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A Multi-Matrix Approach to Studying Microplastic Pollution in Lake Baikal: Where Were the Highest Concentrations Found?

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Abstract

Microplastic pollution of ecosystems is considered a modern problem. Freshwater ecosystems, despite the interest shown in their study, remain poorly understood. Lake Baikal (Russia) is one of the least studied freshwater ecosystems in this regard. This large lake is distinguished from others by its high level of biodiversity and clean drinking water. The aim of this study is a multi-matrix investigation of microplastic pollution in one of the lake's bay. The following matrices are used: surface water, water column, sediment, macrophytes, macroinvertebrates, and fish, as well as ice and snow during the winter. The results show that certain locations exhibit high concentrations of microplastic particles. In some cases, this was due to the properties or characteristics of these locations (littoral zones near the water's edge, macrophytes with mucus sheaths, ice and snow (potentially, the near-surface water layer after ice melt)), while in others, it was due to localized pollution (pier and ship mooring areas). An analysis of the polymer types of the detected microplastic particles reveals the presence of both common (polypropylene, polyethylene terephthalate, polystyrene, polyethylene, polyvinyl chloride) and rare (polyvinyl alcohol and alkyd resin). Moreover, in some locations, the latter two polymers predominate, a phenomenon rarely observed in other studies. Further research was recommended to focus on the chronic effects of microplastic particles on organisms associated with areas of elevated particle concentrations.

Keywords: Lake Baikal; microplastic pollution; freshwater ecosystems; biodiversity; microplastic transport

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1. Introduction

In the classical sense, microplastics are microparticles of artificial polymers with a size from 300 µm to 5 mm [1,2]. This lower limit was determined by the use of hydrobiological

tools (plankton and neuston nets) with corresponding mesh sizes [1,2]. However, a number of studies have emerged recently showing that the number of particles below this limit is many times greater than the amount typically detected [3]. This serves as evidence that both field work and laboratory experiments require lowering the lower limit of detectable plastic particles. Moreover, the modern size classification of plastic particles is as follows: >5 mm—macroplastic, from 1 µm to 5 mm—microplastic, from 1 nm to 1 µm—nanoplastic. It is worth noting that, based on their morphological structure, the particles themselves are divided into a number of types: foam, granules, films, fibers, and fragments [4]. The most common are fragments (formed as a result of the physical degradation of plastic waste) and fibers (resulting from washing clothes) [1,2,5,6].

Nowadays, microplastic particles can be found everywhere, even in remote areas [1,2,7–10]. However, the problem of pollution of aquatic ecosystems with microplastic particles was first raised just over 50 years ago [11,12]. The main focus has been on the pollution of marine ecosystems by microplastic particles [4,13,14], or more precisely, even individual parts of them—the near-surface water layer (and, accordingly, experiments have begun to be conducted on the effect of microplastics on planktonic and pelagic organisms) [15]. However, over time, it became clear that freshwater bodies are even more susceptible to microplastic pollution, since they are much more closely related to urbanized areas, unlike marine ecosystems [16]. In addition, it has become obvious that microplastics settle over time and their concentration must be assessed not only at the surface of a reservoir, but also at different horizons, with the final place of accumulation of microplastic particles being the bottom sediments [10,14,17,18].

Currently, the vast majority of experiments assessing the impact of microplastics on living organisms significantly overestimate their concentrations compared to those found in natural environments. However, reports have begun to emerge describing ecologically significant concentrations of microplastics in the wild, which may already be affecting resident organisms [18]. Therefore, studies that simultaneously analyze microplastic concentrations in both environmental samples and living organisms are of particular interest [10,19].

Regarding the impact of microplastics on living organisms, at present, a considerable amount of periodically contradictory and ambiguous information exists. This can be interpreted as the fact that the impact of plastic particles depends on their morphological shape, size, type of polymer and is species-specific [5,6,20,21]. To date, microplastics have been detected in natural environments in many organisms, from zooplankton to aquatic mammals [10,19], with most research still focusing on marine organisms [4,22]. Microplastic particles are transferred through the food chain [10,16,18,19], with organisms at higher levels consequently harboring higher numbers of particles. Moreover, in the same ecosystems, for example, bottom-dwelling fish are found to have a greater number of particles than pelagic fish [23], which confirms that plastics tend to accumulate in bottom sediments and enter the food web.

Microplastics are also consumed by herbivores [22], which can be facilitated by their adsorption onto aquatic plants [23]. Microplastics adsorbed onto macrophytes are subsequently consumed by mollusks. It is worth noting that mollusks and crustaceans (in particular, amphipods) are currently the most convenient and frequently used organisms both in studying microplastic consumption in natural settings and as model organisms for microplastic experiments [18,24–26]. In fact, the ability of microplastics to be adsorbed on plants is in itself capable of influencing these plants, both phytoplankton and macroalgae [21,23], and higher aquatic plants [27], where an obstruction of photosynthesis and a reduction in root length are observed (while everything, apparently, will again depend on both the morphology and size of the particles, and on the specific species). Microplastics

can also be adsorbed onto the underside of ice [9,28], which can be an additional habitat for many species of animals and plants [29].

The first studies of microplastic pollution in Lake Baikal (Russia) began only in 2015 [30,31], with some work conducted in 2016 [32], and the first published data only appeared in 2020 [33]. Until now, studies conducted on Lake Baikal have been unsystematic, sporadic, and primarily conducted during the summer months [30–34]. Only one preliminary study has examined microplastic pollution of the lake during the winter season [28]. Several other studies have assessed microplastic contamination within the lake's watershed [2,33,35]. These studies show that fibers are the most common type of microplastic particle in the lake, with fragments being the second most common [30–33], while the amount of microplastic particles is significant and comparable to that found in the North American Great Lakes [1,32]. It is worth noting that almost all of the studies cited relate exclusively to the collection and analysis of samples in the surface water layer [28,30–33].

There is even less data on the ingestion of microplastics by living organisms. There is evidence of microplastics in the Baikal planktonic crustacean *Epischura baicalensis* Sars, 1900 [36], as well as data on the incorporation of large quantities of microplastic particles into the cases of caddisfly larvae [37]. Experimental conditions have confirmed the ability of gastropods from Lake Baikal to consume microplastics of various morphological structures [38].

Thus, to summarize all of the above, we see a lack of data on microplastic pollution in Lake Baikal across many topics. Given the lake's size and unique biodiversity, the aim of our study is to assess microplastic pollution in one of the lake's bay using multiple matrices. We decide to use as matrices: (1) the near-surface water layer at different distances from the shoreline, (2) different layers in the water column, (3) sediments, (4) macrophytes, (5) gastropods, amphipods and fish; and in addition, (6) the underside of the ice in winter and (7) snow cover on top of the ice.

2. Materials and Methods

2.1. Study Area

Lake Baikal is a large continental lake. It contains 20% of the world's fresh drinking water. The lake is located in the southern part of Eastern Siberia (Russia), between the Irkutsk region and the Republic of Buryatia. The lake is home to over 2500 animals and plants, approximately two-thirds of which are endemic.

Bolshie Koty Bay is located in the southern part of Lake Baikal in Irkutsk region (Figure 1). The distance to the opposite shore is approximately 40 km, and the distance to the southern end of the lake is approximately 90 km. A pier and ship mooring are located deep within the bay. The bay and the village of the same name are difficult to access. There is no road to the village; access is by water (or across ice in winter) or on foot along a hiking trail.

2.2. Sampling in Winter

Snow samples were collected from the ice surface, as well as samples of ice and aquatic organisms living near the ice-water interface. Sampling took place in late February 2024. For sampling, ice was cut along a transect at six locations (in Bolshie Koty Bay, Southern Baikal) ranging in distance from the shore (Table 1). Three ice samples were collected at each location (ice was taken from the bottom 20 cm of the ice layer). In addition, snow samples were collected from the ice surface at the first three locations (at least three samples at each location).

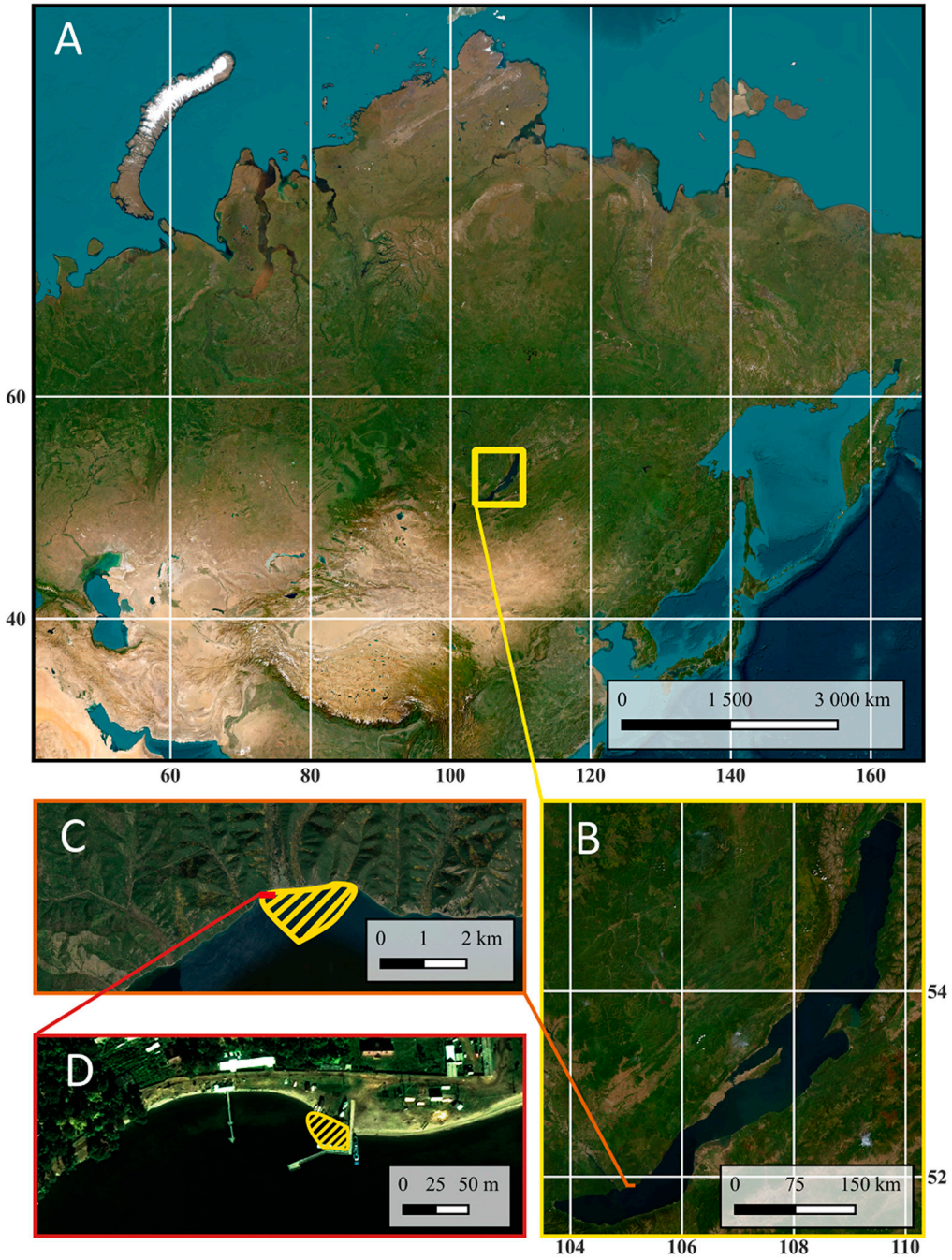


Figure 1. Location of Lake Baikal and Bolshie Koty Bay: (**A**)—general plan, (**B**)—Lake Baikal, (**C**)—Bolshie Koty Bay (the study area is highlighted with shading), (**D**)—pier and ship mooring area in Bolshie Koty Bay (the study area is highlighted with shading) (an ESRI satellite was used as a baseline).

Table 1. Characteristics of ice, snow and aquatic organism sampling sites.

Point No.	Coordinates	Depth, m	Distance from the Shore, m
1 **	51°54′09.5″ N 105°04′13.0″ E	4.3	65
2 **	51°54′04.9″ N 105°04′13.1″ E	24.3	205
3 **	51°54′03.3″ N 105°04′13.6″ E	46.8	254
4 *	51°53′57.2″ N 105°04′13.9″ E	147	442
5 *	51°53′52.4″ N 105°04′13.7″ E	192.5	592
6 *	51°53′40.9″ N 105°04′13.4″ E	370	947

Note: *—sampling of ice and aquatic organisms, **—sampling of ice, snow and aquatic organisms.

At all sites, after ice and snow sampling, at least three aquatic organism samples were collected using a Juday plankton net (UfaPribor, Ufa, Russia) (mesh size 100 μm). This was done to identify the aquatic organism community associated with the lower ice layer and, therefore, most susceptible to the potential impact of microplastics.

After collection, ice and snow samples were melted indoors at room temperature, filtered using a mesh sieve (100 μm), and concentrated. The volume of filtered water was measured using a graduated cylinder. Samples collected with the Juday net were fixed in a 4% formalin solution.

2.3. Sampling in Summer

Samples were collected in the near-surface water layer and at various depths in Bolshie Koty Bay, including bottom sediment sampling, macrophyte sampling, macroinvertebrate sampling (amphipods and mollusks), and fish. Additionally, we collected bottom sediment samples in the pier and ship mooring area, as well as samples from the near-surface water layer (under wave and calm conditions), and qualitatively assessed the biodiversity in this area. Sampling was conducted in August 2024.

2.3.1. Sampling in the Surface Layer of Water and at Various Depths, as Well as Sampling of Sediments

Samples over the littoral and pelagic zones were collected in summer using a neuston net with an entrance area of 0.1 m^2 (100 μm). This sampling was carried out in several replicates (at least 3) along the transect with increasing distance from the shore (starting from the water's edge and ending at a distance of 1 km). The trawling length at the water's edge was 10 m, above the pelagic zone 200 m. There were 5 locations in total, which differed in their distance from the coastline: 1. at the water's edge along the shore; 2. at a distance of 70–200 m along the shore; 3. at a distance of 360–510 m along the shore; 4. at a distance of 600–700 m along the shore; 5. at a distance of 900–1000 m along the shore.

Sampling at different depths (in different layers of the pelagic zone) of Lake Baikal was carried out at a point with coordinates: 51°52′44.5″ N 105°04′52.8″ E. This sampling was carried out using a Juday closing net (inlet diameter 37.5 cm, 100 μm) in the following layers: 0–5, 5–10, 10–25, 25–50, 50–100 m.

Bottom sediment samples were collected at points with coordinates: 51°54′10.9″ N 105°06′12.8″ E (near the Varnachka area) and 51°54′11.6″ N 105°04′12.1″ E (directly near Bolshie Koty settlement). The depth at the sampling site was 0.5 m, and three samples were collected in total. These samples were collected using a manual bottom grab. After collection, the sediment samples were placed in a glass container.

2.3.2. Sampling of Macrophytes, Macroinvertebrates and Fish

Macrophyte samples (at least three samples of each species) were collected to study the adsorption of microplastic particles on plants in natural conditions. A total of six species were sampled: *Elodea canadensis* Michx., *Draparnaldioides baicalensis* (K.I. Meyer) Vishnyakov, *Ulothrix zonata* (F. Weber et Mohr) Kützing, *Stuckenia* sp., *Myriophyllum spicatum* L., and Bryophyta (from partially submerged rocks near the shore). Plant samples were cut directly in the water and carefully transferred to a glass container without removing them from the water. Near the shore (*E. canadensis*, *U. zonata*, Bryophyta), this was done by entering the water in boots, at a depth of 2–3 m (*D. baicalensis*, *Stuckenia* sp., *M. spicatum*) with the help of divers.

In addition to macrophytes, individuals of five amphipod species (*Eulimnogammarus cyaneus* (Dybowski, 1874), *Eulimnogammarus vittatus* (Dybowski, 1874), *Eulimnogammarus verrucosus* (Gerstf., 1858), *Pallasea cancellus* (Pallas, 1772) and *Macrohectopus branickii* (Dybowski, 1874)) and two mollusc species (*Radix auricularia* (L., 1758), *Benedictia baicalensis*

(Gerstfeldt, 1859)) were collected. Amphipods and mollusks were collected in quantities of at least 30 individuals of each species. All organisms were placed in glass containers and fixed with 96% ethanol.

Fish were captured using a hydrobiological net. We specifically targeted *Paracottus knerii* (Dybowski, 1874). This species is abundant in the littoral zone of Lake Baikal and is also benthic. A total of six specimens were captured. All were fixed in individual vials in 96% ethanol.

2.3.3. Sampling in the Pier and Ship Mooring Area

In the pier and ship mooring area, we collected samples from the near-surface water layer both during wave activity and in calm conditions. Sediment samples were also collected at this location. All samples were collected in the same manner as described in the previous sections and were collected in quantities of at least three.

Furthermore, we collected qualitative samples at this location to assess biodiversity in this area. After collection, these samples were fixed with 96% ethanol.

2.4. Processing of Samples

2.4.1. Processing of Snow, Ice, Water and Sediment Samples

The samples were processed in accordance with a well-known protocol [39] with some modifications. These modifications were introduced due to the fact that we initially suspected the presence of a number of potentially brittle polymers in the samples [34,37]. Therefore, to minimize potential damage or destruction of these polymers, the samples were processed and dried at 55 °C, and KOH was used instead of H_2O_2 and 0.05 M Fe(II) [34,40,41].

Glass fiber filters (with a pore diameter of 1 µm) obtained after vacuum filtration were analyzed for microplastic particles under a stereo microscope (Unitron Z850, Boston, MA, USA). The lower limit of the analyzed particles in this study was 100 µm and was determined by the mesh size used in the plankton and neuston nets. In addition to particle size, particle color was also analyzed. The polymer type of the microplastic particles was determined using an M532 Raman microscope (EnSpectr, Chernogolovka, Russia) with a similarity coefficient of at least 0.7 [34]. This model has a laser wavelength of 532 nm and a spectral resolution of 6–8 cm^{-1}. EnSpectr PRO spectral libraries (e.g., RamanLife (~24,000 spectra), Polymers (~2200 spectra)) were used for analysis.

2.4.2. Processing of Samples Containing Living Organisms

After collection, the samples were transported to the laboratory. In the laboratory, the plants were transferred to beakers containing 200 mL of a 5 M NaCl solution. The water in the containers with the plants was filtered through a mesh sieve (100 µm), and the contents were transferred to the beakers with the macrophytes. The beakers were then covered with foil and placed on an orbital shaker at 130 rpm for 2 h. After this, the contents were pipetted into a funnel with a filter and filtered using a vacuum pump. When 50 mL remained, the plants were removed, washed in distilled water, transferred to the filter in a Petri dish, and placed in a drying oven until completely dry (all samples were subsequently examined under a microscope to minimize the "loss" of microplastic particles; after this, the dry weight of the samples was determined on an analytical balance). The remaining water, as well as that in which the plants were washed, was also filtered. The resulting filters were placed in Petri dishes and examined for microplastic particles under a stereomicroscope. This technique had previously been tested [42].

In the laboratory, the mollusks were removed from their shells, and the length and width of each shell were measured. The collected mollusks and amphipods were then divided into separate samples of five specimens each. Each sample was placed in a separate

250 mL beaker. 100 mL of a 10% KOH solution (56 g/mol) was added, the beakers were covered with foil, and left for 24–48 h in a drying oven at 55 °C until the organic matter was completely dissolved (some samples with large amounts of organic matter were additionally shaken to improve the dissolution process). As a control, at least three beakers of KOH solution were poured and the same manipulations were performed as with the samples. After the organics had dissolved, 100 mL of hot water and NaCl were added to each sample until saturation (until the salt ceased to dissolve, approximately 60 g per 200 mL). This was then left to settle for another 24 h. After settling, the supernatant was transferred to a filter funnel using a pipette and filtered using a vacuum pump. After each sample, the funnel and pipette were rinsed with distilled water. Glass fiber filters with a pore diameter of 1 µm, similar to those described above, were used for filtration. The resulting filters were placed in Petri dishes for subsequent microplastic particle counting under a stereomicroscope at x96 magnification. All detected particles were counted and categorized into groups based on their morphological structure. Further analysis of the synthetic polymer types was performed using a Raman microscope, similar to the one described above.

Fish samples were processed in a similar manner. The exception in this case was that only the gills and gastrointestinal tract, rather than the entire fish tissue, were subjected to alkaline hydrolysis. The gills and gastrointestinal tract were processed separately. Ethanol was used to remove saponified fats [43].

2.4.3. Processing of Hydrobiological Samples

Quantitative samples collected at six locations during the winter, as well as qualitative samples collected during the summer in the pier and anchorage areas, were processed using standard hydrobiological methods. Samples were processed in small portions under a UNITRON Z850 stereomicroscope. All organisms were sorted into groups, and, where possible, organisms were identified to species level.

2.5. Precautionary Measures

All samples were collected and processed with utmost care. Sampling was performed wearing cotton clothing or using cotton capes over clothing (in winter). All sampling equipment was rinsed with water before and after use. Sample processing took place under a pre-prepared fume hood. Contamination monitoring was performed during sample processing.

2.6. Data Analysis

Data analysis and visualization were performed in the R software environment (V. 4.4.2). The Mann–Whitney test was used for statistical comparisons of two samples. For comparisons of three or more samples, the Kruskal–Wallis test was used, followed by Dunn's post hoc test with Holm's correction. Spearman's correlation analysis was used to clarify the relationship between particle number and depth. The strength of the relationship was determined using the Chaddock scale [37,38]. Additional data visualization was performed using multidimensional scaling. The Euclidean distance was used as a measure of similarity.

3. Results

3.1. Results of Sampling During the Winter Period

Three types of particles were detected in snow samples based on their morphological structure: fibers, fragments, and films. The number of microplastic particles in snow over ice cover ranged on average from 1.6 ± 0.5 to 6.4 ± 2.0 particles·L^{-1} (Table 2, Figure 2).

Although fibers predominate over fragments (Table 2, Figures 2 and 3), there are no statistically significant differences in the number of microplastic particles between the points. This statement corresponds to both the comparison of the total number of particles (p-value = 0.1) and the comparison of the same types of particles by morphological structure (between fibers (p-value = 0.2), between fragments (p-value = 0.06)). There are also no significant differences between the number of fibers and fragments.

Table 2. Microplastic particles in snow on top of ice.

Point Number	Amount of Microplastics, Particles·L^{-1} (Min/Max)			
	Fibers	**Fragments**	**Films**	**Total**
1	4.6 ± 3.1 (2.2/6.8)	1.7 ± 0.7 (0.8/3.1)	0	6.4 ± 2.0 (3.1/9.9)
2	1.6 ± 0.5 (0.6/2.1)	0	0	1.6 ± 0.5 (0.6/2.1)
3	4.0 ± 2.5 (0.3/8.8)	1.8 ± 0.6 (0.7/2.8)	0.1 ± 0.1 (0/0.3)	5.9 ± 3.2 (1.0/12.0)

Note: n = 3.

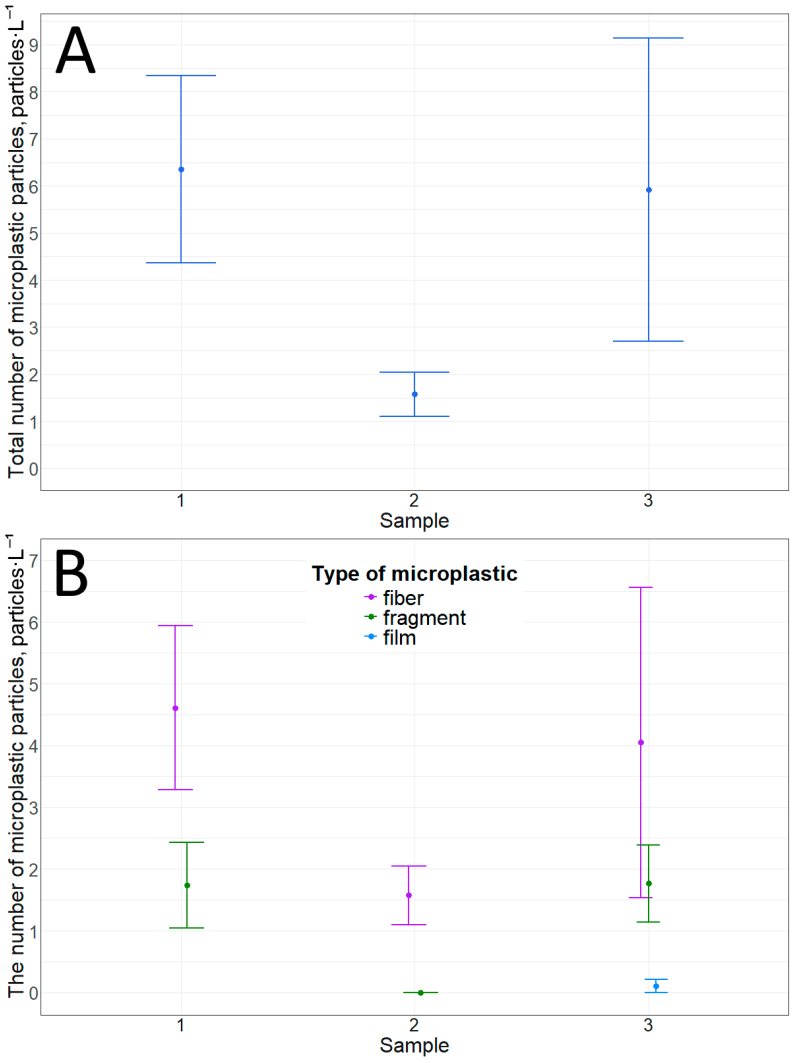


Figure 2. Microplastic particles in snow cover on top of ice: (**A**)—total amount; (**B**)—number of particles with different morphological structures.

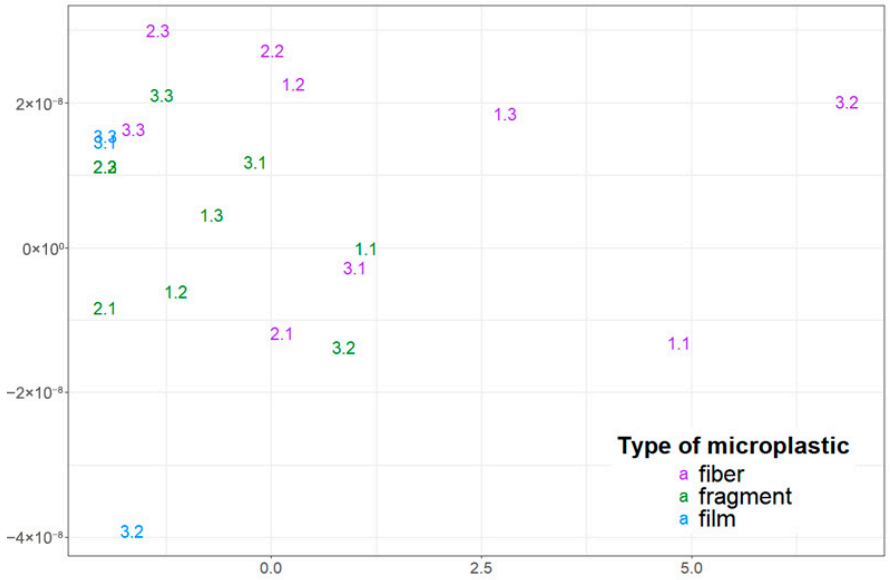


Figure 3. Visualization of the distribution of microplastic particles with different morphological structures in snow cover using multidimensional scaling (the first digit corresponds to the sampling point number, and the second digit indicates the sample number).

Ice sample analysis showed that the total number of microplastic particles at any distance from the shore in this study did not differ statistically (p-value = 0.9) (Figure 4). The number of microplastic particles ranged from 0.5 ± 0.04 to 0.8 ± 0.6 particles·L^{-1} (Table 3). Only two types of particles were detected in the samples: fibers and fragments. Moreover, in most cases, fibers were the predominant type of microplastic particle (based on average values) in terms of morphological structure (Figure 4). It is worth noting that there are no statistically significant differences between the number of fibers and fragments at each point (Table 4). Overall, the analysis confirms our previous preliminary data on microplastic particles from the underside of ice [28]. The available data lead us to believe that microplastic particles are most likely brought into Bolshie Koty Bay by gyre currents (which are present in Lake Baikal), which in turn are transported from the waters of the Selenga River.

Table 3. Microplastic particles from the underside of ice.

Point Number	Amount of Microplastics, Particles·L^{-1} (Min/Max)		
	Fibers	Fragments	Total
1	0.7 ± 0.2 (0.5/1.2)	0	0.7 ± 0.2 (0.5/1.2)
2	0.7 ± 0.5 (0/1.7)	0.1 ± 0.1 (0/0.2)	0.8 ± 0.6 (0/1.9)
3	0.4 ± 0.2 (0/0.8)	0.4 ± 0.4 (0/1.1)	0.8 ± 0.4 (0/1.5)
4	0.5 ± 0.3 (0/0.9)	0.06 ± 0.06 (0/0.2)	0.5 ± 0.2 (0.2/0.9)
5	0.5 ± 0.04 (0.4/0.5)	0	0.5 ± 0.04 (0.4/0.5)
6	0.3 ± 0.1 (0/0.5)	0.5 ± 0.5 (0/1.6)	0.8 ± 0.4 (0.3/1.6)

Note: n = 3.

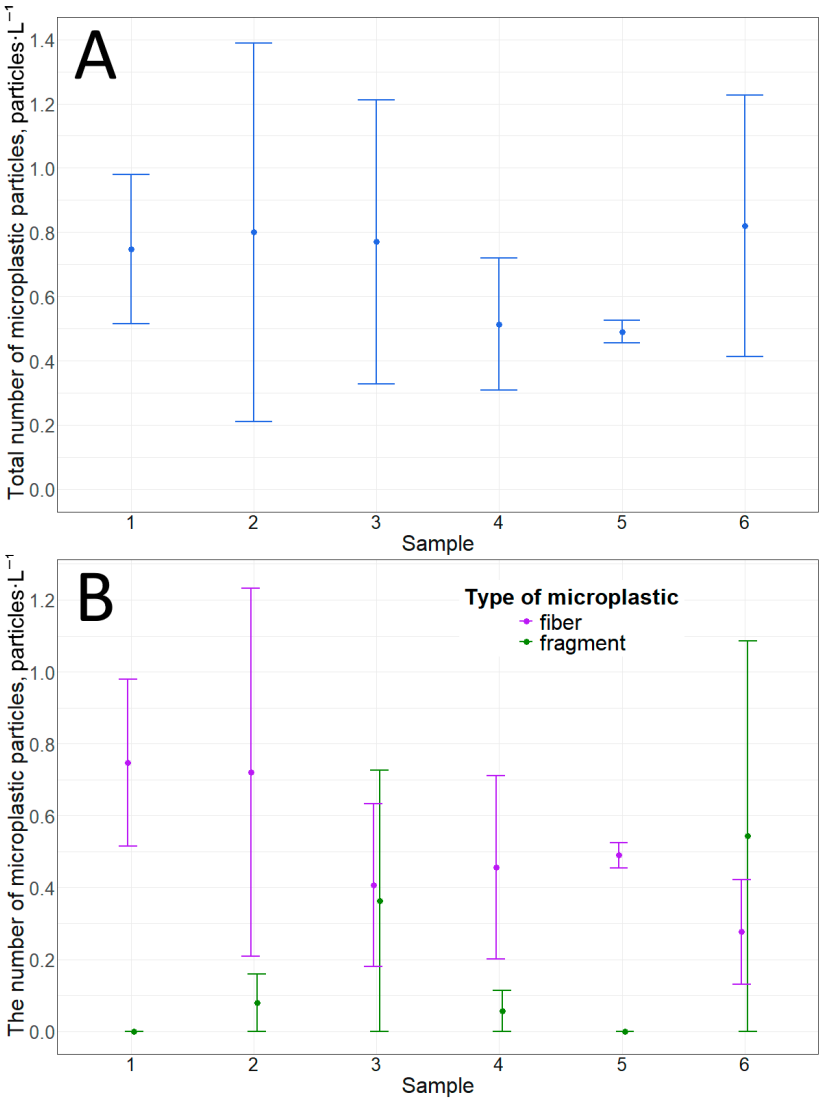


Figure 4. Microplastic particles from the underside of ice: (**A**)—total amount; (**B**)—number of particles with different morphological structures.

Table 4. Comparison of the number of microplastic fragments with the number of microplastic fibers in ice samples using the Mann–Whitney test.

Sampling Point Number	Value *p*
1	W = 9, *p*-value = 0.06
2	W = 7, *p*-value = 0.3
3	W = 5, *p*-value = 1
4	W = 7, *p*-value = 0.3
5	W = 9, *p*-value = 0.06
6	W = 5, *p*-value = 1

Analysis of zooplankton samples collected by the Juday net near the ice-water boundary showed that the absolute majority (in percentage terms) of organisms at this boundary are *Copepoda nauplii* (namely, *E. baikalensis* (the number of which fluctuates in the range from 1209 ± 611 to 24,757 ± 6205 specimens·m^{-3} and is 99–100%)) (Table 5). *Cyclops kolensis* Lilljeborg, 1901, and representatives of Cladocera, Ostracoda, and Harpacticoida were also present in small percentages at various sites. The last two groups are benthic organisms, but are occasionally observed in plankton, which may be due to passive transport by currents (during diurnal vertical migrations) [44,45].

Table 5. Occurrence of different groups of organisms in the community under ice, %.

Organisms	No. of Sampling Points					
	1	**2**	**3**	**4**	**5**	**6**
E. baikalensis	0.97	0	0	0	0.3	0.3
Nauplii *E. baikalensis*	99.03	99.94	100	99.8	99.5	99.7
C. kolensis	0	0.04	0	0	0	0
Cladocera	0	0	0	0.1	0	0
Ostracoda	0	0.02	0	0.1	0	0
Harpacticoida	0	0	0	0	0.2	0

3.2. Microplastic Particles in Water and Sediments During Summer

Two types of microplastic particles based on their morphological structure (fibers and fragments) were detected in the near-surface water layer. The total number of microplastic particles in the near-surface water layer ranged on average from 2.7 ± 0.9 to 17.0 ± 3.2 particles·m^{-3} (Table 6). Analysis of the obtained data on tracks in the near-surface water layer with increasing distance from the shoreline showed that there were no statistically significant differences in the total number of microplastic particles (p-value = 0.7). Moreover, microplastic fragments were present in only one of the samples collected at a distance of 360–510 m from the shore. Microplastic fibers were observed in all samples collected, with the highest concentrations observed near the water's edge. Given a number of factors (shallow depth and active wave action), microplastic particles cannot settle quietly to the bottom in this location and remain suspended. A pairwise comparison revealed some statistically significant differences in fiber concentrations (near the water's edge). Thus, the concentration at location #1 was statistically significantly different from the concentrations at locations #2 (600–700 m from the shore) and #5 (900–1000 m from the shore). It is possible that with a larger number of samples collected, differences would also be observed at locations #3 and #4. However, confirming this pattern would require a larger number of samples.

Table 6. Microplastic particles in the surface layer of water.

Point Number	Amount of Microplastics, Particles·m^{-3} (Min/Max)		
	Fibers	**Fragments**	**Total**
1	17.0 ± 3.2 (12.0/23.0)	0	17.0 ± 3.2 (12.0/23.0)
2	3.0 ± 1.5 (0.9/6.0)	0	3.0 ± 1.5 (0.9/6.0)
3	7.1 ± 0.6 (6.0/8.2)	0.02 ± 0.02 (0/0.1)	7.2 ± 0.6 (6.0/8.2)
4	6.9 ± 1.1 (4.9/8.6)	0	6.9 ± 1.1 (4.9/8.6)
5	2.7 ± 0.9 (1.0/4.0)	0	2.7 ± 0.9 (1.0/4.0)

Note: n = 3.

In turn, analysis of the obtained data on the distribution of microplastic particles in the pelagic layers showed that there may be a slight tendency for the concentration of microplastic particles to decrease with increasing depth (Table 7). Fibers remain the predominant type of microplastic particles in terms of morphological structure. The analysis reveals a fairly high (R_S = −0.9), but statistically insignificant correlation coefficient (p-value = 0.08).

Table 7. Microplastic particles in different layers of the water column.

Water Column Layer, m	Amount of Microplastics, Particles·m^{-3}		
	Fibers	Fragments	Total
0–5	21.5	1.5	23
5–10	10	0	10
10–25	11.3	0	11.3
25–50	6	0	6
50–100	3.8	0	3.8

Note: $n = 3$.

Sediment sampling took place at two sites: a relatively undisturbed area near Varnachka and directly near the village of Bolshie Koty. Significant concentrations of microplastic fragments were detected near the water's edge near the village of Bolshie Koty (Table 8). It is worth noting that no statistically significant differences in the number of microplastic fragments and fibers were found near the village of Bolshie Koty (Table 9).

Table 8. Microplastic particles in sediments.

Location	Amount of Microplastics, Particles·(100 g dw)$^{-1}$ (Min/Max)		
	Fibers	Fragments	Total
Near the village of Bolshie Koty (deep in the bay)	4.1 ± 1.2 (2.8/6.6)	189.1 ± 31.0 (149.1/250.0)	193.2 ± 30.2 (155.7/253.0)
Near the Varnachka area	10.6 ± 2.4 (6.7/17.6)	0	10.6 ± 2.4 (6.7/17.6)

Note: $n = 4$.

Table 9. Comparison of the number of microplastic fragments with the number of microplastic fibers.

No.	Location	Value *p*
1	Near the village of Bolshie Koty (deep in the bay)	W = 0, *p*-value = 0.1
2	Near the Varnachka area	W = 12, *p*-value = 0.04, r = 0.58

3.3. Microplastic Particles in the Pier and Ship Mooring Area

An additional sampling site was the pier and ship mooring area. Water and sediment samples were collected here. Water samples were collected both during wave activity and in calm conditions.

Microplastic fibers and fragments were detected at this location. Furthermore, stormy weather significantly increases the concentration of microplastic particles in the water (Table 10). The total particle concentration increases sixfold. This increase is due to the increased concentration of microplastic fragments. Wave activity increases the concentration of microplastic fragments by more than 20 times (Table 10, Figures 5 and 6).

Table 10. Microplastic particles in the water in the pier and ship mooring area.

Condition	Amount of Microplastics, Particles·m^{-3} (Min/Max)		
	Fibers	Fragments	Total
Without wave	0.4 ± 0.2 (0.1/0.8)	0.1 ± 0.1 (0.0/0.2)	0.5 ± 0.1 (0.3/0.8)
With wave	0.4 ± 0.2 (0.0/1.0)	2.7 ± 0.4 (2.0/3.9)	3.1 ± 0.6 (2.1/4.8)

Note: $n = 4$.

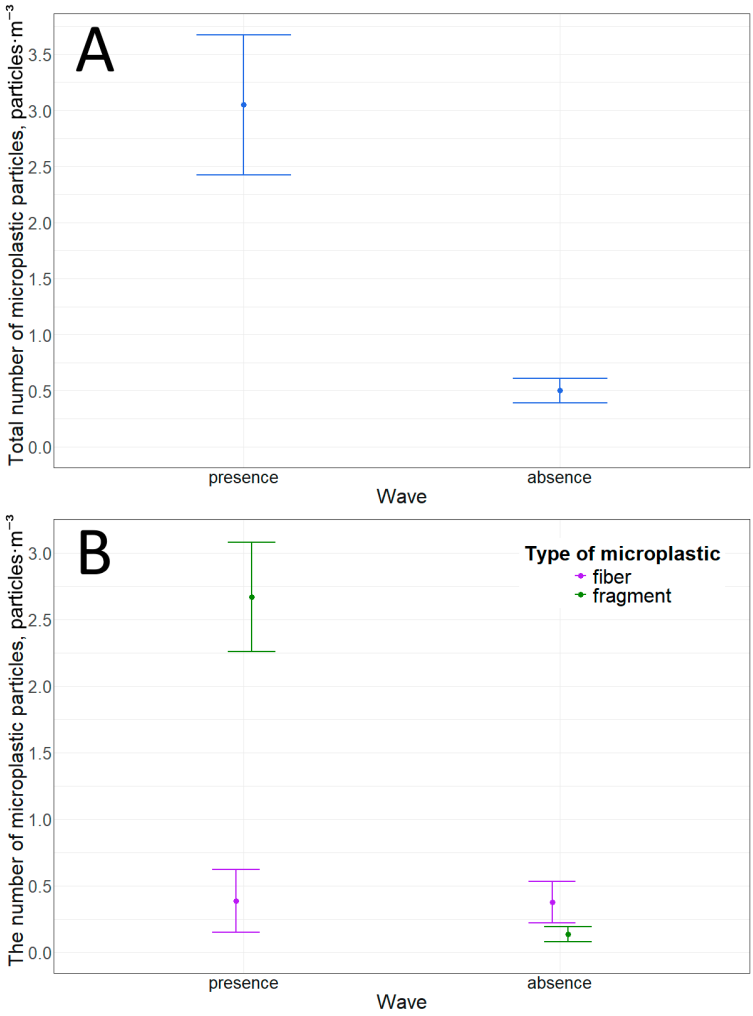


Figure 5. Microplastic particles in the surface water layer in the pier and ship mooring area: (**A**)—total quantity; (**B**)—quantity of particles with different morphological structures.

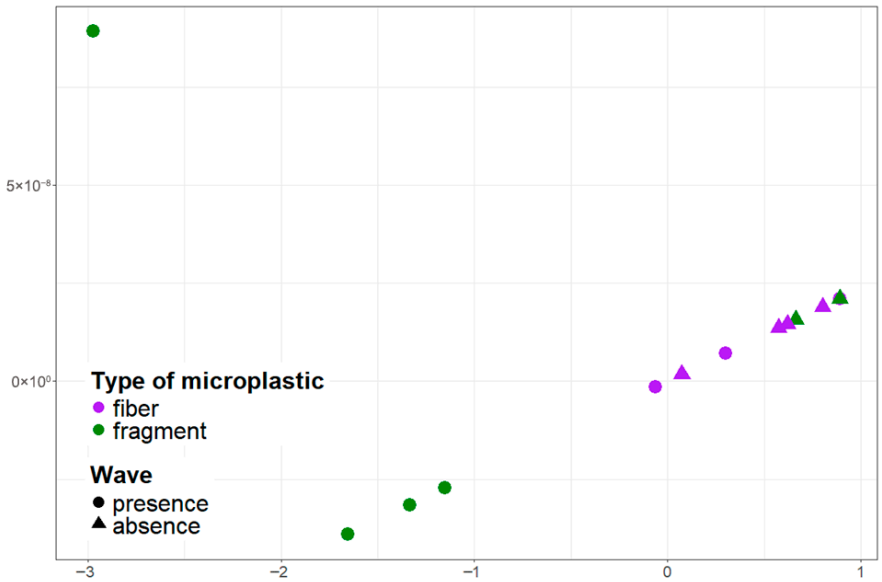


Figure 6. Visualization of the distribution of microplastic particles with different morphological structures in the near-surface water layer in the pier and ship mooring area using multidimensional scaling.

We also collected sediment samples at this location. Data analysis revealed that the concentration of microplastic particles in sediments at this site was 1550.9 ± 168.0 particles·(100 g dw)$^{-1}$ (min—1238.0, max—1813.5). This concentration was primarily composed of fragments—1543.7 ± 167.4 particles·(100 g dw)$^{-1}$ (min—1230.8, max—1803.1). Fibers account for a minority of particles—7.2 ± 1.8 particles·(100 g dw)$^{-1}$ (min—4.1, max—10.4). The obtained values of microplastic particle concentration significantly exceed the values obtained in this study for other locations (Figure 7). However, statistically significant differences were found only between particle concentrations in the pier area and the Varnachka area (p-value = 0.01, r = 0.62).

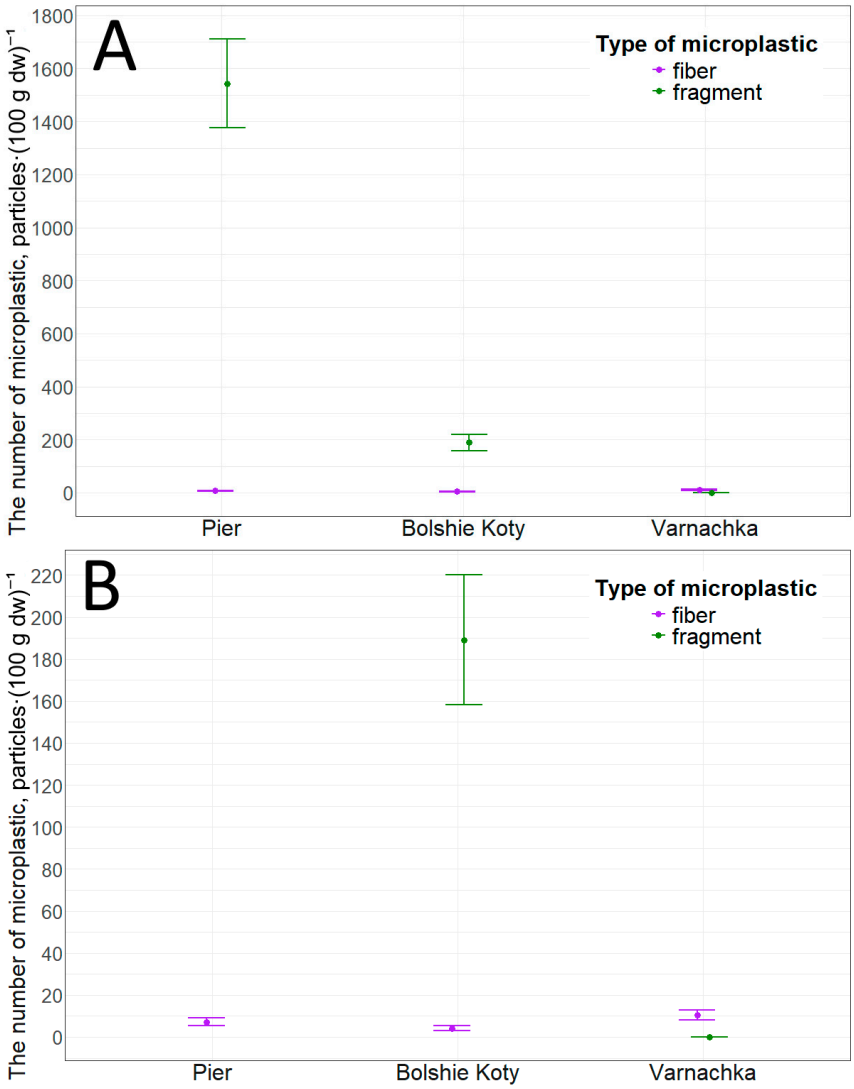


Figure 7. Microplastic particles in littoral sediments: (**A**)—general plan; (**B**)—close-up plan.

Analysis of qualitative samples (combined with visual observations) showed that despite the high level of pollution (evidently caused not only by microplastic particles), a fairly large number of aquatic organism species are observed in this location. We recorded more than 25 species (Table 11). Some of the organisms are planktonic or nektonic. However, the majority of the species are benthic organisms native to this location.

Table 11. Biodiversity in the pier and ship mooring area, as determined by qualitative sampling and visual observations.

No.	Group	Family	Species
1	Piscis	Cottidae	*P. knerii*
		Cyprinidae	*Phoxinus phoxinus* (Linnaeus, 1758)
		Cobitidae	*Cobitis melanoleuca* Nichols, 1925
		Cottidae	*Leocottus kesslerii*
2	Amphipoda	Micruropodidae	*Micruropus vortex vortex* (Dybowsky, 1874)
		Carinogammaridae	*Gmelinoides fasciatus* (Stebbing, 1899)
		Pallaseidae	*Pallasea cancelloides* (Gerstf., 1858)
		Gammaridae	*Eulimnogammarus cyaneus* (Dybowsky, 1874)
		Carinogammaridae	*Echiuropus* spp.
3	Trichoptera	Apataniidae	*Baicalina thamastoides* Martynov, 1914
		Apataniidae	*B. bellicosa* Martynov, 1914
		Limnephilidae	*Hydatophylax nigrovittatus* McLachlan, 1872
4	Mollusca	Planorbidae	*Choanomphalus angulatus* (Dybowski & Grochmalicki, 1925)
		Planorbidae	*C. eurystomus* Lindholm, 1909
		Planorbidae	N/A
		Lymnaeidae	*Radix auricularia* (L., 1758)
		Baicaliidae	N/A
		Sphaeriidae	N/A
5	Turbellaria	Planariidae	*Phagocata sibirica* (Sabussow, 1903)
6	Copepoda	Temoridae	*E. baikalensis*
		Cyclopidae	*C. kolensis*
		Harpacticidae	*Harpacticella inopinata* Sars, 1908
7	Cladocera	N/A	N/A
8	Diptera	Chironomidae	N/A
9	Nematoda	N/A	N/A

3.4. Adsorption of Microplastic Particles by Macrophytes

The lowest total number of adsorbed microplastic particles was found in *E. canadensis* (5.1 ± 1.4 particles·(g dw)$^{-1}$), while the highest was found in *D. baicalensis* (390.4 ± 105.3) (Table 12). The number of adsorbed particles in Bryophyta was close to that in *E. canadensis*. In contrast, *Stuckenia* sp. and *Myriophyllum spicatum* occupied an intermediate position in terms of the number of adsorbed microplastic particles, but tended overall toward *E. canadensis* (Figure 8). However, *U. zonata* and *D. baicalensis* showed the opposite pattern. Pairwise comparisons of the total number of adsorbed particles revealed statistically significant differences only between Bryophyta and *D. baicalensis* (p-value = 0.04, r = 0.62), and between *D. baicalensis* and *E. canadensis* (p-value = 0.02, r = 0.64). Examination of particle types showed that fibers predominated in all taxa (Table 12), and in some cases (*Stuckenia* sp., *M. spicatum*, Bryophyta) they were the only type. This pattern likely reflects difficulty for fragments to adhere to the macrophyte surface, especially under conditions of wave activity, and also by the fact that their overall abundance in the lake water is significantly lower. In *E. canadensis*, the presence of adsorbed fragments can be explained by the relatively wide leaf blades (at least when compared with other species presented in this study). The highest concentrations of both fragments and fibers were found in *D. baicalensis* and *U. zonata*. This increased adsorption capacity can be explained by the presence of mucus on the surface of these algae. It should be noted that *E. canadensis* does not have mucus, while *D. baicalensis* and *U. zonata* are filamentous algae. It is worth noting that a comparison of adsorbed fibers and fragments between each taxon did not reveal statistically significant differences. Pairwise comparison of the number of adsorbed fragments between taxa also

revealed no differences, and pairwise analysis of the number of fibers revealed differences only between *D. baicalensis* and *E. canadensis* (p-value = 0.01, r = 0.62).

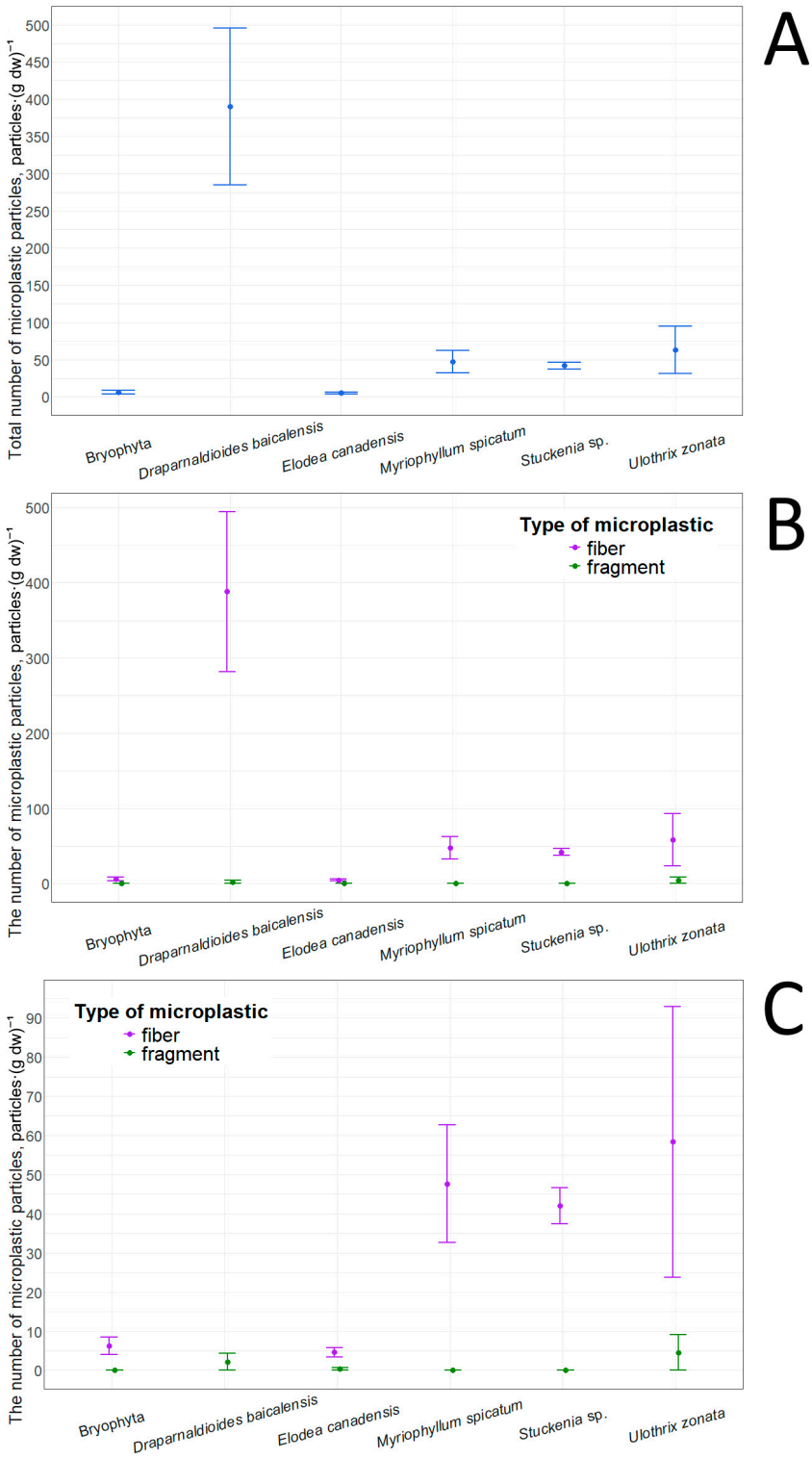


Figure 8. Microplastic particles adsorbed on macrophytes: (**A**)—total quantity; (**B**)—quantity of particles with different morphological structures; (**C**)—quantity of particles with different morphological structures in an enlarged format.

Table 12. The amount of microplastic particles adsorbed by plants.

No.	Taxon	Amount of Microplastic Particles, Particles·(g dw)$^{-1}$		
		Fibers	Fragments	Total
1	*E. canadensis*	4.7 ± 1.2	0.4 ± 0.3	5.1 ± 1.4
2	*D. baicalensis*	388.2 ± 106.6	2.19 ± 2.19	390.4 ± 105.3
3	*U. zonata*	58.3 ± 34.6	4.5 ± 4.5	62.9 ± 31.7
4	*Stuckenia* sp.	42.1 ± 4.6	0	42.1 ± 4.6
5	*M. spicatum*	47.6 ± 15.0	0	47.6 ± 15.0
6	Bryophyta	6.3 ± 2.2	0	6.3 ± 2.2

Note: n = 6.

3.5. Microplastics in Macroinvertebrates and Fish

Among amphipod species, the highest concentrations were recorded for *E. verrucosus* (0.3 ± 0.02 particles·individual^{-1}) and *M. branickii* (0.33 ± 0.05 particles·individual^{-1}) (Table 13). In addition, the recorded concentrations statistically differed significantly from concentrations in other amphipod species (Table 14). It is worth noting that microplastic fibers were detected in all species, fragments only in *E. vittatus* and *E. verrucosus*, and films only in *M. branickii*.

Table 13. The amount of microplastic particles ingested by aquatic organisms.

No.	Taxon	Amount of Microplastic Particles, Particles·Individual^{-1}			
		Fibers	Fragments	Films	Total
1	*E. cyaneus*	0.03 ± 0.01	0	0	0.03 ± 0.01
2	*E. vittatus*	0.1 ± 0.04	0.03 ± 0.01	0	0.13 ± 0.04
3	*E. verrucosus*	0.2 ± 0.03	0.06 ± 0.02	0	0.3 ± 0.02
4	*P. cancellous*	0.06 ± 0.01	0	0	0.06 ± 0.01
5	*M. branickii*	0.3 ± 0.04	0	0.06 ± 0.02	0.33 ± 0.05
6	*R. auricularia*	0.1 ± 0.02	0	0	0.1 ± 0.02
7	*B. baicalensis*	0.08 ± 0.02	0	0	0.08 ± 0.02

Note: n = 6 samples, where one sample is 5 individuals.

Table 14. Comparison of microplastic particle counts between amphipod species.

Taxon	*E. cyaneus*	*E. verrucosus*	*E. vittatus*	*M. branickii*
E. verrucosus	0.0004			
E. vittatus	1	0.01		
M. branickii	9.6×10^{-6}	1	0.001	
P. cancellous	1	0.009	1	0.0005

Only microplastic fibers were detected in the mollusks (Table 13). However, statistically significant differences in the number of microplastic particles ingested were observed between mollusks (p-value = 0.04, r = 0.51).

Of the six *P. knerii* individuals, microplastic particles were detected in three. In two cases, particles were found in the gills (1 and 2 fibers, respectively) (Table 15), and in one case, in the gastrointestinal tract. The number of microplastic particles detected was 48. All particles were fragments.

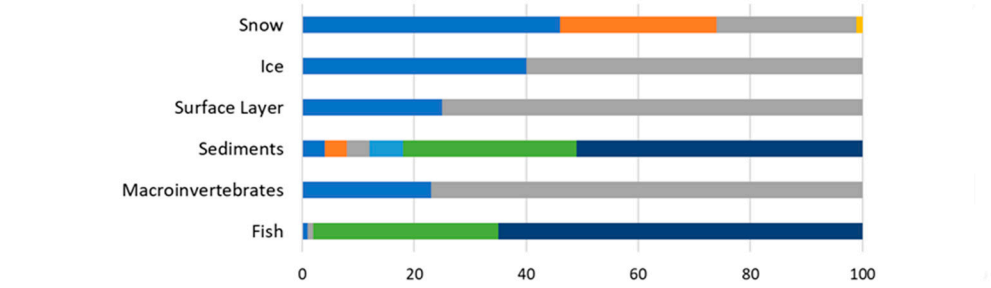
Table 15. The amount of microplastic particles in fish.

No.	Matrix Type	Number of Microplastic Particles, Particles·Individual^{-1}		
		Fibers	Fragments	Total
1	Gills	0.5 ± 0.3	0	0.5 ± 0.3
2	Gastrointestinal tract	0	8.0 ± 8.0	8.0 ± 8.0

Note: n = 6.

3.6. Size, Color, and Polymer Composition of Microplastic Particles

Analysis of microplastic particles revealed the presence of seven types of synthetic polymers (Figure 9): polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyethylene (PE), polyvinyl chloride (PVC), polyvinyl alcohol (PVA), and alkyd resin. Different polymers predominate in different matrices. For example, polystyrene is found in ice, the surface layer, and macroinvertebrates; alkyd resin is found in sediments and fish; and polypropylene is found in snow.



	Fish	Macroinvertebrates	Sediments	Surface Layer	Ice	Snow
Polypropylene (PP)	1	23	4	25	40	46
Polyethylene Terephthalate (PET)	0	0	4	0	0	28
Polystyrene (PS)	1	77	4	75	60	25
Polyethylene (PE)	0	0	0	0	0	1
Polyvinyl Chloride (PVC)	0	0	6	0	0	0
Polyvinyl Alcohol (PVA)	33	0	31	0	0	0
Alkyd Resin	65	0	51	0	0	0

Figure 9. Polymer composition of microplastic particles (%).

The results of this study show that in most cases, particles in the 0.1–0.5 mm size range predominate (Figure 10). However, in some cases, a relatively even distribution between the ranges is evident. Turning to color, it can be said that the color spectrum of microplastic particles is quite diverse (Figure 11). The most common colors are black, red, blue, white, light blue, and yellow.

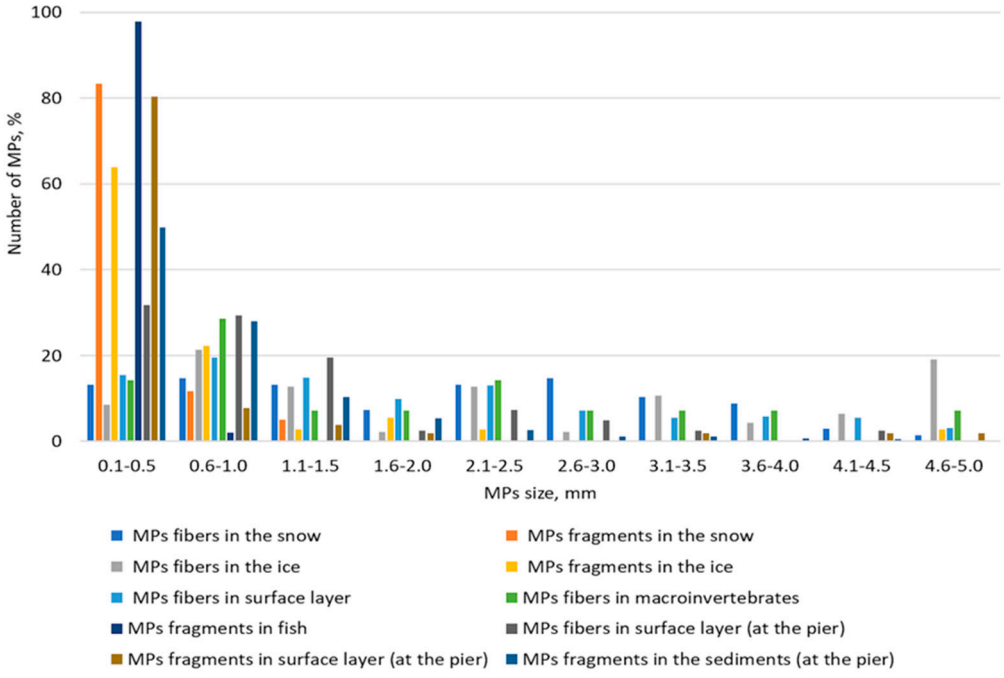


Figure 10. Particle size distribution of microplastics (%).

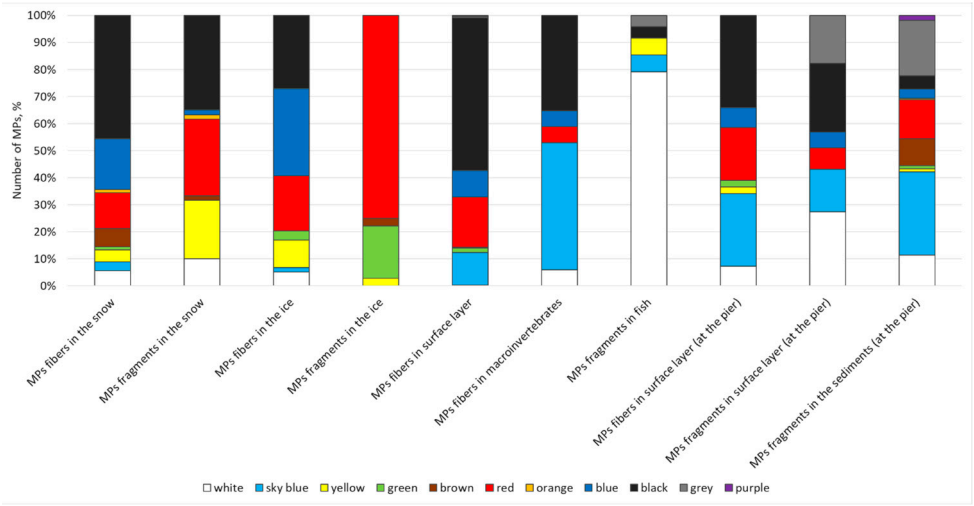


Figure 11. Color range of microplastic particles (%).

4. Discussion

4.1. Microplastics in Snow and Ice

Atmospheric precipitation is one source of microplastic particles [46]. Wind also influences the transport of microplastic particles. Therefore, snow cover is often used as a matrix for determining microplastic concentrations among researchers. Our study analyzed the concentration of microplastic particles in snow over ice cover with increasing distance from the coastline. Microplastic particle concentrations in this study are comparable [47] or significantly lower than those reported in other studies [48,49]. Some studies [49] note that snow concentrations may decrease with distance from the coastline (or settlement). This is not reliably confirmed in this study, but the distance from the coast was also insignificant.

The concentration of microplastic fibers in Lake Baikal ice in this study was slightly lower than in our earlier study [28]. However, a comparable number of fragments was observed. Studies of other lake ecosystems have reported varying concentrations of microplastics, for example, 7.8 ± 1.2 particles·L^{-1} (Vesijärvi lake and Pikku Vesijärvi pond (Finland)) [50], from 269 ± 84 to 915 ± 117 particles·L^{-1} (Lake Ulansuhai (China)) [51]. It is worth noting that ice typically contains higher concentrations than water beneath it. Moreover, according to our data, microplastic concentrations are higher on the underside of the ice, near the boundary between the two aggregation states [28]. The danger in this case is that many organisms use the underside of the ice as a habitat during the winter [29]. With this in mind, we conducted water sampling directly under the ice to determine the composition of aquatic communities that may be in direct contact with, and therefore potentially exposed to, microplastics. This study showed that 99 to 100% of the community was represented by *E. baikalensis* nauplii. A recent study [36] demonstrated a relatively high frequency of microplastic particles among individuals of this species. Is it possible that microplastic particles are ingested by nauplii during the winter? This question remains unanswered.

4.2. Microplastics in Water and Sediments

In this study, the concentration of microplastic particles in the near-surface layer ranged from 2.7 ± 0.9 to 17.0 ± 3.2 particles·m^{-3}. These concentration values are consistent with those in previous studies, where the average concentration in Lake Baikal ranged from 0.27 to 291 particles·m^{-3} [3,30–33]. However, it is worth noting that these studies used different sampling methods, filtered different volumes of water, and identified particles using different methods. Furthermore, the lower detection limits for par-

ticles also varied. Moreover, these concentration values (even taking into account the maximum values) are currently significantly lower than concentrations observed for a number of other lakes. For example, for Lake Ladoga with its tributaries (Russia) the value is 20–2400 particles·m^{-3} [52], for Lakes Al-Asfar and Al-Hubail (Saudi Arabia)—700–9000 particles·m^{-3} [53], for the Altai lakes (Russia)—11,000 particles·m^{-3} [54], for Lake Poyang (China)—5000–34,000 particles·m^{-3} [55], for the Great American Lakes basin with tributaries from less than 10 to 100,000 particles·m^{-3} [56], for Rewalsar Lake (India)—130,000 particles·m^{-3} [57].

Microplastic concentrations in different layers of Lake Baikal's water column likely demonstrate a decrease in the number of microplastic particles with increasing depth (Table 7). Similar decreases in concentrations are generally observed in other aquatic ecosystems [58].

It is worth noting that the concentration of microplastic particles in lake water is significantly lower than in snow or ice. This has been observed in other studies and is due to the fact that microplastics are adsorbed and concentrated in ice [51,59], and also accumulate in snow over the winter. Despite low concentrations in the near-surface water layer, the concentration of microplastic particles apparently increases significantly in late spring. This is because melting ice and snow leads to a massive release of microplastic particles into the near-surface water layer [59].

The recorded average concentration of microplastic particles in lake sediments is currently 129 particles·(100 g dw)$^{-1}$ [60]. In our case, the concentration away from the village is 10.6 ± 2.4 particles·(100 g dw)$^{-1}$ (which is significantly less than the average), and the concentration directly near the village (on the contrary, slightly higher than the average) is 193.2 ± 30.2 particles·(100 g dw)$^{-1}$. At the same time, for lakes around the world, concentrations of microplastic particles in sediments range from 0.5–1 to 1810 particles·(100 g dw)$^{-1}$ [61–66].

4.3. High Concentrations of Microplastic Particles in the Pier and Ship Mooring Area

The concentrations of microplastic particles we found in the pier and ship mooring area deserve special attention. The maximum recorded amount of microplastic particles in this location was 1813.5 particles·(100 g dw)$^{-1}$, similar to the maximum concentration recorded for lake sediments (1810 particles·(100 g dw)$^{-1}$) [66]. Furthermore, it has long been known that microplastics in sediments can be displaced into the water column by wave activity [67]. In our case, wave activity causes the concentration of microplastics in the water column in this local area to increase more than 20-fold. Apparently, despite the fact that this area is very local, wave activity causes the displaced particles to settle over a larger area. Also, given the relatively large number of both benthic and planktonic organisms in this location, the potential risk of ingesting these particles also increases. Relatively recently, we recorded caddisfly larvae utilizing microplastic particles and incorporating them into their cases in large quantities [37]. Locations such as this are precisely the source of microplastics for caddisflies.

4.4. Adsorption of Microplastics on Macrophytes, as Well as Microplastics in Macroinvertebrates and Fish

In this study, the highest concentrations on a dry weight basis were observed for *D. baicalensis* and *U. zonata*. Both macrophyte species are among the most dominant in Lake Baikal. Furthermore, *U. zonata* forms a vegetation belt right at the lake's edge, the same zone where we observed elevated concentrations of microplastic particles in the water. Both species have a mucous sheath [68], which apparently determines their enhanced adhesive properties. Published data fully confirms these assertions, indicating that the morphological and physiological characteristics of plants determine their adsorption capacity [42,69,70].

The amount of microplastic ingested by organisms depends on its concentration in water and sediment [26]. Given the low concentrations in these matrices in our study, we also recorded low concentrations in the organisms themselves. In our case, the highest concentrations were observed in *E. verrucosus* and *M. branickii*. We previously noted that in summer, *E. verrucosus* can be found near the water's edge, where concentrations of microplastic particles in the water are significantly higher. The second species, in turn, is a pelagobiont and actively feeds on the planktonic copepod *E. baicalensis*. Furthermore, this species undergoes diurnal vertical migrations, including during the winter period, to the upper water layers and to the water-ice boundary [44]. Both of these circumstances could have led to our results. Furthermore, given that the sample sizes in this study were small, the data obtained should be considered preliminary and require further verification.

4.5. Types of Artificial Polymers, Morphological Structure, Size and Color

The types of artificial polymers we discovered have already been noted for Lake Baikal in various studies [3,32,34,36]. The type of matrix and the location of the study points can apparently influence the polymer ratio to some extent.

In this study, artificial polymers such as PVA and alkyd resin were observed in the pier area. This is directly related to the permanent mooring of ships in this area, as PVA and alkyd resin are components of modern paints. Similar findings have been observed in other areas of the lake [34]. The presence of these polymers in the fish's stomach can be explained by the fact that at some point, the fish swam into this area and hunted there. It is worth noting that these fish are unique in that they are benthic and have wide jaws. When hunting, they make sharp movements toward their prey, thereby stirring up silt from the bottom (suspending it in the water). Given this, it is most likely that the microplastic particles were accidentally ingested by the fish while hunting.

The consumption of PP and PS by macroinvertebrates can be explained by their predominance in Lake Baikal water. These types of synthetic polymers are widely used in industry. Furthermore, due to their density, these polymers do not sink well and concentrate near the surface of water.

Although we identified three particle types based on morphological structure in this study (fibers, fragments, and films), fibers are the predominant type. This has been confirmed for many water bodies [6,7,71], including Lake Baikal [28,33,34]. The predominance of microplastic fragments in the pier and mooring area is associated with localized contamination [34].

In our study, the largest percentage of particles in many cases falls within the 100–500 μm range. This is confirmed in many studies [34,43]. Moreover, there is currently a need to shift the particle detection limit downwards [3]. The latter requires improvement and standardization of sampling and processing methods.

The diverse color range of microplastic particles primarily demonstrates the diversity of different dyes, which can also (and perhaps to a greater extent than the plastic itself) affect organisms [72–74]. This circumstance, in combination with the different types of artificial polymers, highlights the complexity and ambiguity in interpreting the obtained data.

4.6. Resume

Lake Baikal currently exhibits relatively low concentrations of microplastic particles in many matrices. These concentrations are expected to be even lower away from human impacts and populated areas [49]. However, summarizing the accumulated literature and based on the results of this study, it can be concluded that there are a number of zones of the lake where elevated concentrations of microplastic particles may be present. Four such zones can be identified. First, there are the ice and snow covers. In the former,

particles are adsorbed from the water, while in the latter, microplastics, carried by wind and precipitation, accumulate. When the ice melts, all this plastic instantly ends up in the surface water layer. Second, there is the water's edge zone. Due to wave activity, microplastics are constantly suspended here. Furthermore, microplastics accumulated in snow on land during the winter also end up here. Third, attention should be paid to macrophytes with a slimy sheath. This feature allows them to adsorb more microplastic particles than other macrophytes. Fourth, these are areas around piers and long-term moorings of ships. Artificial polymers from paints and varnishes are released into the water during the painting process or during the degradation of old coatings, and then settle and accumulate on the bottom in these areas. The detected concentrations are comparable to the highest concentrations recorded worldwide.

Regarding the potential toxicological impact of microplastics, it should be noted that this issue is quite complex [58]. On the one hand, the toxicological effects of "large" microplastic particles themselves have not yet been demonstrated (apparently, after ingestion, they pass through the gastrointestinal tract and are eliminated from the body naturally). In turn, "small" microplastic particles (several microns in size) can be retained and accumulate in the body and even pass through the walls of organs and individual cells, potentially remaining there for long periods [75]. An additional danger here is associated, among other things, with the fact that organisms (mainly crustaceans and, in particular, amphipods) have been observed that are capable of fragmenting large microplastic particles and converting them into smaller fractions [26,76]. On the other hand, the term microplastic encompasses a fairly broad range of substances. However, it is important to understand that the toxicological effects will depend on the type of synthetic polymer, as well as on the dyes, additives, and contaminants that can adsorb to the polymer surface [72–74]. Furthermore, pathogenic microorganisms can settle on the surface of plastic [9].

Our study was not designed to examine toxicological impacts, but it does provide insight into both the types of polymers encountered and the variety of colors (and, consequently, dyes). Furthermore, given the location in the pier and ship mooring area, it is clear that paints and varnishes are not the only contaminants there. Particles in this zone can potentially adsorb fuels and lubricants and many other substances, which must be taken into account when assessing toxicological effects under natural and experimental conditions. Furthermore, some studies note that low concentrations of particles may pose a hazard, but only under conditions of chronic exposure [77]. It is worth noting that the results of some recent experiments show that microplastic particles, for example, can mitigate the toxic effects of copper, while the results for other pollutants are highly variable [78]. Such results confirm the ambiguity and difficulty of interpreting the effects of microplastic particles and the need for further research (including studies on the occurrence of oxidative stress) [77].

5. Conclusions

This study was the first for Lake Baikal to utilize a multi-matrix approach. The results demonstrate the presence of distinct pockets of microplastic particle concentration. In this case, four such pockets were identified: ice and snow cover (potentially the near-surface layer during ice and snow melt), the lakeshore, macrophytes with mucus, and the pier and mooring area. The dominant type in terms of morphological structure is fibers; however, in some cases associated with localized contamination, microplastic fragments may predominate. Regarding the polymer composition, in the case of fragments, it was found that polymers such as alkyd resin and polyvinyl alcohol can be found in large quantities in localized areas.

A multi-matrix approach to studying microplastic pollution in aquatic ecosystems provides a more comprehensive picture than studies that analyze concentrations using only

a single matrix. We recommend that future research focus on the effects of microplastic particles on organisms associated with areas of highest concentrations, taking into account chronic exposure to both microplastic particles and associated factors (other pollutants, dyes, etc.).

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