Plastic waste pollution in freshwater systems: key challenges and perspectives for future research

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Abstract
The increase in world plastic production in recent years, mainly single-use plastics, combined with poor waste management, is producing an emerging environmental problem due to plastic pollution in aqueous systems. Plastic waste can be classified, according to their size, in microplastics, mesoplastics and macroplastics. In recent years, fewer studies have been reported on mesoplásticos and macroplastics compared to microplastics. Plastic debris can cause great harm to wildlife; the most common are ingestion, entanglement and plastic usage. The adsorption capacity and subsequent release of toxic contaminants increases the risk of toxic effects on organisms when they are ingested. The presence of microplastics in humans has also been reported, with consequent health problems. This work presents experimental studies that has been carried out in the Composite Materials and Polymeric Mixtures research group of IFIMAT-Universidad Nacional del Centro de la Provincia de Buenos Aires, Argentina about the presence of plastic waste of different sizes in freshwater systems. Plastic pollution was studied in the Langueyú stream basin and the Del Fuerte lake, both located in the city of Tandil. The Langueyú stream receives discharge from the effluents of two wastewater treatment plants, which contributes with a high level of microplastic contamination in the stream water, while the banks receive and accumulate larger plastic waste due to poor waste disposal by the population. The Del Fuerte lake is a touristic attraction of the city of Tandil and receives high quantity of visitors, which produces plastic pollution that, when fragmented and degraded, ends up contaminating the lake with microplastics. Depending on the type of sample analyzed and the sample pretreatment procedure, it is possible to study plastic residues of different sizes present in water, soil and sediment samples. The joint analysis of plastic waste present in different types of samples allows for a comprehensive analysis of this problem.

Keywords: Plastic pollution, freshwater systems, microplastics, mesoplastics, macroplastics.

1.- Introduction

World plastics production has been experiencing continuous growth in recent years, reaching a production of 400.3 million tons in 2022 (Plastics Europe, 2023). Of this amount, 90.6% is fossil-based, and the largest percentages of production correspond to polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC). Of the total plastic production, the Central and South American region produces 4% of the total. The largest world plastic market is packaging (Plastics Europe, 2022). This increase in the production of plastics, mainly single-use plastics, combined with the inadequate disposal of post-consumer plastic waste, has generated an emerging environmental problem due to the ubiquitous presence of plastic waste in different environments around the world. Nearly a quarter of the world's plastic waste is improperly managed, meaning it is not stored in secure landfills, recycled or incinerated (Ritchie, 2023). Approximately 19 million tons of waste ends up in the environment: around 13 million tons pollute terrestrial environments, while the remaining 6 million tons pollute rivers or coasts.

According to their size, plastic waste can be classified as (Lippiat et al., 2013):

- Microplastics: with sizes between 1 µm and 5 mm.
- Mesoplastics: with sizes between 5 mm and 2.5 cm.
- Macroplastics: with sizes greater than 2.5 cm.

The number of publications on plastic waste in different environments has increased rapidly in recent years, especially after 2017. Between 2017 and 2024, there has been an increase of almost 1000% in the number of publications reported on ScienceDirect (www.sciencedirect.com) about plastic waste (Figure 1a). Data were counted in articles published during 2014 to 2024, and reported by September 2024, in the environmental science field and with the terms: microplastics, mesoplastics and macroplastics. Figure 1(b) shows the number of articles published each year relating to different types of plastic waste, according to their size. An accelerated increase in publications on the subject of microplastics is observed, while those on the subjects of mesoplastics and macroplastics show a slight increase. Considering the year 2024, 5405 articles were published on the subject of microplastics, while only 161 were published on mesoplastics and 406 on macroplastics. For each type of plastic waste and in the period between 2014 and 2024, around 80% of the articles corresponded to Research articles, while 20% corresponded to Review articles. There is growing interest in the presence of microplastics in aquatic systems, however, studies on mesoplastics and macroplastics are scarce (Gallitelli and Scalici, 2022). It is interesting to note that in recent years, fewer studies have been reported on mesoplastics compared to macroplastics. This behavior has also been found in studies that reflect the impact and incidence of each type of plastic waste on marine ecosystems, which are the most abundant (Campoy and Beiras, 2019). Campoy and Beiras attributed this behavior both to the fact that mesoplastics are susceptible to being degraded and converted into microplastics, and to the fact that until 2011, only microplastics and macroplastics were distinguished, and from that year onwards the term mesoplastic was introduced (Campoy and Beiras, 2019).

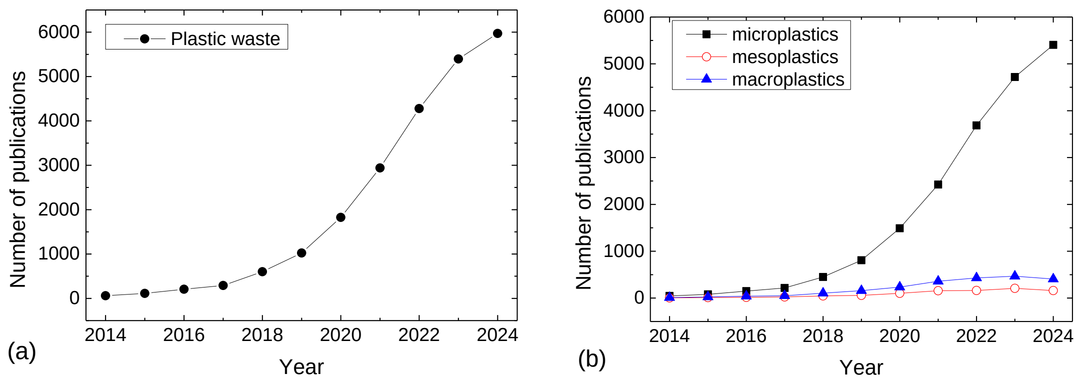

Figure 1. (a) Number of publications about plastic waste from 2014 to 2024. (b) Number of publications about microplastics, mesoplastics and macroplastics. Data were counted in articles reported by ScienceDirect (www.ScienceDirect.com).

2.- Effects of plastic waste on wildlife and humans

It has been reported that plastic debris can cause great harm to wildlife. The most common problems of plastic debris are ingestion, entanglement and plastic usage (plastic as nesting material, vector for biota transport and refuge) (Blettler et al., 2021; Campoy and Beiras, 2019; Lippiatt et al., 2013; NOAA, 2014; Rodrigue, 2017) (Figure 2). Rodrigue studied the effect of macroplastics on marine vertebrates and found that they causes mortality of marine vertebrates and affects entire ecosystems (Rodrigue, 2017). NOAA reported that at least 115 species of marine mammals, sea turtles, sea birds, fish, and invertebrates in United States are affected by entanglement with macroplastics (NOAA, 2014). Higher entanglement rates occur in areas with high population densities, human fishing zones and areas of high debris accumulation. The dispersal of plastic debris by the fishing industry is the cause for most cases of entanglement of marine vertebrates (Rodrigue, 2017). Seals are more commonly entangled around the head and appendages in net fragments, monofilament lines, packing straps, rope, and rubber products (NOAA, 2014). Whales and dolphins are affected by marine debris entanglement when line and net fragment are attached through the mouth or around the tail and flippers. Sea birds are also affected by entanglements, most commonly related to fishing gear such as monofilament lines and hooks. The behavior of sea turtles makes them particularly vulnerable to entanglement, due to young sea turtles tend to seek shelter under floating objects to avoid predation. Other marine species becoming entangled in marine debris, including fish, invertebrates, and corals. Crustaceans may be victims of "ghost fishing", where nets continue to "fish" if lost at sea. Nets or lines can also cause destruction of corals when wave action pulls the debris that snag on the colony back and forth (NOAA, 2014). The presence of macroplastic waste has also been found to cause asphyxiation, shading, tissue abrasion and coral mortality (Richards and Beger, 2011). Another ecological effect caused by macroplastics is their function as a vector for transporting exotic or invasive species (Campoy and Beiras, 2019).

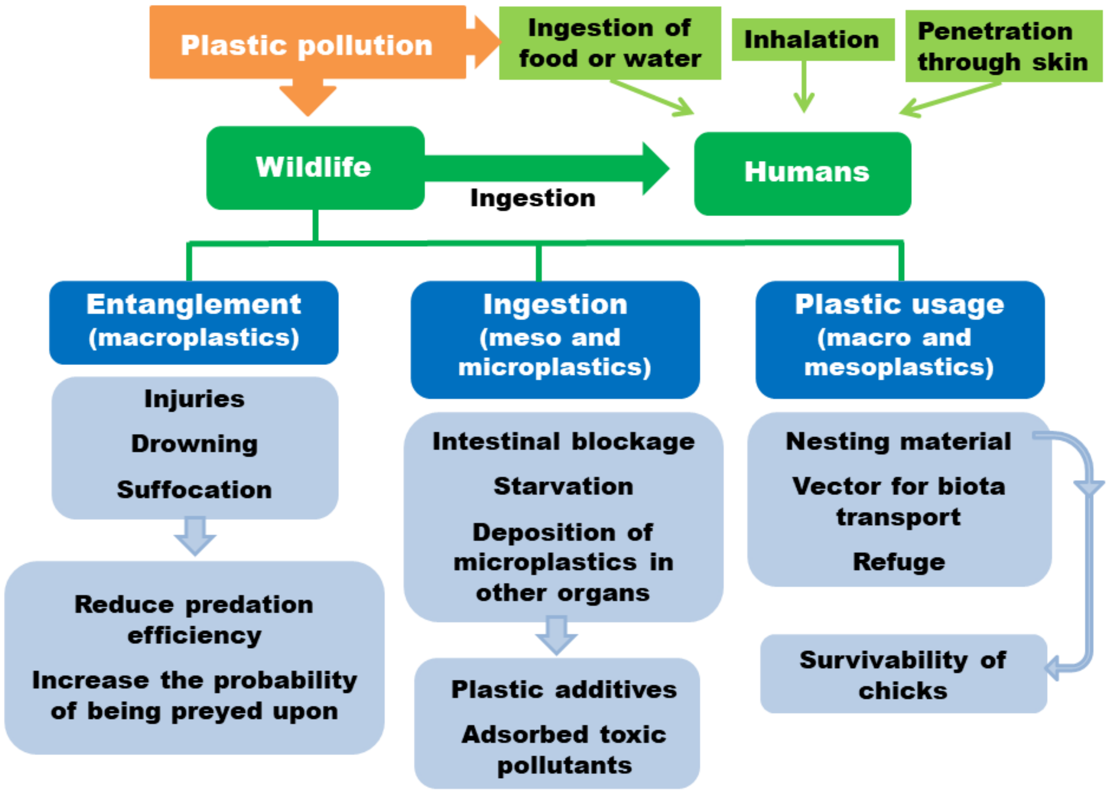

Figure 2. Flowchart of the effects of plastic pollution on wildlife and humans.

The ingestion of plastic waste is also a major problem for wildlife, especially respect to mesoplastics and microplastics (Campoy and Beiras, 2019). There is abundant research supporting the occurrence of plastic debris in the digestive tracts of marine vertebrates (Rodrigue, 2017; Sultana et al., 2024). Sultana et al. reported the presence of mesoplastics in the digestive tract of fish in the Bay of Bengal Coast in Bangladesh (Sultana et al., 2024). Another study in the Duck River, south of the San Juan province in Argentina, showed that out of 26 fish studied, 10 showed the presence of plastic fragments in the form of filaments, wound between the food in the stomach and intestine (Gómez et al., 2019). Plastics can cause starvation or intestinal blockages upon ingestion. Microplastics can also be deposited in the mucus layer secreted by the cells of the gut wall and be transported to other organs or tissues via circulation (Wang et al., 2021). The ingestion of small plastic waste by different species, in addition to the damage it can cause to their organisms, causes them to enter the food chain.

On the other hand, birds are also impacted by plastic debris via ingestion and entanglement, and they can also incorporate plastic debris into nests (Rodrigue, 2017). One of the possible causes of accidental consumption of plastics by sea birds is that they confuse small pieces of plastic with food, especially in zooplantivorous species (Campoy and Beiras, 2019). Entanglement can lead to injuries, drowning and suffocation, which can also reduce predation efficiency and increase the probability of being preyed upon (Wang et al., 2021). The presence of plastic material in bird nests can affect the survivability of chicks because they may consume or entangle themselves in the debris.

Although most studies have focused on the effect of plastic waste on marine species, there are some studies about its effect on other ecosystems (Blettler et al., 2021). Blettler et al. studied the effect of the macroplastics on freshwater and terrestrial wildlife, and documented and analyzed 90 different encounters cases (Blettler et al., 2021). Of these, 72.2% of the cases were birds, and the dominant type of plastic-fauna encounter was the use of plastic as nesting material, and in second place was entanglement. Most of entanglements had lethal consequences for the organism, being particularly dangerous and frequent entanglement in ghost fishing gear and bottle rings.

Another problem associated with the ingestion of plastic debris is the effects of plastics-derived additives and plastics-adsorbed toxic pollutants, such as organics and heavy metals on wildlife organisms (Kaur et al., 2022; Sridharan et al., 2022). The accumulation of plastic additives has been reported in several seabirds, and can cause malnutrition, endocrine disruption, and issues in the reproductive biology of several species (Wang et al., 2021). It was reported that puffin chicks who consumed plastic debris had altered body sizes which were likely result of the additives associated with plastic debris (Rodrigue, 2017). The adsorption capacity and subsequent release of toxic contaminants increases the risk of toxic effects on organisms when they are ingested (Kaur et al., 2022; Sridharan et al., 2022). At the same time, MPs can act as transport vectors for other contaminants.

Recent studies have reported the presence of MPs in humans, especially in blood, placenta, feces, respiratory tract and lungs, with its consequent health problems (Emenike et al., 2023; Zhao et al., 2024). A study in the United State reported that average American children and adults consume around one hundred thousand of microplastics and nanoplastics every year (Sridharan et al., 2022). The primary route of microplastics exposure to the human body is through the food chain and seafood consumption, but they have been also found in edible products, like salt, honey and sugar (Zhao et al., 2024). Microplastics can be also ingested through drinking water, especially bottled and tap water. Studies have estimated that humans have weekly ingestion of 0.1 to 5 g of microplastics through various sources (Zhao et al., 2024). Microplastics can also be inhaled by humans, due to their ubiquitous occurrence in the atmosphere. They have been found in lung tissue samples from non-smoking adults and in bronchoalveolar lavage fluid. The less significant route of exposure is the penetration through human skin. After absorption, microplastics can entered to the circulatory system and further systematically distribute to different organs or tissues. For example, translocation of inhaled microplastics to placenta and fetal tissues has been confirmed (Zhao et al., 2024).

3.- Plastic pollution in different freshwater systems

As part of the experimental studies that are being carried out in the Composite Materials and Polymeric Mixtures research group of IFIMAT-Universidad Nacional del Centro de la Provincia de Buenos Aires, Argentina, the presence of plastic waste of different sizes has been analyzed in freshwater systems in the city of Tandil. The city of Tandil is located in the southeast of the province of Buenos Aires (Figure 3). This is a medium-sized city, with around 150 thousand inhabitants according to the 2022 census (INDEC, 2023). Tandil is a city that has shown high population growth in recent years, and is also a city that is considered an important tourist destination during every season of the year. To show the different methodologies used to study water and soil samples containing plastic waste of different sizes, studies that are being carried out in different systems will be shown below. Plastic pollution was studied in two freshwater systems located in the city of Tandil, the Langueyú stream basin and the Del Fuerte lake (Figure 4).

Figure 3. City of Tandil, province of Buenos Aires, Argentina.

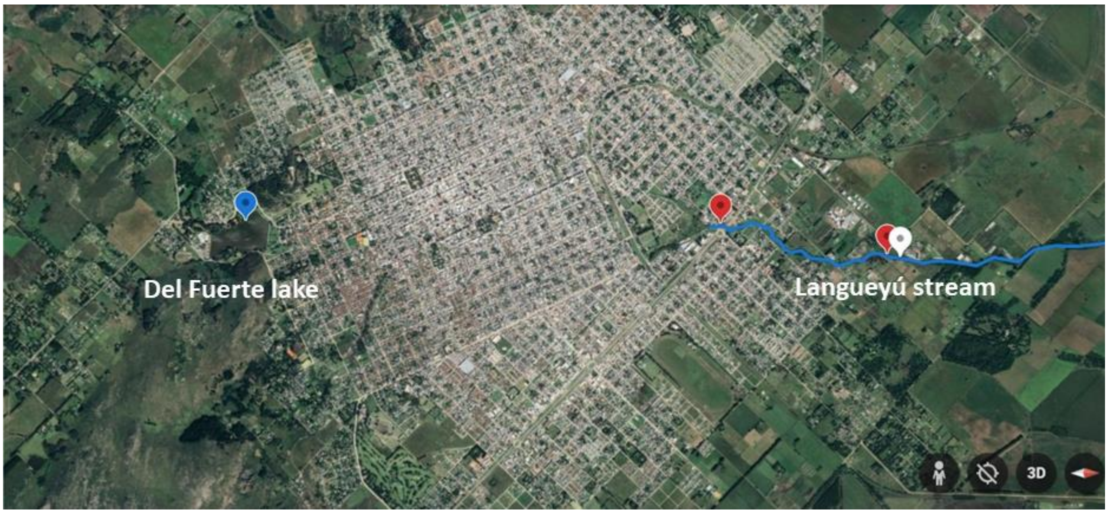

Figure 4. Langueyú stream and Del Fuerte lake located in the city of Tandil.

3.1.- Study of the Langueyú stream basin

The Langueyú stream originates from the confluence of the Blanco and Del Fuerte streams, heading northeast to the depression of the Salado river. This stream receives the effluent discharge from the wastewater treatment plants (WWTP) of the city of Tandil, which are discharged into the stream at the points indicated in red in Figure 4.

In previous studies by the group, the spatial distribution of microplastics present in water samples from the stream was studied at different sampling points located along the Langueyú stream (Montecinos et al., 2021; Montecinos et al., 2022). A decrease in water quality was found due to the discharge of effluents from the WWTPs. The maximum concentration of microplastics was around 72000 of microplastics per liter at a point located after discharge of both WWTPs, in the area called “El Molino”, which is indicate with a white point in Figure 4. In this point, 97% of the total microplastics came from the effluent from the WWTPs, while the rest came from storm drains and discharge of tributaries. In a subsequent study, the temporal variation of microplastics present in the water samples at the most contaminated point was analyzed (Montecinos et al., 2024). Higher concentration of microplastics were found in winter, which corresponds to the dry season, with approximately six times the concentration found in summer and autumn, which corresponds to the wet season. This difference would be associated with a seasonal variation of the type of clothing used and washed in cold season. Microfibres come from the fragmentation of textile fibers, which are released during household laundry. The microfibres are transported from homes to the WWTPs through the sewers, and are subsequently released into the stream with the discharged effluent.

To understand plastic pollution in a more comprehensive way, the presence of plastic waste present in the soil on the banks of the stream was studied in the area most contaminated by microplastics in the water, according to previous work, that is, in the "El Molino" area (Figure 5(a)). The sampling methodology was based on those used in previous studies in rivers, but adapted to the characteristics of the sampling area (Lippiatt et al., 2013). Surface plastics were extracted from areas measuring 1 m × 1 m, two of which were bordered by the stream and the other two were adjacent to it. Excess of vegetation was first carefully removed and then the surface plastics found were manually extracted. A soil sample from a 0.5 × 0.5 m sub-area was also analyzed. The sample was removed with a metal spatula to a depth of 3 cm, vegetation remains were removed, the sample was dried at 70°C, and the dried material was passed through a 1 mm mesh steel sieve and plastic residues were extracted manually. The plastics extracted from the surface and from the soil sample were washed, dried and characterized according to their color and category, based on their visual characteristics. They were weighed, the density was estimated by the floatation method, and the softening temperature was measured.

Based on the studies carried out, a total of 58 plastic wastes were found on the surface, equivalent to 14.5 items/m^2. Four of them were mesoplastics and the rest were macroplastics. If we were to place all the surface plastics found side by side, 19.4% of the area would be occupied by plastic waste. In relation to the classification, bags were the most abundant, also being those that occupied the largest area. On the other hand, 362 plastics were found in the soil sample, 340 of them corresponding to mesoplastics and the rest to macroplastics. The presence of plastic debris in the soil sample was equivalent to 48.6 items per kg of dry soil. Considering the observed colors of the plastics found on the surface and the macroplastics found in the soil sample, 68% of these were white or transparent, and most had areas smaller than 100 cm^2.

Figure 5. Langueyú stream (a) and Del Fuerte lake (b).

3.2.- Study of the Del Fuerte lake

Studies were carried out to analyze the presence of microplastics in water samples taken from Del Fuerte lake (Figure 5(b)). The lake is a tourist attraction in Tandil, both for the city's inhabitants and for visitors from other parts of Argentina, especially during the weekends. Various recreational activities are carried out there, such as fishing, water sports, hiking, and picnics, among others.

Water samples were extracted from different points in the lake using previously washed glass bottles. To determine the presence of microplastics, the samples were filtered using a 45 µm mesh metal filter, subjected to a digestion process for 2 h at 70°C, washed and filtered. Using a micropipette, sub-samples of 100 µl were taken and placed on glass slides. At least 3 sub-samples from each location were analyzed using optical microscopy. From the micrographs obtained, the quantity of microplastics found, their type (microfibers and microparticles) and their dimensions were studied.

The aforementioned study is ongoing, however, it can be mentioned that abundances of between 500 and 1000 microplastics/liter of lake water were found at different points. From the studies that are being carried out in the different systems in the city of Tandil, Table 1 shows the results obtained. The results shown for the Langueyú stream correspond to samplings carried out in the "El Molino" area. Other results reported by the group in previous works are also included (Montecinos et al., 2022; Ponce et al., 2022). Depending on the type of sample analyzed and the sample pretreatment procedure, it is possible to study plastic residues of different sizes present in water, soil and sediment samples. The abundance results obtained are reported in units of items/l for water samples, items/m^2 for plastics found on the soil surface, and in units of items/kg of dry soil or dry sediment for soil and sediment samples.

Table 1. Abundance of plastic debris obtained in different systems.

Place/system	Type of sample	Plastic debris	Abundance
Langueyú stream	water	microplastics	72000 items/l *
Langueyú stream	sediment	microplastics	14.3 million items/m^2 **
Langueyú stream	soil surface	mesoplastics macroplastics	13.5 items/m^2 1 item/m^2
Langueyú stream	soil	mesoplastics macroplastics	45.6 items/kg soil 2.9 items/kg soil
Del Fuerte lake	water	microplastics	500 – 1000 items/l

* value reported in (Montecinos et al., 2022)
** value reported in (Ponce et al., 2022)

4.- Key challenges and perspectives for future research

The abundances found and shown in Table 1 show the degree of contamination of the two aqueous systems studied located in the city of Tandil, which suggests the need to take preventive and remedial measures. An adequate characterization of the plastic debris present allows us to understand the main sources of contamination, which is the first step to understanding the problem of plastic contamination. For example, the main source of microplastic contamination in the Langueyú stream is the discharge of microfibers from household laundry that are discharged into the stream by the effluents of the WWTPs. On the other hand, the main source of microplastic contamination in the Del Fuerte lake would be the plastic waste discarded by visitors who come to this tourist site. Large plastic waste fragments and disintegrates due to the action of sunlight and the mechanical work to which they are exposed.

Being able to relate the results found in water, sediment and soil samples from the banks of the Langueyú stream allows us to better understand the relationships between the different plastic waste present and their interaction when the river floods, both the plastics that are deposited from the stream to the banks, as well as those that are deposited on the banks and then transferred to the stream. In the system studied, it was found that the mesoplastics and macroplastics found on the banks of the stream would come mostly from waste deposited by people due to poor waste management, which corresponds mainly to remains of plastic bags. The excess vegetation on the banks helps to retain these residues, which over time are degraded and fragmented. In the results obtained, a greater quantity of macroplastics was found on the surface of the soil and a greater quantity of mesoplastics in the soil sample, which would confirm this behavior. The macroplastics present on the surface would fragment into mesoplastics and would be buried in the soil, accumulating. Relationships between the residues present in the water and sediment samples, as well as comparisons between different points in the stream that do not contain external sources, allow us to understand the transport processes of the microplastics present, such as deposition and resuspension.
For the reliability of the microplastic abundance data obtained, it is necessary to take measures to prevent external contamination during the pre-treatment and analysis process of the samples. For the treatment of the studied samples, a clean chamber was used during the treatment and storage of the samples. In addition, glass or metal material was used whenever possible, cotton clothing and the use of latex gloves. To quantify possible microplastic contamination, blanks were made using distilled water samples, which were subjected to the same treatment as the samples taken from the stream, including filtering, digestion and quantification of the microplastics present. The recovery rate associated with the sample treatment methodology used was also determined, for which plastic samples with known weight and similar sizes to those studied were quantified, and the weight of the sample was measured after being subjected to the same methodology as the water samples from the stream.
There is much future work to be done in order to understand in depth the problem of plastic waste pollution in different systems. The first stage is to carry out adequate and comprehensive diagnoses of this problem, find the possible sources of this pollution and propose prevention and remediation measures. An important aspect is to ensure that the information generated by the scientific community reaches the political actors who make decisions and to be able to raise awareness of this problem on the part of the general population. We can all contribute to this in order to limit the further expansion of this problem and the effects that it has on ecosystems.

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