management practices combined with a lack of awareness among the local people in these areas.

### *3.3. Potential Impact of Marine Macro- and Microplastic Litter*

The pollution generated by marine plastic litter is deemed irreversible and widespread globally, posing threats to ocean health, wildlife, food safety, human health, coastal tourism, and climate regulation [81,82]. This concern arises from the persistence of plastics and their harmful impacts. The issue extends beyond visible floating litter, plastic debris stranded on beaches, especially in the form of pellets and MPs, further exacerbating the pollution issue and threatening the coastal environments [17].

Governments and local authorities may face increased costs in managing and cleaning up marine plastic litter associated with beach cleanups, waste disposal, and the development of strategies to address this issue.

#### 3.3.1. Socio-Economic Impact

Marine plastic litter can pose direct threats to human health as they can be exposed to MPs through the consumption of seafood [83–88]. By carrying harmful chemicals and toxins [89,90], MPs have the potential to enter the food chain through seafood, affecting communities that rely on marine resources [91]. Since most of these chemicals are not chemically bonded, they can leak out of the plastics in which they are incorporated. The buildup and fragmentation of plastic in oceans may pose a growing eco-toxicological concern for marine animals due to the plastic additives. A study examined several significant plastic additives, assessing their frequency in marine environments [92] and concluded that the most widely used plastic additives were BPA, organophosphates (OPEs), and phthalates (phthalic acid esters–PAEs) [93]. Furthermore, numerous investigations have shown that these plastic compounds are transferred to marine organisms [94–96]. If humans then consume these contaminated organisms, it can lead to health issues [97], including disruptions to the endocrine system and increased cancer risk [98]. Research on the direct and indirect impacts of MPs on human health, including potential toxicological effects such as endocrine disruption and oxidative stress, is critical [99,100]. Recent evidence even suggests the presence of MPs and NPs in human placenta and meconium, indicating widespread exposure for pregnant women and infants [101,102].

Coastal communities dependent on fishing and tourism could encounter economic setbacks due to the potential harm caused by marine plastic litter, including damage to fisheries, depletion of fish stocks, and adverse effects on tourism. The presence of plastic debris on beaches and in the water diminishes the aesthetic appeal of coastal areas, affecting the recreational and tourism value of these environments [103]. The presence of garbage on the shore is despised and is frequently cited as a major deterrent for tourists, causing them to avoid particular locations or spend less time in such settings [104]. Both tourists and seafarers are vulnerable to a variety of accidents, including cuts from sharp objects, tangles with nets, and contact with unhygienic materials. It has also been shown that spending time on beaches covered with litter is demonstrated to have detrimental effects on their mental and emotional health [105]. On the other hand, avoiding the coast due to these risks can also have negative consequences on health by preventing individuals from taking advantages that coastlines generally provide, such as encouraging physical activity, facilitating meaningful social interactions like fortifying family ties, and enhancing both physical and mental well-being [106]. There are several financial repercussions to this, including increased cleaning costs and a decline in tourism income.

The adverse effects of marine plastics on fisheries are extensive, including damage to gear and vessels, operational disruptions, reduced catch, and contamination of fish and shellfish. Reduced fish stocks due to plastic pollution can also result in lower catches and income for those dependent on fisheries. Globally, the UNEP has estimated that the economic impact of marine plastics (apart from MPs) is ~$13 billion annually, taking into account the losses to fisheries and tourists. It is estimated that the fishing fleet in the European Union alone loses $81.7 million (61.7 million euros) annually [16]. Interaction with marine plastic litter can directly harm fishing vessels and gear, leading to the need for repairs or replacements with associated economic costs. Studies reveal entangled propellers in over 45% of fishing vessels and gear fouling in over 30%, causing direct losses in revenue [107]. In Scotland, the annual cost due to the action of marine plastic litter to fishing vessels is estimated to range between €17,000 and €19,000 per vessel. European fishing fleets incur an annual cost of 61.67 million euros due to marine litter, nearly 1% of their revenue [108]. The accumulation of marine plastic litter in trawls can block grids, leading to commercial losses [109]. Static nets contaminated with litter reduce visibility to fish, resulting in decreased yield. Benthic and suspended plastic items make it challenging for divers to detect marine organisms, reducing catch amounts. Derelict fishing gear, especially ropes, poses a significant threat to divers harvesting marine organisms from the seafloor [110,111]. These items, designed to be less visible underwater, can entangle divers, leading to difficulties escaping or calling for help [112].

#### 3.3.2. Environmental Impact

Plastic pollution can disrupt marine ecosystems by altering habitats and interfering with the natural behavior of species. This can have cascading effects on the food web and ecosystem function [113]. A wide range of species, from small fish to marine mammals and seabirds can ingest or become entangled in plastic debris, leading to injury or death [114,115]. Filter feeders like mussels and oysters are particularly at risk, as MPs not only affect them but also ripple up the food chain, affecting predators and overall ecosystem stability [116,117]. Laboratory studies frequently documented using fluorescent spheres or histological sections on a variety of species, including crustaceans [118,119], bivalves [120], and zooplankton [121] have demonstrated that MPs remain in the body without being eliminated for several days even after exposure has stopped, raising the possibility of gastrointestinal blockage and inflammation [122]. Studies showed that in the case of crab *Carcinus maenas*, MPs were observed in the system after 14 days since initial exposure [118] and that particle shape influences the retention time [123]. Commercially available MPs have a smooth, spherical shape that makes them easy for organisms to quickly pass them through their digestive systems. In a study, 99% of daphnia exposed to microspheres exhibited elimination of MPs within 24 h, while only 1% of daphnia exposed to micro-fragments showed a similar elimination rate [116]. Plastic microsphere transfer has been found experimentally in the lysosomal and circulatory systems of *Mytilus galloprovincialis* [124], the liver of *Danio rerio* zebrafish [125], and the hepato-pancreas of crabs [126]. According to exposures in laboratories, ingesting MPs rarely results in an organism's death. Nevertheless, disruptions at several sizes, including molecular, cellular, individual, and population, may result from the buildup or straightforward passage of these particles in the digestive system and external organs (such as the gills) [127].

The oxidative stress induced by MPs is a major concern, affecting defense systems, immune regulation, and molecular pathways related to apoptosis [128]. MPs can directly alter an organism's behavior or cause cellular or energy disturbances [127]. MPs intake have been demonstrated in the lab to cause daphnia immobilization [129], decrease sea flea jumping ability [130], and change fish feeding and motility [131]. Furthermore, zooplankton species may change their preferred feeding habits in response to different types of plastic particles (such as spheres or fibers) in order to reduce the likelihood of eating particles that resemble their natural prey [132].

Entanglement in larger plastic items poses a significant concern, causing physical injuries and impairing movement, especially in bigger animals such as marine mammals and sea turtles [133]. Sea turtles often mistake plastic bags for jellyfish, a staple in their diet and ingesting plastic can cause internal injuries, blockages, and, in some cases, death [2,134]. These fascinating aquatic animals are extremely valuable to humans, and an array of data indicates that people benefit from the certainty that these animals exist and will continue to do so for future generations—even though they may never encounter them directly [135]. Similarly, seabirds may feed plastic particles to their chicks, leading to malnutrition and developmental issues [136,137].

Plastic debris can damage or smother benthic habitats such as coral reefs and sea grasses, affecting the health and biodiversity of these critical ecosystems [135].

Furthermore, an increase in bacterial and algal colonization on plastic, which, despite seeming beneficial, could negatively affect the broader ecosystem. Unlike natural debris (kelp and wood) which degrade and sink relatively quickly, plastic's durability allows it to remain buoyant for extended periods, enduring exposure to UV radiation and wave action [138]. This prolonged buoyancy facilitates the movement of organisms across different biomes, potentially expanding their bio-geographical range and contributing to the spread of invasive species and diseases [139]. Marine plastic, acting as a substrate for colonization, serves as a mechanism for organisms to travel vast distances, exceeding 3000 km from their source [140].

The presence of plastic in marine environments has the potential to significantly alter the ecology of these systems, as highlighted by Galloway et al. [127]. Floating plastics pose a risk as potential vehicles for introducing invasive species into the marine ecosystem, shifting ocean temperatures, ocean acidification, and overexploitation of marine resources. The combined impacts of these stressors might result in more severe damage from marine plastic than is currently acknowledged [103].

## 4. Technologies for Recycling of Plastic Litter

Recycling pathways are predominantly constrained to pre-processed, sorted, and segregated polymer fractions. Addressing marine plastic litter introduces extra complexities, given that the plastic is not only extremely diverse, but also profoundly affected by various environmental factors including mechanical degradation from wave movement and sandy shores, as well as deterioration due to UV radiation, oxidation, and the overall biofouling process. Additionally, the leaching of chemical additives like plasticizers from the polymeric chains [141] is influenced by external factors and, further, modifies the material properties.

The innovative InNoPlastic Project—Innovative approaches towards prevention, removal and reuse of marine plastic litter, has developed several clean-up technologies, which include combining flocculants with drum screens to agglomerate nanoparticles, using blockchain technology, and fabricating a robot designed to collect macro plastic litter [142].

A schematic diagram of technologies for recycling of marine plastic litter is illustrated in Figure 1.

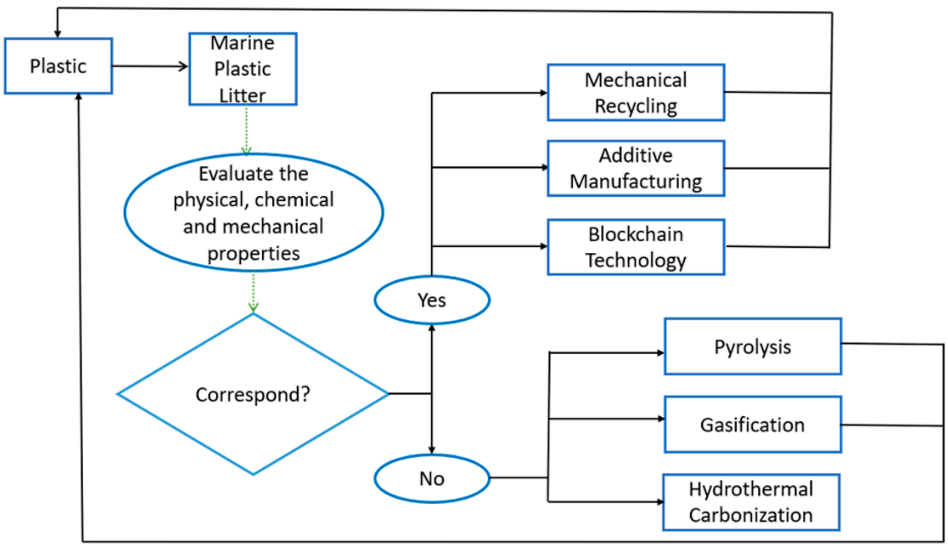


**Figure 1.** Scheme for recycling of marine plastic litter.

### *4.1. Mechanical Recycling*

Mechanical recycling technology has already been implemented for the management of plastic waste derived from anthropogenic activities. The criteria for considering marine plastic litter for upcycling purposes involve no significant decrease in chemical, physical, and mechanical properties compared with virgin polymers. Conversely, if significant changes are observed, downcycling of the littered plastic would be recommended [143].

Mechanical recycling of marine plastic litter has been reported for PET bottle waste [64,144], fishing gear waste made of PE, PA, and PP [145,146], buoys and pontoons from EPS [59,146], and waste electrical and electronic equipment (WEEE) [147]. The findings are associated with enhancing the recyclability of marine plastic litter.

The ongoing initiatives of the European Commission outline ambitious targets aimed at mitigating the prevalence of lost fishing gear. These objectives include achieving a 50% collection rate of abandoned fishing nets and a 15% recycling goal, with both targets set to be accomplished by 2025 [148]. Thus, PE waste from fishing gear underwent recycling by incorporating it in quantities ranging from 0.25% to 2.00% by weight, serving as fiber reinforcement in gypsum-based materials [145]. Mechanical tests were conducted to evaluate the properties of these gypsum-based materials, indicating an improvement in post-crack performance. In a similar study, ground waste fishing net (GN) and ground waste rope (GR), together with different fiber contents (1%, 2%, and 3%) were employed as fiber reinforcement in the development of high-performance cementitious composites [149]. The flexural strength of obtained composites was enhanced up to 19.7%.

In another paper, the utilization of cryogenic grinding enabled the transformation of four distinct plastic materials: PET sourced from land-based household waste, EPS from buoys, along with PA and PP derived from abandoned fishing nets and ropes into fibers aimed at increasing the strength of concrete [146]. In the case of fishing nets and ropes, the resultant concrete displayed a strength value similar with that of conventional concrete, coupled with a 35% increase in elongation. In the case of PET, a ~30% enhancement in strength was successfully achieved.

However, despite its potential benefits in terms of resource recovery, mechanical recycling of marine plastic litter has a pronounced impact on the environment—see Table 2.

**Table 2.** Advantages and disadvantages of mechanical recycling.

| Main Findings | Limits | Solutions |
|---|---|---|
| • Resource recovery<br>• Well-established technique for SUP<br>• Economic benefit<br>• Does not use toxic chemicals<br>• Maturity at industrial scale | • Worse mechanical properties | • Virgin polymers are incorporated together with recycled plastics |
| | • Impact on the environment due to the various contaminants, such as salt water, marine organisms, biomass, and other pollutants, as well as plastic degradation process | • Washing of plastic waste<br>• Sorting of plastic according to its composition<br>• Innovative pontoon waste management strategy: on-site dissolution/precipitation using *D*-limonene [59] |
| | • Mechanical fragmentation of marine plastic litter (the estimated MPs counts in raw recycling wash water ranged between $5.97 \times 10^6$ and $1.12 \times 10^8$ MPs $m^{-3}$) [63] | • The specific filtration measures are necessary in the rotating drum and knife mill wash tanks, as well as in the compounding and wash tanks [63] |
| | • Adverse effects resulting from degradation | • Incorporating additives such as colorants [64] |
| | • The transportation, sorting and cleaning steps for the recycling are labor-intensive and costly | • Chemical recycling |

Marine plastic litter is difficult to recycle due to various contaminants, such as saltwater, marine organisms, biomass, and other pollutants, and other types of plastics, as well as their degradation process. For instance, the recycling of WEEE collected from southwest England into consumer, industrial, and marine (fishing gear) plastics was considered as a significant pathway for introducing hazardous chemicals into the environment and a potential source of wildlife exposure to these substances [147]. An analysis of WEEE (N = 264), particularly those colored black, using X-ray fluorescence (XRF) spectrometry revealed maximum concentrations of 43,400 mg $kg^{-1}$ for Br, 2080 mg $kg^{-1}$ for Cd, 662 mg $kg^{-1}$ for Cr, and 23,800 mg $kg^{-1}$ for Pb [147].

Marine plastic litter reprocessing is also associated with a decrease in mechanical properties. Usually, virgin polymers are incorporated together with recycled plastics into melting machines. For instance, 40 wt% virgin HDPE was introduced during the injection-molding technology of PE and PP marine litter, collected from a sandy beach located in the northern coast of Latium Region (Central Italy), in order to obtain new plastic products with adequate mechanical properties [71]—see Figure 2. Also, by applying pyrolysis technology, PE and PP marine litter items were transformed into fuel or reduction agents, which could be used in the metallurgical and cement industries [71].

To overcome the environmental impact of mechanical reprocessing, Xayachak et al. [59] proposed on-site dissolution/precipitation of EPS pontoons as an innovative waste management strategy. The use of *D*-limonene, recognized as an eco-friendly solvent in dissolving EPS, offers several advantages including ease of transporting the solvent to the beach site, the ability for dissolution/precipitation to occur at ambient temperature, and the feasibility of transporting the PS-limonene mixture to a recycling facility.

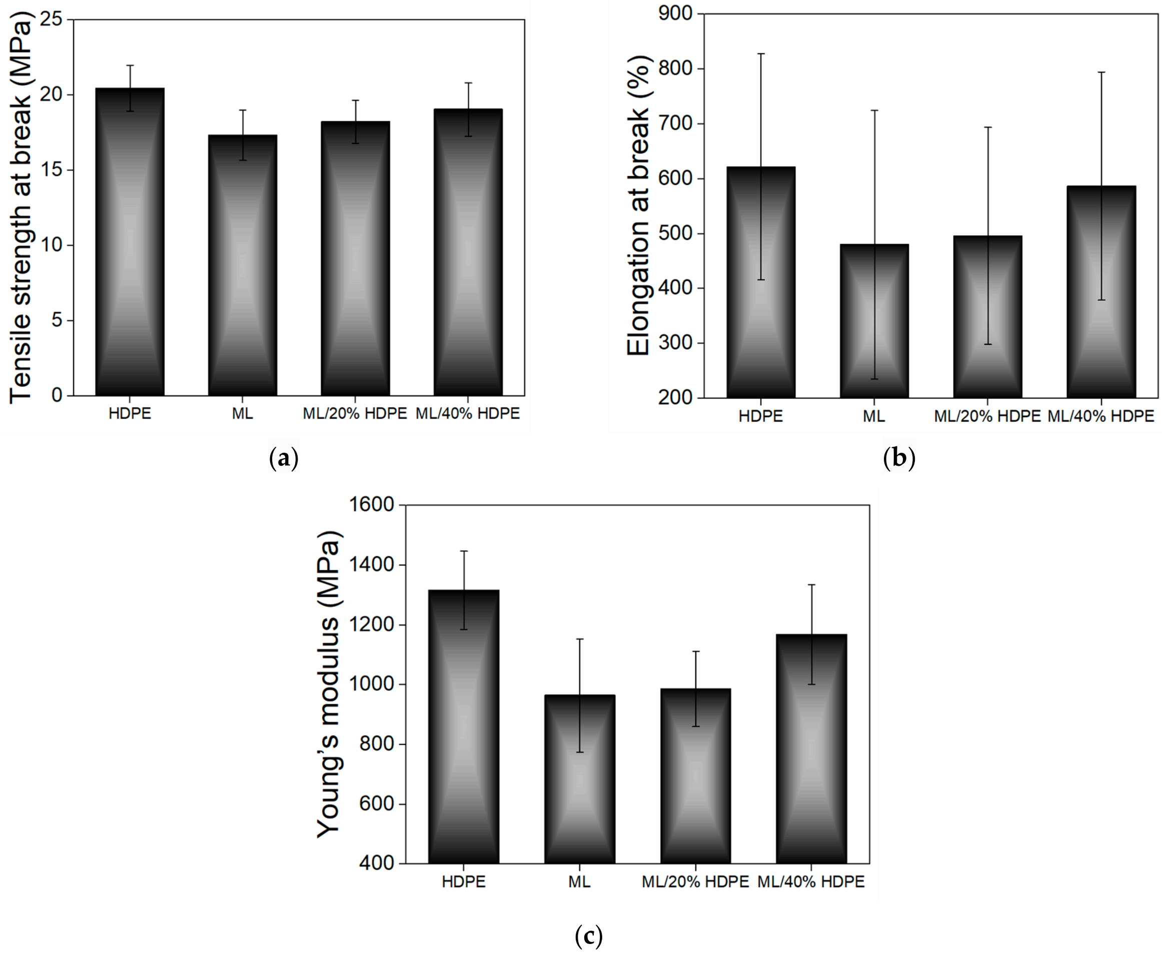


**Figure 2.** Mechanical properties of marine plastic litter containing varying percentage of HDPE (0–40 wt%) compared with those of virgin HDPE. (**a**) Tensile strength at break; (**b**) elongation at break; (**c**) Young's modulus. Adapted from [71].

### *4.2. Additive Manufacturing*

The fused deposition modeling (FDM) technique, among the most extensively utilized additive manufacturing methods, is a key component of Industry 4.0 for rapidly prototyping polymer and composite components and is recognized for its simplicity, high speed, and cost-effectiveness [144].

The recyclability of PET derived from bottles collected from the seaside involves the following steps: collecting the bottles, washing them, cutting and grinding followed by extrusion to form a thin wire. Subsequently, 3D printed samples were produced from this extruded material. By optimizing the processing conditions for PET extrusion, a decrease in crystallinity was achieved, making it easier to process through 3D printing [144].

The study conducted by Cañado et al. [150] demonstrated that repurposing PA66 fishing nets collected from the Biscay Bay (Atlantic Ocean) through 3D printing reduced the environmental impact, as the Life Cycle Assessment (LCA) methodology indicated. The findings revealed a 3.7-fold decrease in global warming potential compared to bio-based polyamide and a 1.8-fold decrease compared to virgin petroleum-based polyamide.

### *4.3. Chemical Recycling*

Innovative recycling technologies and methods have been specifically developed for marine plastic litter, which cannot be recycled mechanically. The chemical recycling of marine plastic litter yields fuel, pyrolysis oil as valuable chemical platforms, and a solid residue. This method requires less technical effort for processing, allows for the storage or direct reuse of end products [45], and provides the possibility of use in areas most affected by marine pollution without access to sophisticated engineering solutions [20]—see Table 3.

**Table 3.** Advantages and disadvantages of chemical recycling.

| Main Findings | Limits | Solutions |
| --- | --- | --- |
| • 30% overall reduction in nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC) emissions compared to neat diesel [26,151]<br>• Pyrolysis of plastic marine litter "as is" | • Composition of pyrolysis oil indicates the potential for corrosion of reactor due to HCl and other organic acids | • Catalytic hydrothermal treatment to remove chlorine from pyrolysis products and diluting of oil with naphtha to meet specifications<br>• Introduction of calcium oxide (CaO) [20,151] |
| | • Decrease in VN yield | • Removing of components that are not of plastic origin from marine plastic litter and sorting them [26] |

Due to the substantial annual consumption of fuel in global maritime transportation (amounting to 207 million metric tons in 2017 and over 36 million metric tons in 2019 within EU nations) [151], chemical recycling also presents a viable opportunity to introduce recyclable marine litter products as part of a circular economy framework. Although pyrolysis provides an effective means of recycling plastic marine litter, its energy demands are significant. Nevertheless, this method of chemical recycling is favored for nonrecycled plastics, hospital plastics posing severe biohazards, and plastic marine litter. To obtain base chemicals for the production of second-generation virgin-quality polymeric materials, pyrolysis oils need to undergo subsequent steam cracking. Therefore, pyrolysis of marine plastic litter "as is" followed by distillation process allowed the obtaining of a light, naphtha-like product suitable for steam cracking [20]. The analysis of marine litter naphtha revealed a boiling point of ~240 °C and larger amounts of linear paraffins and $\alpha$-olefins. The linear paraffins, $\alpha$-olefins, a specific sequence of $\alpha,\omega$-diolefin, and n-paraffin examined by the two-dimensional gas chromatography (GC $\times$ GC) analysis indicated a higher concentration of PE in the collected marine litter [20] due to the waste-derived naphtha fractions.

The CHNS/O analysis by inductively coupled plasma-optical emission spectrometry (ICP-OES) combined with inductively coupled plasma mass spectrometry (ICP-MS) analyses after microwave-assisted acid digestion was conducted to determine the trace metals content. The results highlighted the following concentrations: oxygen ~2500 ppm, chlorine ~297 ppm, vanadium and tungsten metals 5.9 ppm, calcium ~3 ppm, potassium and sodium, under LOD (50 ppb), and silicon 1.900 ppm (21). The highest tolerable concentrations of some important contaminants found in pyrolysis oils were reported by Kusenberg et al. [152] and include: 100 ppm for nitrogen, nickel, and oxygen, 3 ppm for chlorine, 1 ppb for iron, 125 ppb for sodium, 50 ppb for vanadium, 0.5 ppm for calcium, 20–200 ppm for potassium, 0.4 ppm for zinc, $< 1$ ppb for iron, and 0.5–1 ppm for silicon. It is evident that the composition of pyrolysis oil obtained through the valorization of marine plastic litter exceeds the threshold values for industrial steam crackers [20], indicating the potential for corrosion.

The literature revealed the use of marine plastic litter for pyrolytic recycling "as received" [20,26,151] or after the plastic separation step [153]. In a study performed by Faussone et al. [26], ~100 kg of marine debris composed from mixed containers, mussel nets, eco-leather, mooring lines, trawl fishing nets, and mixed floating litter were gathered from the Venice Lagoon, and transformed "as is" into marine gas oil (MGO), intermediate fuel oil (IFO), and virgin naphtha (VN) products. The characteristics for VN reported as research octane number (RON) and measured octane number (MON), estimated according to the ISO 5164 [154] and ISO 5163 [155] standards, indicated low values of 68.8 and 65.3, respectively, compared with 95 and 85 values, respectively, as prescribed by EN228:2012 [26]. Given that the VN aligns with the gasoline's distillation range, lower values may be attributed to the relatively higher presence of low-octane hydrocarbons like hexane and heptane, offset by the presence of aromatics. Of this output, around 50% by volume was identified as MGO. The authors suggested that removing the components that are not of plastic origin from marine plastic litter and sorting them could contribute to the increase in yield [26]. Conversely, Veksha et al. [153], found that it is unnecessary to wash sorted PET waste before pyrolysis, as the quality of the resulting products remains unchanged.

By comparing commercial marine gasoil and gasoil obtained from marine litter pyrolysis [151], it was found that the gasoil derived from marine litter fully adheres to the ISO 8217 standard [156]. In contrast, VN is notably abundant in BTX, ethylbenzene, styrene, and alpha olefins, all of which are valuable recoverable platform chemicals for industrial upcycling. The identification of the 2,4-dimethyl-1-heptene by gas chromatography–mass spectrometry (GC-MS) serves as a chemical component of all marine litter pyrolysis, differentiating between commercial and pyrolysis marine gasoil [151].

The environmental assessment of marine plastic litter recycling, including PET bottle sorting, pyrolysis and chemical vapor deposition (CVD) of seashore (SP) and underwater plastics (UP) waste, showed that marine PET debris recycling could be a promising and sustainable strategy for scale-up, associated with the provision of multi-walled carbon nanotubes (MWCNTs) [153].

Hee et al. [11] reported an innovative approach to utilize the condensable fractions, generated by the pyrolysis process, of two heterogenous marine plastic litter batches collected from the North Sea and agricultural mulch foil, as reference, for biotechnological upcycling. Thermogravimetric analysis (TGA) conducted to simulate pyrolysis mass losses of investigated marine plastic litter revealed values of 79 wt% for marine plastic litter Sylt, 88 wt% for Norderney, and 91 wt% for mulch foil. In all cases, the TGA and Derivative Thermogravimetry (DTG) signals displayed a gradual continuation of mass loss beyond 500 °C, suggesting the migration of fixed carbon to the volatile phase for all materials. After the incineration process, different ash contents of 13.52 wt% for marine plastic litter Sylt, 10.55 wt% for marine plastic litter Norderney, and 0.83 wt% in the case of mulch foil resulted, due to the heterogeneity of the collected marine plastic litter or the calcination of contained carbonates at temperatures above 550 °C in TGA. The carbon content in pyrolysis condensates was identified as 77.0 wt% for marine plastic litter Sylt, 72.7 wt% for marine plastic litter Norderney, and 56.6 wt% for mulch sample indicating a potential utility of carbon source for biotechnological upcycling within the framework of a circular economy concept. The caloric value was 41,500 kJ/kg for marine plastic litter from Sylt, 37,210 kJ/kg for marine plastic litter from Norderney, and 42,170 kJ/kg for the mulch sample.

### *4.4. Hydrothermal Carbonization*

Hydrothermal carbonization (HTC) is a promising technology that aligns with the principles of a circular economy and sustainable waste management. The final products resulting from HTC are solid hydrochar, the liquid fraction and a small quantity of gases. The hydrochar could be used as fuel [10], adsorbent materials for dye, heavy metal, and emerging pollutant removal [157]. Compared to pyrolysis and gasification methods, HTC it less energy-intensive and provides a better control of the emitted gases. It operates at a relatively moderate temperature and pressure for transforming plastic waste into fuel.

An innovative approach of HTC was developed by Iñiguez et al. [10], who used, for the first time, marine water as an inexpensive and abundant solvent in the process, contributing to the overall sustainability of the technology and environmental impact. By investigating the hydrochar characteristics resulted from the processing of four common types of polymers found in seawater at 200 °C and 250 °C, respectively, the increase in the carbon and hydrogen contents was observed. If low CO emissions were observed with an increase in temperature, the authors suggested that 250 °C could be considered effective for a possible transformation of marine plastic litter into hydrochar, especially when the plastics cannot be recycled by other methods.

*4.5. Blockchain Technology*

Using blockchain technology (BCT) with a digital token system and identity recognition mechanism is another innovative approach to addressing the management of marine plastic litter [158]. BCT proves to be instrumental in overcoming challenges related to marine debris management, contributing to public awareness about recycling, establishing a global recycling network, and intensifying societal and consumer oversight. In this strategy, each unit of plastic waste that is collected or recycled is represented as a digital token on the blockchain. Tokens can be used as incentives awarded to individuals or organizations that participate in cleanup efforts, correlating them with the amount of plastic collected. These tokens function as a digital product passport, confirming the authenticity and origin of the plastic waste. The characteristics of digital wallets and distributed ledgers within this approach have the potential to effectively replace traditional paper documents and cash transactions in the conventional recycling chain, thus, reducing the global impact on local economies, and ultimately enhancing efficiency and safety. The blockchain ledger ensures a transparent and traceable movement of tokens, providing a comprehensive history for each plastic item from its collection point to its processing or recycling stage. By using a decentralized identity system, individuals or entities involved in cleanup initiatives can retain control over their own identity information, thereby enhancing privacy and security.

According to BCT, Waste2Wear, a Chinese company, transformed recycled plastic bottles collected from the ocean into textiles for various purposes, including uniforms for workers, hotels, hospitals, schools and household items like curtains, bed sheets, and pillows [158].

*4.6. Cleaner Manufacturing Processes*

Only one study was dedicated to recycling waste MPs derived from PET bottles, foam and EPS with an average size < 500 µm [159], by their incorporation as filler into a bio-based matrix resulting in the creation of an innovative open-cell foam material. This foam exhibits versatility, finding applications in acoustic and thermal insulation across various domains, including industrial, civil, and maritime.

## 5. Policy Support in Addressing Marine Plastic Litter

Policies with regard to waste management and marine pollution were adopted in the early 1970s by countries such as Japan, USA, Norway and China. However, only in the late 1980s were the first legislations addressing plastic pollution in the marine environment implemented (for example, the USA's Marine Plastic Pollution Research and Control Act from 1987). Political actions on marine plastic pollution were triggered by the growing number of research studies and initiatives [160] that had been developed a decade earlier and that showed the threat to marine life and entire ecosystems, posed by the continuously increasing annual production of plastic products and the quantity of mismanaged plastic waste drifting towards oceans. Thus, involvement from authorities, and the public and private sectors has accelerated over the decades. Approximately 68% of the actions studied here were implemented or have been prepared for implementation in the past 10 years. The increasing number of actions initiated by researchers and citizens gave the issue a sense of urgency, in particular due to the emergence of microplastics and their impact to aquatic ecosystems and human health. The media and non-governmental organizations (NGOs) also played a crucial role in driving policies. Walther et al. [161], highlighted that a cascade of actions occurred, starting from NGOs and media towards governments and industry.

Most of the marine plastic pollution laws specifically addressed sea-based sources of pollution (Figure 3).

| Topics | Micro- and macroplastic actions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Policy | Strategy | Plan | Initiative | Coalition | Convention | Campaign | Programme | **Total** |
| land-based sources | 4 | 3 | 7 | 1 | 0 | 2 | 0 | 3 | **20** |
| sea-based sources | 7 | 2 | 5 | 2 | 0 | 5 | 0 | 0 | **21** |
| monitoring | 7 | 1 | 5 | 10 | 0 | 0 | 1 | 3 | **27** |
| cleanup | 3 | 1 | 3 | 14 | 1 | 0 | 7 | 2 | **31** |
| ban/restriction of SUPs | 43 | 2 | 3 | 3 | 1 | 0 | 0 | 0 | **52** |
| ban/restriction of MPs use | 7 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | **8** |
| taxes/charges/return for SUPs | 14 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | **19** |
| finding alternatives to plastics | 4 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | **11** |
| collection | 6 | 2 | 3 | 1 | 1 | 1 | 1 | 0 | **15** |
| separation | 4 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | **6** |
| reduction | 25 | 11 | 11 | 7 | 4 | 5 | 1 | 6 | **70** |
| recovery | 5 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | **7** |
| recycling | 21 | 5 | 7 | 7 | 4 | 2 | 2 | 4 | **52** |
| reuse | 11 | 2 | 2 | 6 | 2 | 1 | 0 | 2 | **26** |
| disposal | 5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **6** |
| EPR | 15 | 0 | 2 | 6 | 1 | 0 | 0 | 0 | **24** |
| polluter pays | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **2** |
| design & labelling | 12 | 0 | 3 | 5 | 1 | 0 | 0 | 0 | **21** |
| circular economy | 9 | 6 | 4 | 4 | 5 | 0 | 0 | 1 | **29** |
| investment in infrastructure | 1 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | **7** |
| training | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | **3** |
| stakeholder engagement | 1 | 0 | 6 | 3 | 2 | 2 | 0 | 0 | **14** |
| education & awareness | 8 | 4 | 10 | 22 | 1 | 0 | 6 | 2 | **53** |
| sustainable consumption | 1 | 1 | 5 | 2 | 3 | 0 | 0 | 0 | **12** |
| RD&I (support) | 3 | 3 | 5 | 6 | 1 | 0 | 0 | 4 | **22** |
| microplastic focus | 7 | 3 | 4 | 2 | 2 | 1 | 0 | 5 | **24** |
| **total** | **226** | **49** | **91** | **106** | **34** | **21** | **21** | **34** | |

**Figure 3.** Classification of actions dealing with plastics depending on focus.

Previous studies also reported a disproportionate policy focus on sea-based sources of plastic pollution [162], despite estimations [55] showing that 80% of plastic waste leaks through rivers from land-based sources. However, in the recent years plans, strategies and programs have started to consider land-based sources. One particular type of legislation, which may have an impact on land-based sources of marine plastic pollution, regards SUP. Most of the legislation banned or restricted the manufacture, use and sale of SUP, or imposed a tax/return scheme on certain SUPs. Bangladesh was the first country to give a nation-wide ban on plastic bags, in 2002, and 126 other countries followed suit [163]. Some countries also banned plastic tableware, straws, plastic-stemmed cotton buds, or cups and lids. However, recent reports suggested that bans on SUP products were not effective in reducing plastic consumption or litter, as the public shifted towards other plastic products [161,164]. Studies highlighted that factors such as socio-economic conditions and involvement of the public from the proposal stages of the law should be considered for increased success in policy implementation [162,165–167]. Nevertheless, only eight legislative acts mentioned education and awareness, and stakeholder engagement as part of their measures. Such policies included, the EU's "Plastic Bags Directive" or the "Law to combat plastic pollution and protect the environment" in Costa Rica. Moreover, proposals, such as those for the EU's Directives, were posted online for public consultation and discussed in stakeholders' workshops. However, it is not clear if consultations and discussions reached local or isolated communities.

Initiatives, plans and campaigns were developed to increase public education and awareness with regard to marine plastic pollution and the influence on ecosystem and human health (Table S1, Supplementary Materials). In particular, initiatives and campaigns led by civil societies may have had an impact on vulnerable communities for education and awareness, in order to detect and reduce pollution, as in the case studies reported by Calil et al. [168]. Civil societies can be the link between increased education and awareness, and law enforcement at local levels [169]. For example, India has a limited capacity to construct, maintain and operate recycling plants [168] and relies on informal waste pickers to deal with the large amounts of waste. Thus, campaigns have been implemented by civil societies to train and support informal waste pickers in collecting and segregating plastic waste [170].

Several actions were targeted towards reducing, recycling and reusing plastic waste in the environment. Most of the recycling policies are legislative acts, which deal with waste management in general, such as the EU "Waste Framework Directive", the "National Sustainable Waste Management Bill" in Mexico or the "Recycling and Waste Reduction Act" in Australia. Other regions developed policies specific to plastic waste, such as the "Plastic Pollution Control Action Plan" in China and the "Fishing Net Waste Recycling" in Taiwan. Relatively recent policies focused on ensuring a circular economy of plastics. Notable examples include the "Strategy for Plastics in a Circular Economy" in the EU, the "Plastic Innovation Challenge" in the USA, the "Act on Promotion of Resource Circulation for Plastics" in Japan or the "General Law of Circular Economy Initiative" in Mexico. A report of OECD showed that, globally, only 9% of plastic waste is recycled, while 22% evades waste management systems and can leak into aquatic ecosystems [171]. Since most of the policies on recycling and circular economy have been adopted in the past five years, their impact on reducing marine pollution has yet to be determined.

An important component of a circular economy is the implementation of the Extended Producer Responsibility (EPR). Simply put, EPR shifts the responsibility from consumers to producers with regard to providing funding for collection, recycling and safe disposal of products [52,172]. EPR is largely used in the EU and it regards several goods, including those made of plastic. With the EPR, the aim is to reduce the use of virgin material, focus on eco-design, reduce pollution during production and reduce waste volumes [173]. Countries outside the EU have also implemented the EPR schemes (for example, Turkey, Saudi Arabia, UK, Norway, India, South Africa or Chile) or have them in preparation (Mauritius). Wang [174] argued that the EPR scheme is successful in developed countries, but it would be difficult to introduce it in developing countries, who lack infrastructure for advanced recycling and are the victims of plastic waste transfer. Wang [174] also points out that EPR allows an imbalanced distribution of responsibility between manufacturers and consumers. However, in a recent G20 report [175], even developed countries, such as Australia, Norway or the USA, acknowledged challenges in the recycling systems sector. Larrain et al. [176] stated that the best results can be achieved by a combination of policies that target economic support.

However, economic support in infrastructure or the research and development sector is rarely included in policies. Investment in infrastructure improvement is a part of some plans, such as the "National Action Plan on Marine Litter and Marine Contaminated Sediment" in South Korea or the "Action Plan to Combat Marine Litter" developed by the nations forming the G7 group. Also, the research, development and innovation sector is supported mostly by programs. Notable are the EU's research programs, "Horizon 2020" and "Horizon Europe". However, these programs are implemented in developed countries. For the developing countries, Larrain et al. [176] mention that lack of innovation could be compensated by allowing companies more time to react and adapt to adopted policies. Nevertheless, some financial support has been provided towards the research, development and innovation sector in developing countries, through USA government programs (for example, Building Capacity for Environmentally Sound Management of Plastic Waste in Senegal) or Norway programs (for example, Small Grant Program on Plastic Waste, with the cooperation of the Basel Convention and Stockholm Convention centers). Improved and concerted support can be achieved mainly by global programs.

Figure 4 shows the constellation of main coalitions, networks and policies developed at the global level and their area of potential impact.

A total of eight major coalitions have been developed, covering multiple continents, such as The Global Partnership on Plastic Pollution and Marine Litter (GPMPL) or only a region, such as the Australia, New Zealand, and Pacific Island Countries Plastics Pact (ANZPAC). These coalitions include political leaders, entrepreneurs, scientists, advocates or social influencers aiming to shape policies and actions in order to reduce marine plastic litter. An important role is played by the EU and UNEP in driving international commitment towards a common goal. The EU has implemented several laws to address litter, some of them with focus on plastic waste. In 2015, the EU adopted the Plastic Bags Directive, and in 2018 and 2019 the "Plastics in Circular Economy" and the "Single-Use Plastics"

Directive. Finally, in 2023, the EU proposed a regulation to prevent plastic pellet losses in order to reduce MPs pollution and an action plan against MPs. The EU also amended the REACH Regulation to restrict the use of all MPs with sizes below 5 mm. Once adopted, all EU member states must comply, which may lead to a more positive impact on the marine environment than actions taken at individual level. In 2017, the United Nations Environmental Assembly (UNEA) adopted a resolution regarding marine litter and MPs. Following the resolution, amendments on plastic waste were added in the Basel Convention, and the G20 group formed the Osaka Blue Ocean Vision in order to provide effective implementation of policies and improved outreach. In 2022, the resolution 5/14 "End Plastic Pollution: Towards an International Legally Binding Instrument" was adopted by the UNEA. Recently (November 2023), UNEP held its third meeting in order to prepare an international legally binding instrument on plastic pollution, including in the marine environment [177]. The UNEA resolutions led to the formation of the High Ambition Coalition to End Plastic Pollution (HACEPP) and the Business Coalition for a Global Plastics Treaty (BCGPT) to facilitate the adoption of the legally binding instrument.

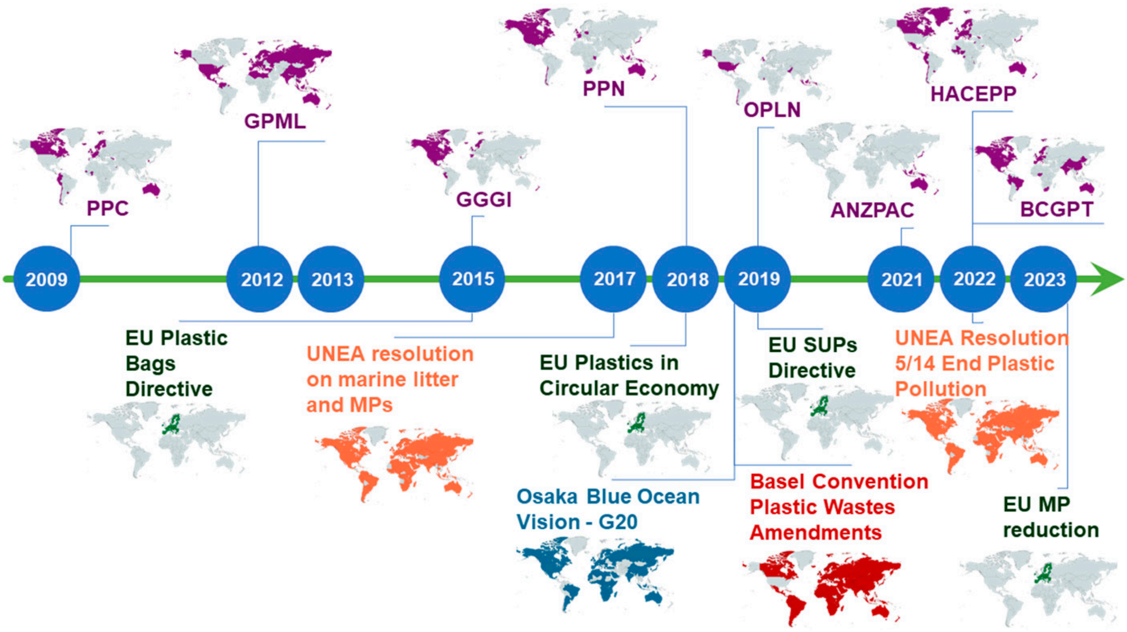


**Figure 4.** Main policies and coalitions with regional and global impact regarding marine plastic pollution. PPC (Plastic Pollution Coalition); GPMARINE PLASTIC LITTER (Global Partnership on Plastic Pollution and Marine Litter); GGGI (Global Ghost Gear Initiative); PPN (Plastics Pact Network); OPLN (Ocean Plastics Leadership Network); ANZPAC (Australia, New Zealand, and Pacific Island Countries Plastics Pact); HACEPP (High Ambition Coalition to End Plastic Pollution); BCGPT (Business Coalition for a Global Plastics Treaty). Maps created with mapchart.net.

UNEA's resolutions, the Basel Convention, the Osaka Blue Ocean Vision and the Business Coalition for a Global Plastics Treaty, which involve nations from across the globe, have the potential to deliver positive changes in Asian and African countries, where estimations indicate the largest inputs of mismanaged plastic waste to the marine environment [178]. According to the estimations of Jambeck et al. [178], China, Indonesia, Philippines, Vietnam, Sri Lanka, Thailand, Egypt, Malaysia, Nigeria and Bangladesh represented the top ten countries with the highest mismanaged plastic waste. However, only 10% of the policies, shown in the Supplementary Material, originated from these countries. Out of these, most of the policies were adopted by China, the "National Sword Initiative", the "Circular Economy Promotion Law" and the "Plastic Pollution Control Action Plan" being the most notable. China has also introduced campaigns for clean-up events and the promotion of education. More importantly, the ban on waste imports, through the "National Sword Initiative" in

2017, has led to a substantial decrease in plastic waste in the country and potentially forced exporting countries to improve their recycling systems [179]. Indonesia has also taken a series of actions to reduce mismanaged plastic waste and leakage into the ocean [180,181]. The "National Plan of Action on Marine Plastic Debris" aims to reduce 70% of the marine plastic pollution by 2025. Also, the "National Plastic Action Partnership" brought together the private and the public sectors under a common goal, which is to increase investment, innovation and education on the issue. Despite campaigns from citizens to clean-up marine litter, studies showed that behavior towards plastic use has not changed at the community level in Indonesia [180]. In addition, the "National Plan of Action on Marine Plastic Debris" failed to meet its target and needed an extension [180]. Sri Lanka also started to strengthen its policies towards plastic waste, including a ban on SUP products and the "National Action Plan on Plastic Waste Management". On the African continent, the top two importers of plastic waste, Egypt and Nigeria [182], are also amongst the highest with mismanaged plastic waste [178]. African countries have the highest number of policies that ban plastic bags [183]. However, a limited number of policies on plastic waste management are implemented because of the lack of national commitment and strategies, fragmentation of initiatives, disproportionate allocation of funds, inadequate infrastructure, etc. [183]. The legally binding instrument proposed under UNEA is seen as an opportunity for cooperation and coordination between countries for effective implementation of policies and reduction of marine plastic waste. A robust international framework would drive national legislation, in particular in the countries with limited recycling capabilities and where environmental injustice may interfere with enforcement [168]. It would also allow all countries to voice their concerns and find solutions for plastic waste that are equally acceptable for all involved parties. In addition, a strong international framework may determine powerful stakeholders to find solutions to eliminate plastic waste pollution instead of shifting it around [168].

## 6. Conclusions and Perspectives

Marine plastic pollution poses significant long-term threats to marine ecosystems and, potentially, human health, emphasizing the urgent need for global initiatives to mitigate this ubiquitous form of pollution [184]. The aim of this review was to examine recent technologies for marine plastic litter valorization. The following conclusions and research directives were found:

- The specific characteristics of marine plastic litter influence the choice of recycling technology.
- The traditional mechanical recycling methods are widely applied to SUP. However, for marine plastic litter, the technology is impractical, due to a combination of plastic types and poor mechanical properties. The important challenges include establishing the mechanical properties of marine plastic litter, incorporating virgin polymers, if necessary, and identifying the appropriate product for processing.
- A promising approach for addressing marine plastic litter involves thermochemical recycling (pyrolysis). However, due to the complex chemical composition of marine plastic litter as well as the presence of biomass, heavy metals, salts, and toxic gases during heat treatment, chemical recycling of marine plastic litter has not been developed at an industrial scale.
- Marine plastic waste can constitute raw materials for different applications such as 3D samples, fiber reinforcement in gypsum-based materials, fuel, energy, and adsorbent materials for dye, heavy metal, and emerging pollutant removal.
- BCT could be investigated for its significant potential to transform waste management practices, offering a contribution to making plastic waste management more sustainable, environmentally friendly, and economically efficient.
- Further research and development, such as the integration of Industry 4.0 technologies for creating sensors and IoT devices, analyzing data with machine learning algorithms, and exploring new methods for transforming collected plastic waste into high-value

products through advanced processing and 3D printing technologies, is necessary to overcome associated challenges and improve the efficiency of existing monitoring and recycling methods for marine plastic litter.

Despite the development of recovery and recycling technologies, efforts to reduce plastic pollution at the source, such as by implementing policies to limit the use of SUP and promoting sustainable practices, should be addressed in order to reduce plastic pollution in marine ecosystems. Financial support for the innovation and research sector, and technological transfer and training must be offered towards developing countries to increase their recycling capabilities. Implementing effective waste management systems to handle marine plastic litter and prevent it from entering the ocean involves substantial financial investments. However, clear targets and commitments of law enforcements are needed from developing countries. Also, the link between civil societies and authorities must be strengthened to ensure public education and awareness, and policy enforcement.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling9020030/s1, Table S1: The actions supporting the management of marine macro- and microplastic litter.

**Author Contributions:** Conceptualization, M.R., E.M.C. and C.L.P.; methodology, M.R., E.M.C. and A.A.Ș.; software, A.G.D. and S.I.D.; validation, M.R. and C.L.P.; formal analysis, E.M., A.M.P., C.P. and S.I.D.; investigation, M.R., E.M.C. and A.A.Ș.; data curation, A.G.D.; writing—original draft preparation, M.R., E.M.C. and A.A.Ș.; writing—review and editing, M.R., E.M.C. and C.L.P.; visualization, E.M. and A.M.P.; supervision, C.P.; project administration M.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by EU-Horizon 2020 (InNoPlastic) G.A. no. 101000612.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** E.M.C., C.L.P. and S.I.D. acknowledged the Ministry of Research, Innovation and Digitalization, and CNCS—UEFISCDI, through the following projects: 18PFE/30.12.2021 and Core Program OPTRONICA VII PN23 05 (11N/2023).

**Conflicts of Interest:** The authors declare no conflicts of interest.

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