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Review

Perspectives on Micro(Nano)Plastics in the Marine Environment: Biological and Societal Considerations

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Abstract: Marine litter is a global problem which has been negatively affecting the environment. Plastic materials are the most commonly found marine debris, with potential biological (not only for aquatic organisms but also for humans) as well as socio-economic impacts. Considering that it is an anthropogenic problem, society could play an important role to minimize it. Although a considerable amount of research has addressed the biological effects of plastics (micro(nano)plastics) on biota, few studies have addressed how scientific information is being transmitted to the public and the potential role of citizen environmental education. The current paper discusses known effects, researched topics and how scientific knowledge is currently being transmitted to the public.

Keywords: marine litter; microplastics; nanoplastics; COVID; education; effects

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1. Marine Litter

Defined as any persistent, manufactured or processed solid material discarded, disposed of, or abandoned on the coastline or in the sea [1], marine litter is currently considered a major threat to the marine environment [2–5]. Around 80% of the marine debris originates from numerous land-based sources such as poorly managed burials in landfills, untreated sewage, inadequate industrial control, recreational use of coastal areas, and tourist activities [6,7]. These materials can be transported to water bodies via storm drains, rivers, and weather events. Marine debris is also associated with ocean-based sources such as shipping and fishing. Although a wide variety of marine litter can be found (e.g., glass from different sources—carpentry, jars, glass beverage and bottles; metals—aluminum cans being the most commonly found metal item; textiles; papers), plastics are the most abundant type [4,8,9], associated with high production and use, as well as high resistance to degradation and persistence in the environment [4]. Cigarette butts are among the most frequent litter discarded and found in beaches [8,10,11]. It has been estimated that, of the 6 trillion cigarettes yearly smoked worldwide, 4.5 trillion are discarded as litter in the environment [8,11,12]. This type of litter is of environmental concern as a large number of compounds may be found in cigarettes, some of which have carcinogenic and mutagenic potential. Furthermore, the burning of cigarettes promotes the generation of new compounds that may also be harmful to aquatic organisms [8,11,13]. In addition to cigarette butts, plastic bottles and bottle caps are among the most collected items, followed by food wrappers, plastic grocery bags, plastic lids, straws, glass beverage bottles, plastic bags, and take-away containers.

The potential consequences of the presence of plastic particles in the environment has only recently attracted the attention of the public, although it was raised for the first time in the 1970s with the reports of the presence of microplastics in coastal areas and oceans by Carpenter [14,15]. Nonetheless, plastic production kept increasing along with single-use plastic products.

Nowadays, plastic pollution is recognized as a global problem with pernicious effects reported on several aquatic species [16,17], and potential effects on humans considered [18]. The cost-effective nature of plastics, associated with an increasing population, resulted in a continuously increased production of plastics since the 1950s, reaching, in 2018, 359 million tonnes [19]. Asia was the largest producer of plastics (51%), followed by NAFTA (Canada, Mexico, United States) (18%), and Europe (17%). Most of the plastic used in daily life is for packaging (39.9%), and it is also used in activities like building and construction (19.8%), medicine and engineering (16.7%), and the automotive industry (9.9%) [19]. The most produced synthetic polymer is polyethylene (Figure 1), followed by polypropylene (PP), and polyvinyl chloride (PVC) [19].

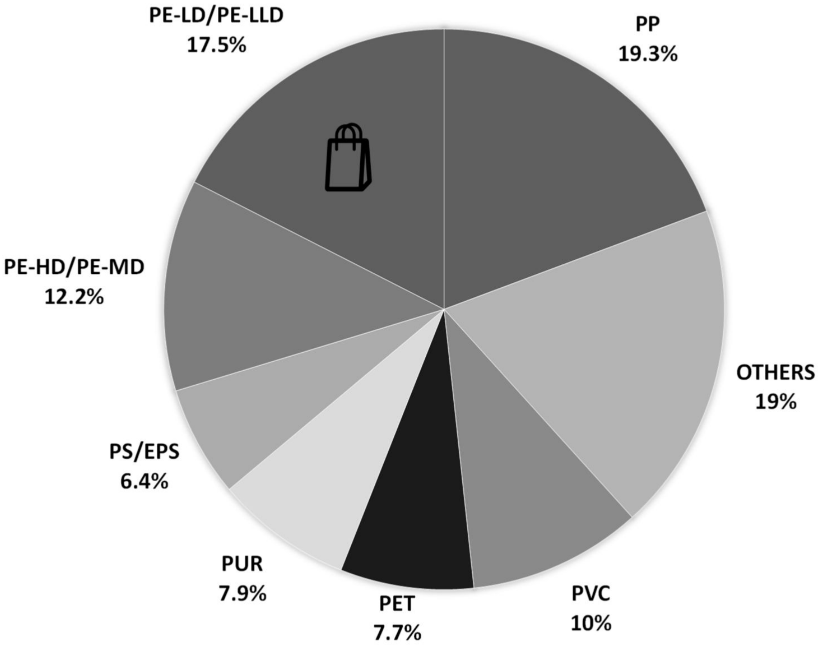

Figure 1. Conversion percentage of plastic polymers. Abbreviations are as follows: PE-LD: polyethylene low density; PE-LLD: polyethylene low linear density; PE-HD: polyethylene high density; PE-MD: polyethylene medium density; PS: polystyrene; EPS: polystyrene expandable, PUR: polyurethane; PET: polyethylene terephthalate; PVC: polyvinyl chloride; PP: polypropylene; others includes polymethylmethacrylate (PMMA), vinyl ester resins, acrylic resins. Note: Data for the construction of the graphic were collected at https://www.plasticseurope.org/, published in 2019.

Lebreton and Andrady [20] estimated that in 2015, between 60 and 99 million tonnes of mismanaged plastic waste were produced and that, by 2060, levels could reach 155–265 million tonnes. Plastic products may enter the environment through different pathways associated with land-based activities associated with human daily routine, product wear (e.g., clothes releasing synthetic fibers) and behaviors such as littering, inadequate industrial disposal of products, inadequate waste management, and recreational activities in coastal areas. Storms and sewer overflows, run-off, and wind promote a higher dispersion of these products. However, several items may also be associated with marine-based activities like naval shipping and fishing (e.g., ghost nets).

At the end of its service life, if properly handled, the plastic collected can be processed for recycling, energy recovery, and landfill (Figure 2). After recycling or energy recovery, plastic waste can be reused in phases 1, 2, and 3 (Figure 2) of plastic life cycle [19].

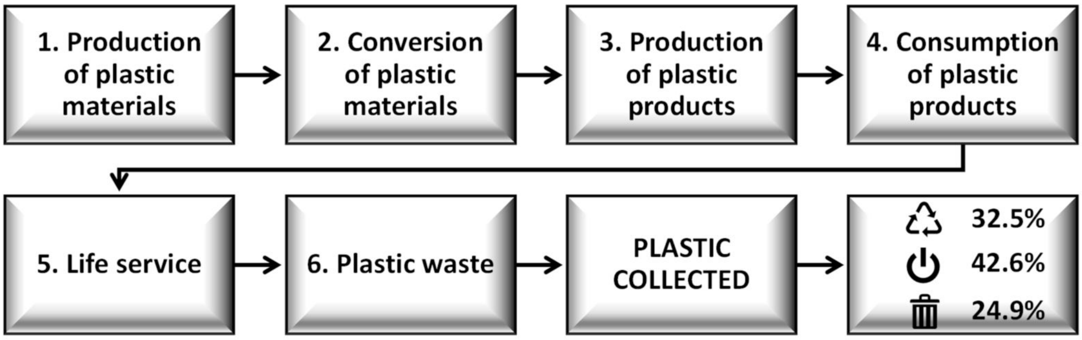

Figure 2. Flow chart representing the main steps in the life of plastic products. The symbols stand for: ♻—recycling; ⏻—energy recovery, 🗑—landfill. Note: Data for the construction of the graphic were collected at https://www.plasticseurope.org/, published in 2019.

Currently, plastic debris is of particular concern due to its abundance and persistence in the environment [21]. Once in the environment, the characteristics of plastics will be determinant in their distribution and degradation. For example, the density of plastics is considered an important property that influences its behavior in the marine environment [22]. The buoyancy of plastics increases its dispersion through the ocean [18,21]. The type and size of the polymer are important factors that dictate the buoyancy of the materials. A meta-analysis performed by Erni-Cassola et al. [23], focusing on plastic distribution, concluded that less dense plastic polymers (e.g., PE and PP) are expected to be present in sea surface, whilst denser ones are expected to end up at deeper levels. Nonetheless, the effect of buoyancy on the plastic transport is probably one of the most complicated and, so far, no large-scale models have taken into account the inertial effects. A study by Stocchino et al. [24] suggests that for negatively buoyant particles, the inertial effects dominate and the resulting horizontal distance of a single particle under the effect of the sea wave drift can reach a maximum of few wavelengths, whereas for plastic particles which are positively buoyant, the Stokes drift proves to be an effective way of transport, since the particles tend to remain in a superficial layer where the drift is more intense. In this case, other processes, such as biofouling, have been shown to modify the density and, ultimately, the settling velocity.

Plastics in the environment may break down into smaller pieces—microplastics (sizes bellow 5 mm) and nanoplastics (sizes below 100 nm) [21,25]—making removal and quantification harder [21] but increasing plastics' bioavailability [18]. Considering the size microplastics and nanoplastics reach the environment, they may be ranked as primary, those released directly into the environment in their originally small size (e.g., via domestic and industrial effluents, direct spills, and sewage discharge of consumer products such as synthetic fibers, cosmetics, medicine, paints, and raw materials), often as a result of inefficient removal processes at wastewater treatment plants [25,26]. Small particles resulting from the breakdown of larger items already present in the environment are considered secondary particles and result from a variety of actions associated with UV radiation, mechanical transformations, and biological degradation by microorganisms. This size-based distinction may help to identify potential sources and mitigation measures to reduce their input to the environment [22].

Aside from size, plastic particles found in the environment may vary considerably in what concerns their shape. Particles can be present in the form of spheres, frequently used in cosmetic and pharmaceutical industries; fibers, associated with textiles; films, associated with food packaging and agriculture (e.g., LDPE films used to protect agricultural crops, suppress weeds, increase temperature, and retain irrigation water in the soil); fragment/sheet which could possibly originate from the exposure of larger plastic items to strain, fatigue, or UV light; foam, resulting from the damage of styrofoam; and present irregular shapes [21,26–29]. This variety of shapes and densities cause different dispersion rates and bioavailabilities, as well as potential physical impacts on biota occupying different habitats [26]. The decrease in size increases the concerns associated with the presence of plastics in the environment as it promotes increased bioavailability, ability to cross biological barriers and bioaccumulate, as well as food web transfer [9]. Furthermore, the small-sized particles may play an important role as a vector of dispersion and concentration of an increasing number of contaminants (e.g., metals, organic compounds like polycyclic aromatic hydrocarbons and pharmaceuticals) [18,30]. The toxicity of these contaminants has also been shown to be modulated by the presence of micro(nano)plastics, increasing or decreasing, depending on the chemical structure of the contaminants and the nature of the polymer [31]. The ability of small plastic particles to aid in the dispersion of microorganisms may play a determinant role in the increase of pathogenic and antibiotic resistant microorganisms [18,32].

2. Impacts of Marine Litter

The consequences of marine litter are diverse. Although the biological impact of marine litter is the most acknowledged one in creating growing awareness [33], social and economic impacts may also be substantial and affect coastal communities or those depending on coastal activities.

2.1. Biological Impacts on Marine Organisms

Marine litter is currently perceived as a major threat to marine biodiversity [34,35], due to its ability to impact a large and increasing number of marine species [3,33], such as microorganisms, invertebrates and vertebrates including marine megafauna (fish, birds, sea turtles and mammals) [17,36]. The effects of micro and nanoplastics on marine organisms have been studied in different organisms and effects described at different levels of biological organization (from molecular up to the individual level) [21,31,37,38]. However, the sensitivity of marine organisms is affected by several factors associated with the characteristics of the plastics (e.g., polymers, size, surface charge, age, additives, and adsorbed contaminants) as well as the characteristics of the organisms (e.g., size, feeding strategy, distribution in the water column, pre-exposure to contamination, surrounding environment, nutritional state) [21].

The most commonly reported biological impacts of litter involve micro- and macroplastics ingestion which may provoke physical damage, blockage of the intestinal tract leading to a sense of false satiation, starvation and be potentially lethal [18,21] and entanglement on plastic debris that may compromise organisms' development and mobility (e.g., ability to capture prey, escape predators) [17,39]. Entanglement of seabirds in fishing gear, marine mammals and turtles in nets and ropes is frequently reported [33,40] and recognized as pernicious effects of these materials. However, for fishes, entanglement is not often reported or considered [17], as it is harder to observe in these organisms.

The ingestion of plastics may occur directly, when the animal ingests the material due to similarity with their prey (e.g., plastic bags and balloons mistaken for gelatinous animals) or organisms filter feed (e.g., particle beads), or indirectly when organisms feed on preys containing plastics inside the body or adhered to their surface [41]. Micro- and nanoplastics can be available to plankton, organisms present at the base of the food web [18], with potential effects on the trophic web. Despite the knowledge that particles in the nm size range become biologically more reactive and that these particles may be formed from the degradation of larger particles, the study of its effects to marine biota can be considered scarce [25,42]. Nonetheless, the available studies demonstrate that phyto- and zooplankton, the most important producers and consumers of the ocean, have shown sensitivity to micro(nano)plastics. The reported effects revealed that micro(nano)plastics may affect the growth rate of phytoplankton [25,43,44], compromise photosynthesis efficiency of phytoplankton [43], impair zooplankton growth [35], feeding [45], reproduction [43,46], and survival [25]. An ability of micro(nano)plastics to be incorporated by these organisms may result in the risk of bioaccumulation and biomagnification along the food web [4,18], with potential several effects at higher trophic levels. Fishes are reported target organisms for micro(nano)plastics ingestion, as a result of direct ingestion often due to plastic particles similarity, in terms of size and color, to planktonic organisms like copepods and crustacean larvae or indirectly by feeding on contaminated preys.

Biological Models Used in Plastics Ecotoxicity Studies

Different aquatic species have been used to assess the potential effects of micro(nano) plastics [21,38,42,47]. The available reports suggest that ingestion may be the main route of microplastics entrance in biota and that filter feeding organisms may be more susceptible. Nonetheless, a wide range of organisms at different positions in the water column may be affected by the presence of micro(nano)plastics. Among the organisms most widely used to assess the effects of micro(nano)plastics are mussels [48]. These organisms are important components of benthic assemblage, that act as ecosystem engineers via occupation of primary space, filtration, and provision of secondary habitat. Filter-feeding, organisms of the genus *Mytilus* have been widely used as biological models to study the effects of pollution in coastal areas [49] and, more recently, the effects of micro(nano)plastics (e.g., [50]). The high filtration rate of these organisms, use of waterborne particles as food [49], and ability to bioconcentrate waterborne contaminants and sessile nature, make these organisms good models to study the impact of these emerging contaminants of concern. *Mytilus* are widely used as a test model and bioindicators due to its wide availability and global distribution [48]. These organisms are especially vulnerable because, as non-selective filter-feeders, they can consume a large variety of microplastics particle type and sizes, with the potential to bioaccumulate [51]. Previous studies have investigated the impacts on tissues [52,53], filtration rate [54], particles ingestion [48,54,55], and molecular and biochemical endpoints associated with biotransformation, cell damage, genotoxicity, and immune function [50].

An increasing number of studies have also focused on marine polychaetas, the most abundant group of organisms in benthic communities. Polychaetes are key species in estuarine and coastal food webs (prey for a variety of crustaceans, fishes, and birds), thus playing an important role in the structure and functioning of these ecosystems. These organisms have been considered very relevant models for biomonitoring [56–58]. *Hediste diversicolor*, for example, stands out as a model species to study the effects of these particles on this group of organisms, demonstrating a high responsiveness to environmental micro(nano)plastics exposure. The presence of 10 and 50 mg particles/kg of sediment of a mixture of microplastics of PP and PS (polystyrene) with sizes ranging from 0.4 to 400 μm was able to impair cell viability in *H. diversicolor* [58]. PS particles of 100 nm demonstrated the ability to affect *H. diversicolor* neurotransmission enzymes (inhibited cholinesterase activity) without significant effects in oxidative stress-related endpoints at concentrations of 0.005 mg PS/L but with the ability to induce protein oxidation at higher concentrations [38]. The same study revealed, in accordance with the cholinesterase's activity, borrowing capacity as a very sensitive endpoint in these organisms, since the authors observed that at the lowest tested concentrations (0.005, 0.05, and 0.5 mg PS/L) organisms took longer to fully burrow in the sediment. Taking advantage of the regenerative ability of the ragworm, the same authors found that the same concentrations influencing borrowing activity also decreased their ability to regenerate lost parts [37]. In line with the late finding, other studies reported similar impacts of microsized PS on other important estuarine worms. Leung and Chan [59] observed that *Perinereis aibuhitensis* exposed to PS beads took longer to regenerate their amputated parts, although organisms exposed to 8–12 μm sized PS beads regenerated fewer segments than those exposed to 32–38 μm. Other polychaetas, such as tube-dwelling polychaetas, are believed to have a special role in the transport, fate, and distribution of small plastic particles, since they may use them as building materials [56,60,61]. For instance, in a study comprising sediment and tube-dwelling polychaeta samples from the Norwegian Continental Shelf and the Barents Sea, Knutsen et al. [56] found that tubes could contain six to eleven times more microplastics (≥45 μm) than the organisms' soft tissue. The same was valid for *Gunnarea gaimardi*, an indigenous reef-building polychaete of the coast of South Africa [61]. Overall, polychaetas have demonstrated a high sensitivity to plastics, being responsive in waterborne exposure conditions (that may be considered more representative of environmental conditions), as well as to spiked sediments.

Fishes, representing the third major source of dietary protein for humans [62], have been the subject of different studies aiming to detect the presence of micro(nano)plastics in wild organisms and organisms from aquacultures, as well as the effects of these particles [42]. Considering the relevance of these organisms as human food source, the effects of micro(nano)plastics is of great concern due to their potential horizontal transfer. Field studies indicated that fishes have the potential to accumulate large quantities of debris in their tissues. For example, Barboza et al. [63], who examined the presence of microplastics on a total of 150 fish of three highly consumed species (*Dicentrarchus labrax*, *Trachurus trachurus*, *Scomber colias*), observed the presence of microplastics in almost half of the samples (49%), distributed through the gastrointestinal tract (35%), gills (36%), and in the dorsal muscle (32%). Similarly, Li et al. [64] verified that the sharp belly fish (*Hemiculter leucisculus*) collected in a heavily industrialized area (surrounded by plastic production facilities) could retain in their guts up to 1.9–6.1 particles/individual, whilst organisms collected at a reference site presented an average of 0.2 ± 0.01 particles/individual. The available studies addressing the effects of micro(nano)plastics show that plastic may promote a decrease in cell viability, as demonstrated in vitro in fish cell lines from *Sparus aurata* (SAF-1) and *D. labrax* DLB-1 exposed to PS nanoplastics [31]. The ability of micro(nano)plastics to deregulate metabolic pathways related with fatty acids metabolism and immune responses, induce genotoxicity and alter oxidative status [65,66] and neurotransmission [67], induce histopathological changes [68] and alter fish swimming [69], and feeding behavior [70], among other effects, has been reported in estuarine/marine fish. Such effects may be later translated into lower nutritional quality of fish muscle, which is of high concern, particularly for fish with commercial value.

Jellyfish are a group of organisms, abundant in marine environments, that provide important ecosystem services including habitat provisioning and food source for megafauna [71], contributing to carbon and macronutrient dynamics [71–73]. Considering that these organisms commonly feed on zooplankton and fish eggs, jellyfish may be potential targets of plastic pollution. Furthermore, the distribution of some of these organisms and plastics is influenced by winds and currents, promoting their presence in regions with a high concentration of marine litter [73]. The available studies have shown that both pelagic and benthic jellyfish are able to incorporate microplastics. Macali et al. [73] found that the mauve stinger *Pelagia noctiluca* can internalize marine litter and potentially serve as a vector of plastics dispersion along marine trophic webs [73]. Costa et al. [74] reported that *Aurelia* sp. ephyrae jellyfish could ingest microplastics (1–4 μm PE), which affected its health and impaired both survival and behavior. However, no physiological or histological effects were detected by Sucharitakul et al. [72] in *Aurelia aurita* medusae following microbead ingestion. In the benthic upside-down jellyfish (*Cassiopea xamachana*), microplastics have been detected in organisms sampled in estuaries [71], supporting the idea that these organisms may serve as potential bioindicator species.

Occurrences of plastic ingestion, entanglement, suffocation, or others, in mammals, seabirds, or marine reptiles have become common. Sea birds that eat floating plastics, stranded or washing ashore whales and/or dolphins are among the most noticed effects in the news and on social networks in general. High trophic level taxa can be considered as sentinels for changes in their environment, with plastic pollution being no exception. In a study covering 50 individuals from three large mammal groups (whales, $n = 22$; dolphins, $n = 21$; seals, $n = 7$) from the British coast, microplastics were found in all animals, with particular higher incidence in the stomachs than the intestines [75]. In alignment with the previous report, seabirds may also be impaired by plastic pollution either by ingestion (e.g., [16,76]) or entanglement (e.g., [77]).

2.2. Biological Impacts on Humans

Humans may be the subject of the pernicious effects of micro(nano)plastics trough a wide range of products and environmental sources (e.g., water, seafood, table salt). However, as for other animals, the concern about effects of the presence of these particles should also consider the toxicity of plastics additives and environmental contaminants that adsorbed onto plastics surface, in contaminated environments. Besides cosmetics, medicines, or air-borne particles, food items and drinks are considered a major source of human exposure to micro(nano)plastics (these include items such as drinking (bottled) water and other beverages such as beer, honey, table salt, and seafood) (e.g., [18,48,78–82]). Food preparation processes and/or storage can play an important role in the presence of micro(nano)plastics in food items (e.g., [18]).

The trophic transfer of small plastic particles in the aquatic environment has been a concern. It has already been reported that particles ingested by organisms at the lower trophic level of the food web such as zooplankton, can be passed up the food web to higher trophic levels such as fish, and may eventually end up for human consumption [18]. Common human dietary food items such as bivalves and fish are examples of potential sources of plastics through human diet [18,83,84]. For instance, Davidson and Dudas [85] reported that in Manila clam (*Venerupis philippinarum*), microplastics were present in farm organisms and organisms collected in reference locations in Baynes Sound (British Columbia), with plastic levels able to reach 5.47 particles per gram of organism. Similarly, in a study comprising a greater number of commercial fish and bivalves (11 species from Makassar, Indonesia and 13 species from California, USA), Rochman and co-authors [86] found plastic debris in over 50% of the samples, with the highest percentage of synthetic particles being fibers.

Despite the reported effects on aquatic organisms, the impacts of micro(nano)plastics on humans are not clear and should be addressed in more research studies (e.g., through in vitro human cell lines testing) [18,21]. Stock et al. [87] studied the uptake and transport of 1, 4, and 10 µm of PS on different cell lines, reporting uptake of 40 to 80% of 4 µm PS particles by THP-1-derived macrophages with no observed effect on cellular metabolism or viability. Using cell line BEAS-2B (human lung epithelium), Dong et al. [88] verified that PS microplastics (>10 µg/cm^2) were very cytotoxic to cells causing a cell viability decrease in the order of 60 to 70%, with many of the remaining viable cells presenting alterations on their shape and size (rounded and smaller than control), accompanied by massive production of reactive oxygen species.

Despite this evidence, so far, the link between human exposure to environmental micro(nano)plastics and adverse effects on humans has not been established [9,18]. More studies are needed to increase the current scientific knowledge.

2.3. Socio-Economic Impacts

Marine debris can have considerable socio-economic costs, particularly in countries with economies based on sea activities like aquaculture, fishing, and tourism [18,89]. The presence of high levels of plastic debris and other marine litter items in a particular area may compromise the health of biota and, in turn, compromise the market value of products like fish and shellfish [18]. It is expected that products from areas labelled as highly polluted and/or with reported presence of micro(nano)plastic can be suspected to be hazardous to humans and thus less likely to be commercialized. The decreased value may even be higher for aquaculture-related products, given the importance of plastic materials (feeding material, cages, nets) in this activity. This may also have a serious impact in seafood-based restaurants. The idea of economic losses may motivate industry to adopt more pro-environmental actions, that may include product design and life cycle consideration. In addition, the presence of marine litter in coastal areas is also an unattractive landmark, decreasing aesthetic and intrinsic value of costal systems like beaches and reefs [2]. For instance, among the several aspects that influence tourists intent to visit a particular coastal area is the beach length, water quality, and/or shoreline characteristics, which can be negatively affected by the presence of marine debris [90]. This may have tremendous consequences at local and national level, particularly for countries that have as main revenue source beach and aquatic activities related tourism. This notion motivates national and local authorities as well as beach activities associated merchants to support/organize beach cleaning actions, to remove the marine litter constantly brought by sea currents and winds. Although many of these activities are promoted among the community and often take place with the help of volunteers, they still involve costs. For instance, to aid maintaining tourism revenue, in the UK, removal of beach debris from 20,000 km of coastline alone, represents a yearly cost of €18 million [22]. The presence of marine litter may also compromise sports activities in the waters (e.g., surf events and schools) and sand (e.g., beach volley events), not only for the aesthetic aspects but also for potential health risks [18].

Although there is no consensus on how to solve the plastic pollution problem, it is important to develop actions to minimize micro(nano)plastics formation and environmental release. This can be achieved at different levels, from production (e.g., design of products) to consumer usage and product selection (e.g., avoidance of single use materials and items considered potential hazards to environmental and human health) and increased recycling rates [18]. Society plays an important role for this type of pollution via its lifestyles, choices, and behavior [89]. Despite the European legislation to reduce single-use plastics and the removal of plastic beads from cosmetic products, it is necessary to educate and promote campaigns targeting schools, communities, and industry to promote changes in people's behaviors. Plastic consumption reduction, increased reuse and recycling should be encouraged to decrease the problem of plastic debris. This may be achieved through economic stimuli. A recent study performed by the research group in Portugal revealed that the bio-ecological impacts of plastics are recognized, but more environmentally friendly behaviors could be achieved with financial incentives or counterparts (unpublished data). Measures like a refund for returned plastic beverage containers or tax benefits in the reuse of plastics for industries and consumers are some examples of social economic stimuli that may aid in minimizing the release of plastics to the environment and ultimately the presence of micro(nano)plastics. Scientists and environmental groups are considered as the most competent and motivated to reduce marine litter but, on the other hand, they are the least responsible for marine litter.

3. Plastic Use in the COVID-19 Scenario—Additional Environmental Stress

In late December 2019, a novel infectious disease with human-to-human transmission (COVID-19) was identified in Wuhan (China), that quicky turned into a global pandemic [91]. Most governments ordered citizens to stay at home to contain coronavirus outbreak which led, for the first time, to a global decrease of production and a decrease in planetary environmental pressure. This confinement led to decreased levels of gas emissions (e.g., from industries and cars) [91–93] and decreased levels of other pollutants on beaches around the world [92,93]. However, negative indirect effects of confinement were also observed. In countries such as USA, some authorities suspended recycling programs to minimize the risk of spreading the virus in recycling centers; Italy prohibited infected residents from sorting their waste [93]; some trade companies that once encouraged consumers to bring their bags reconsidered the disposable bag bans and increasingly switched to single-use packaging [93]; medical products waste increased along with organic waste—for example in Wuhan (China), the epicenter of worldwide pandemic, hospitals produced an average of 240 tonnes of medical waste per day during the outbreak, compared to their previous average of fewer than 50 tonnes [93]. These reports suggest that COVID-19 will lead to alterations in the numbers presented in Figure 2. Thus, it may be assumed that the amount of plastics processed for recycling as well as harnessed for energy recovery will certainly decrease, whilst the amount directed to landfills will increase. The recommendation for individual protection involved the use of face masks. In most countries, at least in the first months of the pandemic event, most face masks used were of non-woven fabrics made from plastics like PP, with a recommended maximum use of a few hours. There has been an increase in garbage from personal protective equipment containing a substantial proportion of plastic [94], in health professionals and regular citizens (e.g., masks and gloves [95]). However, the generalized use of these items has also been associated with inadequate discarding of these materials after use (e.g., in the streets, in parking lots of supermarkets after shopping, beaches, coastlines, and rivers) [95]. Furthermore, the pandemic event increased the preference of plastic packaging and single-use plastic bags over other environmentally friendly alternatives [94]. The restrictions imposed by health authorities and concerns associated with public spaces promoted the increased consumption of takeout food (over going to restaurants), which is associated with single-use food packaging leading to increased waste generation grown up [94]. As observed for other contaminants, aquatic systems are the ultimate recipient of these materials and aquatic biota have received new plastic stressors. In this perspective, it is expected that this pandemic event will put additional pressure on aquatic systems, already under the pernicious effects of other plastic debris.

4. Marine Litter Awareness and Environmental Education

Marine litter and associated plastic pollution are a human-caused problem, mainly associated with a short-lived single-use nature and lack of proper management of plastic products. Humans are involved in plastic pollution and micro(nano)plastic presence in the environment in different dimensions of the problem: they caused it, can help address it, and may suffer from its impact [2,18,96]. Thus, it becomes highly relevant to understand societal perceptions about this environmental problem and its potentials impacts on the environment [97]. It is recognized that society's environmental behavior can be modulated by knowledge, attitudes, and concern level, as well as motivation to engage in solutions [5,18,98]. Thus, to reduce human impacts on the marine environment, there is a need to increase public knowledge about this issue [99]. Environmental education in formal contexts in collaboration with communities may be one of the most important approaches to help solve pollution problems associated with human daily behaviors, and to develop sustainable lifestyles that can result in meaningful socio-ecological outcomes [18]. Education can encourage behavioral changes more prone to sustainable lifestyles, and thus promote a healthier future. However, it is essential to understand the current knowledge and social representations of society about marine litter for successful action in terms of education, communication, promotion of reduction, or mitigation of effects [89].

Marine litter pollution has resulted in an increasing number of citizen science projects to study the scale of the issue. Most of the citizen projects to date have focused on macroplastics because they are much easier to observe, identify, and sample than microplastics [100]. The involvement of society in research (citizen science) and dissemination of scientific knowledge may be an asset to increase awareness about environmental problems, such as the marine litter issue, and motivation to contribute to their mitigation [99–101]. To address the problems of marine litter, different types of activities have been developed, such as beach clean-ups, where participants count, report the types of plastic products they find, and remove them [3,100]; policy and consumer action, such as petitions to cosmetics companies (microbeads) or avoiding certain products have also been organized. Concomitantly, mass communicative instruments, such as the internet and media, have been gaining importance as a means to alert society to environmental problems related with plastics consumption. Advertising campaigns aiming to reduce consumption and littering behavior have been organized by groups such as "Beat the microbead", an international campaign against plastic in cosmetics, which is one example of success. This example highlights that if the public is well informed about risks and available alternatives, society's turn of mind and behavior might change accordingly. A literature review in the Scopus database, performed on 29 September 2020, revealed 1610 articles about marine litter. However, when the keyword "education" was introduced in the database search, the number of results decreased to 71. The number was even lower (8) when the keyword "microplastics" was included in the combined search. The scarcity of studies associated with nanoplastics is also easily depicted in this search, as no results were found when the keyword "nanoplastics" was introduced. A literature search with the keywords "marine litter" and "public perception" revealed only 29 results. Within the 71 papers found with the search "marine litter" and "education", almost half were published between 2017 and 2020: a total of 27 papers were published between 2017 and 2019 and 9 were published in 2020 (Figure 3). The search with keywords "marine litter", "education", and "microplastics" yielded zero results between 2010 and 2016 (Figure 3). In general, the literature review supports that there is an increased trend for the involvement of society and/or addressing impact of plastic pollution on society, but the scientific papers on this subject can be considered limited. However, there is a gap between what is being published and what is going on in society. Scientific publications scarcely accounted for civil society actions with recognized societal impacts. Actions that challenged society to look for microplastics in cosmetics, such as "Beat the microbead", or promote beach cleanups like "The Great

Nurdle Hunt", or "2minutebeachcleaning" were able to mobilize society and become international movements promoting environmental awareness.

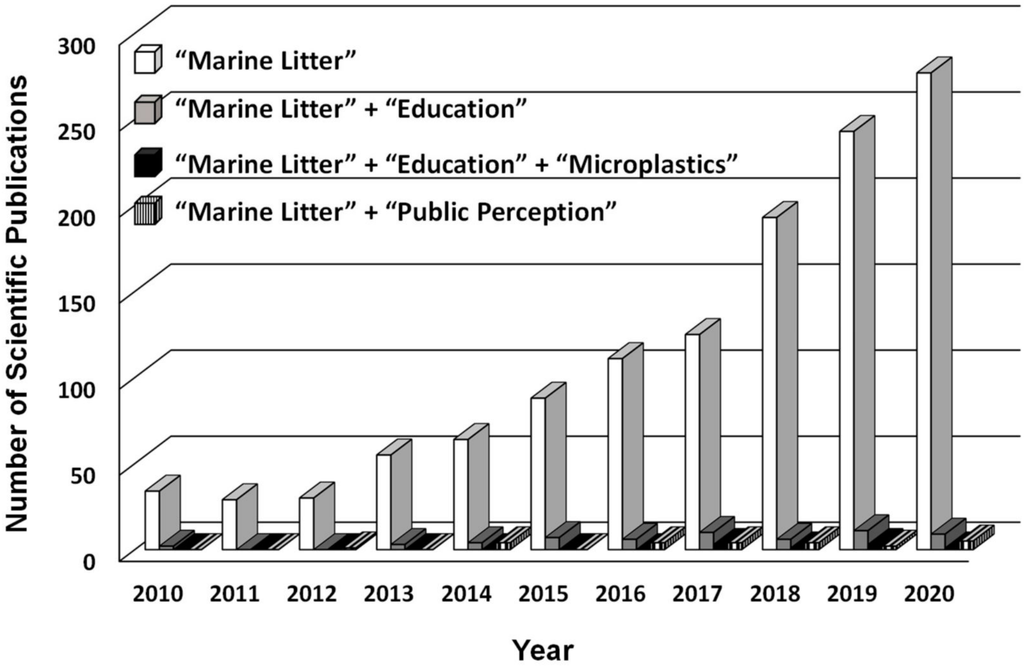

Figure 3. Number of scientific publications in the Scopus database published since 2010, obtained after literature search with the keywords "marine litter."

Scientific studies about environmental education addressed the topic of plastic pollution through development of educational courses/workshops (e.g., [3,89,99,102], and social media [34] to test perception of different types of target public with different methodologies. An analysis of the papers in terms of methodologies used to transmit knowledge to the target public revealed diverse approaches (e.g., courses, hands-on activities like beach cleaning) with the same final goal. The target public of educational activities in schools are mostly schoolchildren aged 8–13 [5] and high school students [7,89,99,103].

Currently, younger generations, when compared to adult generations, are aware of environmental problems, such as pollution, but they can have greater difficulty understanding the causes and solutions to environmental issues [5,98]. This age group (15–18 years old) is often a target for dissemination activities because young people can learn and change their habits but also have a strong potential to act as change agents in communities [5,98] and at home, and encourage their relatives [102]. However, in a study addressing the public perception of marine litter (focusing on causes, consequences, and pathways to change), older participants with greater competence reported higher willingness to act [89].

There has been an increased concern of scientists to engage society in the problem of marine litter, promoting educational activities and assessing the best methodologies to disseminate scientific knowledge. Some studies (e.g., [5,102]) involve pre- and post-intervention questionnaires to explore the effectiveness of the applied educational program. This approach may be of high value to understand the factors that may motivate people to understand and act on the marine litter problem.

5. Final Considerations

The problem of marine litter, particularly the presence of plastic particles, is one of the most urgent issues to be addressed by governments and society. Although the scientific community has been focusing on the presence and effects of plastic particles, the currently available knowledge on the effects of small plastic particles, particularly in the low µm to nm size range can be considered scarce. Several factors such as polymer, size, shape, presence of additives, and age and type of organisms may yield a considerable variation of effects, making the risk assessment of plastics a difficult task. Nonetheless, it is clear that the presence of small plastic particles may affect biota directly or by modulating the effects of other environmental contaminants. A better characterization of the most dangerous polymers may aid authorities to promote the use of alternative materials. The impact of even small plastic particles like micro(nano)plastics should lead to the reconsideration of conservation and planning measures aimed at protecting aquatic species, since the increase in marine pollution, namely plastics, can have serious consequences for the dynamics and viability of these populations, if consumption behavior and products management are not adequately addressed. From this perspective, and considering the importance of plastics to society, it is clear that societal plastic use and handling must take into consideration that these materials are not innocuous and do not disappear by dilution. Plastics are dispersed in the water column and reach different habitats, and may fragment, increasing the bioavailability and reactivity. The concerns associated with plastic degradation and interaction with other environmental contaminants is increasing. The formation of smaller, more bioavailable, and more difficult to remove plastic pollutants allied with a higher reactivity associated with size decrease make plastics a global challenge with biological and economic effects. Several authors consider that education and dissemination of scientific knowledge may be valuable for society to handle these materials, with greater environmental conscience. An increase of scientific studies and projects to enhance knowledge and motivate society to more pro-environmental behaviors has been observed. It is thus important to emphasize that the consequences of the presence of micro(nano)plastics in the environment may be unpredictable and humans are not immune to its effects. Considering the available data, it becomes clear that the scientific knowledge must be transmitted to society. The approaches may be varied but activities in schools targeting adolescents and young adults, who are considered disseminating agents and conscious consumers, may be a valuable approach.

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