limnological review

MDPI

Article

Microplastics in Sediments of the Littoral Zone and Beach of Lake Baikal

Anastasia Solodkova [1], Sofya Biritskaya [1], Artem Guliguev [1], Diana Rechile [1], Yana Ermolaeva [1], Arina Lavnikova [1], Dmitry Golubets [2,3], Alyona Slepchenko [1], Ivan Kodatenko [1], Alexander Bashkircev [1], Natalia Kulbachnaya [1], Darya Kondratieva [1], Anna Solomka [1], Dmitry Karnaukhov [1,4,*] and Eugene Silow [1,*]

[1] Institute of Biology, Irkutsk State University, 1, Karl Marx St., Irkutsk 664025, Russia; solodkovaanastasiya147@gmail.com (A.S.); biritskaya.sofya@mail.ru (S.B.); aguliguev29@gmail.com (A.G.); rechile.diana@mail.ru (D.R.); erm.yana@mail.ru (Y.E.); lavnikova_arina@mail.ru (A.L.); aloyna.sl@icloud.com (A.S.); kodatenko.ivan194014@yandex.ru (I.K.); alexandr.bashkirtsev.06@mail.ru (A.B.); natalalen@mail.ru (N.K.); kondratievads@gmail.com (D.K.); anya.solomka@bk.ru (A.S.)
[2] Institute of Monitoring of Climatic and Ecological Systems SB RAS, 10/3 Academic Ave., Tomsk 634055, Russia; dima.golubets1203@gmail.com
[3] V.B. Sochava Institute of Geography SB RAS, 1, Ulan Batorskaya St., Irkutsk 664033, Russia
[4] Baikal Museum SB RAS, 1A, Akademicheskaya St., Listvyanka 664520, Russia
* Correspondence: karnauhovdmitrii@gmail.com (D.K.); eugenesilow@gmail.com (E.S.)

Abstract

Most studies on microplastic pollution in aquatic ecosystems have focused on the quantitative and qualitative assessment of particles in surface waters. However, the highest concentrations and accumulation of microplastic particles are observed in bottom sediments. The aim of this study was to determine the concentrations of microplastic particles of different morphology in sediments in the beach and littoral zones of Lake Baikal. This study is the first in relation to Lake Baikal to focus specifically on the analysis of microplastic particles in bottom sediments. The results of the study showed that the registered values of concentration of microplastic particles do not exceed the average values for lakes around the world. The predominant type of particles in both the littoral zone and the beach is microplastic fibers. An exception is observed only for one of the locations. This exception is related to the permanent mooring of vessels in this place. Analysis of the types of artificial polymers showed that the microplastic fibers were represented by polyester, and the fragments were represented by alkyd resin (66%), polyvinyl alcohol (32%) and polyvinyl chloride (2%). Shown for the first time in this study, the presence of large numbers of microplastic particles with rare types of artificial polymers suggests that these particles may be under-reported in other studies. The underestimation of particles may be due either to the selection of sampling locations located far from heavily contaminated areas, or to the fragility of these polymers. Although the harm of these types of polymers has not yet been confirmed, the large number of these particles in local areas of lakes should be taken into account. This is due to the large number of organisms, which is usually characteristic of littoral areas, including Lake Baikal, with its diversity of fauna and flora.

Keywords: microplastics; artificial polymers; Lake Baikal; littoral zone; aquatic ecosystems

check for updates

Academic Editor: Gabriel-Ionut Plavan

Received: 13 August 2025
Revised: 21 September 2025
Accepted: 23 September 2025
Published: 24 September 2025

Citation: Solodkova, A.; Biritskaya, S.; Guliguev, A.; Rechile, D.; Ermolaeva, Y.; Lavnikova, A.; Golubets, D.; Slepchenko, A.; Kodatenko, I.; Bashkircev, A.; et al. Microplastics in Sediments of the Littoral Zone and Beach of Lake Baikal. *Limnol. Rev.* **2025**, *25*, 46. https://doi.org/10.3390/limnolrev25040046

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Plastics (artificial polymers) are a widely used material in industry, agriculture, medicine and trade [1]. The widespread use of plastic has led to an increase in the amount

of waste that accumulates and pollutes the environment. At the same time, large amounts of plastic can be found in aquatic ecosystems. In coastal areas, plastic is subjected to mechanical grinding and ultraviolet radiation, which leads to its degradation into microplastics [2]. Microplastics are plastic fragments, fibers, foams, granules and films up to 5 mm in size [3–6]. Due to their small size, animals can mistake microplastics for food particles, eat them and pass them along the food chain, which can potentially harm both animals and humans [7].

Further events with microplastics in water depend on several factors related to both the water body (wind, currents, geographic location, etc.) and the properties of plastic particles (morphological structure of particles, type of polymer) [8,9]. However, while aging plastic waste easily settles on beaches, causing pollution in a certain area, plastic particles in the water column inevitably sink to the bottom [10,11]. The main factor that leads to the settling of microplastic particles to the bottom is biofouling (algae and microorganisms settling on the surface of the plastic lead to its weight and sinking) [12]. Considering this, accumulation and maximum concentrations of plastic particles in water bodies should be expected precisely at the bottom [13]. Despite this fact, historically, most information on microplastic particle concentrations is known in relation to the near-surface layer [14–19], and the study of particle concentrations in sediments has long been ignored.

Marine ecosystems are currently the most well studied in terms of microplastic pollution [20,21]. Freshwater ecosystems have received much less attention [8,16,22]. In this regard, Lake Baikal (Russia) is no exception. For a long time, no such studies have been conducted on this lake. However, Baikal experiences significant anthropogenic pressure. There are many settlements on its shores, many of which are not equipped with modern infrastructure, and the annual flow of tourists exceeds hundreds of thousands of visitors [23]. The first studies on the issue of microplastics were conducted in 2015 [24,25]. Subsequently, a number of studies made comparisons with other large lakes [22], determining the concentrations of microplastic particles above the pelagic zone [15], in the lake ice [26], particles were found in some representatives of the lake fauna [27]. However, there have been no studies on the contamination of bottom sediments of Lake Baikal with microplastic particles. In addition, examples of the use of microplastic particles in large quantities by various species of caddisflies in Lake Baikal have been documented [28]. The latter prompted us to conduct a study to determine the concentration of particles in the sediments of the littoral zone of Lake Baikal, as well as in the beach area. The aim of our study was to determine the concentration of microplastic particles in sediments of both the beach zone and the littoral zone of Lake Baikal in places with different anthropogenic loads.

2. Materials and Methods

Lake Baikal is located in the southern part of Eastern Siberia. It is one of the largest lakes in the world and has unique endemic flora and fauna. The population density on the shores of Lake Baikal is low. However, the lack of infrastructure for waste disposal and wastewater treatment leads to fairly high concentrations of microplastic particles in the pelagic zone of the lake (which can be carried by currents) [15,26]. Taking this into account, locations (a total of 7 sampling points) were selected for this study with no population at all (e.g., the location at the mouth of the Cheremshanka River), with intermittent human presence (locations in Peschannaya Bay, near the village of Davsha, on Ogoy Island), and with a permanent population (e.g., near the village of Listvyanka, the village of Maksimikha, next to the Zagza recreation center). These locations are spatially distributed on both sides of the lake, and, in addition, they differ in the presence or absence of a ship anchorage (port) (Figure 1, Table 1). Sampling of bottom sediments from the lake's littoral and beach areas was carried out in August 2024.

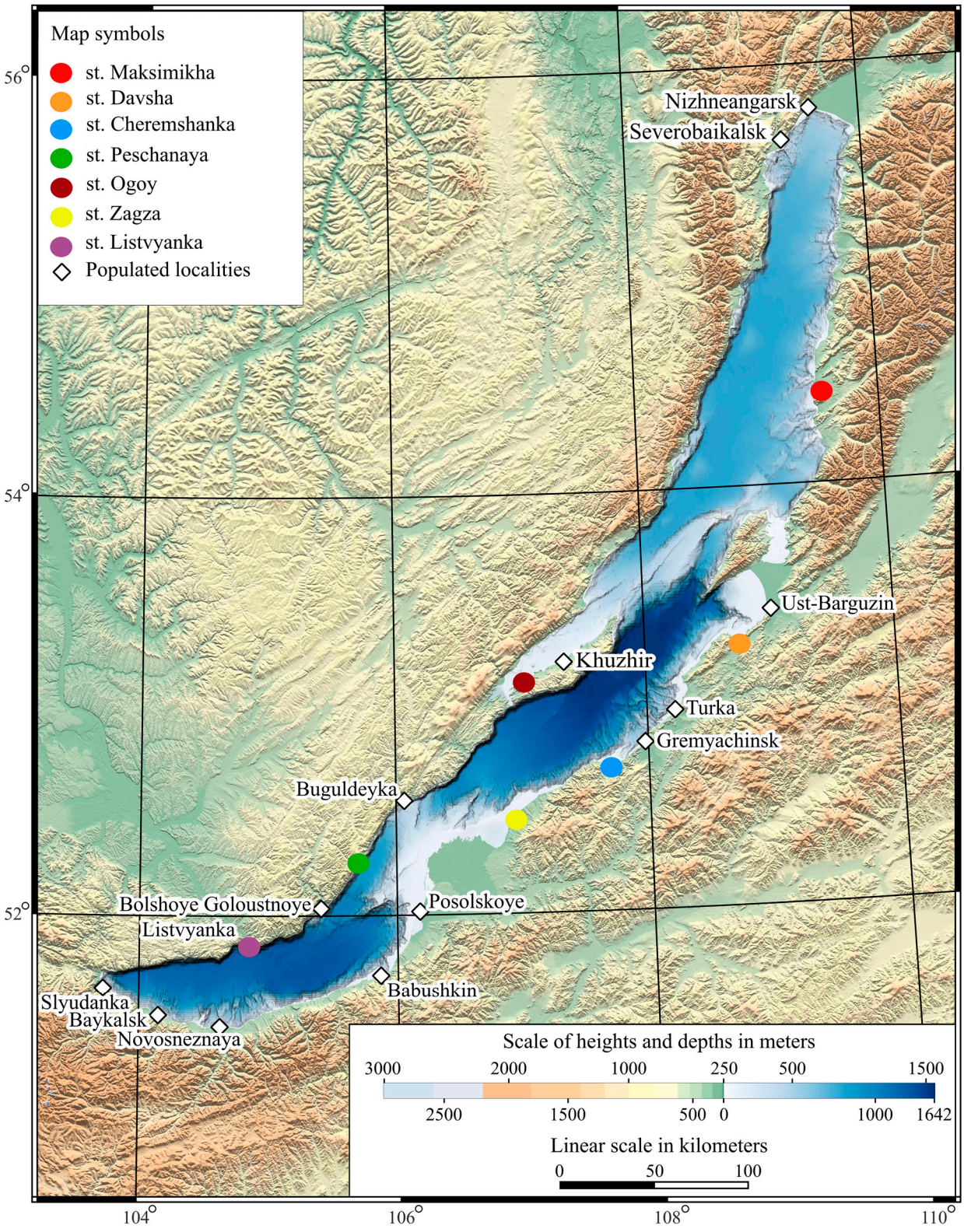

Figure 1. Location of sampling points.

Table 1. Characteristics of sampling points.

№ Sampling Point	Sampling Location	Coordinates	High Recreational Load, + or —	Availability of Ship Anchorage, + or —
1	near Maksimikha village	N 53°16′05.7″ E 108°44′20.9″	+	—
2	near Davsha village	N 54°21′23.1″ E 109°30′00.6″	+/—*	—
3	near the mouth of Cheremshanka river	N 52°42′07.6″ E 107°41′40.6″	-	—
4	in Peschanaya Bay	N 52°15′43.3″ E 105°42′27.1″	+/—*	+
5	Ogoy Island	N 53°07′37.6″ E 106°59′50.9″	+/—*	+
6	near Zagza recreation center	N 52°31′26.8″ E107°03′15.2″	+	—
7	near Listvyanka village	N 51°50′52.0″ E 104°52′17.7″	+	+

* Note: +/—-average level of recreational load.

Samples were collected with all precautions (sample containers were washed, containers were closed immediately after the sample was placed there, sampling took place in cotton clothing) manually in sealed containers using a metal hand bottom grab and scoop (which were washed each time before and after use). At each sampling point, at least three samples were collected in the littoral zone at a depth of 0.5 m and a similar number of samples in the beach zone. We used the generally accepted method for processing the samples [29]. This method involves drying the samples, removing organic matter, flotation in a hypersaline solution and subsequent filtration. However, given that we knew in advance what types of artificial polymers we might encounter, there were two deviations from this method. Firstly, we dried the samples at 55 °C. Secondly, instead of H_2O_2 we used KOH. This was necessary to minimize the amount of damage and destruction of microplastic particles [30,31]. Preparation for drying, as well as all subsequent actions, were carried out in a closed room under a fume hood. To control contamination, filters moistened with distilled water were placed in Petri dishes inside the hood.

The Glass Fiber Filters (1 μm pore size) obtained after vacuum filtration were examined for further microplastic particle counting under a stereo microscope (UNITRON Z850, Boston, MA, USA). All particles were retained on filters in Petri dishes. The lower limit of the analyzed particles in this study was 70 μm. The classification of particles as fibers or fragments was performed visually based on the aspect ratio and surface structure of the particle. It is worth noting that the color was recorded for all particles (both fibers and fragments). The type of polymer particles (all particles were analyzed) was determined using a Raman microscope M532 (EnSpectr, Chernogolovka, Russia). The laser wavelength was 532 nm; the spectral resolution was 6–8 cm^{-1}. A microplastic particle was assigned to a specific polymer type with a similarity coefficient of at least 0.7.

Statistical processing of the data obtained during the study was carried out using Past (version 4.03). The Mann–Whitney criterion and the Kruskal–Wallis criterion and Dunn's post hoc test with Bonferroni correction were used to compare the number of particles.

3. Results

During the study, microplastic particles were found in sediments at all sampling points. At one of the points (near the Zagza recreation center), only fibers were found (Table 2). It is also worth noting that no other types of microplastic particles by morphological structure except fragments and fibers were found.

The quantity of fibers in the beach area ranged from 2.3 ± 0.6 particles/100 g (near the Zagza recreation center) to 32.7 ± 0 particles/100 g (near the village of Davsha) (Table 2). The quantity of fibers in the littoral sediments of the lake ranged from 2.3 ± 0.8 parti-

cles/100 g (near the village of Davsha) to 22 ± 8.7 particles/100 g (near Peschanaya Bay). In turn, the number of fragments in the beach zone fluctuated from 0 (at the mouth of the Cheremshanka River, the Zagza recreation center and the Ogoy Island) to 58.5 ± 19.1 particles/100 g (near the village of Listvyanka), and in the littoral zone from 0 (near the village of Maksimikha and the Zagza recreation center) to 130.7 ± 27.3 particles/100 g (near the village of Listvyanka). Moreover, if we compare the total amount of microplastic particles, the minimum concentration was noted for the location near the Zagza recreation center (1.2 ± 0.7 particles/100 g), and the maximum concentration was noted for the location near the village of Listvyanka (50.4 ± 29.5 particles/100 g). We additionally weighed the microplastic particles found near the village of Listvyanka. The weight of the particles in the beach zone was 0.08 ± 0.03 g/100 g, and in the littoral zone was 0.39 ± 0.12 g/100 g. The average particle count for Baikal based on this study is 13.2 ± 6.4 particles/100 g. It is worth noting that the significant dispersion of microplastic particle concentrations observed for Lake Baikal is typical for the distribution of microplastic particles in other ecosystems [32]. Such dispersion can be explained by the purely random distribution of particles in the water body [33].

Table 2. The amount of microplastic particles in sediments of the littoral zone and beach zone (per 100 g): mean ± standard error, min/max values.

Sampling Locations	Fibers		Fragments		Average Number of Microplastic Particles
	Beach Zone	Littoral Zone	Beach Zone	Littoral Zone	
near Maksimikha village	31.3 ± 1.7 28.1/33.9	16.6 ± 4.4 8.7/23.9	0.9 ± 0.9 0/2.9	0	12.2 ± 7.4
near Davsha village	32.7 ± 0 32.7/32.7	10.5 ± 0 10.5/10.5	0.3 ± 0 0.3/0.3	0.2 ± 0 0.2/0.2	10.9 ± 7.7
near the mouth of Cheremshanka river	8.5 ± 1.02 7.3/10.5	5.8 ± 0.5 5.0/6.8	0	0.2 ± 0.2 0/0.6	3.6 ± 2.1
in Peschanaya bay	19.5 ± 1.7 16.1/21.7	22 ± 8.7 6.3/36.5	0.2 ± 0.2 0/0.6	0.5 ± 0.5 0/1.6	10.5 ± 5.9
Ogoy Island	9.9 ± 1.8 6.8/12.9	5.1 ± 1.6 1.7/7.8	0	0.2 ± 0.2 0/0.7	3.8 ± 2.4
near Zagza recreation center	2.3 ± 0.6 2.2/2.4	2.3 ± 0.8 0.8/3.6	0	0	1.2 ± 0.7
near Listvyanka village	8.6 ± 1.3 6.6/12.1	3.8 ± 1.9 0.8/7.2	58.5 ± 19.1 13.7/96.6	130.7 ± 27.3 82.3/176.9	50.4 ± 29.5
Average value	16.1 ± 4.5	9.4 ± 2.8	8.6 ± 8.3	18.8 ± 18.6	13.2 ± 6.4

When statistically processing the results using the Mann–Whitney test, no significant differences were found between the number of fibers in the beach zone and in the littoral zone, the same applies to microplastic fragments. However, when comparing the number of fibers and fragments in the beach zone, there are statistically significant differences (p = 0.03), and the same applies to the littoral zone (p = 0.03). This confirms our observations that fibers are the dominant morphological group of microplastic particles, both in water and sediment.

Pairwise comparison of all sampling points with each other using the Kruskal–Wallis criteria and Dunn's post hoc test with Bonferroni correction gave the following results. When analyzing the amount of microplastic fibers in the beach area, statistically significant differences were found between the location near the Zagza recreation center and the location near the village of Maksimikha (p = 0.02), and when analyzing the amount of fibers in the littoral zone, differences were found between the location near the Zagza recreation center and the location in Peschanaya Bay (p = 0.01). When comparing the number of fragments both in the beach zone and in the littoral zone, statistically significant differences exist between the location near the village of Listvyanka and all other sampling sites.

In percentage terms, the obtained data look as follows (Table 3). Microplastic fibers are the most prevalent type of particles by morphological structure. The percentage distribution

of microplastic particles between the beach and littoral zones varies depending on the sampling location. However, in general, it can be considered equivalent. The obtained average percentage alignment (where fibers account for 54.8%, and fragments 45.2%) was influenced by samples taken near the village of Listvyanka.

Table 3. Percentage ratio of the number of microplastic particles with different morphological structures at sampling sites (%).

Sampling Locations	Fibers		Fragments	
	Beach Zone	Littoral Zone	Beach Zone	Littoral Zone
near Maksimikha village	58.2	41.5	0.3	0
near Davsha village	69	30.6	0.2	0.2
near the mouth of Cheremshanka river	33.3	64.4	0	2.3
in Peschanaya bay	38.9	58.9	0.3	1.9
Ogoy Island	49	49	0	2
near Zagza recreation center	16	84	0	0
near Listvyanka village	5.5	1.6	34.5	58.4
Total percentage	54.8		45.2	

Determination of the polymer type using Raman spectroscopy showed that all the fibers that could be analyzed were polyester. In turn, the fragments were alkyd resin (66%), polyvinyl alcohol (32%) and polyvinyl chloride (2%).

In addition, we analyzed the distribution of microplastic colors relative to their morphological structure (Figure 2). The most common colors among the fibers are black (52.9%), blue (28.7%) and green (10.8%). Among the fragments, the most common colors are white (40.4%), blue (25.3%) and red (15.2%).

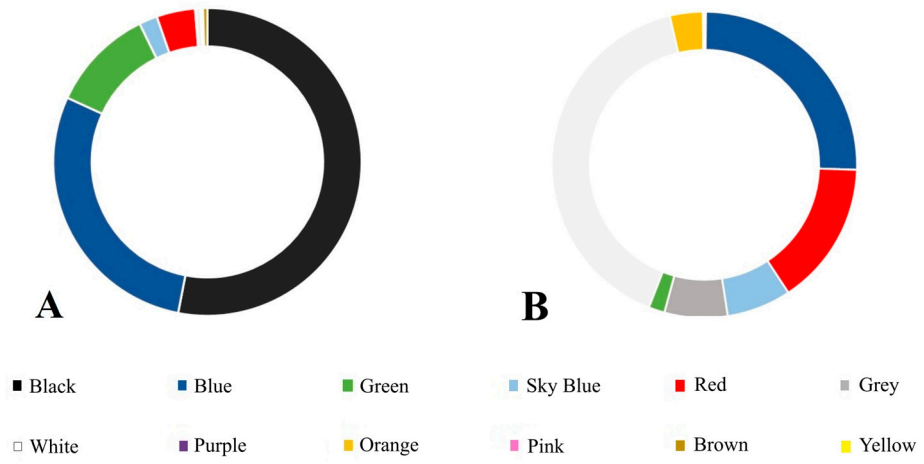

Figure 2. Overall distribution of microplastic colors across all sampling points ((**A**) microplastic fibers; (**B**) microplastic fragments).

Another parameter analyzed was the size of microplastic fibers (Figure 3) and fragments (Figure 4). Our study detected particles ranging from 0.07 to 5 mm in size. However, the majority of microplastic particles in both cases were smaller than 1 mm.

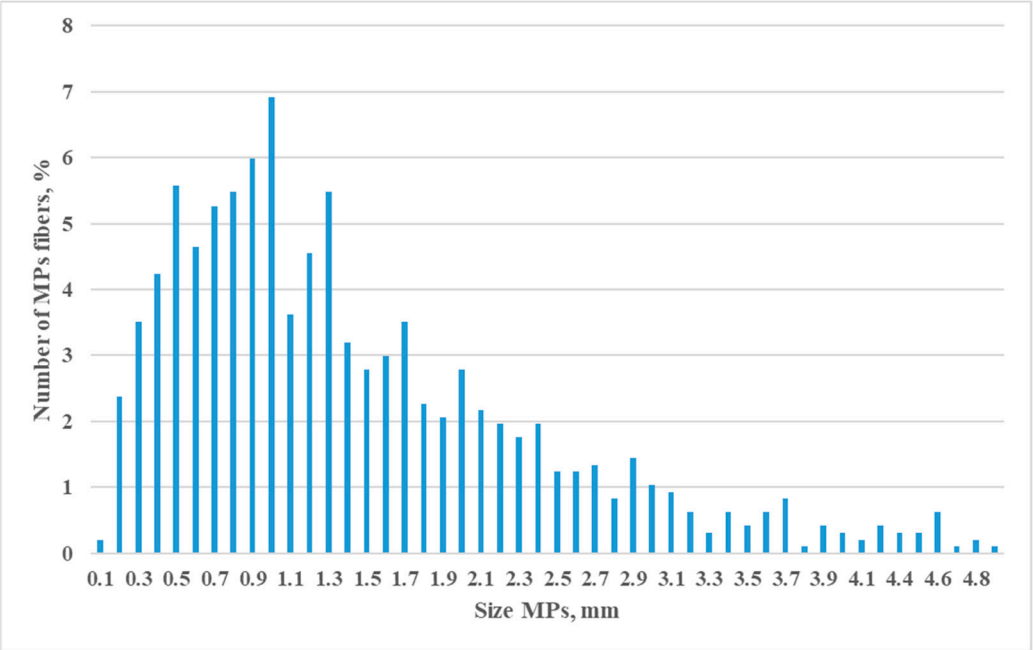

Figure 3. Percentage of microplastic fibers of different sizes.

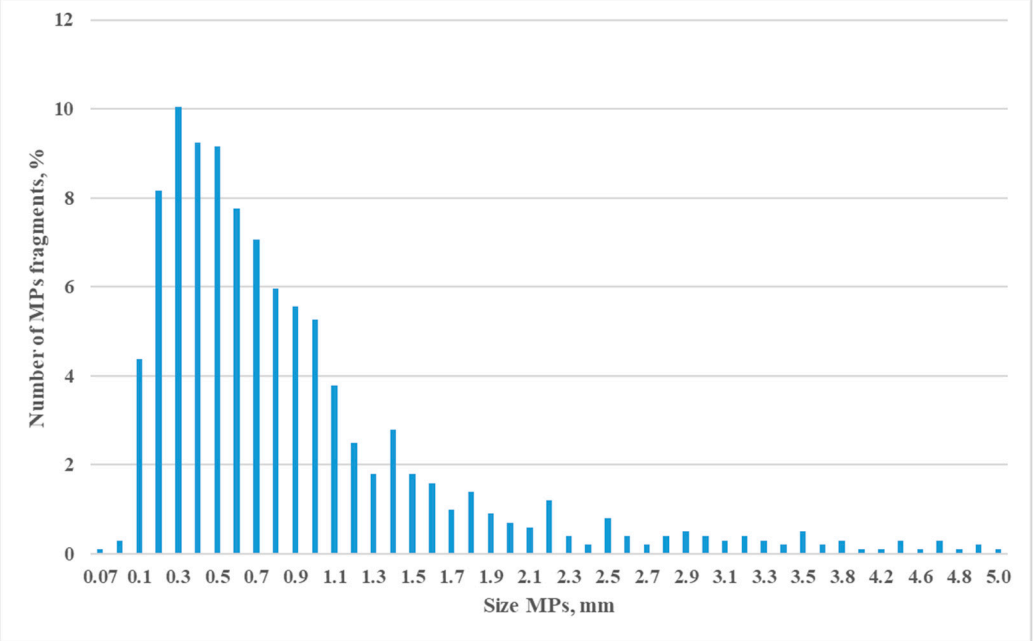

Figure 4. Percentage of microplastic fragments of different sizes.

4. Discussion

There have been no previous studies of microplastic particle concentrations in Lake Baikal sediments. Therefore, we are unable to compare our data with those obtained previously. However, despite the fact that most attention has been paid to marine ecosystems, there are data on microplastic concentrations in freshwater ecosystems (of course, it is worth considering that comparisons of concentrations from different sources should be approached with caution, given the methodological differences between studies). Thus, at the moment, the average concentration of microplastic particles for lake ecosystems worldwide is 129 particles/100 g [34]. This value is similar to the one we can observe near the village of Listvyanka (130.7 ± 27.3 particles/100 g in relation to microplastic fragments), but if we

take the average for the same location, we obtain 50.4 ± 29.5 particles/100 g (which is less than the world average for lakes). In general, concentrations of microplastic particles in freshwater ecosystems range from 0.5 to 1 to more than 700 particles/100 g [16,35–39] and even up to 1810 particles/100 g [40]. In our study, concentrations at three points at once (at the mouth of the Cheremshanka River, near Ogoy Island, near the Zagza recreation center) are close to the lower limit of those recorded in the world. Moreover, some of the highest concentrations can be observed in urban lakes, where from 74.1 to 770.7 particles/100 g are recorded [35]. These values exceed the concentrations found for marine ecosystems [41].

Based on global practice of microplastic research, the most common particles are fibers and fragments [42–44]. In this study, with the exception of the location near the village of Listvyanka, fibers predominate among the microplastic particles. A similar pattern is characteristic of both freshwater and marine ecosystems [16,44] and is associated with the widespread use of textile products and artificial polymers in their composition [40,45]. Our data on both the polymer type identification and the color range detected confirm this. It is worth mentioning that in the case of Lake Baikal, the entry of microplastic fibers into the lake is aggravated by the significant wear and tear of wastewater treatment systems, or their complete absence (in the context of the ever-increasing number of tourists) in most populated areas on the shores of the lake. A similar picture (predominance of fibers) for bottom sediments is characteristic of other lakes in Russia [16] and the world [46]. In addition, the ubiquitous presence and uneven distribution of fibers (as well as the discrepancy between this distribution and areas with high and low anthropogenic load) confirm that these particles are distributed in the water area of Lake Baikal with the help of currents [17,26]. In addition, the fiber structure (elongated shape, large surface area) promotes the adsorption of organic matter on the surface, which leads to increased density and sedimentation in bottom sediments. In turn, a significant number of microplastic fragments near the village of Listvyanka is directly related to the presence of the port. The polymers found (alkyd resin and polyvinyl alcohol) are components of paints that peel off from ships, and boats are made from polyvinyl chloride. However, there is also a mooring of ships near Ogoy Island, but this mooring is temporary. Apparently, the creation of such significant concentrations of these polymers in sediments is possible in port conditions, where ships repeatedly undergo the process of painting. Moreover, the dominant colors of the paints for the fragments correspond to the main colors used on ships in the waters of Lake Baikal. Insignificant concentrations of fragments of these polymers in other places we studied are also apparently associated with peeling paint from ships or from buildings on the shore [47,48].

The polymers we found are usually rare in other studies, and when found, they are found in small quantities [17]. This may, of course, be due to the fact that these types of polymers may be absent from some spectral libraries. However, we believe that such a pattern is due to other factors. (1) Typically, the sites used for research are near populated areas or at some distance from them. In our case, the sampling point was located right in the port of this village. However, the other points were located in relatively untouched territory, or with a complete lack of anthropogenic impact. It is worth considering that microplastic fragments related to the same types of polymers were also found on them. (2) These types of polymers are quite fragile. This circumstance in the process of classical preparation of samples with microplastics can significantly crush the fragments, which subsequently significantly hinders their identification.

It is worth mentioning that the vast majority of studies on microplastics take into account particles with sizes from 300 microns to 5 mm. However, studies show that most particles are less than 1 mm in size [40]. Moreover, using Lake Baikal as an example, it has been shown that particles smaller than 330 μm can account for 88% of the total number

of microplastic particles [17]. Similar studies show that microplastic particles in many bodies of water, including Lake Baikal, are under-reported. In this study, the detection limit of microplastic particles was 70 μm; however, we understand that this is not enough to guarantee the detection of all particles. Researchers should move from classic methods of accounting for microplastics to more modern (for example, completely abandon the use of the lower limit of 300 μm, and also use μFTIR spectroscopy or high-resolution Raman spectroscopy) ones in order to be able to account for particles several microns in size.

The place of the highest concentration of microplastics in aquatic ecosystems is the littoral zone, as it is characterized by high wave activity and low current speed, which facilitates the transfer and sedimentation of particles from the pelagic zone [49]. Various research groups have noted high concentrations of microplastic particles in bottom sediments compared to the water column [50,51]. In this study, we collected samples in both the littoral zone and the beach zone. It is worth mentioning here that, given the significant fluctuations in the water level in Lake Baikal, the beach area bordering the water's edge is also periodically flooded [52].

Most water bodies in the littoral zone have a high taxonomic diversity, from algae and higher aquatic plants to invertebrates and fish. Constant access to light and organic matter promotes the development of a rich food base, and dynamic environmental conditions lead to a diversity of community structure. In Lake Baikal, the littoral zone is also the richest in species diversity. The dominant groups inhabiting the littoral zone are amphipods (about 100 species and subspecies) and gastropods (about 80 species). In general, the littoral zone of the lake is inhabited by more than 400 species of aquatic organisms [52]. However, high concentrations of microplastic particles in the bottom sediments of the littoral zone can contribute to the inclusion of microplastics in food chains, which can potentially lead to disruptions in physiological processes in aquatic organisms, which in turn can contribute to a decrease in the number, biomass and biodiversity of communities [7,53]. At the moment, it is not possible to name the potentially most and least susceptible species, including amphipods and gastropods. This is due to both the lack of studies on Baikal species and the lack of studies assessing the impact of the artificial polymers found in large quantities in this study. However, if we take into account other types of artificial polymers, there is evidence that high concentrations of microplastic particles can potentially lead to the fact that species with low competitiveness will give up their place in ecosystems to more competitive species [54]. In relation to Lake Baikal, this may indicate that in some local areas the share of widespread species will potentially increase, and the share of endemic species will decrease. However, it should be recognized that such statements require additional research.

At present, the concentration of microplastic particles in the sediments of Lake Baikal cannot be called high compared to other freshwater ecosystems. However, already now for Lake Baikal, a case has been registered of caddisflies using microplastic particles in large quantities when building their cases. In addition, a relationship was noted between the length of caddisfly larvae and the amount of embedded microplastic particles [28]. Microplastic particles in close proximity to the body's integuments can potentially have a toxic effect on caddisfly larvae, which, as in the case of amphipods, can lead to a restructuring of aquatic communities. This circumstance tells us about the need to conduct complex multi-matrix studies both on Lake Baikal and on other freshwater and marine ecosystems.

In addition, in further studies to determine the concentrations of microplastic particles both on matrices in Lake Baikal and in other water bodies, the close location of piers and permanent ship moorings should be taken into account. During the painting of ships (which occurs once every few years), a significant portion of both old and new paint may end up on the bottom. In the future, this paint will spread to adjacent areas under the

influence of wave-dynamic processes. Amendments to the legislation that would regulate the process of painting ships and would also oblige ship owners to carry out painting on the shore or in dry docks would help reduce the amount of paint ending up in the aquatic environment. In turn, to minimize the ingress of microplastic fibers into the aquatic environment, repairs or installation of new treatment facilities in populated areas on the shore of Lake Baikal are necessary.

5. Conclusions

The first results obtained in this study of bottom sediment pollution in Lake Baikal have revealed that microplastics are found in sediments in all three basins of the lake, in places with different levels of anthropogenic load. According to the morphological structure, the dominant type of microplastic in the sediments of the littoral zone and the beach zone of Lake Baikal are fibers. However, in the case of a port and a ship mooring, fragments may already occupy a dominant position. It is worth noting that the types of polymers that make up the detected microplastic fragments are components of paints and are generally rare in aquatic ecosystems. This may be due either to the fact that researchers prefer to collect samples in cleaner places or to the fact that such polymers can be partially excluded from the analysis due to their fragility.

The study of the microplastic pollution of the littoral zones of water bodies is a promising direction. Moreover, studies based on a multi-matrix approach are needed. This will allow us to expand our understanding of the processes occurring in aquatic ecosystems and predict possible risks associated with increasing anthropogenic load.

Author Contributions: Conceptualization, D.K. (Dmitry Karnaukhov); methodology, A.L., S.B. and D.K. (Dmitry Karnaukhov); software, Y.E.; validation, Y.E. and D.K. (Dmitry Karnaukhov); formal analysis, D.K. (Dmitry Karnaukhov); investigation, A.L., N.K., A.S. (Anastasia Solodkova), I.K., A.G., D.R., D.K. (Darya Kondratieva), A.S. (Alyona Slepchenko), A.S. (Anna Solomka) and A.B.; resources, S.B. and D.K. (Dmitry Karnaukhov); data curation, D.K. (Dmitry Karnaukhov); writing—original draft preparation, A.S. (Anastasia Solodkova); writing—review and editing, A.S. (Anastasia Solodkova), S.B. and D.K. (Dmitry Karnaukhov); visualization, A.S. (Anastasia Solodkova) and D.G.; supervision, D.K. (Dmitry Karnaukhov) and E.S.; project administration, D.K. (Dmitry Karnaukhov); funding acquisition, D.K. (Dmitry Karnaukhov). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a grant from the Russian Science Foundation No. 24-24-00371, "https://rscf.ru/project/24-24-00371/ (accessed on 5 August 2025)".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data used are included in the article. In addition, any data used for this study will be provided upon request by the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Liu, Y.; Hao, R.; Shi, X.; Zhang, S.; Sun, B.; Zhao, S.; Huotari, J. Application of a microplastic trap to the determination of the factors controlling the lakebed deposition of microplastics. *Sci. Total Environ.* **2022**, *843*, 156883. [CrossRef]
2. Sagawa, N.; Kawaai, K.; Hinata, H. Abundance and size of microplastics in a coastal sea: Comparison among bottom sediment, beach sediment, and surface water. *Mar. Pollut. Bull.* **2018**, *133*, 532–542. [CrossRef]
3. Pagter, E.; Nash, R.; Frias, J.; Kavanagh, F. Assessing microplastic distribution within infaunal benthic communities in a coastal embayment. *Sci. Total Environ.* **2021**, *791*, 148278. [CrossRef]
4. Imhof, H.; Ivleva, N.; Schmid, J.; Niessner, R.; Laforsch, C. Contamination of beach sediments of a subalpine lake with microplastic particles. *Curr. Biol.* **2013**, *23*, R867–R868. [CrossRef]

5. Chubarenko, I.; Esiukova, E.; Zobkov, M.; Isachenko, I. Microplastics distribution in bottom sediments of the Baltic Sea Proper. *Mar. Pollut. Bull.* **2022**, *179*, 113743. [CrossRef] [PubMed]
6. Bellasi, A.; Binda, G.; Pozzi, A.; Boldrocchi, G.; Bettinetti, R. The extraction of microplastics from sediments: An overview of existing methods and the proposal of a new and green alternative. *Chemosphere* **2021**, *278*, 130357. [CrossRef]
7. Celine, M.; Sharif, J.; Maria, K.; El Rahman, H.A.; Myriam, L.; Myriam, G.; Anthony, O.; Rachid, A.; Milad, F. First assessment of microplastics in offshore sediments along the Lebanese coast, South-Eastern Mediterranean. *Mar. Pollut. Bull.* **2023**, *186*, 114422. [CrossRef]
8. Pozdnyakov, S.R.; Ivanova, E.V. Estimation of the microplastics concentrations in the water column and bottom sediments of Ladoga lake. *Reg. Ecol.* **2018**, *4*, 48–52. (In Russian) [CrossRef]
9. Bellasi, A.; Binda, G.; Pozzi, A.; Galafassi, S.; Volta, P.; Bettinetti, R. Microplastic contamination in freshwater environments: A review, focusing on interactions with sediments and benthic organisms. *Environments* **2020**, *7*, 30. [CrossRef]
10. Leiser, R.; Wu, G.; Neu, T.; Wendt-Potthoff, K. Biofouling, metal sorption and aggregation are related to sinking of microplastics in a stratified reservoir. *Water Res.* **2020**, *176*, 115748. [CrossRef] [PubMed]
11. Nava, V.; Leoni, B. A critical review of interactions between microplastics, microalgae and aquatic ecosystem function. *Water Res.* **2021**, *188*, 116476. [CrossRef] [PubMed]
12. Lofty, J.; Wilson, C.; Ouro, P. Biofouling changes the settling dynamics of macroplastic plates. *Commun. Earth Environ.* **2024**, *5*, 750. [CrossRef]
13. Huang, Y.; Fan, J.; Liu, H.; Lu, X. Vertical distribution of microplastics in the sediment profiles of the Lake Taihu, eastern China. *Sustain. Environ. Res.* **2022**, *32*, 44. [CrossRef]
14. Free, C.M.; Jensen, O.P.; Mason, S.A.; Eriksen, M.; Williamson, N.J.; Boldgiv, B. High-levels of microplastic pollution in a large, remote, mountain lake. *Mar. Pollut. Bull.* **2014**, *85*, 156–163. [CrossRef]
15. Il'ina, O.V.; Kolobov, M.Y.; Il'inskii, V.V. Plastic pollution of the coastal surface water in the middle and southern Baikal. *Water Resour.* **2021**, *48*, 56–64. [CrossRef]
16. Frank, Y.; Ershova, A.; Batasheva, S.; Vorobiev, E.; Rakhmatullina, S.; Vorobiev, D.; Fakhrullin, R. Microplastics in Freshwater: A Focus on the Russian Inland Waters. *Water* **2022**, *14*, 3909. [CrossRef]
17. Moore, M.V.; Yamamuro, M.; Timoshkin, O.A.; Shirokaya, A.A.; Kameda, Y. Lake-wide assessment of microplastics in the surface waters of Lake Baikal, Siberia. *Limnology* **2022**, *23*, 265–274. [CrossRef]
18. Zhao, S.; Kvale, K.F.; Zhu, L.; Zettler, E.; Egger, M.; Mincer, T.J.; Amaral-Zettler, L.A.; Lebreton, L.; Niemann, H.; Nakajima, R.; et al. The distribution of subsurface microplastics in the ocean. *Nature* **2025**, *641*, 51–61. [CrossRef]
19. Dar, M.A.; Palsania, P.; Satya, S.; Dashora, M.; Bhat, O.A.; Parveen, S.; Patidar, S.K.; Kaushik, G. Microplastic pollution: A global perspective in surface waters, microbial degradation, and corresponding mechanism. *Mar. Pollut. Bull.* **2025**, *210*, 117344. [CrossRef]
20. Yeo, B.G.; Mizukawa, K.; Takada, H. Microplastics in global marine waters and biota: Effectiveness of potential bioindicators in mirroring local pollution levels. *Environ. Monit. Contam. Res.* **2023**, *3*, 43–68. [CrossRef]
21. Sharma, S.; Sharma, V.; Chatterjee, S. Microplastics in the Mediterranean sea: Sources, pollution intensity, sea health, and regulatory policies. *Front. Mar. Sci.* **2021**, *8*, 634934. [CrossRef]
22. Karnaukhov, D.Y.; Biritskaya, S.A.; Dolinskaya, E.M.; Teplykh, M.; Silenko, N.; Ermolaeva, Y.; Silow, E. Pollution by macro-and microplastic of large lacustrine ecosystems in eastern Asia. *Pollut. Res.* **2020**, *39*, 353–355.
23. Korytny, L.M. *Geographical Encyclopedia of the Irkutsk Region*; General Essay; Publishing House of the V. B. Sochava Institute of Geography SB RAS: Irkutsk, Russia, 2017; p. 336.
24. Meyer, M.; Ozersky, T.; Woo, K.; Shchapov, K.; Galloway, A.W.E.; Schram, J.B.; Snow, D.D.; Timofeyev, M.A.; Karnaukhov, D.Y.; Brousil, M.R.; et al. A unified dataset of colocated sewage pollution, periphyton, and benthic macroinvertebrate community and food web structure from Lake Baikal (Siberia). *Limnol. Oceanogr. Lett.* **2022**, *7*, 62–79. [CrossRef]
25. Meyer, M.F.; Ozersky, T.; Woo, K.H.; Shchapov, K.; Galloway, A.W.E.; Schram, J.B.; Rosi, E.J.; Snow, D.D.; Timofeyev, M.A.; Karnaukhov, D.Y.; et al. Effects of spatially heterogeneous lakeside development on nearshore biotic communities in a large, deep, oligotrophic lake. *Limnol. Ocean.* **2022**, *67*, 2649–2664. [CrossRef]
26. Karnaukhov, D.Y.; Biritskaya, S.A.; Dolinskaya, E.M.; Teplykh, M.; Ermolaeva, Y.; Pushnica, V.; Bukhaeva, L.; Kuznetsova, I.; Okholina, A.; Silow, E. Distribution Features of Microplastic Particles in the Bolshiye Koty Bay (Lake Baikal, Russia) in Winter. *Pollution* **2022**, *8*, 435–446. [CrossRef]
27. Yang, P.; Yamashita, R.; Ogawa, H.; Sheveleva, N.G.; Penkova, O.G.; Yamamuro, M.; Moore, M.V. Microplastics in freshwater copepods of Lake Baikal. *J. Great Lakes Res.* **2025**, *51*, 102495. [CrossRef]
28. Karnaukhov, D.Y.; Lavnikova, A.V.; Nepokrytykh, A.V.; Zhdanov, I.A.; Salovarov, K.V.; Guliguev, A.T.; Osadchy, B.V.; Biritskaya, S.A.; Ermolaeva, Y.K.; Maslennikova, M.A.; et al. Baikal endemic and Palearctic species of caddisflies (Trichoptera) build cases from microplastics. *Acta Biol. Sib.* **2024**, *10*, 649–659.

29. Masura, J.; Baker, J.; Foster, G.; Arthur, C. *Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments*; NOAA Technical Memorandum NOS-OR&R-48; NOAA Marine Debris Division: Siver Spring, MD, USA, 2015; 31p. [CrossRef]
30. Gulizia, A.M.; Brodie, E.; Daumuller, R.; Bloom, S.B.; Corbett, T.; Santana, M.M.F.; Motti, C.A.; Vamvounis, G. Evaluating the Effect of Chemical Digestion Treatments on Polystyrene Microplastics: Recommended Updates to Chemical Digestion Protocols. *Macromol. Chem. Phys.* **2022**, *223*, 2100485. [CrossRef]
31. Di Fiore, C.; Ishikawa, Y.; Wright, S.L. A review on methods for extracting and quantifying microplastic in biological tissues. *J. Hazard. Mater.* **2024**, *464*, 132991. [CrossRef] [PubMed]
32. Beiras, R.; Schönemann, A.M. Currently monitored microplastics pose negligible ecological risk to the global ocean. *Sci. Rep.* **2020**, *10*, 22281. [CrossRef] [PubMed]
33. Tanaka, M.; Kataoka, T.; Nihei, Y. Variance and precision of microplastic sampling in urban rivers. *Environ. Pollut.* **2022**, *310*, 119811. [CrossRef]
34. Yin, Z.; Zhao, Y. Microplastics pollution in freshwater sediments: The pollution status assessment and sustainable management measures. *Chemosphere* **2023**, *314*, 137727. [CrossRef]
35. Dong, M.; Luo, Z.; Jiang, Q.; Xing, X.; Zhang, Q.; Sun, Y. The rapid increases in microplastics in urban lake sediments. *Sci. Rep.* **2020**, *10*, 848. [CrossRef]
36. Malla-Pradhan, R.; Phoungthong, K.; Suwunwong, T.; Joshi, T.P.; Pradhan, B.L. Microplastic pollution in lakeshore sediments: The first report on abundance and composition of Phewa Lake, Nepal. *Environ. Sci. Pollut. Res.* **2023**, *30*, 70065–70075. [CrossRef]
37. Fojutowski, M. Lake sediments as microplastic sink: The case of three lakes from Northern and Central Poland. *Quaest. Geogr.* **2024**, *43*, 103–112. [CrossRef]
38. Hamdhani, H.; Maleni, R.; Eppehimer, D.E.; Abdunnur, A.; Rizal, S.; Ardianor, A. Microplastic Pollution in Waters and Sediments in a Lentic System: A Case Study in a Tropical Wet Urban Lake of Samarinda, Indonesia. *Lakes Reserv. Res. Manag.* **2025**, *30*, e70008. [CrossRef]
39. Liu, X.; Cao, J.; Zhao, W.; Jiang, J.; Wu, H.; Du, C.; Deng, Y.; Liu, X.; Zhu, H.; Li, L. Unveiling the co-occurrence of microplastics and heavy metals in surface sediments of Dongting Lake: Distribution characterizations and integrated ecological risk assessment. *J. Environ. Chem. Eng.* **2025**, *13*, 118802. [CrossRef]
40. Chen, D.; Wang, P.; Liu, S.; Wang, R.; Wu, Y.; Zhu, A.X.; Deng, C. Global patterns of lake microplastic pollution: Insights from regional human development levels. *Sci. Total Environ.* **2024**, *954*, 176620. [CrossRef] [PubMed]
41. Kazour, M.; Jemaa, S.; Issa, C.; Khalaf, G.; Amara, R. Microplastics pollution along the Lebanese coast (Eastern Mediterranean Basin): Occurrence in surface water, sediments and biota samples. *Sci. Total Environ.* **2019**, *696*, 133933. [CrossRef] [PubMed]
42. Dodson, G.Z.; Shotorban, A.K.; Hatcher, P.G.; Waggoner, D.C.; Ghosal, S.; Noffke, N. Microplastic fragment and fiber contamination of beach sediments from selected sites in Virginia and North Carolina, USA. *Mar. Pollut. Bull.* **2020**, *151*, 110869. [CrossRef]
43. Boettcher, H.; Kukulka, T.; Cohen, J.H. Methods for controlled preparation and dosing of microplastic fragments in bioassays. *Sci. Rep.* **2023**, *13*, 5195. [CrossRef]
44. Rebelein, A.; Int-Veen, I.; Kammann, U.; Scharsack, J.P. Microplastic fibers—Underestimated threat to aquatic organisms? *Sci. Total Environ.* **2021**, *777*, 146045. [CrossRef] [PubMed]
45. Daget, T.M.; Tassew, D.F. A shift from synthetic to bio-based polymer for functionalization of textile materials: A review. *Int. J. Biol. Macromol.* **2025**, *306*, 141637. [CrossRef]
46. Yang, L.; Zhang, Y.; Kang, S.; Wang, Z.; Wu, C. Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Sci. Total Environ.* **2021**, *754*, 141948. [CrossRef]
47. Dizman, C.; Kaçakgil, E.C. Alkyd resins produced from bio-based resources for more sustainable and environmentally friendly coating applications. *Turk. J. Chem.* **2023**, *47*, 1–23. [CrossRef]
48. Guminetskii, S.G.; Sakhnovskii, M.Y.; Kotik, A.F.; Kunetskii, M.G. Spectrophotometric characteristics of paints based on BaSO4 with polyvinyl alcohol. *J. Appl. Spectrosc.* **1979**, *31*, 890–892. [CrossRef]
49. Diaz-Jaramillo, M.; Islas, M.S.; Gonzales, M. Spatial distribution patterns and identification of microplastics on intertidal sediments from urban and semi-natural SW Atlantic estuaries. *Environ. Pollut.* **2021**, *273*, 116398. [CrossRef]
50. Maes, T.; Van der Meulen, M.D.; Devriese, L.I.; Leslie, H.A.; Huvet, A.; Frère, L.; Robbens, J.; Vethaak, A.D. Microplastics baseline surveys at the water surface and in sediments of the North-East Atlantic. *Front. Mar. Sci.* **2017**, *4*, 135. [CrossRef]
51. Pozdnyakov, S.R.; Ivanova, E.V.; Guzeva, A.V.; Shalunova, E.P.; Martinson, K.D.; Tikhonova, D.A. Studying the concentration of microplastic particles in water, bottom sediments and subsoils in the coastal area of the Neva Bay, the Gulf of Finland. *Water Resour.* **2020**, *47*, 599–607. [CrossRef]
52. Rusinek, O.T.; Takhteev, V.V.; Gladkochub, D.P. Baikalovedenie. In *Book 2*; Nauka: Novosibirsk, Russia, 2012; p. 664. (In Russian)

53. Jimenez-Guri, E.; Paganos, P.; La Vecchia, C. Developmental toxicity of pre-production plastic pellets affects a large swathe of invertebrate taxa. *Chemosphere* **2024**, *356*, 141887. [CrossRef] [PubMed]
54. Rani-Borges, B.; Meitern, R.; Teesalu, P.; Raudna-Kristoffersen, M.; Kreitsberg, R.; Heinlaan, M.; Tuvikene, A.; Ivask, A. Effects of environmentally relevant concentrations of microplastics on amphipods. *Chemosphere* **2022**, *309*, 136599. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.