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Review

Macroplastics in Lakes: An Underrepresented Ecological Problem?

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Abstract: Lakes are the greatest reserve of available superficial inland fresh water and concurrently one of the most threatened ecosystems. Among the many pollutants, plastics contaminate lakes worldwide; notwithstanding that, little is known on the impacts of macroplastics. The aim of this work is to provide the first global overview of scientific articles researching macroplastic pollution in lakes. Articles were selected from Web of Science and Scopus databases. We performed a bibliometric analysis of the results on the publication trend, geographical distribution of study areas, investigated matrix (i.e., water, sediment, biota), as well as abundance and type (i.e., shape, litter category, polymer) of lacustrine macroplastics. We also compared the articles' methodologies. Fourteen articles were collected (the publication trend is increasing in recent years), showing a diffuse contamination by macroplastics. Research efforts are mostly focused on shoreline assessments. There is a lack of information and methodological standardisation (i.e., macroplastic size definition, sampling protocol, shape, litter categories), which limits the comparison of article outputs. We propose the definition of lacustrine macroplastics as plastics >5 mm and the adoption of the UNEP/IOC protocol to sample lake shoreline. We suggest focusing future investigations on (1) testing the methodological standardisation, (2) understanding the factors influencing macroplastic dispersal, and (3) assessing the impacts on biota.

Keywords: lacustrine macroplastics; lakes; freshwater; plastic pollution; meta-analysis; methodology

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1. Introduction

Freshwaters provide essential ecosystem services for human well-being [1]. However, these ecosystems are largely threatened by various stressors, such as climate change, invasion by alien species, and chemical contamination, which cumulatively cause biodiversity loss [2]. Among these emerging contaminants, plastics widely affect biota and ecosystem services [3–5].

In particular, it is known that macroplastics (MAs; plastics > 5 mm, *sensu* Gallitelli and Scalici [6]) have a negative impact on aquatic wildlife, for instance, organisms can be entangled or suffocated, their ingestion can cause the occlusion of the gastrointestinal tract, and plastic fishing nets can cause the phenomenon of ghost fishing [7,8]. In addition, as MAs are degraded by abiotic factors [9] and biotic factors [10,11], they can originate from smaller particles called microplastics (MPs; 10^{-3} mm < plastics < 5 mm) and nanoplastics (plastics < 1 µm). Micro- and nano-plastics showed several ecotoxicological and detrimental effects on aquatic wildlife [12]. In brief, investigations carried out in the natural environment showed that organisms are widely exposed and impacted by MPs (see [5,13]). Conversely, environmental studies on nanoplastics still do not thoroughly explain their sources, dispersion, and impacts [14].

In the last two decades, the scientific literature addressing the issue of plastic contamination in freshwater ecosystems has focused especially on MPs rather than MAs [6]. However, it is pivotal to understand the accumulation and distribution of MAs as they affect freshwater ecosystems per se [15], as well as because they are a source of micro- and nano-plastics [16]. Although research on freshwater MAs was neglected in the past, the scientific interest has recently increased [17]. The studies published on MAs in fresh waters focus more on investigating the contamination of rivers than the one of lakes. Rivers were mostly studied in regard to MA transport [6,18,19], possibly due to finding the pathway and fate of land-based plastics to the sea, facing the accumulation into the plastic garbage patch [20,21]. In fact, rivers can be considered the largest vectors of plastics to the seas [22]. The different riverine zones along the entire river rod participate actively as highways transporting plastics to the sea [6,23].

Considering that lakes are large reservoirs of fresh water and provide many ecosystem services (e.g., water supply, irrigation), it is important to monitor the threats that may affect the health status of communities inhabiting the lake, ecosystem functionality, and water quality. Research on plastic pollution in lakes mainly focuses on MPs, describing the wide occurrence and abundance of MPs in biota, water, and sediment of lakes worldwide including remote regions [24], and recently, studies are shedding light on the settling process of MPs in sediment [25–28]. As MAs are sources of MPs, they are supposed to widely contaminate lakes as well as MPs. However, the detailed process describing the contribution of lacustrine MAs to the contamination of lakes by MPs is not clear yet. Even without considering the link to MP pollution, the scientific literature poorly describes qualitatively and quantitatively MA ecological impacts as an independent field of research. Indeed, the detrimental effects of MAs on ecosystems could be further investigated.

The current scientific context shows limited and fragmented information on lacustrine MAs. To clarify the starting point of research on the MA pollution of lakes, we provide the first global review of scientific literature. In particular, this work (i) evaluates the scientific productivity by bibliometric data; (ii) provides the scientific community with an up-to-date global overview by study area, investigated matrix (water, sediment, biota), polymer, category of litter, shape; (iii) provides insights towards a standardisation of the methodology. As outputs, the scientific interest on lacustrine MAs is evaluated, the focal points of research and knowledge gaps are highlighted. The contamination scenario is described by the above parameters to identify the common grounds and main issues that should be addressed.

2. Materials and Methods

This review follows the PRISMA guidelines of systematic reviews [29]. The bibliographic search was carried out by Web of Science and Scopus search engines, which make it possible to search scientific material based on various criteria, including time interval and keywords. The time interval considered for this review starts from a non-fixed start date to include all available scientific publications from the past, until 16 October 2022. The keywords used to select the scientific material on the topic of interest of this review were "macroplastic* and lake*", "macroplastic* and lacustrine", "macroplastic* and lentic", "macroplastic* and freshwater", "mesoplastic* and lake*", "mesoplastic* and lacustrine", "mesoplastic* and lentic", and "mesoplastic* and freshwater". The bibliographic search also included the term "mesoplastic" because the size range of MAs is not standardised; hence, for some authors, the smallest size range of MAs are called mesoplastics (i.e., 5 mm < plastics < 25 mm; see Gallitelli and Scalici [6] and Lippiatt et al. [30]). Only peer-reviewed scientific articles were selected. Duplicate articles were eliminated by a preliminary screening based on the title of articles. Not pertinent articles were excluded after verifying abstracts. The entire manuscript content of the remaining articles was carefully checked for suitability as a final step. Thereafter, the list of results was obtained.

The articles collected from the bibliographic search were analysed in terms of (1) bibliometric information, (2) experimental information. The bibliometric information details the publication temporal trends and the rank of most frequent journals publishing on this topic. For each article, the bibliometric parameter collected for calculating the publication temporal trends is the year of publication, while the name of the journal is noted to evaluate the frequency of occurrence.

The experimental information collected from each article was MA class size definition, study area characterisation (continent, lake origin, e.g., volcanic, glacial, etc.), the investigated matrix (e.g., water, sediment, biota), MA shape (i.e., fragment, fibre, bead), the category of litter (e.g., bottle, fishing net), main plastic polymers detected, and the ratio between the length of the transects sampled and the lake shoreline total length. For the length of the lake shoreline, the values were initially searched for in the scientific literature, but if not found, the shoreline length was extrapolated by Google Earth measurements (Figure S1).

3. Results

3.1. Bibliometric Analysis

Overall, 94 publications were collected by Web of Science and 92 by Scopus. After duplicates were removed, 63 publications remained, including articles or reviews or correspondence or book chapters. We only selected original articles, which were 46. The screening of abstracts selected 23 articles (Figure S2). Fourteen articles are the result of the bibliographic search (Table 1). Although the articles have a non-standardised method as well as a lack of information in some articles compared to others, hindering the comparison, for the purpose of this review all articles were included. The information of the differences between the outputs provided by the articles is itself indeed a highlight of this review.

The scientific literature researching the contamination of lakes by MAs has been increasing sharply in recent years (Figure 1), suggesting that this topic will draw further attention in the future. The graph shows a slightly slower growth between 2020 and 2021, possibly due to the COVID outbreak. The journal with the highest number of articles is *Science of the Total Environment* (Figure 2). However, as the number of published articles per journal ranges from 1 to 3, no journal stands out among the others (Figure 2).

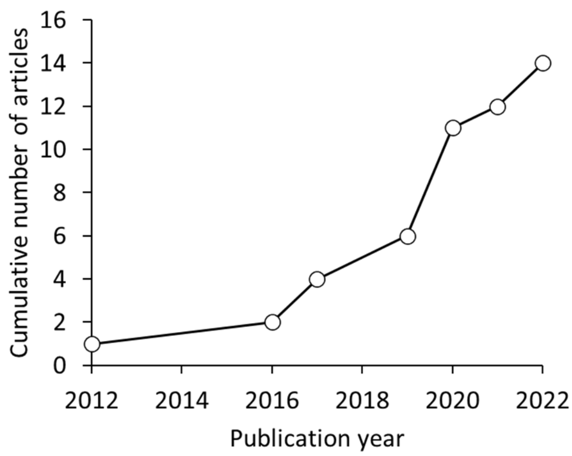

Figure 1. Publication trend on lacustrine macroplastics in lakes.

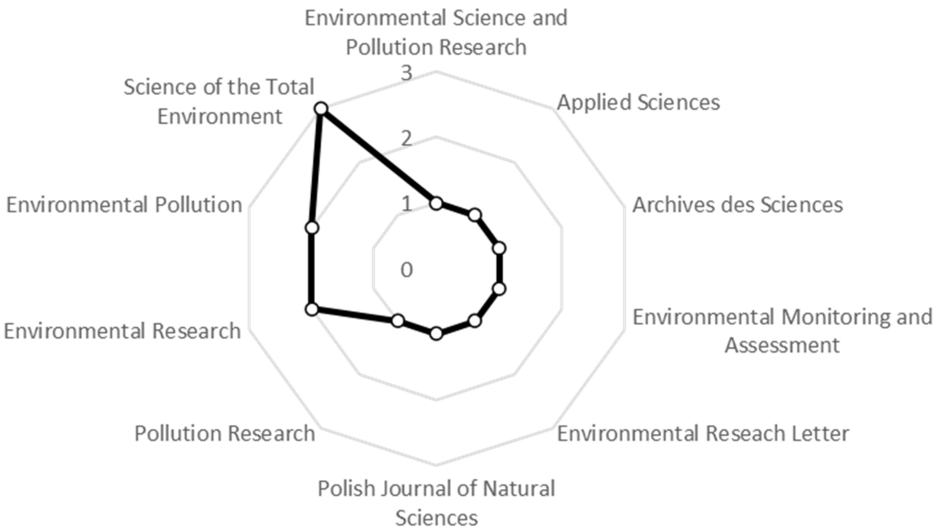

Figure 2. List of journals ordered by number of articles published.

3.2. Macroplastic Size Definition

The information provided in Table 1 on the definition of the size range of MAs shows that there is an evident lack of standardisation. For this reason, the values on the abundance of MAs are not compared between different articles as the results could be misleading. There is no prevalent trend to the definition of size classes in the reviewed articles. Six studies describe MAs as plastic items >25 mm, five articles affirm that they are larger than 5 mm, one article describes MAs as plastic items larger than 20 mm, and two articles do not report the size (Table 1). The more frequent size classes are >25 mm and >5 mm. The lack of standardisation on the size of MAs in fresh waters has been discussed [6]. After reviewing the scientific literature, Gallitelli and Scalici [6] proposed to use the size class of >5 mm for the analysis of MAs in rivers, as widely used among authors investigating MAs in rivers [31–36]. Using the same size classification for lacustrine MAs would allow for a comparison of results between different freshwater ecosystems. Additionally, using the class size >5 mm will make it possible to include the mesoplastics into the MAs, thus removing the class "mesoplastics". It would be useful as the utilisation of "mesoplastic" is marginal in the scientific literature compared to MPs and MAs, and it does not seem that they have unique characteristics which make them substantially different from macroplastics. Hence, the proposed size class of MAs in lakes shall be >5 mm.

3.3. Sampled Lakes Description

A few lakes are investigated, i.e., 21, and they are unevenly distributed worldwide (Figure 3). Isolated reports of contamination are available from all continents: Europe is the most investigated (occurrence 33%), followed by North America (24%). Africa and Asia are equally investigated (19%), while South America is the least investigated (5%) (Figure 4a).

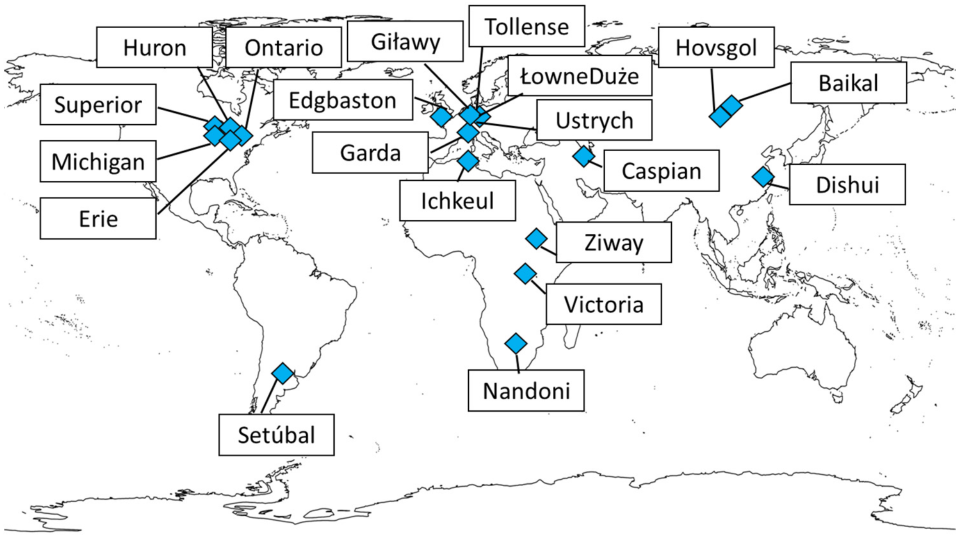

Figure 3. The locations of the study areas are indicated by rhombus and the names of the lakes are shown in the labels.

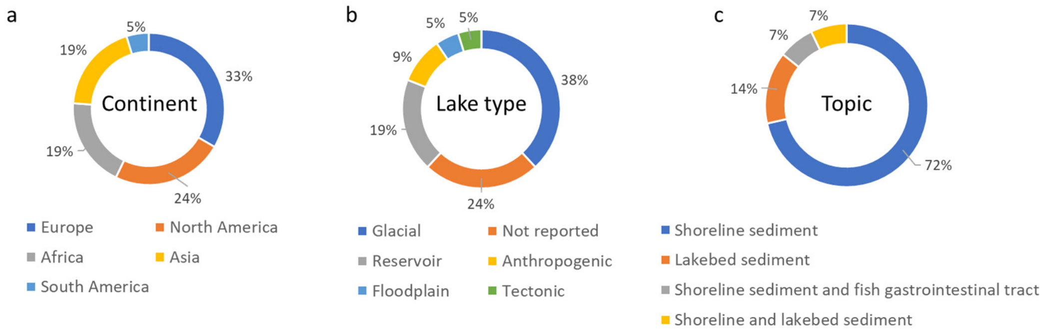

Figure 4. Frequency of investigated articles by (**a**) continent; (**b**) lake type; (**c**) topic.

The origin of the lakes could be a relevant parameter to provide indirect information on the abundance and distribution of MAs, for instance, due to different characteristics of shorelines and the effects of dams (for anthropogenic lakes), although it has not been evaluated yet. As data on the origin of lakes could be exploited in the future, this review includes them in the results. Both natural and anthropogenic lakes are investigated by current scientific literature on this topic. The highest number of sampled lakes has glacial origin (38%), glacial origin (38%), not reported (24%), reservoir (19%), anthropogenic (10%), floodplain and tectonic (both 5%) (Figure 4b). The listed group of glacial lakes is mostly comprised by the American Great Lakes [37]. Each of the American Great Lakes is considered singularly for this metric. There is a lack of information on several types of lakes which is surely connected to the low number of articles available on this topic.

Table 1. List of scientific articles tackling the issue of MAs in lakes. Information on MA size definition and abundance is reported, according to the unit of measurement.

#	Authors	Article Title	Doi	Definition MAs (mm)
1	Arturo and Corcoran	Categorisation of plastic debris on sixty-six beaches of the Laurentian Great Lakes, North America	10.1088/1748-9326/ac5714	25–1000
2	Blettler et al.	Plastic pollution in freshwater ecosystems: macro-, meso-, and microplastic debris in a floodplain lake	10.1007/s10661-017-6305-8	>25
3	Czarkowski et al.	Composition and seasonal changes of litter along the shorelines of selected water bodies in Warmia and Mazury region (North-Eastern Poland)	not available	>5
4	Dalu et al.	Assessing factors driving the distribution and characteristics of shoreline macroplastics in a subtropical reservoir	10.1016/j.scitotenv.2019.133992	>25
5	Egessa et al.	Occurrence, distribution, and size relationships of plastic debris along shores and sediment of northern Lake Victoria	10.1016/j.envpol.2019.113442	>25
6	Faure et al.	Pollution due to plastics and microplastics in Lake Geneva and in the Mediterranean Sea	not available	>5
7	Ghaffari et al.	The influence of human activity and morphological characteristics of beaches on plastic debris distribution along the Caspian Sea as a closed water body	10.1007/s11356-019-05790-y	>25
8	Hengstmann and Fischer	Anthropogenic litter in freshwater environments—study on lake beaches evaluating marine guidelines and aerial imaging	10.1016/j.envres.2020.109945	>25 (referring to anthropogenic litter)
9	Hengstmann et al.	Microplastics in lakeshore and lakebed sediments—external influences and temporal and spatial variabilities of concentrations	10.1016/j.envres.2021.111141	>5 (includes also mesoplastics)
10	Karnaukhov et al.	Pollution by macro-and microplastic of large lacustrine ecosystems in eastern Asia	not available	not reported
11	Jaouani et al.	Seasonal and spatial distribution of microplastics in sediments by FTIR imaging throughout a continuum lake–lagoon beach from the Tunisian coast	doi.org/10.1016/j.scitotenv.2022.156519	>5
12	Liu and Fang	Coastal lakes as a buffer zone for the accumulation and redistribution of plastic particles from continental to marine environment: A case study of the Dishui lake in Shanghai, China	10.3390/app10061974	>20
13	Merga et al.	Distribution of microplastic and small MA particles across four fish species and sediment in an African lake	10.1016/j.scitotenv.2020.140527	>5
14	Vaughan et al.	Microplastics in the sediments of a UK urban lake	10.1016/j.envpol.2017.05.057	Not reported

3.4. Sampled Environmental Matrices

All articles describe the contamination of sediment. Most of the investigations (71%) focus on the contamination of shoreline sediment, a minor number of investigated lakebed sediment (14%), and only one article also investigates the ingestion of MAs by fish (7%) (Figure 4c).

3.5. Shape of Sampled Macroplastics

Five articles examine the shape of the items collected, finding that fibres are the most frequent shape. However, in addition to shape, the MA items can also be described in different categories according to their use. The top-three categories described in different lakes are: bags, bottles, beverage bottles, bottle caps, cellophane bags, fishing lines, food wrappers, packaging material, plastic canisters, plastic plates, and synthetic clothes (Figure 5). The categories are not standardised across the articles. To allow for the comparison, the categories are renamed by classifying them according to the United Nations Environment Programme/Intergovernmental Oceanographic Commission (UNEP/IOC) Guidelines on Survey and Monitoring of Marine Litter [38] (Table S1). This new dataset shows that there is no category significantly more abundant than the others if the number of items if considered, while plastic bottles are the main contaminant if mass (g) is evaluated. However, this result is based on a limited amount of information from the scientific literature so it cannot be generalised.

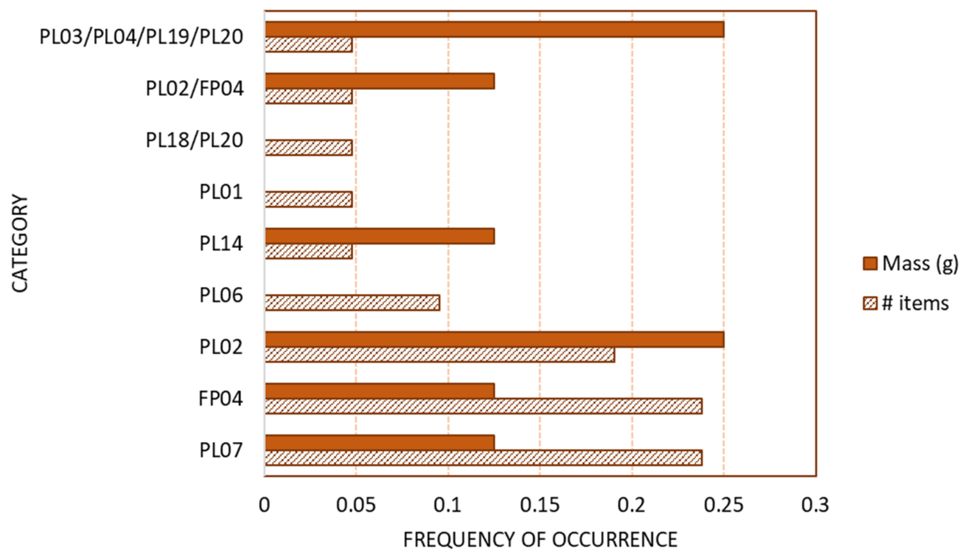

Figure 5. The most frequent categories of litter are shown according to mass and number of items. The category codes follow the standards of UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter [38] (Table S1).

3.6. Main Polymers of Sampled Macroplastics

Four articles examine the type of polymer of MAs in seven lakes. It is shown that polypropylene (PP) and polystyrene (PS) are the most frequent polymers among the top-three ranking polymers (Figure 6). In detail, PP is described in all articles examining the chemical composition of the MAs, while PS in three of four articles, and the other polymers in only one article each. The lower abundance of PE is in contrast with the study of Gallitelli and Scalici [6], which reviews the contamination by MAs in rivers and assesses that HDPE and LDPE are the main contaminants with PP and PS being below 10% of occurrence each. This could be due to the different habitat sampled or by the smallest dataset available on lakes. Conversely, the result of this study is partially in agreement with the results reviewed on microplastics contaminating freshwater ecosystems [13], which show that the main microplastic polymers found in water and sediment are PP and PE (more than 50% of occurrence). The presence of a certain MA polymer could explain the presence of microplastics of the same polymer type that generated the fragmentation of MAs. The relationship between the plastic items of these two class sizes is to be taken into account in future investigations of lake contamination.

3.7. On the Transect Length—Shoreline Length Ratio

Data on the shoreline length could be obtained from all 21 lakes, while the values of transect length could be collected from 16 lakes (Table S2). The median transect length is 440 m and the minimum length is 40 m, while the maximum one is 950 m. The length of transects is significantly lower than the shoreline length (Kolmogorov–Smirnov, $p < 0.01$). Only 0.12% of the shoreline is sampled (median value) with the minimum sampled transect being 0.0006% of the total shoreline and the maximum being 100% of the whole shoreline. These figures call into question the representativity of results if generalised over the entire lake. There are no guidelines assessing the minimum shoreline to be sampled to have a precise and accurate assessment of lake contamination by Mas, nor on how to choose the sampling stations, i.e., which beaches to sample. Additionally, it should be taken into account that the sampling efforts required to sample along the shoreline are greater in larger lakes than in smaller lakes to maintain a high ratio transect length—shoreline length.

We provide some suggestions on how to carry out the sampling on lake shorelines in the following chapter.

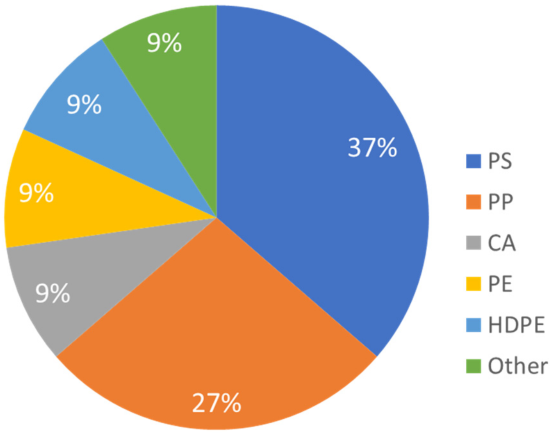

Figure 6. Occurrence of the top-three most abundant polymers in the four articles examining this parameter. PS = polystyrene; PP = polypropylene; CA = cellulose acetate; PE = polyethylene; HDPE = high-density polyethylene.

4. Methodological Discussion

4.1. How to Select the Sampling Stations on Lake Shorelines

There is not a standardised protocol to select the sampling stations. Arturo and Corcoran [37] select the stations "according to public accessibility while trying to keep the spacing between each location as regular as possible". Accessibility is also a parameter taken into account by Merga et al. [39]. Most articles take into consideration the anthropogenic pressures for choosing the sampling stations: high and low population density [40–42]; type of anthropogenic activity [39,41,43–45]. Topography and exposition are also parameters taken into consideration [41,43,44].

In order to create some standardisation on shoreline sampling, the methodologies adopted by the scientific literature on sampling marine ecosystems is discussed for applications in lake shorelines. In particular, the Guidelines for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area (OSPAR guidelines) and the Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean by the National Oceanic and Atmospheric Administration (NOAA guidelines) are among the most cited ones to describe methodological protocols to monitor litter on marine beaches [30,46]. They are used as reference to evaluate whether the consolidated methodology on macroplastics in beaches can be applied for lake shorelines as well. In order to decide how to select the sampling stations, OSPAR and NOAA suggest dividing the coast in sectors, each representative of a marine area. The same reasoning could be applied to lakes, i.e., to divide the lake shoreline in sectors according to topography and exposition. As an example, considering the simplest case study, i.e., a circular shoreline of a volcanic lake, at least four sectors should be chosen, one at each cardinal point to detect the effects of wind and currents. However, the knowledge of the local lake chosen as study area by the authors is a requisite in order to divide the lake in representative sectors. As the identification of lake sectors is a relevant factor to choose the sampling sites and interpret the results, it is recommended to be thoroughly explained in the methodological section. As an additional variable, the division in sectors is scale-dependent: coves or inlets can be considered singularly or cumulatively at different scales. The relevance of the scale at which the investigation should be carried out is to be evaluated by further research.

Thereafter, based on the scientific literature outputs, we suggest two methodological steps for selecting the stations: (1) within each sector, perspective stations shall be chosen according to their accessibility; (2) among the stations chosen in step 1, it is auspicated that the perspective stations shall be representative of all anthropogenic pressures impacting that lake sector as well as areas supposed to be pristine. To evaluate the pressures impacting the lake sector, the land use could be observed, the presence of tributaries, and a local survey could identify local types of anthropogenic activities impacting the perspective stations. A reasonable minimum of one station for each sector is recommended to be sampled to provide an overview of the variability of contamination across the lake shoreline sectors.

4.2. Sampling Unit Methodology

There is no homogeneity in the methodology to sample the shoreline stations, and some authors do not describe their applied methodology in detail [47–49]. The use of transects is prevalent but they can be set either parallel to the shoreline or perpendicular to the shoreline [44,45], and there can be one transect [37,50] or more transects (usually three) [40,42–44]. Additionally, some authors sample along all transects [36,44,48,49], while others sample quadrat plots along that line [40,42–44]. About half of the articles do not provide references to support their sampling methodology [37,39,41,47–49,51]. Among the ones that do refer to previous work, the references used are Fisher et al. [44,52], Heo et al. [43,53], Hidalgo-Ruz et al. [43,54], Loder and Gerdts [43,55], NOAA guidelines, i.e., Lippiatt et al. [30,40,50], and OSPAR guidelines [45,46,56]. The NOAA and OSPAR guidelines are the most used methods as they are repeated by two papers each. These few repetitions hardly provide sufficient strength to recommend the NOAA or OSPAR sampling methods. A study comparing these methods is not available; hence, it is not possible to identify the most appropriate one to date.

As there is no scientific consensus, our suggestion is to follow the UNEP/IOC guidelines [38], where the authors describe that the length of the transect is not fixed strictly but should be appropriate to the amount of litter contaminating the beach to provide reliable data, i.e., poorly contaminated beaches shall have a higher sampling effort. The minimum sampled transect should be 100 m while the maximum length is usually 1000 m, or even multiples of 1000 m in almost pristine beaches [38]. The sampling should cover from the water edge to the back of beach, defined by vegetation [38]. The items are described in categories according to UNEP/IOC guidelines.

We highlight a recent publication describing guidelines for the monitoring of plastics in freshwater ecosystems: "Monitoring Plastics in Rivers and Lakes: Guidelines for the Harmonization of Methodologies" by the United Nations Environmental Programme (UNEP) [57]. It includes a proposal of sampling methodologies of plastics in lakes, including both water, sediment, and shoreline. The application of the described methods for lacustrine MAs could be tested to provide support for further investigations in lakes.

5. Conclusions and Recommendations

The outputs of this review aim at representing a contribution to researching a widespread contaminant affecting lentic ecosystems worldwide, yet which is still poorly investigated, by critically discussing the knowledge gaps and providing future perspectives. It will hopefully be useful as a starting point to researchers approaching lacustrine MAs for the first time as well as an opportunity for experienced researchers to contextualise their research in a global scenario.

In detail, this overview shows that lakes are polluted in different geographical areas with various levels of contamination. In particular, the single-use plastic is the main lacustrine MA category polluting the shoreline. It is noticed how the contamination of nearshore is the focus of research. Conversely, the floating lacustrine MAs and the entrapment by vegetation are scarcely investigated. However, a lack of methodological standardisation is also highlighted.

Research on the impacts of lacustrine MAs has been neglected until recent years, but given the growing interest on this topic of research, the sampling effort is desirable to increase in the futures to provide a clearer overview and quantification of the impact of lacustrine MA pollution. In detail, we suggest focusing the research efforts on identifying the factors positively relating with the abundance and spatiotemporal variability of MAs and quantifying their contribution; describe the dispersal process and identify the sinks (including the role of vegetation to MA entrapment); evaluate the characteristics of biofouling (e.g., taxa, ecological succession) and impacts on organisms (e.g., entrapment). We also suggest disseminating information on the detected abundance and litter categories of lacustrine MAs to raise public awareness in order to protect the lake ecosystem. However, above all possible fields of research on lacustrine MAs, we strongly suggest prioritising a methodological, thorough investigation to avoid issues on the comparability of results, which often characterise research on plastics. Based on the results of this review, the following recommendations are provided as an output to contribute to increase standardisation and promote a scientific discussion on this topic:

- Use ">5 mm" as class definition for MA items;
- Standardise the sampling methodology to UNEP/IOC guidelines;
- Standardise the definition of plastic litter categories according to UNEP/IOC guidelines;
- Chemically identify the plastic items to evaluate the main polymers.

Due to the several knowledge gaps of the scientific literature, this review can limitedly define the impacts of lacustrine MAs but aims to strongly support and enhance the scientific debate. The results here provided are the first to focalise the scientific community on MAs in lakes. In the future, the issue of lacustrine MAs will hopefully be addressed in the optic to evaluate their abundance, dispersal in the biogeological cycle, and impacts, in order to limit their introduction into the lacustrine environment, mitigate the contamination, and eventually restore the ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15010060/s1, Table S1: categories of litter renamed according to UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter; Table S2: values of transect length collected from 16 lakes. Figure S1: Example of polygon obtained by Google Earth used for measurements of shoreline length of lakes. Figure S2: PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only.

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