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Review

Investigating the Human Impacts and the Environmental Consequences of Microplastics Disposal into Water Resources

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Abstract: During the last decades, one of the most contentious environmental issues has been the investigation of the fate of microplastics (MPs) and detrimental consequences in natural and water resources worldwide. In this respect, it is critical research firstly to track the ways in which MPs are determined as key anthropogenic pollutants in terms of ecological risk and secondly to plan feasible policies under which the role of science and society in tackling this global issue in the future should be prioritized. In this study, a systematic theoretical, technical, and planning analysis was developed in alignment with a Scopus search deployed in the second half of the year 2021 and covering a wide chronological range (from 1970s onwards) and thematic contexts of analysis by using keywords and key phrases organized into two groups. The document results were graphically represented, revealing the main scientific focus of studies. Subsequently, our study investigated the quantitative assessment methods of MPs in marine environments, denoting the range of standard procedures applied for collecting and analyzing samples of water, bottom sediments, and coastal deposits. The technological part of the study includes the presentation of the relevant analytical techniques applied for MPs tracking and monitoring in water resources, determining the wide spectrum of plastic compounds traced. Of particular interest was the determination of environmental depletion and human implications caused, even by extremely low concentrations of MPs, for marine biota, posing potential risks to marine ecosystems, biodiversity, and food availability. Finally, the research proposed the challenges of actions needed to support scientific, industry, policy, and civil society communities to curb the ongoing flow of MPs and the toxic chemicals they contain into water resources, while rethinking the ways of plastics consumption by humanity.

Keywords: microplastics; water sources; environmental pollution; marine environment; freshwater; toxicological effects

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1. Introduction

1.1. Plastics in a Global Environmental Context

Plastics are among the most demanded and commercially marketable materials worldwide. The production of plastics has increased from 1.5 million tons in the 1950s to 335 million tons in 2016 globally, while plastics are degraded, transported, and discharged into a variety of formulations in environment [1]. While plastics are rarely biodegradable, they are commonly fragmented into huge amounts of macro-, micro-, and nanoparticles through different processes and under natural conditions, making them ubiquitously harmful pollutants to the environment worldwide [2–4]. Therefore, the fate of plastics in the environment is determined by their physicochemical properties, including endurance, light weight, and durability in association with low manufacturing costs. These properties make

plastics a unique material for the production of goods in the household, construction, and industrial sectors. According to various estimates, the worldwide annual production of plastics ranges from 275 to 299 million metric tons (Mt), whereas much lower scales of utilization and reprocessing have been reported [4].

Global environmental alarm and social sensitivity revealed that microplastics (MPs) are the most notable type of plastic degradation and pollution that has attracted much attention among researchers, who have detected MP traces in marine and terrestrial environments [5–7]. Plastic debris are recognized as threatening indicators against natural environment and wildlife habitats by human activity. In the past, much attention was paid to investigating the presence and the concentration of plastic debris in ecosystems, mainly in marine environments, seawater, and surface waters [5–7].

MPs are found in marine litter in a wide range of sizes (from nm up to mm) and low density, as well as with both primary and secondary types of occurrence. MPs in environment make them deceptively perceived as food by many living organisms. Since MPs cannot be broken down by an enzymatic system, MPs ingestion by organisms is harmful and potentially fatal by itself [4]. However, the primary concerns arise from the fact that MPs are prone to adsorb contaminants on their surfaces, thereby becoming a secondary source of contaminants. The latter can travel up the food chain and accumulate in higher predators and humans [4].

The amount of MPs increases with decreasing size, thus leading to potential misidentification when only visual identification is performed [8]. Scientific literature extensively describes MP ingestion by aquatic fauna, their transfer into food webs, and their potential action as indicator for toxic compounds or alien microorganisms [9–11]. Although the scientific community addresses the natural path of MPs transformation and transportation as a priority issue of high environmental impact, considerable efforts and many questions still need to be addressed [12].

1.2. Microplastics in Marine Environments

Research estimates that the number of marine plastics in the oceans is currently placed at 5.25 trillion pieces [13]. An increasing number of plastics in marine environments through years could also mean an increase of interactions affecting marine species. The exact mechanisms of the fate of MPs can be better explained since relevant research is gradually advancing [13–15]. Indeed, while MPs are widespread throughout aquatic environments, there is insufficient understanding of the influential factors of MP ingestion by higher fish predators [15]. In addition to better understanding the role of MPs in aquatic environments, numerous studies have been devoted to exploring the severe environmental consequences of MPs, including damages caused to ecosystems and to human health [16–18]. In marine environments, MPs are characterized as persistent organic pollutants of increased surface area, thus, their transportation occurs by their adsorption by living organisms. In this respect, based on the environmental risk of MPs, systematic protocols for qualitative and quantitative analysis are yet to be established, following the patterns and principles of environmental analytical chemistry [19,20].

MPs can also act as an indicator for various toxic contaminants in marine environments, such as metal ions [21,22]. Relevant studies investigated the adsorption characteristics of metal ions on MPs [23,24], whereas the desorption behavior of metal ions from MPs at different marine environments is largely unknown [25]. MPs can also function as indicators for metals, antibiotics, toxic chemicals, pathogenic bacteria Harmful Algal Bloom (HAB)-forming dinoflagellates across the continents, especially through ballast water, serving as "hotspots" in ballast waters for developing and spreading multiple drug-resistant human pathogens through co-selection mechanisms [26].

Regarding the negative biological effects of microplastic (MP) pollution in marine environments, there is evidence that MP particles in aquatic ecosystems are considered emerging and persistent organic pollutants, acting as indicators for hydrophobic chemicals and antibiotics for drug delivery in medical treatments, Figure 1. Figure 1 shows that

antibiotics' adsorption of MP particles results in dispersion of these antibiotics over long ranges and consequently, entry into the food chain. Therefore, MP particles—as carriers of chemicals, antibiotics, and heavy metals—they can ultimately deposit and accumulate in soil, marine, and freshwater sediments, being harmful to organisms [27,28] and infectious to urban wetlands/urban land uses [29].

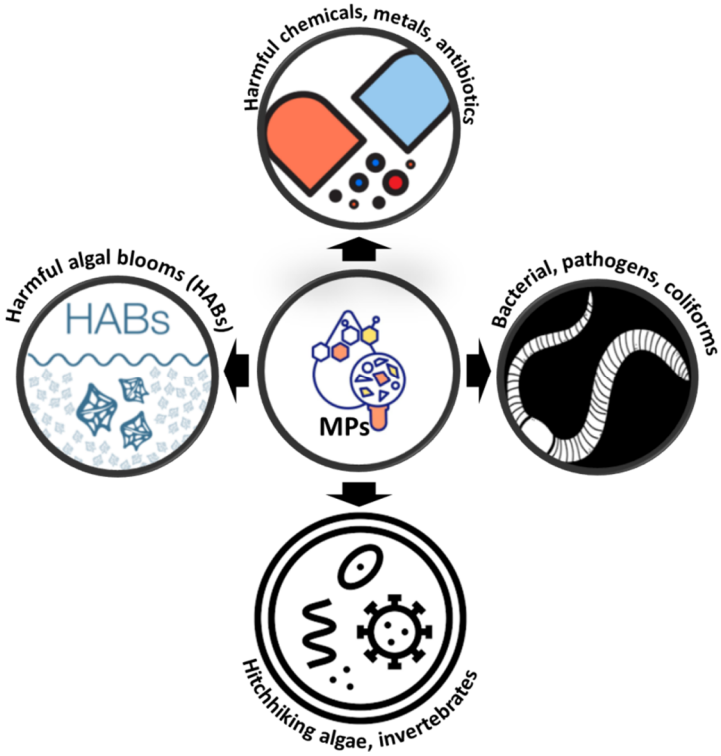

Figure 1. Profile of the fate of MPs for a range of chemicals and biota. Source: Modified from Naik et al. [26] (p. 3).

In the relevant literature, the exact migration and transportation process applied from bacterial communities on MPs in estuarine areas remains unknown [30,31], while limited information is available on MPs' functionality on bacterial communities' dynamics, especially in urban water environments [32,33]. Since the specific density of plastics is close to that of water, synthetic litter in catchment areas is easily channeled from lakes and rivers, transported, and enters the open seas [34,35]. Other studies have focused on relating MPs' fate with their density and food-deceived [36], as well as their sorption capability as pollutant carriers and secondary sources of contaminants [37,38]. The in-field study [39], where MPs were found in Suva coastal environment, capital of the Republic of Fiji, is also noteworthy, while these MPs were associated to land based human activities [39]. Specifically, low levels of MPs were detected at a wide range of different sites selected. The sewage treatment plant contributed to MP levels in sediment but not in water, while high numbers of species ingested MPs in sediments. Therefore, it can be inferred that human-domesticated regions of urban coastal environments having low-populated areas, or Small Island Developing States (SIDS), still need to be examined in the literature [39].

Therefore, challenging research approaches can exhaustively enumerate all possible sources of MPs litter identified while reporting quantitative methods of assessing MP-polluting inputs to natural environments with an emphasis on surface waters [12] and marine environments globally [40]. In this context, there have been no adequate and standard methods to identify, to quantify, and to unify the various types of MPs under specific protocols and procedures. Understanding the environmental fate of MPs should advance the knowledge of mechanisms developed by MPs' transferring and accumulation in the biological chain [41].

1.3. Policies and Regulations of Microplastics' Existence in Marine Environments

MPs are prone to sustaining a high adsorption capacity to hazardous substances, which is the research focus while studying their fate in marine environments and the toxicity caused. Therefore, research outcomes can offer new knowledge on the functionality and the consequences caused by MP pollution, as well as to promote and to formalize the development of relative regulations.

Plentiful policy documents, national procedures, and legal instruments have been put in place globally to assess the release of chemical pollutants; including international treaties, such as the Montreal Protocol, Stockholm Convention, and Minamata Convention [42–44]. Chemical pollutants have been commonly characterized, assessed, and controlled according to their persistence, bioaccumulation potential, and toxicity. Such chemicals are able to control other persistent pollution threats, while MPs are concerned as problematic indicators, since they are not individual entities but a complex mixture of polymers, additive chemicals, absorbed organics, and living substances [45].

Significant behavioral and ecological impacts of different types of plastics, especially those in micro- and nano- scales, are those of the ecocorona. In this context, natural waters contain natural organic macromolecules (NOM) of high humic and fulvic acids content, excreted waste products and exuded lipids and polysaccharides, proteins, and macromolecules. These complex, seasonal, and spatial compounds are varied, and they can interact with particle surfaces in the aquatic environment, assembling the formation of the protein corona in biological fluids. NOM components of a wide range of morphological forms and thickness, from flat monolayers to multilayers, can be absorbed by particles in layers, resembling the hard and the soft protein corona. This implies that MPs can retain a record of their environmental progress in different compartments, similar to the functionality of nano-scale particles in serum and when moving into different cellular locations [45].

It is also noteworthy that MPs can be compared against the criteria for classification as a persistent organic pollutant under the Stockholm Convention, being concerned as significant compounds for further consideration and discussion [45]. Therefore, governmental policies and initiatives should shape a solid basis for discussion for envisaging and issuing future regulations and directives of environmental worth. In this respect, the 2017 Conference of the Parties (COP) of the Basel Convention on hazardous wastes and the Stockholm Convention on persistent organic pollutants (POPs) concluded the dealing with plastic wastes by Regional Centres and consistent reporting, being in the agenda for discussion at the ongoing COP meetings [46]. Indicative proposed measures of reducing marine plastic litter, being relevant to National Implementation Plans for the Stockholm Convention on Persistent Organic Pollutants, are presented below [46]:

- Promotion of green chemistry by avoiding POPs or substituting harmful chemicals in MP and endocrine-disrupting chemicals (EDCs),
- MP waste prevention through developing and implementing safe alternatives to persistent plastics in marine environments,
- Research in the field of environmental and health impacting on marine plastics through EDCs' and POPs' fate at micro- and macro- scales,
- Eco-design packaging and MP waste recycling,
- Promotion of best alternative techniques to control MP leakage to open oceans, while gathering information about input loads, sources, and originating sectors,
- Collection and environmental management of MP waste, while improving the efficiency of the whole treatment,
- Consumerism changes and disposal behavior of MP litter.

1.4. Bibliometric Analysis of Microplastics Reporting in the Scopus Database

A systematic literature search at the Scopus database was undertaken in October 2021 using relevant keywords and key phrases in the field of "microplastics". These document results are reported and graphically represented below in terms of time, subject area,

keyword, country, and languages. In order to better comprehend and analyze the high volume of document results yielded, they are organized into the following two groups of keywords and key phrases applied: Group 1: "microplastic" search in "Article Type, Abstract", yielding 6628 document results; Group 2: "microplastic" search in "Article Title", yielding 1942 document results.

In Figure 2a,b, the document results refer to the highest volume of results (among the two groups), which were the results of Group 1, being further organized into shorter classifications of: (a) per year by source, Figure 3a, (b) by subject area, Figure 3b, and (c) by country, Figure 3c.

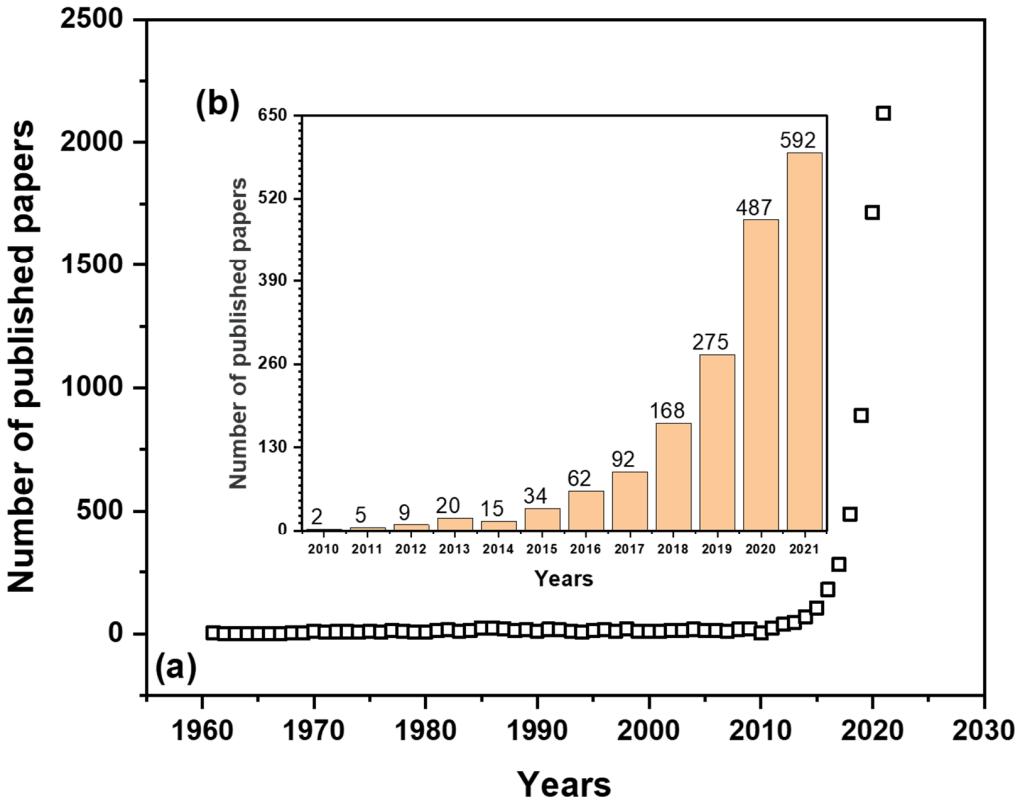

Figure 2. Visual allocation of document results per year of publication: (**a**) Group 1, x-y scatter diagram, (**b**) Group 2, bar diagram.

It is noteworthy that both Figures 2 and 3 reveal an increasing literature production and a vivid research interest in investigating the topic of MPs either in a chronological or in a thematic point of view. This ongoing research interest is also noticeable in comparing the document results for both Groups 1 and 2, the comparable evaluation of which is represented in Figure 4 and Table 1. Subsequently, in the following Figure 4, the comparable dynamics of the top 10 keywords per Group 1 and 2 are shown. It should be signaled that the document results in Group 1 are almost 3.5 times higher than those of Group 2. In this respect, the relevant proportions of the top 10 keywords in Groups 1 and 2, taking the number of results from Group 2 as the basis of comparison, are represented in Table 1.

The total keywords for Group 1 are 80,580 documents and the top 10 keywords for Group 1 are 29,869 documents, or 37%. Similarly, the total keywords for Group 2 are 23,255 documents and the top 10 keywords for Group 2 are 9080 documents, or 39%. Among the most frequently reported keywords for both groups are microplastic(s), plastic(s), water pollutant(s)—chemical, implying high environmental interest and physicochemical mechanisms of degradation or reformations, following the fate of MPs after human use and disposal in nature. It is also noteworthy that through the period of data collection, the 1970s onwards, a relative "stability" in the key parameters investigated has

been reported in the relevant literature, implying the constant environmental concern and monitoring of human-induced MPs pollution, impacting waste generation, water resources, and animals' growth. An indicative collection of relevant keywords and determinants taken from the whole outcomes derived in the groups-related search is visually represented in the form of a word cloud, Figure 5a,b.

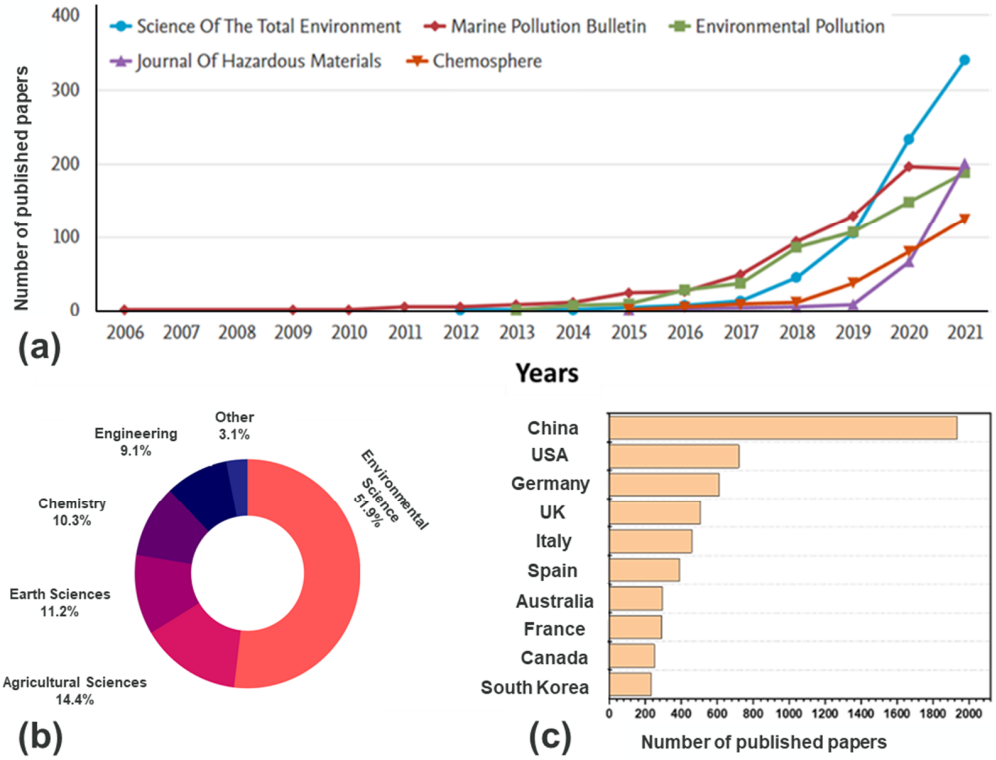

Figure 3. Graphical representation of document results of Group 1: (**a**) per year by source, (**b**) by subject area, (**c**) by country.

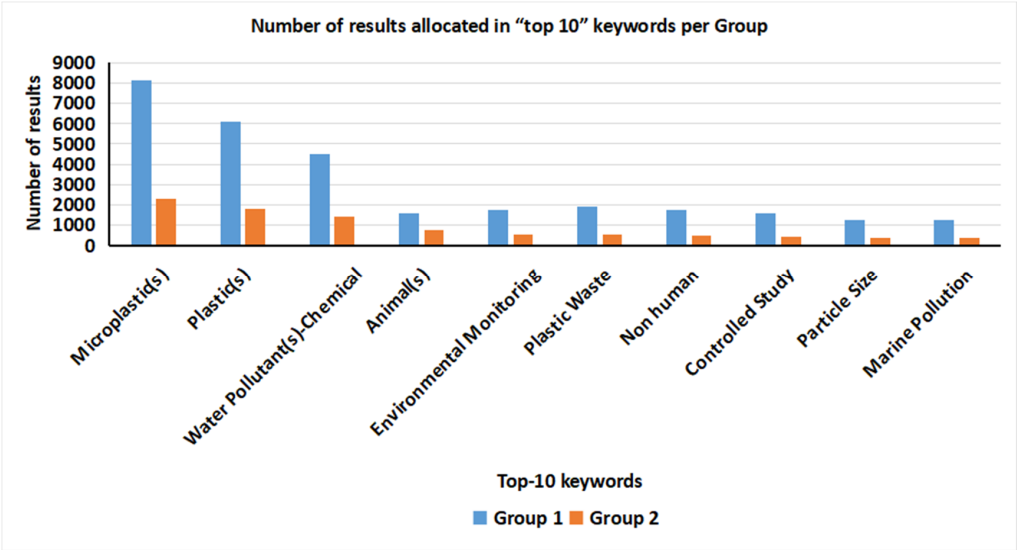

Figure 4. Graphical allocation of top 10 keywords in descending order at Groups 1 and 2.

Figure 5a reveals the co-occurrence and the weighted frequency among the keywords reported in the key analysis on MPs. The densely developed peripheral role and the wide research spectrum of analyses for MPs, mainly related to environmental and socio-technical domains of investigation, is noteworthy. In contrast, the scattering of authorship

countries, as shown in Figure 5b, is less concentrated, implying the worldwide expansion of MPs' research interest, as well as the imperative scientific struggle of deploying feasible approaches of monitoring through post-treatment policies.

Table 1. Numerable allocation of top 10 keywords in descending order per Group (based on Group 2 ordering).

Top-10 Keywords	Group 1	Group 1 (%)	Group 2	Group 2 (%)	ΔGroup (Group 1–Group 2) (Group 2 Basis = "1")
Microplastic(s)	8144	10.11	2317	9.96	2.51
Plastic(s)	6074	7.54	1830	7.87	2.32
Water Pollutant(s)—Chemical	4496	5.58	1400	6.02	2.21
Animal(s)	1604	1.99	785	3.38	1.04
Environmental Monitoring	1741	2.16	564	2.43	2.09
Plastic Waste	1940	2.41	564	2.43	2.44
Non-human	1762	2.19	475	2.04	2.71
Controlled Study	1604	1.99	433	1.86	2.70
Particle Size	1275	1.58	363	1.56	2.51
Marine Pollution	1229	1.53	349	1.50	2.52
Subtotal	29,869 (out of 80,580)	37%	9080 (out of 23,255)	39%	Mean value: 2.31

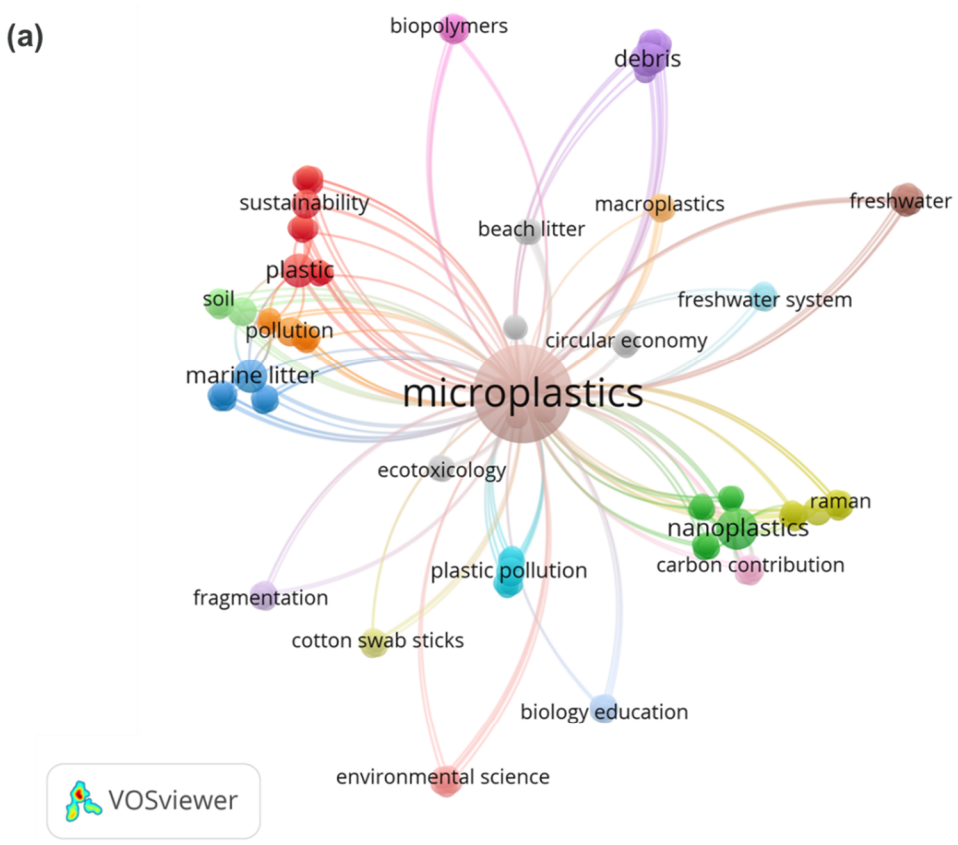

Figure 5. *Cont.*

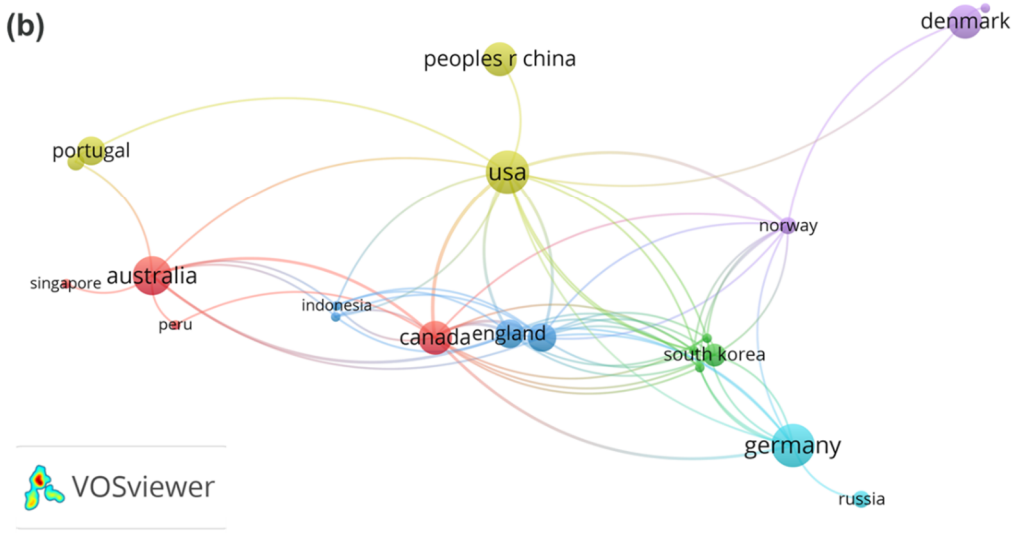

Figure 5. Word clouds of search results in alignment with (**a**) keywords and (**b**) countries of authorship.

In this research context, the scope of our review study is the determination of the environmental conditions, the methods and analyses applied, as well as the main physico-chemical properties and mechanisms that make MPs a source and an environmental/water resources indicator. The other scales of plastic analysis, nano- and meso-, are out of scope, thus they are not investigated further in our review study. Moreover, the route of "polymer waste management" has been holistically approached by focusing on the globally spread polymer type of MPs, while the managerial approach was determined by representing the main analytical techniques of MP detection, size characterization, compound determination, and abiding environmental concerns and challenges.

2. Methods and Analyses

2.1. Definitions and Sampling

Environmental sampling plays an important role in quantitative and qualitative investigation of plastic pollution, especially among highly industrialized countries. Rivers are sourcing and carrying MP litter into the oceans. MP sampling in riverine and coastal environments requires that researchers confront obstacles such as limited access, long time taken, high costs, and lack of experienced human resources [47]. In a similar freshwater-focused study, the adoption of sampling devices such as Albatross Mark 5 and 6 (AM-5 and AM-6), was selected as representative samples of collecting floating and suspended MP at 95 different Japanese locations of freshwater and coastal environments [47]. MPs' polymer composition (by deploying a FTIR analysis), size, and shape (taking microscopic images) were investigated [47]. MPs' concentration and composition were relevant to those of conventional samples where comparison was possible. Furthermore, significant MP size reduction from rivers to coastal areas was observed, while PE and PP were the dominant MP polymer types floating and in suspension detected [47].

The significance of sediment sampling was stressed by Townsend et al. [29], who collected samples from 20 independent urban wetlands, having different types of urban land use within their catchments. MPs were defined as plastic particles smaller than 1 mm, being observed at all wetlands with an average abundance of around 46 items/kg of dry sediment [29]. Specifically, a total of 913 MPs was counted, of which 120 were fibers, 625 fragments, and 168 beads. In this sediment sample, MPs' abundance ranged from 2 to 147 items/kg dry sediment. Fragments were the most frequent, 68.5%, MPs detected at 85% of wetlands. Lower quantities of MPs detected were that of fibers and beads, 60% and 45% of wetlands, respectively [29].

MPs consisting of synthetic polymers can be valued as environmental pollution indicators, but their physical effects on organisms in freshwater systems and organisms remains

poorly understood [48,49]. One research constraint is MPs' relevance as pollutant indicators, whether MPs can be considered receptors from aquatic organisms in comparison to further uptake pathways, e.g., via water or sediment particles [50]. Rehse et al. [50] analyzed how the MPs' presence (polyamide particles, PA) can modify acute effects of the environmental pollutant bisphenol A (BPA) on freshwater zooplankton (*Daphnia magna*) [50]. While PA particles themselves are not negatively affectionate or induced, BPA alone functions in a typical dose-dependent manner. Combining BPA to PA, sorption of particles prior to exposure led to a reduction of BPA in the aqueous phase, although PA, on being BPA-loaded, the particles are ingested by daphnids [50]. Gut solubilization was relatively low compared to wood or biochar natural matter, implying the limited role of MPs as pollutant transfer [50].

2.2. Analytical Techniques and Elemental Analyses

Analytical techniques on MP identification have technological limits with regard to detecting small sized particles (<1 μm), underestimation of MPs with organic contaminants, and physico-chemically altered particles by weathering and photo degradation. Therefore, eco-toxicity and biodegradation caused by MP spread in living organisms through the food chain can be reduced by formulating a systematic protocol of MP identification, quantitative accuracy, analytical reliability, and procedural reproducibility [20].

Another critical parameter of MP analysis is related to specific surface area and to total pore volume, being correlated with the intensity of MPs adsorption [25]. In an indicative study, the sorption capabilities of Cd(II) onto five different types of MPs were compared to examine the relationship between the surface characteristics and the adsorption properties of MPs, showing that the MPs first increased and then decreased with increasing solution pH from 2.0 to 9.0. Moreover, the π–π interaction, electrostatic interaction, and oxygen-containing functional groups played crucial roles in the adsorption of Cd(II) onto the MPs [25].

In another elementary-focused study, more attention was paid to the attachment between MPs and environmental pollutants. A typical type of MPs is the polyethylene (PE) beads whose adsorption performance with Cr (VI) ions under the existence of sodium dodecyl benzene sulfonate (SDBS) was investigated in the study by Zhang et al. [51]. The experimental parameters and analytical conditions of Cr (VI) ions adsorption by PE MPs were PE doses, pH, and SDBS concentrations. The adsorption capability of Cr(VI) ions increased from 0.39 to 1.36 mg/g when the dosage of PE MPs increased from 2 to 14 g/L at pH of 5 with addition of SDBS. In the absence of SDBS, adsorption capability increased from 0.03 to 0.32 mg/g [51]. Therefore, the presence of SDBS affects the adsorption performance of Cr(VI) ions onto PE MPs, showing an optimal adsorption of Cr(VI) ions onto PE MPs at SDBS concentration between 1.0 and 1.5 mM [51].

In a similar study, beaches, fishes, and birds from Lake Geneva were investigated to assess the global plastic pollution, where MPs sampling and counting protocol were examined with samples from the Mediterranean Sea and applied to Lake Geneva once under control [52]. On the surface layer of Lake Geneva, significant quantities of MPs were notably found abiding on the beaches. However, a slight underestimation of MPs' identification and quantification occurred due to large proportion of plankton contained in the samples followed by elimination of plankton, algae, and other foreign matter (such as pollens) and the subsequent plastic-piece losses [52].

MPs' density may not be representative of the lake's average density due to local phenomena; temporal and seasonal variations that can be considered, as well as the weather, regarding water flow and plastic distribution. MPs are also likely to degrade and break up into smaller fragments, creating inter alia more secondary MPs [52]. Their rather long residence time in Lake Geneva, theoretically amounting to almost one decade or more, also offers opportunities for plastic degradation. Subsequently, MPs are potential input channels for adsorbed pollutants or plastic components into the food chain through their intake-desorption cycle by natural biota [52].

In a similar study of fisheries carried out by Horton et al. [53], MPs' ingestion by the roach *Rutilus rutilus* within the non-tidal part of the River Thames was linked to exposure and physiological factors. MPs were found within the gut contents of roach from six out of seven sampling sites, while 33% of sampled fish contained at least one MP particle. The majority of detected particles were fibers (75%), followed by fragments and films at 22.7% and 2.3%, respectively [53]. Additionally, the actual quantity of MPs in the gut at a given exposure was determined by the size of fish, since (mainly female) larger fishes were more likely to intake the maximum possible ingestion of MP particles, comparing to smaller (mainly male) fishes [53].

Similarly, Blarer and Burkhardt-Holm [54] assessed MPs pollution, in particular the ingestion and egestion of polyamide (PA) fibers, and how it affects freshwater invertebrates, noting that fibers were found in the gut after 0.5 h of exposure, while the egestion was rapid and the digestive tract was empty 16 h after exposure ended [54]. In particular, Blarer and Burkhardt-Holm [54] examined the interactions between the amphipod *Gammarus fossarum* and two types of MPs. A remarkable positive correlation was reported between concentration and ingestion of PA fibers where the tested, ingested, and egested PA fibers can impair the health and deter the ecological functions of freshwater amphipods under continuous exposure [54].

2.3. Bacterial-Based Analyses

The role of bacterial activity in marine environments is vital for the sustainable development and the growth of the accommodated organisms. In this respect, bacterial attachment onto the low-density polyethylene (LDPE) polymer within sediments is considered an important variable of MPs detection and tracking. Such detection and tracking can be demonstrated by scanning electron microscopy and catalyzed reporter deposition fluorescence in situ hybridization (CARD-FISH) [9]. In particular, the employment of a 14-day microcosm experiment was performed in order to investigate bacterial colonization of low-density polyethylene (LDPE) MPs within three types of coastal marine sediment from Spurn Point, Humber Estuary, UK [9]. In this research, a log-fold increase in the abundance of 16S rRNA genes from LDPE-associated bacteria within 7 days with 16S rRNA gene numbers on LDPE surfaces was reported. Across sediment types examined, shown significant differences were shown, as noted by the quantitative polymerase chain reaction (PCR) [9]. Harrison et al. [9] demonstrated that bacteria within coastal marine sediments can rapidly colonize LDPE MPs, with evidence for the successional formation of plastisphere-specific bacterial assemblages. Moreover, since hydrocarbon-degrading bacteria were also discovered on plastic fragments in seawater, it was suggested that recruitment of hydrocarbonoclastic bacteria on MPs is likely to represent a shared feature between both benthic and pelagic marine habitats [9].

In a similar study [32], it was hypothesized that tire MPs can function as carriers of bacteria in urban water environment, thus, forming an important source of MPs to the local environment. Therefore, tire MPs can support the composition and the structure of bacterial communities changing with time and, subsequently, the functional diversity of bacterial communities will change and result in an unpredictable impact on (local) urban water environment and ecology. Concurrently, different water factors and physicochemical properties of tire MPs may affect bacterial communities, impeding the correct prediction of risk incurred by the discharge of tire MPs to various water environments. In this context, researchers exploited 16S rDNA high-throughput sequencing in order to characterize bacterial communities on tire MPs while using three different tire brands and tire sizes in two typical urban water environments: an influent pond of constructed wetland (CW) and its subsequent effluent into a landscape river (LR) at one, two, or three months [32]. It was important to note that tire MPs could support pathogenic bacteria in urban water environments [32], thus, tire MPs can be indicated as an emerging environmental pollutant, acting as a carrier for bacterial colonization and microorganisms propagation, entering urban water systems, endangering aquatic and human health, and unbalancing metabolism. Then,

the degradation of microorganisms can increase with time, while ambient environmental factors can nurture bacterial communities on tire MPs. However, the physicochemical factors of particle size, contact angle, and element content sustained lower impact on bacterial growth [32]. In a similar study, it was stated that MPs can enrich particular bacteria (e.g., Halobacteriaceae and Pseudoalteromonadaceae) and weaken the influence of environmental variation [30].

In another bacteria-focused study, Kleinteich et al. [55] tested the sensitivity of natural freshwater sediment bacterial communities (by genetic fingerprint) to exposure to MPs, including polyethylene ranged at 2 and 20 mg/g sediment, as well as MPs loaded with polycyclic aromatic hydrocarbons, mainly PAHs, phenanthrene, and anthracene, at a laboratory level [55]. The bacterial community composition from an unpolluted river section was altered by high concentrations of MPs following two weeks of incubation. However, the downstream community at the wastewater treatment plant was unchanged [55]. Low MP concentrations loaded with phenanthrene or anthracene induced a less pronounced response in the sediment communities, compared to the same total amount of phenanthrene or anthracene in isolation from each other. Moreover, biodegradation of the PAHs was reduced. Conclusively, it is noteworthy that MPs can affect bacterial community composition, mainly in unpolluted freshwater sediments [55].

2.4. Modeling of Microplastics—Analytical Techniques

The potential for solving issues without the need for physical understanding of the underlying system can be deployed with the aid of deep learning, hence offering an elegant solution to complex problems. Convolutional neural networks for the identification of MPs in different aquatic environment were demonstrated while carrying out real-time measurements using a Raspberry Pi, a digital microscopic camera, and neural network computation, all composing a portable and low-cost environmental aquatic sensor [13]. A total of 1000 datasets, allocated as 70% for training and validation and 30% for testing, were utilized in the network model, showing that the deep learning approach produced a good performance with more than 84% each for training-validation-testing accuracy for the Convolutional Neural Network model. Moreover, actual field tests showed a high percentage of 90% accuracy on different aquatic environments, compared to laboratory tests using Ultraviolet Visible Spectroscopy. The reported 1.18 h of average discharging implied the ability of a long period of time in using the scanning device [13].

In a river-focused study, the characterization and the quantification of MPs sized 2.8 mm–11 µm were performed by the efficiency of light and scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS). For the processing of field data quantification, researchers properly collected bank sediment samples, twice from the River Kelvin in Glasgow, which were size-fractionated and processed for extraction of MPs by density separation. The reported total abundances were 161–432 MPs kg^{-1} dry sediment, with fibers as the dominant type, comprising more than 88% of total counts [56]. While SEM-EDS made a quick screening of plastic vs. non-plastic pellets possible and supported better identification of smaller fragments, fibers' identification necessitated more advanced techniques [56]. The distribution of microscopic debris in urban rivers that are running close to marine environments in highly industrialized areas, such as at the west of Scotland is remarkable; it is vital in order to assess concentration and distribution of primary and secondary MPs [56]. Fibers in blanks suggested potential contributions from atmospheric contamination. Moreover, fibers concentrated mainly in fractions of less than 0.09 mm imply the influential role of fine sediment dynamics in rivers. While no primary MPs were observed, metallic and glass pellets can be detected in high abundances among settled material, thus being easily misidentified by visual inspection. Therefore, compositional analysis is proactive against misidentification or overestimation of MP occurring [56].

Similar to the use of the SEM-EDS analytical technique, Scopetani et al. [57] deployed a non-destructive method using Fourier transform infrared spectroscopy (FTIR) 2D imaging for MPs' identification and analysis. In such a sampling procedure, the three sampling

points of sediment, snow, and ice core samples were collected near the shore of two aquatic systems showing mean concentrations of MPs detected as 395.5 ± 90.7 MPs kg^{-1}, 117.1 ± 18.4 MPs L^{-1}, and 7.8 ± 1.2 MPs L^{-1}, respectively [57].

In addition to the aforementioned analytical techniques, pyrolysis coupled with gas chromatography/mass spectrometry (Py-GC/MS) was used for polymer composition and MP identification. Such an optimization and validation of the Py-GC/MS method was performed by determining limit of detection (LOD) for eight common polymers, showing effectiveness of carrying optimization on multiple GC parameters by using polyethylene (PE) and polystyrene (PS) microspheres [8]. Despite the fact of decreasing signaling over time, good repeatability and intermediate precision tests were reported in calculating limit of detection (LOD) for common polymers or plastics isolated from sea water surface at below 1 µg in the marine environment [8].

Among the analytical techniques for MP detection and tracking, that of Capozzi et al. [58] is noteworthy; they stated that mosses are well known as biomonitors of fresh water for metal pollutants. In the view of using moss transplants for MPs detection in fresh water environments, the use of *S. palustre* transplants can monitor MPs contamination. In addition, exposure time is a proven key indicator of careful evaluation in field conditions, since post-exposure washing induces a loss of larger aggregates [58].

Based on the overview of models and techniques, Table 2, it can be concluded that MP pollution in the marine environment can be reviewed and discussed in a wide geographical coverage worldwide in alignment with the key aspects of identification and qualification methods, source and distribution, sampling at natural sites, such as wetlands, and catchments supporting high industrial land use or close to residential densities [59], all contributing to species toxicity in their marine ecosystems [2,5,12,29,47].

Table 2. Overview of MPs sampling sites, quantities of MPs detected, and the relevant analytical techniques applied.

Regions	Sampling Sites at Freshwater, Coastal, Urban Environments	MPs Concentration—Abundance	Sampling Procedure Characteristics	Ref.
North America, USA	North Atlantic Ocean	Fibers (87%), Fragments (13%), 1.62 particles/gram tissue of *Hymenaster pellucidus* species	ATR-FTIR-microscopy	[5]
	USA	0–2.08 × 10^2 particle day^{-1}	Total daily discharge from WWTP; sieves of 10–40 µm; FTIR analysis; efficiency: 99%	[12]
	USA	0.20 million metric ton/year	13% of plastic production annually leads to mismanaged plastic marine debris	[2]
	USA, Bay	4.5 particles/m^3	Mesh opening size >100 µm	[47]
	USA, Riverine, Wayni	0–13.7 particles/m^3	Mesh opening size >100 µm	[47]
South America, Brazil	Brazil	0.25 million metric ton/year	16% of plastic production annually leads to mismanaged plastic marine debris	[2]
	Brazil, Estuary	0.1 particles/m^3	Mesh opening size >100 µm	[47]
	Brazil, Estuary of Goiana	Soft plastic (41.08%), paint chips (29.11%), hard plastic (28.42%), threads (1.4%) 0.26 particles/m^3	Microscopy	[5]
Asia	China	3.50 million metric ton/year	11% of plastic production annually leads to mismanaged plastic marine debris	[2]
	China, Estuary	67.5 particles/m^3	Mesh opening size >100 µm	[47]

Table 2. *Cont.*

Regions	Sampling Sites at Freshwater, Coastal, Urban Environments	MPs Concentration—Abundance	Sampling Procedure Characteristics	Ref.
Asia	China, Estuary of Changjiang	20–340 items/kg dry sediment	Fibers; WTP effluent	[29]
	China, Reservoir of Three Gorges	25–300 items/kg dry sediment	Fibers; larger plastic items	[29]
	China, River	0.1–5.6 particles/m^3	Mesh opening size >100 µm	[47]
	Hong Kong, Coastal zone	49–279 items/kg dry sediment	Fragments; WTP effluent, strormwater discharge, illegal dumping, accidents	[29]
	Indonesia	1.25 million metric ton/year	11% of plastic production annually leads to mismanaged plastic marine debris	[2]
	Iran, Coastal zone, Persian gulf	0–125 items/kg dry sediment	Fibers; WTP effluent, fishing	[29]
	Japan, Riverine	2.0 particles/m^3	Mesh opening size >100 µm	[47]
	North Korea	0.20 million metric ton/year	9% of plastic production annually leads to mismanaged plastic marine debris	[2]
	Pakistan	0.25 million metric ton/year	13% of plastic production annually leads to mismanaged plastic marine debris	[2]
Europe	Denmark	(8.16–460) × 10^6 particle day^{-1}	Total daily discharge from WWTP; sieves of 10–40 µm; FTIR analysis; efficiency: 95–99.8%	[12]
	Finland	(1.21–1.68) × 10^6 particle day^{-1}	Total daily discharge from WWTP; sieves of 10–40 µm; FTIR analysis; efficiency: 95–97.1%	[12]
	Germany	4.19 × 10^4–1.24 × 10^7 particle day^{-1}	Total daily discharge from WWTP; sieves of 10–40 µm; FTIR analysis	[12]
	Hungary, Riverine	3.52–32.05 particles/m^3	Mesh opening size >100 µm	[47]
	Italy, Subalpine Lake Garda	PE (33%), PS (33%), PP (25%), PA (8%) 75 particles/m^3	Raman	[5]
	Mediterranean Sea, Central-Western	Fragments (93.2%), Pellets (2.2%), Films (1.6%), Foams (3.1%) 1.25 particles/m^3	ATR-FTIR-microscopy	[5]
	Mediterranean Sea, Western	Filaments (86.36%), Fragments (12.12%), Film (1.51%) 0.34 particles/individual *Galeus melastomus* shark species	FTIR-microscopy	[5]
	Scotland, Intertidal zone, Scapa Flow	730–2300	Fibers; WTP effluent, marine litter	[29]
	UK, Channel	0–1.5 particles/m^3	Mesh opening size >100 µm	[47]
	Beaches	72–1512 items/kg dry sediment	Fibers; WTP effluent, marine litter	[29]
Africa	Egypt	0.40 million metric ton/year	13% of plastic production annually leads to mismanaged plastic marine debris	[2]
	Nigeria, Riverine	0–0.2 particles/m^3	Mesh opening size >100 µm	[47]
	South Africa	0.35 million metric ton/year	12% of plastic production annually leads to mismanaged plastic marine debris	[2]
	South Africa, Estuary	1–7 particles/m^3	Mesh opening size >100 µm	[47]

Table 2. *Cont.*

Regions	Sampling Sites at Freshwater, Coastal, Urban Environments	MPs Concentration—Abundance	Sampling Procedure Characteristics	Ref.
Oceania	Australia	(8.16–460) × 10^6 particle day^{-1}	Total daily discharge from WWTP; sieves of 10–40 μm; FTIR analysis	[12]
	Australia, Melbourne	2–147 items/kg dry sediment	Fragments, larger plastic items	[29]
	Australia, Sydney Harbour	Fibers (83%), Granules (17%), 0.2–4.6 particles/individual fishes	ATR-FTIR-microscopy	[5]

Notation: Data have been presented in alphabetical order of the "Sampling sites at freshwater, coastal, urban environments" entries, following firstly the wider "geographical" naming and, secondly, the aquatic/aquifer "siting" naming.

3. Compounds Detected in Microplastic Samples

3.1. Sizing and Characterization of Microplastics

MPs have been mainly detected at beaches and surface layers of lakes in significant quantities [52,60–62]. Statistically significant particle size reduction has been reported from riverine to coastal areas, where the prevailing polymer types are that of polyethylene (PE), polypropylene (PP) [47], as well as polyester and synthetic dye [53].

MPs abundance can be traced to closely populated areas, as well as at municipal and industrial effluent discharges [48]. In this context, MPs in sediments were reported and their MP concentrations were determined, for the first time, in the surface sediment of seven streams around the lagoon of Bizerte (Northern Tunisia), using a saturated NaCl flotation technique. Categorization of MPs was based on type, color, and size using a stereoscopic microscope [48]. Precisely, sampling certainly contains secondary MPs in the descending quantities of fibers, fragments, and films, while the reported colors are black, clear, white, red, blue, green, and yellow for fibers; white, blue, black, and red for fragments; and red, white, clear, green, and blue-black for films. In the same study, it was reported that MP particles in sampling ranged from 0.2 to 5.0 mm in length. Different stream-sites of sampling revealed significant MPs type differences, ranging at Khima stream (min concentration of 2340 ± 227.15 items kg^{-1} dry weight) up to Jedara stream (max concentration of 6920 ± 395.98 items kg^{-1} dry weight) [48].

While in the relevant literature it is not exactly reported which synthetic substances can be classified as MPs, the sources of MPs detection in water resources in the environment can be precisely determined as plastic granules, or pellets, serving as a raw material for manufacturing plastic sheets or ready-to-use items, while the cosmetic industry also uses microgranules (microspheres, nanospheres, microcapsules, nanocapsules) [4]. An indicative classification according to the dimensional range of MPs particle sizing, in alignment with relevant methods that measure their distribution in water resources, is represented in Figure 6.

Based on Figure 6, there is no scientific affirmation about the exact particle size defining the MP particles, whereas there is a widely accepted agreement that MPs are those particles having a range size 0.5–5 mm and attributing them in their larger dimension. Another proposition of MP sizing is proposing a lower limit close to 0.3 mm, taking into consideration the widespread techniques of water sampling using zooplankton nets of 333 μm mesh size [4]. However, it remains unclear in defining the maximum particle size of MPs, being a continuing matter of discussion [4]. It is scientifically correct to propose that particles ranged at 0.5–5 mm should be conventionally considered as a typical range of definition, since substantial technical difficulties have to be confronted while analyzing particles smaller than 0.5 mm [4].

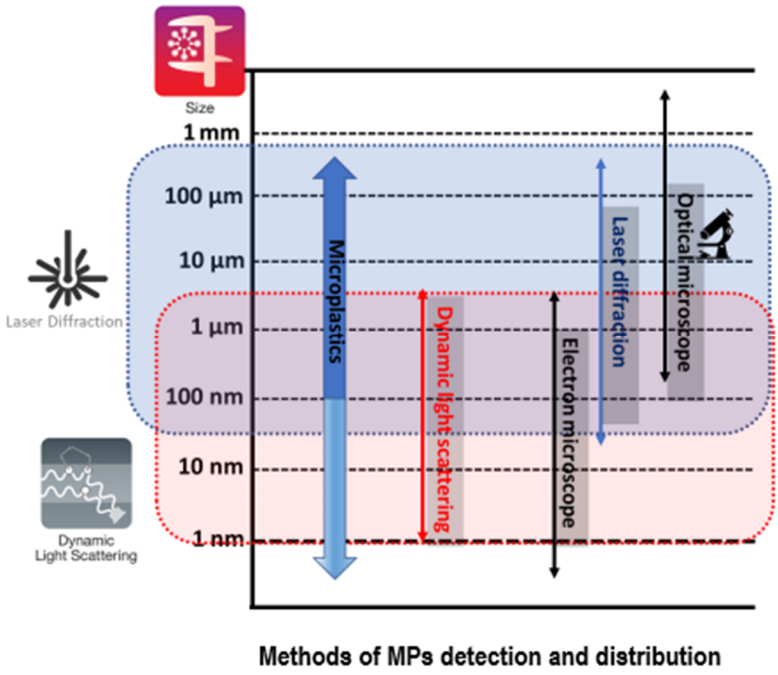

Figure 6. Methods of MPs detection and distribution, in alignment with their particle size. Source: Lee and Chae [20] (p. 6).

Based on Figure 6 and Table 3, it can be stated that among the MP detection methods, vibrational spectroscopy and thermosanalysis both necessitate diversified preparation of sampling with reference to specified methodology. A typical application of such a sampling can include the protocol of sampling, the filtration, the digestion of acid, and the density separation. This procedural analysis is case-specific in alignment with the aquatic environment: marine, wastewater effluent, surface water, bottled water [20]. Moreover, the fact that interfering materials are different in each matrix cannot be undermined, thus, a variety of different samples should follow preparation protocols for each case. The scope of such a formalized analysis is the running of accurate and reliable information, based on the size distribution, the chemical composition, and the concentration by mass and particle numbers. Subsequently, a multiple analytical technique should be executed, compared to the traditional analytical approach of a single methodology. MP analysis showed that polymer identification, the particle size, and the MP abundance can be satisfactorily investigated by FTIR and Raman analyses, while mass concentration can be measured by GC-MS coupled with thermal decomposition [20].

Table 3. Representative types of MPs and the corresponding characteristic compounds, limit of detection (LOD), retention index (LRI), mass to charge ration (m/z), and density.

Polymeric Substance	Characteristic Compound [1]	LRI [2]	m/z [3]	LOD (µg)	Density (g/cm^3)
PP	2,4-dimethyl-I-heptene	846	70	0.027	0.85–0.92
PE (LD and HD)	I-Decene (C10)	993	83;97	0.070	0.89–0.97
PA-6	ε-caprolactam	980	113	0.110	1.14 (PA–66)
PS	Styrene	898	78;104	0.003	1.04–1.08
PMMA	Methyl methacrylate	743	41;69;100	0.029	1.18–1.20
uPVC or PVC	Napthalene	1206	128	0.592	1.16–1.41
PET	Acetophenone	1076	51;77;105	0.015	1.38–1.70

[1] Marker compound used to calculate limit of detection (LOD); [2] Retention index; [3] Mass to charge ratio (ion indicator) Source: [20,59].

Another criterion of characterizing MPs' intake and environmental damage caused to fisheries is the maximum number of MPs ingested by each fish, which is strongly correlated

to exposure, being measured on the distance counted from the source of the river [53]. The integrated representation of the process followed for MPs' identification and quantification is visualized at Figure 7.

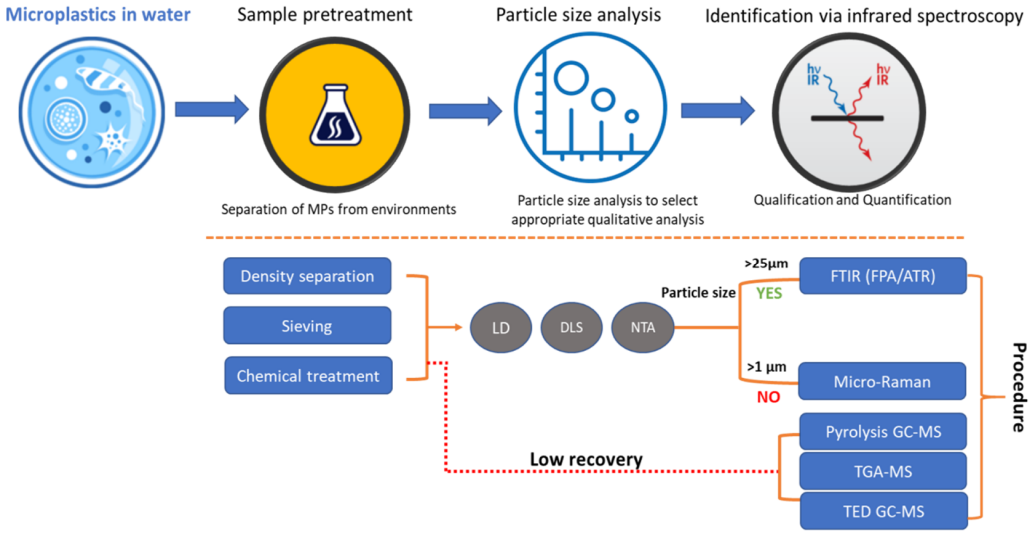

Figure 7. Graphical representation of quantitative/qualitative analyses of MPs identification. Source: Lee and Chae [20] (p. 12).

Based on Figure 7, it has been shown that the naturally abundant polymers of polypropylene and polyethylene can be mainly detected by FTIR analysis [48]. The quantification of MPs by FTIR analysis showed that the predominant MP (in abundance terms) is the polyamides (up to 53.3%), followed by polyethylene and polypropylene (up to 17.1%). Comparably, the planting compounds showed the abundance of natural fragments such as cellulose and wood at proportions of more than 45.8% and 18.8%, respectively [56]. In a similar study, the plastic fragments were identified as being of the most prevalent types of MPs, accounting for 68.5% among all MPs found [29]. Consistent with other studies, as shown in Table 4, it can be argued that MPs' abundance can be positively correlated with fragments' abundance at an increased catchment urbanization, being also commonly composed by the polymeric substances of PET, PP, PE, PS, PAM, and PVC at various mass proportions [20,25].

3.2. Microbiology and Toxicological Conditions of Microplastics

From a microbiology point of view, MP particles of ~40 µm can be related to a low concentration level of 1% of the food particles, being reformulated to an average of ~30 particles in the digestive tract. This correlation resembles a high MP contamination but it is still reflecting on a natural situation. Interestingly, neither increased mortality nor morphological changes in the body and tail spine lengths and width or reproductive abnormalities have been reported for adult water fleas of *Daphnia magna* (a freshwater zooplankton species) [49]. It is also noteworthy that the channeling of MP particles in marine environments is unavoidably influenced by the characteristics of size, shape, type, and age, while those rather weak effects detected in a laboratory may result in reduced fitness in a natural multi-stressor environment [49].

From a toxicological point of view, it can be stated that MPs are prone to absorbing organic contaminants, metals, and pathogens from marine environments into organisms, thus, exacerbating their toxicology features while interacting and causing greater toxic effects. While it has been well known that in marine environments, MPs' accumulation commonly occurs, MPs are ingested from marine vertebrates that seabirds use as bioindicators [2]. Therefore, MP debris causes asphyxiation through drowning, but a restriction in feeding intensifies the symptoms of starvation, skin abrasions, and skeletal injuries.

Furthermore, MP ingestion can block the guts, causing injuries of the gut lining, morbidity, and mortality. Subsequently, small-sized MPs can accelerate their translocation across gastro-intestinal membranes of organisms via endocytosis-like mechanisms into tissues' and organs' distribution. Furthermore, MPs can increase dysregulation of gene expression required in biological systems, while the malfunctions caused are those of MPs' induction of oxidative stress, immunological responses, genomic instability, disruption of endocrine system, neurotoxicity, reproductive abnormities, embryotoxicity, and trans-generational toxicity [2].

Table 4. Overview of polymeric composition at MP types. Adopted from [20,25].

MP Characteristics	PP	PE	PS, PAM, PVC
Atlantic Ocean water, 1.15 particles/m^3	Polyester: 49%	PA/acrylic polyester: 43%	Analysis: FTIR
Atlantic Ocean water, size distribution	0.25–0.5 mm: highest number	0.25–0.5 mm: highest number	-
Density (g/cm^3)	0.85–0.92	0.89 (LDPE); 0.94 (HDPE)	1.04–1.08 (PS) 1.16–1.41 (PVC)
European coastal waters, 13–501 particles/m^3	48%	48%	4% PS; 11% PA Analysis for concentration and particle size distribution: slight microscopy
Size distribution	5–10 µm: 30–40%	>10 µm:<10%	>100 µm: <2%
Size distribution	1–5 µm: 25–60%		5–10 µm: 30–50%; 10–50 µm: 10–60%; 50–100 µm: 0%
Size distribution (µm)	-	-	62.38 (PS); 53.58 (PA); 59.97 (PVC)
Surface area (m^2/g)	-	-	4.13 (PS); 9.51 (PA); 5.29 (PVC)
Surface seawater, 545 particles/m^3	11.1%	77.8%	PE/EA: 11.1% Analysis: FTIR spectroscopy
Surface seawater, Size distribution	<0.5 mm: highest number	<0.5 mm:highest number	0.5–5 mm
Total pore volume (cm^3/g)	-	-	0.044 (PS); 0.090 (PA); 0.051 (PVC)
WTP drinking water	16–33%	0–35%	PAM, PVC < 10% PS, PAM, PVC < 10%
WTP raw water	16–26%	0–24%	Analysis: 10 µm: FTIR; <10 µm: Raman; SEM

Notation: Polyamide (PA); polypropylene (PP); low-density polyethylene (LDPE); high-density polyethylene (HDPE); polystyrene (PS); nylon 66 (PA 66); poly(methyl methacrylate) (PMMA); polyvinyl chloride (PVC); polyethylene terephthalate (PET); polyacrylamide (PAM); poly Ether Amide (PE/EA); water treatment plant (WTP).

Conclusively, research focus should be based on the recognition of new sources of MPs that possibly represent major environmental inputs, compared to those previously considered. In addition to the already renowned sources, pollutants such as the MPs can be also released by embrittlement of plastic litter, microbeads released from personal care products, washing of synthetic clothes, abrasion of vehicle tires, or weathering of different types of paints [12].

4. Discussion, Environmental Considerations, and Challenges

The literature coverage of this review study certainly evidenced the fact of MPs' release into water resources, mainly reported in stormwaters and human-related activities, including sport and recreational activities. In recent years, global research has focused on MPs in marine ecosystems, but data on presence, monitoring, and assessment in freshwater environments are still scarce [57]. This research limitation can closely approach the occurrence, distribution, and chemical composition of MP pollution, mainly in European ponds, aquifers, and water resources [57]. In this research context, a systematic flow-chart of the presence of MPs in surface waters through land and sea origins is presented in Figure 8.

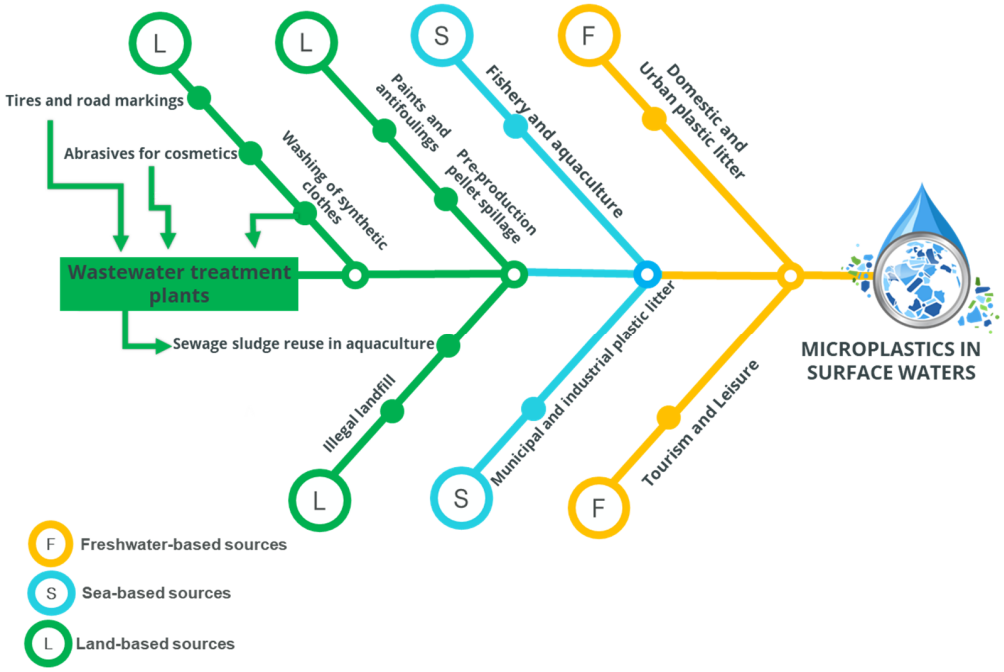

Figure 8. Flow-chart of the presence of microplastics in surface waters trough land and sea origins. Source: Modified and enhanced from Galafassi et al. [12] (p. 133499).

Figure 8 collectively represents that critical and challenging issues for researchers are the conceptualization of MP as a complex, dynamic mixture of land-, sea-, and freshwater-based sources. In the relevant literature, it was shown that polymers and additives, to which organic material and contaminants can successively bind to form an ecocorona, can increase the density and surface charge of particles and change their bioavailability and toxicity. However, there exists a major research gap on ecocorona formulation and in-field applicability in natural water resources [45]. It is also noteworthy that chronic exposure to MPs is rarely lethal, but it adversely affects individual animals, since MPs reduce food and deplete energy stores, with knock-on effects for fecundity and growth. Therefore, it is important for researchers to discover and comprehend the exact ecological processes that affect altered behaviors, bioturbation, and behavioral changes of carbon flux to the deep ocean [45].

There is growing evidence that MP contamination is extended even to freshwater ecosystems, a fact that can lead future studies and risk assessments [48]. Moreover, reporting MPs in freshwater and other water sources suggests that the mechanism of secondary MPs can be delivered by diffuse sources of pollution, especially among rivers and other water bodies of circulating currents, no stagnant waters. Secondary MPs sources in these types of flowing systems are determining the food chain through their intake by fauna, thus, consecutive desorption, fate, and risks around world deserve further research attention both in field and laboratory studies [47,56]. These studies should explore the ways in which MPs are ingested by freshwater fish and, then, evidencing those factors that influence ingestion and exposure hazardous matter to fish and marine biota [53].

From a methodological point of view, MPs' identification, comparison of procedures, limitations, and applicability of supplementary types of analysis such as FTIR, Raman spectroscopy, and thermo-analytical methods are recommended [20]. In this respect, future research on vibrational spectroscopy for MP detection is anticipated to minimize misidentification of the potential MPs in the environment. The accuracy and the efficiency of natural sampling are factors of utmost importance of the quantitative analytical procedure, rather than the (decreasing) analysis time efficiency. Moreover, it is analytically challenging to solidify the accuracy of identification of potential MPs traces by FTIR and Raman by the type and size of MPs being priority over decreasing analysis time, while considering a

25 mm filter area taking over 7 h to analyze [20]. There is a wider possible application of FPA-micro-FTIR and it has a feasible application to water and wastewater treatment. Analytical improvements contain the tracing capability, the accuracy, and the time efficiency of FTIR, while electron-multiplying charged coupled device detector (EM CCD) showed a low signal to noise ratio [20].

Advancements of analytical techniques can be further recommended for degrading (by weathering) MPs to be collected at spectral libraries, enabling the identification and the quantification of such degraded MPs in samples analyzed. Moreover, IR and Raman analysis can be designed and developed for the better preparation of samples, since minimizing the chemical modification of the MPs samples can cause a misinterpretation by the IR spectra [20]. Another analytical challenge of complementary to μ-Raman spectroscopy is that Py-GC/MS pigment, containing particles, fibers, and sea sediment particles, are all identified as plastics [8]. From a technical point of view, the foundation of systematic protocols for MPs analysis is also suggested [20], focusing on: (a) developing water treatment strategies, (b) setting effective limits for MPs, (c) making thorough conventions of what types of water management are linked to what types of MPs, which are both (water- and MPs- types) characterized as hazardous materials [26].

Another research orientation should provide a better understanding of the MPs-carriers sorption mechanism as well as the desorption behavior under different environmental conditions in water resources [51]. It is noteworthy that water sensing devices can support clean and safe water bodies [13], while the adsorption performance of heavy metals by polymeric MPs can better simulate the surface attachment models developed at different kinds of pollutants [51].

Polymeric MPs can be proven as indicators of emerging environmental pollution, acting as carriers for bacterial colonization and propagation of particularly harmful microorganisms, leading to ecological risks attributed due to high stability, pathogenicity, and stress tolerance of the bacterial communities on MPs [30]. Therefore, new insights can pave the way for understanding bacterial dynamics on polymeric MPs in urban water environments [32]. However, future research should confront MPs pollution with susceptibility regarding MPs' pollution in urban wetlands, stressing out the ubiquitous nature of the prevailing MP fragments, indicating that plastic litter degradation plays a significant role of MPs' sourcing in urban environments and industrial areas [29].

It is also imperative that experimental results should be confirmed by model-based studies, investigating the extent to which MP concentrations are negligible, or not, for the overall pollutant uptake of freshwater indicators, such as zooplankton species, with water as an additional uptake pathway [50]. Such research paths can reveal the contradictions between the level and the severity of MPs presented in water sources, thus, encouraging future studies to:

(a) further and fully investigate how MPs are considered as dominant anthropogenic pollutants of ecological risk,
(b) support the primary scope of science and society in tackling such a global environmental issue in the future [45],
(c) investigate the ways in which MPs pollution and sediment resuspension in shallow lakes are affecting climate change, eutrophication, and resuspension [63–65], emphasizing the role of MPs in intensifying the two environmental effects of climate change and eutrophication [66–69],
(d) reinvent plastics production under the environmental considerations and the social provisions for radical modes of eco-design plastics production, biodegradable plastics production, as well as a circular thinking of manufacturing production, making the used plastic products able to undergo a second round of use after recovering and recycling. Moreover, legislative framework updating and WWTPs' adaptation to the aforementioned directions should be shown to be vital tools to endorse those safety regulations of MP pollution decrease in the contexts of circular economy and the employment of effective practices to control the plastic waste crisis [70,71].

5. Conclusions

In addition to the technical appreciation of MPs, it is of paramount importance that researchers and environmental planners approach marine MP debris in the marine environment as an integrated issue, being a contemporary societal issue that challenges the life convenience of using plastic materials in everyday activities without the environmental consciousness of ecological harm caused by careless disposal [45]. Subsequently, the lack of standard procedures to collect and analyze water natural samples, bottom sediments, and coastal deposits poses additional difficulties in the quantitative assessment of MPs in marine environments [4].

Another key aspect of this review study is the time endurance and the long lifetime of hundreds of years for MPs' degradation in marine conditions, making irreversible the breaking down of their size and their quantities lowering while being taken up by marine biota at the entire food chain. Polymers, chemical additives, and contaminants are enclose endocrine disruptors that are hazardous even at extremely low concentrations for marine biota; thus, there is still need for scientific research to focus on better understanding the impacts of plastic litter in marine environments, food chains, and human health. In addition to supporting actions undertaken by the scientific community, industry, policy, and civil society communities can curb the increased flow of MPs and their side-toxic chemicals contained in natural water resources [46].

Therefore, the environmental impacts and the economic costs even in the short term are necessary for the adoption of immediate strong preventive, proactive no post-treatment measures. Increasing MPs production and consumption generates wasteful uses, thus challenging citizens to rethink ways of plastics consumption and the integrated approach of their treatment following efficient waste collection infrastructures and sufficient waste management facilities in all developing and developed economies [46].

Finally, it cannot be undermined that the adverse consequences of the toxicological effects of MPs will continue to be detrimental to humanity in the near and medium future time, unless action is taken by world environmental groups. In this respect, main considerations are burdening those mostly plastic-emitted countries, in Latin America, Africa, and Asia, being accused as major plastic-pollutant countries globally. Hence, these countries should be among the leaders of reducing, re-using, and re-cycling plastic materials/products to enhance plastic control and MPs monitoring and, at the very end, abatement [2]. Conclusively, it can be stressed that experimental outcomes on MPs' fate and consequences are varied worldwide, without reaching a consensus on MPs' relevance as a pollutant indicator; yet, it is also noteworthy that even if pollutants desorb from MPs, a negative effect only manifests if the pollutant reaches the target tissue. However, tissue concentrations of a pollutant are not necessarily the only causalities of a net pollutant effect reported [50].

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