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Microplastics Occurrence in Fish from Tocagua Lake, Low Basin Magdalena River, Colombia

Lindys Miranda-Peña [1], Milena Urquijo [1], Victoria A. Arana [1], Roberto García-Alzate [1], Carlos A. García-Alzate [2,3,4] and Jorge Trilleras [5,*]

[1] Grupo de Investigación Ciencias, Educación y Tecnología–CETIC, Programa de Maestría en Ciencias Ambientales, Facultad de Ciencias Básicas, Universidad del Atlántico, Carrera 30 No. 8–49, Puerto Colombia 081007, Colombia; lymiranda@mail.uniatlantico.edu.co (L.M.-P.); milena_0918@hotmail.com (M.U.); victoriaarana@mail.uniatlantico.edu.co (V.A.A.); robertogarcia@mail.uniatlantico.edu.co (R.G.-A.)

[2] Grupo de Estudios en Sistemática y Conservación–GESC, Programa de Maestría en Biología, Facultad de Ciencias Básicas, Universidad del Atlántico, Carrera 30 No. 8–49, Puerto Colombia 081007, Colombia; carlosgarciaa@mail.uniatlantico.edu.co

[3] Grupo de Estudios en Sistemática y Conservación-GESC, Programa de Ingeniería Ambiental y Sanitaria, Facultad de Ingeniería Ambiental y Sanitaria, Corporación Universitaria Autónoma del Cauca, Calle 5 No. 3-85, Popayán 190003, Colombia

[4] Grupo de Investigación Biodiversidad del Caribe Colombiano, Programa de Maestría en Biología, Facultad de Ciencias Básicas, Universidad del Atlántico, Carrera 30 No. 8–49, Puerto Colombia 081007, Colombia

[5] Grupo de Investigación en Compuestos Heterocíclicos, Programa de Maestría en Ciencias Químicas, Facultad de Ciencias Básicas, Universidad del Atlántico, Carrera 30 No. 8–49, Puerto Colombia 081007, Colombia

* Correspondence: jorgetrilleras@mail.uniatlantico.edu.co

Abstract: Following global trends, research to determine the presence and abundance of microplastics (MPs) in environmental matrices in Colombia has focused on the coastal and marine environments. However, little scientific information is available on the impact of this pollutant on wetlands and fish. In this study, we provided scientific data on the occurrence and abundance of MPs in water and fish from Tocagua Lake, an important wetland in the Colombian Caribbean, and the unique habitat of wild cotton-top tamarins (*Saguinus oedipus*). Water (72) and fish (228 individuals of six species) samples were collected during four sampling events and two climatic seasons (wet and dry). A total of 1174 microplastic particles were collected in water with an average abundance of microplastics at the six stations sampled during four sampling events of 0.96 ± 0.40 MPs/L, and 648 MPs were identified in the gastrointestinal tract of 191 individuals, corresponding to a frequency of occurrence of 83.7%. Black- and blue-colored fiber MPs were particles that predominated in both matrices (water and fish), and seven types of polymers were identified through attenuated total reflectance Fourier transform infrared spectroscopy analysis. The abundance, type, and color of MPs in water and fish were not significantly different between seasons.

Keywords: ecosystems; fish; lake; microplastic ingestion; surface water; wetlands

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1. Introduction

Among the different materials, plastic is present in many aspects of our daily lives, increasing industrial production considerably as well as its waste, or plastic garbage, which has become one of the challenges of this century as an environmental crisis [1–3]. Plastics are generated in the post-consumer cycle because of inadequate management of these wastes, making them ubiquitous pollutants in the environment [4,5]. According to reports in the literature, despite the increase in plastic waste management techniques and innovative strategies to incorporate plastic waste as a raw material in different sectors, it is necessary to increase capacity, collection, expansion, and recycling rates [6–8]. Colombia produces approximately 1.4 million tons of plastic material annually and 3804 tons of plastic waste. Only 7% of single-use plastics are recycled, which generates pollution problems in various environmental matrices [9–11]. Plastic waste is a mixture of different types of polymers (i.e., polyamide, polyethylene, polyester, polyethylene terephthalate, polypropylene, polystyrene, polyurethane, polyvinyl chloride, polytetrafluoroethylene, and polymethyl methacrylate) that, under environmental conditions, are exposed to mechanical, physical, and chemical factors that break down into tiny plastic particles called microplastics (MPs, 1 μm–5 mm in size) that, through distinct transport phenomena, have been detected in various environmental compartments [12–16]. This is one of the main sources of microplastics (secondary MPs). MPs also reach bodies of water as manufactured microplastics, another source of microplastics (MPs primary), such as pellets or micropellets contained in a variety of products (e.g., beauty, care, personal hygiene products, paint, and coatings) [17].

The effects, impacts, and risks associated with the accumulation of MPs in environmental compartments have been extensively studied [18–29]. The composition of MPs (polymer type and chemical additives), color, size, and shape (fibers, fragments, films, pellets, and foams) make them emergent contaminants that are difficult to remove and constantly accumulate in environmental compartments. Scientific experiments have revealed the associated impacts of MPs on potential human health problems, including the accumulation of fibers in the gastrointestinal tract through the food chain and interaction with the intestinal epithelium. Controlled studies have shown the potential risk of additives that MPs have on organ toxicity and neurotoxic effects [21–25]. Microbial pathogens, hydrophilic and persistent organic compounds, and heavy metals can adhere to the surfaces of different forms of MPs, converting them into vectors that cause unwanted effects in living organisms. These particles are persistent and accumulate in various environmental matrices for long periods of time, which is why studies on the dynamics of contamination in freshwater and the organisms that inhabit it have increased [27–29].

MPs in inland water are distributed depending on factors such as water body size, wind, currents, and particle density and can stay afloat, be suspended in the water column, or become part of the sediment. During the different seasons of the year, there are physical and chemical variations in the water bodies; these modifications that occur during the wet and dry seasons can modify the concentrations of MPs [30,31]. The occurrence and abundance of MPs in aquatic organisms are indicators of the impact and inadequate disposal of plastic debris generated by anthropogenic activities in these lentic environments. Many of these organisms modify their diets during different seasons, which may be related to the concentration of this pollutant [32,33]. The diversity in the shape and color of MPs can influence how fish ingest them. Studies have shown that fish species with different feeding behaviors and dietary preferences may accidentally ingest microplastics by mistaking them for prey or food because of their size, shape, and physical characteristics [26,33–38]. These observations highlight the importance of understanding how different fish species interact with MPs and how the physical characteristics of MPs influence their ingestion. In addition, it allows the identification of the risks associated with the occurrence and abundance of MPs in aquatic life and the trophic webs of freshwater ecosystems. The information available in the literature on the ecotoxicological effects of MPs in fish is the result of controlled laboratory experiments. These results show that the ingestion of MPs and their accumulation in the digestive tract cause blockages in the digestive system and reduce feeding owing to false satiety, which causes structural and functional deterioration in the gastrointestinal tract, in addition to the effects and associated risks of transmitting hazardous chemicals and pathogenic microorganisms to fish [34–38].

In Colombia, there are few investigations on microplastics, and the existing reports in the literature follow the global trend: (i) mostly in coastal and marine environments [39–45]; (ii) the consequences of excessive consumption of plastic and environmental impacts, including MPs pollution emerging in inland waters, are not known in detail [1–3]. Therefore, there is an urgent need to encourage and increase research to determine the effects of MP pollution on aquatic environments in Colombia. This study contributes to expanding the information on MPs pollution to generate scientific data on its abundance, distribution, and ecological impact on continental aquatic ecosystems in the lower basin of the Magdalena River. Tocagua Lake is an important ecosystem located within the regional district integrated management of Palmar del Tití, Luruaco-Atlántico, which is a protected area for the conservation of dry forests and wild primates [46,47].

2. Materials and Methods

2.1. Study Area

Tocagua Lake (10°42′9″ N 75°14′54″ W) is located in the Canal del Dique Basin with an area of 300 ha in the municipality of Luruaco–Atlántico and is part of the Atlántico Department complex of wetlands (Figure 1). Water resources depend on precipitation and networks of streams that flow from hills (Platanal, Guayacán, and Iraca streams) with an ichthyofauna, including six species (*Andinoacara latifrons*, *Astyanax magdalenae*, *Caquetaia kraussii*, *Mugil liza*, *Oreochromis niloticus*, and *Poecilia gillii*) with different feeding behaviors. Tocagua Lake is a wetland within the regional district of integrated management Palmar del Tití (2622.15 ha), a protected area for the settlement of migratory birds that enter Colombia, a nesting site for many species of herons and waterfowl, and a unique habitat for wild cotton-top tamarins (*Saguinus oedipus*) [47]. The population settlement, corregimiento de San Juan de Tocagua, with approximately 200 inhabitants, developed livestock, fishing, and handicrafts that came from the Mokaná–Caribbean, African, and Indigenous heritages [48].

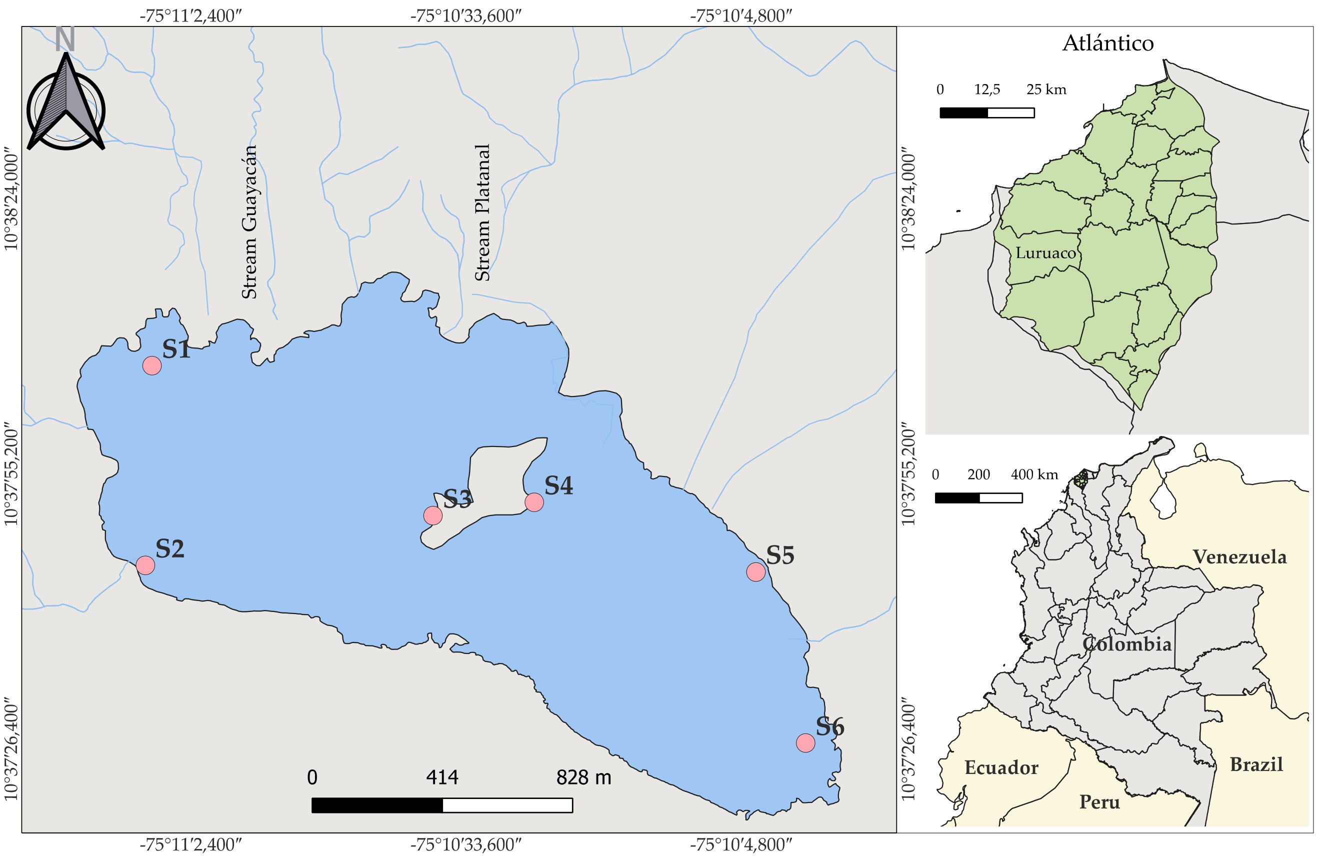

Figure 1. Geographical location of Tocagua Lake, Atlántico–Colombia, and sampling points.

2.2. Water Sampling

Six sampling points were located to cover the lake area, and four sampling events were scheduled. Samples of surface water and fish were collected on the same day in different temporal variations associated with the wet season (September–November 2021) and the dry season (March–May 2022). At each sampling point, lake water was monitored in situ, and conductivity, dissolved oxygen, pH, and temperature were recorded using a multiparameter analyzer (YSI ProPlus, YSI Inc., Yellow Springs, OH, USA). Water samples were collected following a previously reported methodology [49], preserved, and stored for hardness and alkalinity measurements using commercial physicochemical kits (Hanna Instruments; Vöhringen, Germany). A total of 72 samples were collected, with 20 L of surface water/station and three replicates of equal quantity for each sampling event. The abundance of MP particles in the surface water samples was determined as a function of the density of the bulk samples and is reported as MP particles/L. The total MP concentrations are reported as the mean number of microplastics per liter (MPs/L) with a standard deviation (± SD).

2.3. Sampling and Processing of Fish

In each sampling event, fish samples from six species were collected using a trawl (8 m long, 1.5 m high, with 0.5 cm mesh eye size) for small individuals (*Poecilia gillii* and *Astyanax magdalenae*) and a cast net (2 m diameter, 0.5 cm mesh eye). The trawling methodology (trawl net) was performed three times, and the cast net was cast five times at each sampling point to capture individual fish. The captured fish were preserved in an icebox during their transport to the laboratory. All fish specimens (228 in total) were identified, measured (standard length, mm), and weighed (g) (Table 1) [50,51].

Table 1. Morphological description of the fish.

Species	Feeding Groups	N		Total Length (mm) *		Weight (g) ***		K Index	
		Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Andinoacara latifrons	OV	54	12	118.4 (50.2)	59.8 (4.7)	42.0 (44.5)	3.5 (1.2)	0.6 (0.8)	1.4 (0.5)
Astyanax magdalenae	OI	14	0	112.0 (46.6)	NA **	40.2 (66)	NA	0.4 (0.3)	NA
Caquetaia kraussii	OC	23	16	106.3 (41.2)	57.8 (5.1)	34.9 (30)	3.1 (1.3)	0.6 (0.9)	1.3 (0.5)
Mugil liza	DM	13	7	119.7 (49.5)	61.8 (8.8)	39.0 (35.1)	4.2 (1.7)	0.3 (0.3)	1.7 (0.7)
Oreochromis niloticus	OV	23	4	92.7 (55.1)	51.7 (11.9)	26.4 (33.2)	2.5 (1.8)	0.6 (0.6)	1.0 (0.7)
Poecilia gillii	HB	56	6	115.6 (44)	60.6 (6.3)	39.9 (38.2)	4.0 (1.3)	0.3 (0.3)	1.6 (0.5)
		183	45						

OV: omnivorous; OI: omnivorous–insectivorous; OC: omnivorous–carnivorous; DM: detritivores–microalgae; HB: herbivorous. N: total number of individuals analyzed. * Average size of fish species (±SD). ** NA: no specimens were caught. *** Average weight of fish species (±SD). K: value (±SD).

Each specimen was washed with filtered distilled water and dissected using scissors, a scalpel, and forceps on a metal tray. Dissection was performed by making a horizontal incision along the ventral side of the fish from the anal pore to below the pectoral fin. The gastrointestinal tract of each fish from the esophagus to the anal pore was removed, measured (mm), weighed (g), and transferred to an Erlenmeyer flask with 10% potassium hydroxide (KOH) to start the digestion process according to a previously reported method with slight modifications [33,52,53]. The amount of 10% potassium hydroxide (KOH) solution was determined from the weight of the gastrointestinal tract (1p:3v ratio), covered with aluminum foil, and placed in an orbital shaker for 48 h at 60 °C and 250 rpm (Heidolph Incubator 1000 and Heidolph Unimax 1010, Heidolph Instruments GmbH & Co. KG, Schwabach, Germany). To each Erlenmeyer flask, 100 mL of saturated and filtered sodium chloride solution (1.2 g/mL density) was added. The mixture was stirred for 10 min and allowed to rest for 24 h at room temperature. The supernatant was filtered under vacuum (2019 B, Welch, Limenau, Germany) using a metal funnel with a glass microfiber filter (grade GF/C, 1.2 µm, Whatman, Maidstone, UK). Each filter paper was dried at room temperature in a petri dish. The abundance of microplastics in fish was presented as the number of microplastics per individual (MPs/individual).

2.4. Quality Assurance/Quality Control (QA/QC)

To avoid potential contamination by airborne microfibers, laboratory quality assurance and control were performed as previously described [49]. In addition, "procedural controls" (150 mm diameter glass beakers filled with distilled water) were placed in the working environment for each step (n = 3 for each set of samples). Microplastics that were detected in laboratory control experiments with the same typology and color were excluded from each set of samples following the quality criteria reported in the literature for these studies [54,55].

2.5. Physical and Chemical MPs Characterization

The classification of plastic particles based on their morphological characteristics provides reference information and comparable elements for similar investigations [34–38]. Through visual inspection, the morphometric data of the MPs was recorded to determine the relationship between the environmental matrices [26,38]. MPs isolated and collected on the filters were analyzed using a stereomicroscope (SteREO Discovery V20, Carl Zeiss AG, Oberkochen, Germany) to determine the number of particles and record their physical characteristics, such as color, size, and shape (fibers, films, pellets, fragments, and foam), and minimum standardized information in these studies [56–59]. Representative microplastic samples were analyzed using micro-attenuated total reflectance Fourier-transform infrared spectroscopy (μ–ATR-FTIR) (ATR–FTIR microscope, LUMOS II, Bruker Optics GmbH & Co. KG, Mannheim, Germany) with a thermoelectrically cooled mercury cadmium telluride (TE–MCT) detector and an automated ATR probe (Ge crystal). The spectral range was set between 4000 and 670 cm^{-1} at a resolution of 4 cm^{-1} with 64 scans. The obtained spectra were compared with those of the reference (ATR-Polymer library complete (vol. 1–4), KIMW ATR–IR Polymer libraries), and the polymer content was confirmed to be >75% [60,61].

2.6. Statistical Analysis

The association between the number of MPs per individual according to species and diet, including season, was determined by fitting negative binomial regression models [62]. The amount of microplastic particles for each species is represented as the frequency of plastic ingestion (%*FO*, Equation (1)).

$$\%FO = \left(\frac{Ni}{n}\right) \times 100 \tag{1}$$

where Ni is the number of individuals that presented MPs and n is the total number of individuals analyzed. The condition index (K) was calculated using the relationship between the length (L) and weight (W) of each individual (Equation (2)) [50,51].

$$K = 100\left(\frac{W}{L^3}\right) \tag{2}$$

The data were analyzed using a generalized linear model (GLM)-Poisson regression to examine the relationship between the abundance of MPs in fish and their morphometric variables (weight, length, and K index). Permutational multivariate analysis of variance using Bray–Curtis distance matrices (ADONIS) was used to determine the relationship between the color of MPs, species, and diet for the six species, including the interaction with season in each setting. A generalized linear mixed model was used to compare the differences between the abundance of MPs in fish (the response variable) and sampling seasons (the fixed effect variable). The abundance of MPs in the water samples was used as a random variable to estimate the effect of MP contamination on the abundance of MPs in the fish.

The bioconcentration factor (BCF) indicates the relationship between the concentration of the contaminant and the biota (Equation (3)). In this study, we evaluated the accumulation capacity of MPs in wild fish species in the environment [63–65].

$$BCF = \frac{C_b}{C_w} \tag{3}$$

where C_b is the mean concentration of MPs in fish (items/g-individual) and C_w is the concentration of MPs in water (MPs/m^3) [63–65]. The data analyzed using a multivariate model of community composition and similarities of MP colors (ANOSIM) allowed us to relate the types of MPs found in both matrices (water and fish). The dissimilarity matrix calculated using the Bray–Curtis method, includes simple, complete, and average clustering points. Then, through non-metric multidimensional scaling analysis (NMDS), the similarity or dissimilarity of the MP communities in water and fish for their colors was determined [66,67]. Statistical analyses were conducted using R Studio software (version 4.2.2, R Core Team, 2022), including the MASS, vegan, stats, lme4, glmmADMB, broom.mixed, and ggplot2 packages [68].

3. Results

3.1. Habitat Physicochemical Characterization

According to the physicochemical characterization of the habitat, the surface water temperature in the lake presented an average value of 31.4 °C during the wet season (September–November 2021) and an average temperature of 31.5 °C in the dry season (March–May 2022). The conductivity registered average values of 698 and 730 µs/cm during the wet and dry periods, respectively. The alkalinity recorded average values of 155 mg/L $CaCO_3$ and 240 mg/L $CaCO_3$ in the wet and dry seasons, respectively. Regarding the average value of dissolved oxygen, it was low at 5.4 ± 3.7 mg/L; the lake presented moderately hard water with hardness values ranging between 45.0 and 165.0 mg/L, with an average of 95.1 ± 59 mg/L. The pH of the water tended to be acidic during the four sampling events, with a mean of 4.55 ± 3.35. These data indicate that Tocagua Lake was under environmental stress during sample collection.

3.2. Abundance and Characteristics of Microplastics in Water

MPs were detected at six stations sampled from Tocagua Lake during the two seasons. A total of 1174 microplastic particles were collected from Tocagua Lake water, with an average abundance of microplastics at the six stations sampled during four sampling events of 0.96 ± 0.40 MPs/L. According to the results, there was a small variation in the average abundance of MPs between seasons during sampling. During the wet season, the average abundance was 1.04 ± 0.22; in the dry season, the average abundance was 0.88 ± 0.53 MPs/L. Station four (S4) presented a higher abundance of MPs with a value of 1.38 MPs/L and 1.47 MPs/L in the wet and dry seasons, respectively (Table 2) [49].

Table 2. Average of abundance of MPs (MPs/L) according to the shape in water from Tocagua Lake.

Season	Station	Total	Fiber	Fragment	Foam
Wet	S1	1.11	0.97	0.12	0.03
	S2	0.74	0.63	0.09	0.03
	S3	0.97	0.92	0.05	0.00
	S4	1.38	1.00	0.35	0.03
	S5	0.88	0.81	0.07	0.01
	S6	1.17	1.00	0.14	0.03
Dry	S1	1.52	1.24	0.30	0.18
	S2	0.64	0.59	0.05	0.00
	S3	0.75	0.50	0.25	0.00
	S4	1.47	1.19	0.25	0.03
	S5	0.83	0.53	0.28	0.00
	S6	0.10	0.10	0.00	0.00

The microplastic particles were shaped as fibers, fragments, and foams (Figure 2). Fibers (89.5%) were more abundant than fragments (9.9%) and foams (0.6%). Low fluctuations were recorded in the total fibers (wet = 58.0%, dry = 42.0%) and fragments (wet = 51.7%, dry = 48.3%) during the evaluated seasons. The proportion of fragments increased during the dry season (11.2%). In the case of the foam, 86.0% of the particles were in the wet season. The distributions of shapes in the seasons did not present variations in the proportions, and the dominance of the typologies (fibers > fragments > foam) remained the same (Supplementary Materials Figure S1).

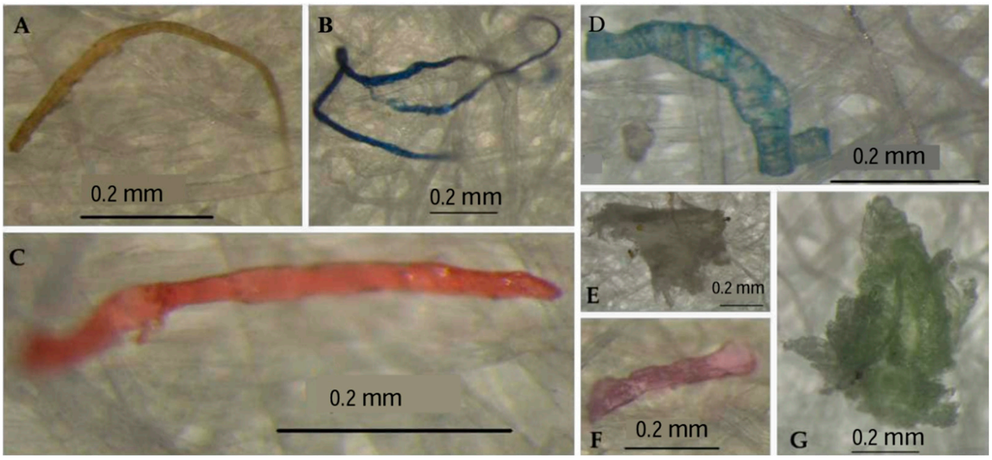

Figure 2. Photographs of some fibers (**A**–**C**), fragments (**D**–**G**) found in water from Tocagua Lake, Low Basin Magdalena River, Colombia.

The MPs presented 13 colors: yellow, blue, white, gold, grey, brown, purple, orange, black, red, pink, transparent, and green. For the analysis, MPs with less presence were grouped into the other categories (yellow, gold, brown, purple, orange, pink, and transparent). The most abundant MPs were blue (43.4%), red (18.4%), and black (15.8%), representing 77.6% of all shapes and sizes (Figure 3A). In the wet and dry seasons, the colors presented variations in proportions, with a lower value of dominance in the colors identified in the dry season: blue (wet = 53.5%, dry = 29.7%), red (wet = 12.0%, dry = 27.0%), and black (wet = 17.0%, dry = 14.5%) were the most frequent colors in both seasons (Supplementary Materials Figures S2A and S3A). The dominant colors in the fibers were blue (48.1%), red (20.4%), and black (17.6%). In the fragments and foam, the dominant colors were white (58.6% and 100%, respectively) (Figure 3B). In the wet and dry seasons, the dominant colors of the fibers were blue (wet = 58.5%, dry = 33.7%), black (wet =18.7%, dry = 16.1%), and red (wet = 12.6%, dry = 30.9%). In the wet season, the fragments showed greater variation in the identified colors. The dry season was characterized by the dominance of white (76.8%) and transparent (10.7%) fragments (Supplementary Materials Figures S2B and S3B). The MPs have a range of 0.1 to 4.7 mm, with a mean value of 2.75 ± 0.93 mm, and 53% present sizes smaller than 2 mm (Figure 3C).

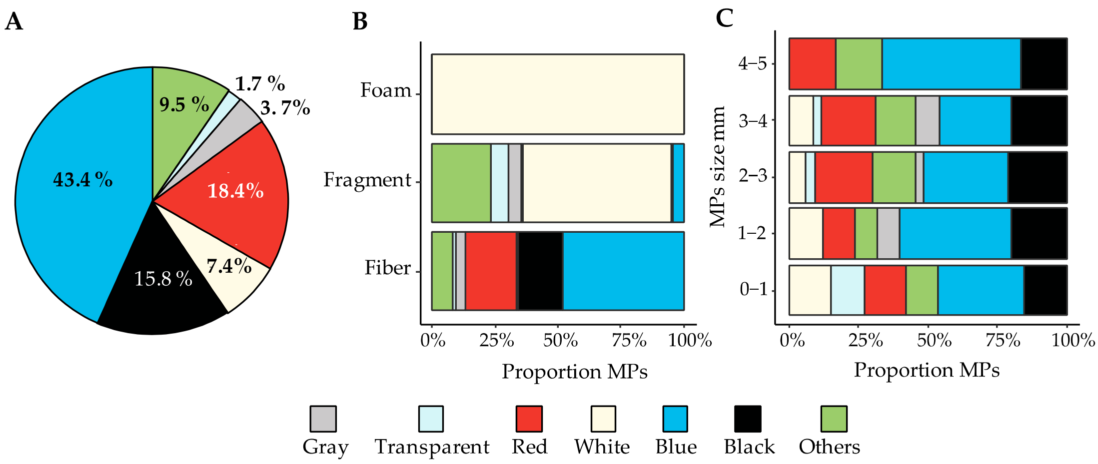

Figure 3. Typological characteristics of the MPs found in water from Tocagua Lake. (**A**) Color all MP particles, (**B**) Shape and (**C**) Size.

A representative group of fibers and fragments was selected for μ-ATR-FTIR analysis of the MPs. Five polymers were obtained: polyester (50.1%), polypropylene (19.2%), polymethyl methacrylate (15.4%), polyamide (11.5%), and polyurethane (3.8%). The percentages of polyacrylate and polyvinyl chloride fragments were 55.0% and 45.0%, respectively.

3.3. Abundance and Characteristics of Microplastics in Fish Samples

A total of 228 individuals from six fish species were collected during the four sampling events. Of the 191 individuals, 648 MPs were identified, corresponding to a frequency of occurrence (%FO) of 83.7%. The number of plastic particles for the fish species analyzed varied from 0 to 20 MPs/individual, with an average of 2.8 ± 2.7 MPs/individual in the wet season and 2.3 ± 3.6 MPs/individual in the dry season. The fish caught during the wet season (n = 158) had a higher abundance of MPs (544 items). *Andinoacara latifrons* (181 items) and *Caquetaia krausii* (49 items) presented the highest numbers of MPs in the wet and dry seasons, respectively. *Caquetaia krausii* presented the maximum number of MPs detected in the gastrointestinal tract during the dry season (20 MPs/individual). *Andinoacara latifrons*, *Caquetaia krausii*, and *Poecilia gilli* had similar %FO values for MP intake in both seasons (Table 3).

Table 3. Abundance MPs in six fish species from Tocagua Lake.

Species	*Ni*		NMPs			%FO		Average (±SD)	
	Wet	**Dry**	**Wet**	**Dry**	**Max.**	**Wet**	**Dry**	**Wet**	**Dry**
Andinoacara latifrons	50	10	181	38	7–12	92.6	83.3	3.4 (2.9)	3.2 (3.9)
Astyanax magdalenae	13	0	50	0	5–0	92.9	0.0	3.6 (1.8)	0.0 (0.0)
Caquetaia krausii	19	13	42	49	4–20	82.6	81.2	1.8 (1.5)	3.1 (4.9)
Mugil liza	10	4	39	6	7–2	76.9	57.1	3.0 (3.1)	0.9 (0.9)
Oreochromis niloticus	17	1	81	2	9–1	73.9	25.0	3.5 (3.5)	0.5 (1.0)
Poecilia gilli	49	5	151	9	6–3	87.5	83.3	2.7 (2.0)	1.5 (1.2)
Total	158	33	544	104					

Ni: number of individuals that presented MPs; NMPs: number of microplastics detected; Max: maximum number of particles detected from one individual per season, wet–dry; %FO: Frequency of occurrence; Average: Average number of MPs in the GT.

The fibers were MPs that predominated (604 items, 93%), followed by irregular fragments of various colors, such as black, blue, red, and transparent. Blue (n = 317) and black (n = 140) fibers and transparent fragments were predominant (Figure 4). The size of MPs did not exceed 2 mm in length, and 75% of the MP particles were smaller than 1 mm [49].

The proportion of blue MP in the fish species was similar in both seasons. Black MP presented a greater variation in proportion between seasons, decreasing in the dry season. The dry season has a higher prevalence of white and transparent fibers and fragments. *C. krausii* and *A. latifrons* were the only species that presented fragments, whereas *C. krausii* did not present fragments during the wet season, similar to *A. magdalenae*. The omnivorous-carnivorous group presented a similar abundance of MPs in both seasons (wet = 42 items, dry = 49 items), but with variation in the proportion of colors; blue MPs predominated in the wet season and white MPs in the dry season. Only the omnivorous group presented fragments (Figure 5).

A representative group of fibers and fragments was selected for μ-ATR-FTIR analysis of the MPs. Four polymers were obtained from the fibers: polyamide (53.8%), polyester (34.7%), polymethyl methacrylate (7.7%), and polytetrafluoroethylene (3.8%). Polymethyl methacrylate and polyester were predominant in the fragments.

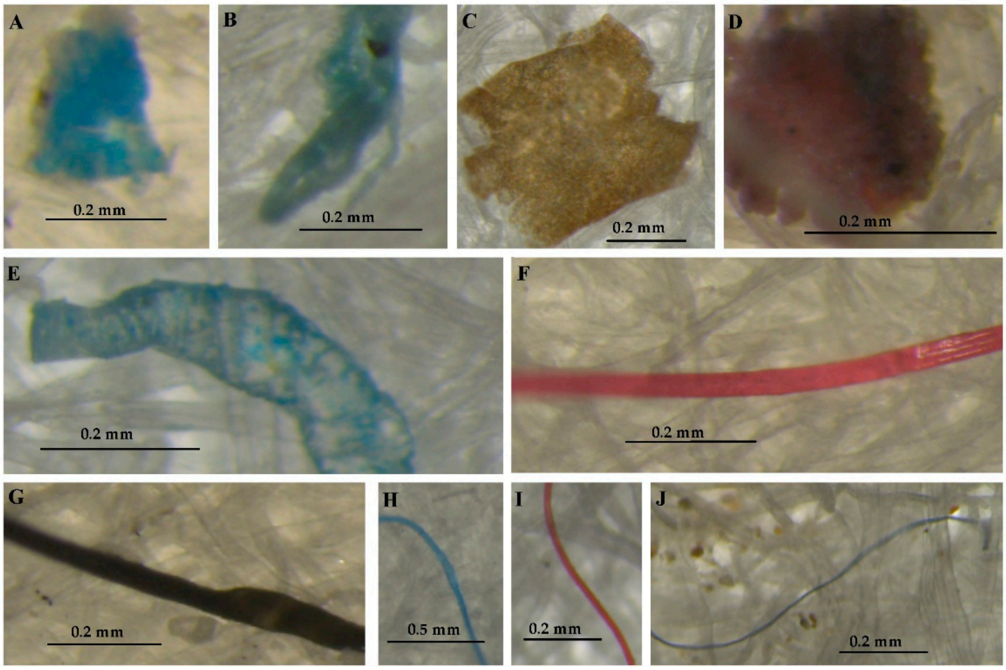

Figure 4. Photographs of some fragments (**A**–**E**) and fibers (**F**–**J**) detected in the gastrointestinal tract of individual fish of six fish species from Tocagua lake.

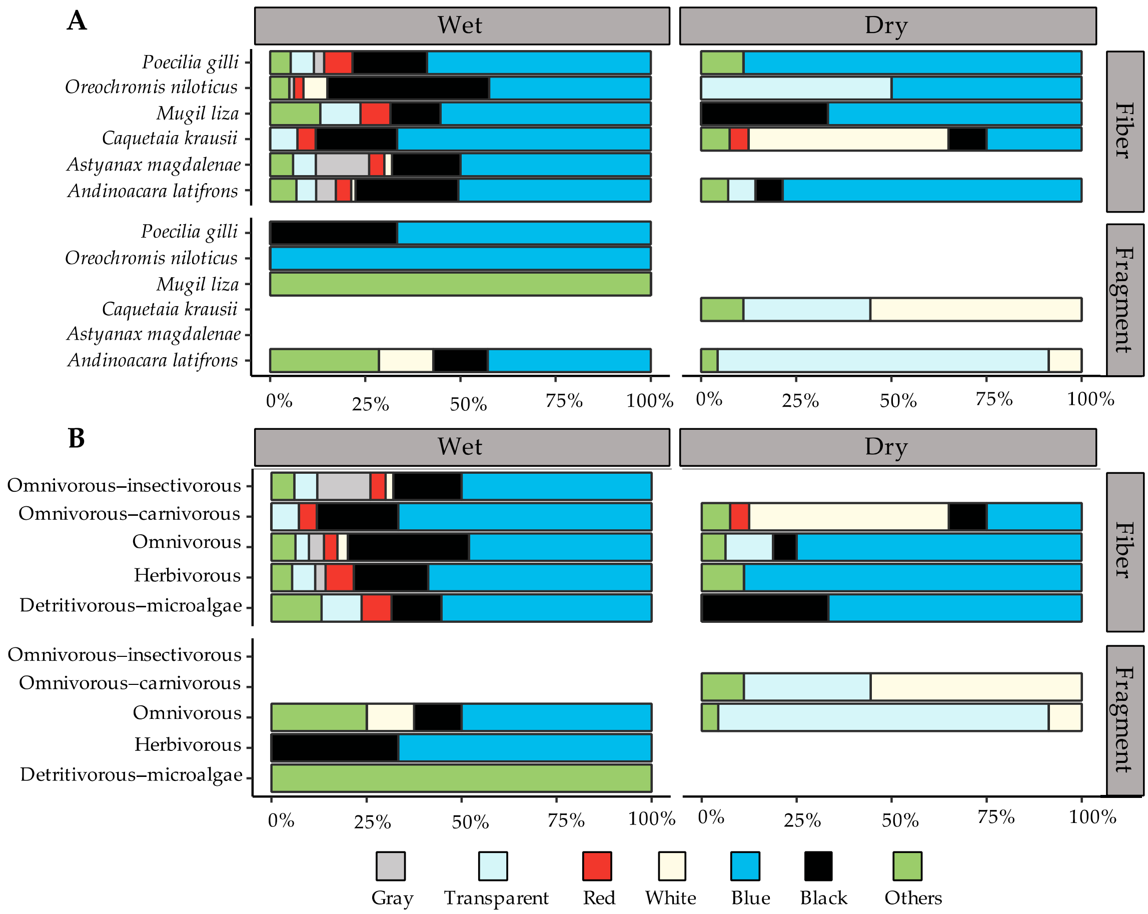

Figure 5. Proportion of MPs (color and shape characteristics) by (**A**) species and (**B**) diet type in fish samples between wet and dry seasons.

3.4. Seasonal Variation of MPs in Fish

The results of the negative binomial regression models of the number of MPs per individual for fish species did not show a relationship with species or diet between wet and dry seasons. The correlation analysis values were not significant ($p > 0.05$; Supplementary Materials, Table S1). In the analysis of the relationship between the abundance of MPs per fish and their morphometric variables, only the weight variable with a negative estimation ($p = -0.0226$) was significant, indicating that the concentration of MPs in the fish decreased logarithmically with increasing body weight. There was no linear relationship between the abundance of MPs and the total length ($p = 0.1613$) or the K factor of the fish ($p = 0.3757$). The PERMANOVA test between both seasons indicated that MP abundance (color characteristics) varied significantly among fish species ($p = 0.038$) and diet ($p = 0.019$), whereas shape characteristics did not significantly differ in the abundance of MP with fish species ($p = 0.178$) and diet ($p = 0.133$).

3.5. Transfer of MPs between Water and Dietary Trends of Fish

The abundance of MPs in water had a significant positive effect ($p = 0.00275$) on the abundance of MPs in fish in both seasons. Similarly, seasonal differences had a strong effect on the increase in the accumulation of MPs in fish. The wet season had the highest estimated coefficient for the second sampling period. This indicates that there is a greater availability of MPs in the environment, which in turn increases the number of MPs in fish.

The communities represented by the colors of MPs in water and fish showed low dissimilarity ($R = -0.052$, $p = 0.6255$) in the ANOSIM analysis. NMDS analysis showed that the colors of MPs clustered slightly distantly in both matrices (water and fish) at each sampling event, with a higher proportion of MPs colored in water. The analysis of multilevel patterns did not show any association between the colors of MPs and the matrices (water and fish). Therefore, the availability and abundance of colored MP particles detected in water and fish during different seasons were not variables that could independently explain the distribution of colored particles detected in fish.

The BCF index did not identify a trophic transfer pattern in the consumption of MPs or diet types. The highest value of the BCF index was observed in the herbivorous fish group (BCF = 0.00708), indicating a strong relationship between the consumption of fibers and fragments in water. In contrast, detritivoreous fish with a tendency to consume microalgae showed a lower BCF index value, which is a group with a lower tendency to consume MP particles in water. During the wet season, the omnivorous–insectivorous group presented a higher amount of fiber-type MPs than the other food groups (BCF = 0.00406). Following the previously observed trend, the MPs-type fragments had lower concentrations in both environmental matrices and showed the lowest BCF index values in the dry season (Table 4).

Table 4. BCF indices for MPs and its characteristics (fiber and fragment) in fish (types of diets) in wet and dry seasons.

Type of Diets	Total	Wet		Dry	
		Fibers	Fragments	Fibers	Fragments
Detritivorous–microalgae	0.00064	0.00015	0.00007	0.00042	0
Herbivorous	0.00708	0.00137	0.0035	0.00221	0
Omnivorous	0.00116	0.00026	0.00042	0.00007	0.00041
Omnivorous–carnivorous	0.00052	0.00013	0	0.00011	0.00028
Omnivorous–insectivorous	0.00406	0.00406	0	0	0

4. Discussion

This is the first descriptive study of microplastic contamination in water from Tocagua Lake and a pioneering study on microplastic contamination in fish from freshwater ecosystems in rural areas of Colombia. It is noteworthy that studies on rural lakes worldwide have low representativeness [69]. In Colombia, contributions to the knowledge of microplastic pollution have focused on marine coastal ecosystems, such as beaches [40–45] and coastal lagoons [39,70–72], and a few have focused on continental wetlands [49]. In this study, the temporal variation did not show differential values for the mean abundance of microplastics in water. Concentrations of 1.04 ± 0.22 MPs/L and 0.88 ± 0.53 MPs/L were found in the wet and dry seasons, respectively. These results differ from the recent study carried out in Luruaco Lake, a wetland with similar characteristics, which showed variation in the concentration of MPs between seasons, 1.9 MPs/L and 0.25 MPs/L in the wet and dry seasons, respectively [49]. The difference in the concentration of microplastics in the nearby bodies of water was due to the different retention times and streams in each lake. In the case of Luruaco Lake, all streams have a semi-permanent flow of water, mainly during the dry season, and the drainage of the streams is of the subparallel type with a fast flow speed [72]. In Tocagua Lake, the mainstream is Platanal, which contributes seasonally; therefore, the residence time in this water body may be longer, generating little seasonal variability. According to the results, microplastic contamination in water was higher in both seasons for stations S1 and S4, with mean concentrations of 1.31 MPs/L and 1.42 MPs/L, respectively (Figure 1, Table 2). S1 is close to the urban center (with a distance of less than 300 m) and is the mouth of the streams to the lake. Some of these streams are roads during the dry season, and once the wet season begins, waste is dragged into the wetland (verified in the field). S4 is on an island, an area of water retention and accumulation of microplastics, and is near the mouth of the Platanal stream, crossing areas of livestock and agriculture, which drag waste into wetlands in the wet season.

In fish, the abundance of microplastics in both seasons did not show significant differences between species or types of diet. An average of 2.8 ± 2.7 MPs/individual in the wet season and 2.3 ± 3.6 MPs/individual in the dry season were found. The sampling events coincided with the fishing season, which began during the wet season in the lake (August–September). Tourism and the incidence of plastic waste in this area have also increased. Most streams in the department of Atlántico cross urban settlements, accumulating large amounts of garbage that is washed away by high rainfall and increasing the concentration and availability of MPs in wetlands [42]. In general, the %FO of MPs detected in the gastrointestinal tract of fish from Tocagua Lake was high at 83.7% (191 individuals). The wet season registered a higher %FO value (86.3%), different from the value in the dry season (73.3%). The biotic, ecological, hydrodynamic, and morphological factors that characterize wetlands make comparisons difficult. However, by analyzing the sampling methodology, laboratory work, and data processing to determine the abundance of MPs in the environmental matrices of small rural lakes, it is possible to provide an overview based on these studies with scientific rigor (Supplementary Materials, Table S2) [73–78]. %FO of MPs are reported in fish from three lakes of economic and cultural importance in China, with values between 91% and 100%, results influenced by the high human population, wastewater, and runoff [75–77]. Scientific studies on small Swiss lakes have reported a low %FO of MPs (12–7.5%), indicating less pollution, possibly because of a less human-influenced and industrialized watershed with better waste disposal [78]. Under this scenario, Tocagua Lake had MP concentrations similar to those found in larger water bodies, indicating high contamination in this wetland.

Analysis of the abundance and color of MPs detected in fish showed significant differences between the seasons. The MPs found in the gastrointestinal tract of fish caught in both seasons were black and blue fibers, although in the wet season, the number of fragments increased to 31%, which was not significant. Our results are consistent with those reported for the rural lakes in China and Switzerland. Black- and blue-colored fiber MPs are particles that predominate in the gastrointestinal tract of fish from the Chinese [75–77] and Swiss lakes [78] (Supplementary Materials, Table S2). This type of MP originates from the fragmentation of blue plastics, with which nets, rope fishing, and textiles are manufactured. Black MP are related to tire wear, abrasives, and plastic bags [79,80].

Analysis of the length, weight, and condition factors *K* data did not show a significant relationship between the morphometric variables of fish and the MPs detected, which was also reported in a recent study [66,67,81], suggesting that other factors influence the ingestion of MPs. In the stomachs of fish with greater weights, such as *M. Liza* (w > 80 g), a low abundance of plastic particles was detected, contrary to the species *C. krausii*, in which one individual (w = 40 g) presented 20 MPs, and generalized behavior in fish with lower gastrointestinal tract weight and higher retention of MPs. Among the factors that influence the retention of food in the gastrointestinal tract are the size of the fish, organ morphology, water temperature, and diet. Studies that evaluate the retention time of MPs do not explain the variations presented by individuals of the same species or expose the possible influence of gastrointestinal tract morphology on the retention of MPs without reporting specific data on the relationship between organ morphology per individual and the number of MPs detected. Similar to our results, these reports detailed the amount, type, and color of MP particles found in ichthyofauna [66,67,75–77,81]. According to our results, the low variation in the concentration and type of MPs between seasons maintained the availability of these contaminants in the water, thereby increasing the probability of their consumption by fish. Regardless of the season, evaluation of the diet and species of fish caught showed significant differences in the consumption of MPs. Omnivores fed a non-selective diet had a higher number of MP particles (fibers and fragments) per individual. Herbivores are the second group with the highest consumption of MPs fibers in both seasons, represented by the species *P. gilli*, whose diet specializes in the consumption of filamentous algae and microalgae [82], which are confused with black and blue MPs fibers. The omnivorous group, with a tendency toward a carnivorous diet, presented a low amount of MP particles, probably because they had more developed sensory systems.

Monitoring MP contamination in fish from rural and urban lakes is becoming more frequent because they represent the highest trophic level and are the most consumed organisms in the biota. The effects of MPs ingestion in fish include neurotoxicity, intestinal obstruction, reduced appetite, inflammatory responses, and translocation to organs and tissues [83]. These effects can be transferred to the population through consumption [84], generating health risks because these fish constitute the principal food source [33–35,39,71,75–77].

BCF values greater than 1 indicate the accumulation of contaminants in the biota. In the present study, the calculated values were less than 1; however, there was an increase in trophic groups, with herbivores and omnivorous fish having higher BCF indices, indicating that *P. gilli* and *A. latifrons* had the highest probabilities of ecological risk. The BCF of MPs values can be explained by the retention time in fish. A study on the selectivity and retention time of MPs in two species of fish determined that these contaminants were excreted with an efficiency greater than 90% between 24 and 48 h after consumption, a situation that can be associated with our results [66,67,81].

The concentration, abundance, type, and color of MPs in water and fish were not significantly different between the seasons. The availability of MP particles in water provides this contaminant to fish. Even in both environmental matrices, MPs of the same color, shape, and type predominated, indicating some connection between MP pollution found in surface waters and in fish. In this study, color did not seem to influence the consumption of MPs by the fish. Neither the predominant colors of the MPs in either environmental matrix provide information about the origin of the fibers and fragments, indicating, as in similar studies, that the relationship with potential sources is intuitive [56–60,75–78]. However, through quantitative analysis methods such as thermogravimetric analysis-differential scanning calorimetry (TGA-DSC), pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS), and thermal extraction desorption-gas chromatography-mass spectrometry (TED-GC–MS), the color can be associated with different types of additives for degradation studies and provide information on historical changes in microplastic sources [12,14,56–59]. Future studies on the degradation of MP particles will lead to a better understanding of the dynamics of this pollutant in Tocagua Lake.

Six types of polymers were identified with respect to the composition of the plastic particles (fibers and fragments). Polyamide, polyester, polypropylene, and polyurethane are the predominant polymers used to make bottles, utensils, packaging, meshes, and nets in the fishing and food industries. Polyvinyl chloride and polymethyl methacrylate, which are dense polymers used to manufacture construction materials, electrical appliances, and electronic devices, have also been identified.

The physicochemical characterization of this water body indicated that it is subjected to environmental stress [85]. High and fluctuating temperatures, together with high conductivity, suggest a significant load of chemical substances from the deposition of domestic wastewater and runoff from agriculture and livestock. The low alkalinity registered indicates a potential process of acidification of the lake, and the reduced value of the dissolved oxygen potential affects the respiration of aquatic biota [86]. By collecting data on the presence and concentration of MPs in different areas of the lake over time, patterns and trends can be identified, and a more complete understanding of the environmental impacts caused by MPs can be obtained. This can help establish clear connections between microplastic pollution and potential negative effects on aquatic ecosystems.

5. Conclusions

This study is the first to document the identification of MPs in Tocagua Lake, a reflection of contamination with plastic waste from the environment and inadequate disposal. MPs were found in both investigated matrices (water and fish), and seven types of polymers were identified. Thirteen colors and two predominant shapes were identified, confirming their ubiquity and distribution. Although no significant differences were detected in the number of MPs in the gastrointestinal tract of the fish during the different climatic seasons, variations were found in the types of MPs throughout the year. In particular, the black and blue fibers, with lengths less than 2 mm, are easily confused with prey by herbivorous and omnivorous species, which suggests a selection by the fish regarding the availability of different types of MP in abiotic environments. The gastrointestinal tract of fish is a key organ for detecting the presence of MPs in water bodies and provides relevant information for future studies evaluating MP contamination in aquatic ecosystems. Our results are similar to those reported for lakes with low variation in MPs concentrations between seasons, maintaining the availability of these particles for different types of organisms and different functional feeding guilds. It is necessary to investigate other biotic, ecological, hydrodynamic, and morphological factors that characterize this freshwater ecosystem and alter the dynamics of microplastics to establish remediation strategies based on the evaluation of biological risks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d15070821/s1, Figure S1. Proportion of the distribution of the shapes of microplastics identified in the water from Tocagua Lake during the wet and dry seasons; Figure S2. Typological characteristics of MPs found in the water of Tocagua Lake during the wet season. (A) Color and (B) shape; Figure S3. Typological characteristics of MPs found in the water of Tocagua Lake during the dry season. (A) Color and (B) shape; Table S1: Results of the negative binomial regression models to determine the association between the abundance of microplastics per individual according to species and diet per season. No significant differences were observed; see Table S2. General description of studies on microplastic ingestion by fish from freshwater lake ecosystems. %FO: is the percentage of fish with at least one microplastic particle in the gastrointestinal tract. References [33,73–78] are cited in the Supplementary Materials.

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