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MICROPLASTICS IN FRESHWATER: A REVIEW OF CHARACTERIZATION, SOURCES, AND IMPACTS

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ABSTRACT

Works regarding the presence of microplastics (MPs) in freshwater environments have been gaining ground since 2015. Addressing this theme, this review aimed to elaborate an overview of the pollution of freshwater environments by MPs (characterization, sources, and impacts). The Web of Science database was used (keywords microplastic and freshwater) from 2015 to 2023. The results obtained show that MPs are less than five millimeters in length, are expressed in items/L, their most common constituents are polypropylene and polyethylene, and fibers are the most common format. The main sources are the discharge of domestic effluents and industrial activities. Knowledge about the impact on human health is limited. There are toxic effects on the biota and MPs are carriers of other pollutants. It is still necessary that research advances to fill observed gaps, so that a more complete panorama for future studies and actions for the conservation of these environments can be achieved.

KEYWORDS: pollution, microplastics, environmental impacts, bodies of water.

MICROPLÁSTICOS EM ÁGUA DOCE: CARACTERIZAÇÃO, FONTES E IMPACTOS

RESUMO

Trabalhos sobre a presença de microplásticos (MPs) em ambientes de água doce vêm ganhando espaço desde 2015. Com isso, esta revisão teve como objetivo elaborar um panorama sobre a poluição de ambientes de água doce por MPs. Foi utilizada a base de dados Web of Science (palavras-chave microplástico e água doce) de 2015 a 2023. Os resultados obtidos mostram que os MPs têm menos de cinco milímetros, são expressos em itens/L, seus constituintes mais comuns são polipropileno e polietileno, e fibras são o formato mais comum. As principais fontes referem-se ao lançamento de efluentes domésticos e às atividades industriais. O conhecimento sobre o impacto na saúde humana é limitado. Há efeitos tóxicos na biota e os MPs transportam outros poluentes. Ainda é necessário que as pesquisas avancem para preencher lacunas observadas, para que se tenha um panorama mais completo para futuros estudos e ações para a conservação desses ambientes.

Palavras chave: poluição, microplásticos, impactos ambientais, corpos hídricos.

1 INTRODUCTION

The use of plastic as a raw material has great advantages. Its wide use in industry is justified by its characteristics, such as low production cost and high malleability (SZYMAŃSKA and OBOLEWSKI, 2020). However, the production of plastic products has reached unsustainable levels, reaching, in 2016, millions of tons (PICO; ALFARHAN and BARCELO, 2019; SAIT et al., 2021). In addition to production, this material mostly has minimal use, making it disposable, a factor that increases both production and disposal (LI; BUSQUETS and CAMPOS, 2020; SZYMAŃSKA and OBOLEWSKI, 2020). Adding to this problem is the inadequate management of solid waste (LI; LIU and CHEN, 2018) and the highly urban and population concentrations (RODRIGUES et al., 2018; WARDLAW and PROSSER, 2020; WONG et al., 2020; ZHANG et al., 2021; MARTINEZ-TAVERA et al., 2021) that contribute to increasing the input of plastics into natural environments.

Thus, with the increase in the presence of plastics in environments, concerns about the possible effects of this pollutant were raised. In 1972, the first research was published which showed the contamination of coastal areas by the use of plastic packaging (SCOTT, 1972). In 1973, a work was published on plastic pollution in the Atlantic Ocean (0.2 to 0.5 cm) and its relationship with the material present in the stomach of seabirds (ROTHSTEIN, 1973). From 1982 to 1987, more work was published on the ingestion of plastics by birds (CONNORS e SMITH, 1982; AZZARELO e VLEET, 1987). For some decades, the theme plastic pollution was studied in an incipient way. From the 2010s, the scientific community increased the number of studies about plastic pollution.

Discussions advance due to the presence of small particles, microplastics (MPs), from the degradation of plastic products. The growing production and use of plastics are threats to the balance of the ecosystem, especially with the production of MPs (SARIJAN et al., 2020). The daily production of plastic in coastal countries is estimated at 275 million metric tons, considering economic and population indicators of the countries in 2010. Thus, millions of items can be released into the environment every day (JAMBECK et al., 2015; PICO; ALFARHAN and BARCELO, 2019). Owing to this, it is essential to understand the formation, agglomeration, and degradation of MPs (WONG et al., 2020). The first research on MPs in water was published in 2006, but in a marine environment. The work included in its methodology the collection of sediment and water samples (NG and OBBARD, 2006). Subsequently, in 2011, one of the first reviews on MPs in marine environments was published, focusing on the generation of these particles and their potential impacts on those ecosystems (ANDRADY, 2011).

The first published research on the presence of MPs in freshwater was in 2011, when the term MP was not yet in use. This survey was carried out on the Los Angeles River, considering MPs from 1 to 4.75 millimeters (MOORE; LATTIN and ZELLERS, 2011). The estuary, characterized as a transitional environment between fresh and salt water, had the first work on MPs published in 2014 (ZHAO et al., 2014). Soon after, a review of MPs in freshwater was conducted in 2015, addressing possible similarities in the behavior of MPs in marine environments, such as their transport by surface currents (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015). From 2015 onwards, studies on MPs in freshwater are frequent (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; SARIJAN et al., 2020).

MPs are characterized by having dimensions smaller than five millimeters, with formats such as fragments, spheres, filaments, among others (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; LI; LIU and CHEN, 2018; MENDOZA and BALCER, 2019; MENG; KELLY and WRIGHT, 2020). Their classification, done according to their composition, can be principally given by the presence of polymers of polyethylene, polypropylene, polystyrene, polyethylene terephthalate (LI; BUSQUETS and CAMPOS, 2020) and polyvinyl chloride (MILOLOŽA et al., 2021), of which polypropylene and polyethylene are the most common ones (RODRIGUES et al., 2018; WANG et al., 2019; CERA; CESARINI and SCALICI, 2020; ERDOGAN, 2020; LI; BUSQUETS and CAMPOS, 2020; BERTOLDI et al., 2021; ZHANG et al., 2021).

Regarding their properties, density stands out, which strongly influences their distribution in the water column (AVIO, GORBI and REGOLI, 2017). With increasing density, there is a tendency for MPs to move into sediments (EHLERS; MANZ and KOOP, 2019), such as polyethylene terephthalate (GARCIA et al., 2021). The concentration of MPs in sediments can be higher than in water due to the increase in density often because of microorganisms colonizing MPs, forming biofilms (AJAY et al., 2021).

MPs are widespread in different environments and organisms, with potential damage to environmental health. Therefore, they are considered emerging pollutants (GEISSEN et al., 2015). When available in water, the accidental ingestion of MPs by organisms such as fish occurs, culminating in cyto and neurotoxicological effects (GUIMARÃES; CHARLIE-SILVA and MALAF, 2021). The existence of MPs in the air contributes to their presence in the most varied environments. Even in regions without anthropic influence, owing to the transport of particles carried in the wind (GONZÁLEZ-PLEITER et al., 2020).

Besides its presence in various environmental compartments and effects on organisms, there are concerns regarding human health (SARIJAN et al., 2020). However, knowledge about the effects of the presence of plastics on humans is incipient. In recent research, MPs larger than 50 µm were detected in placentas and fetal meconium, showing the potential for human exposure to this pollutant (BRAUN et al., 2021).

In the current scenario, the impacts on human health are still unclear and the adversities on the metabolism of animals still present gaps (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; CERA; CESARINI and SCALICI, 2020; SARIJAN et al., 2020; SZYMAŃSKA and OBOLEWSKI, 2020). Furthermore, it is already understood that the smaller the dimensions of these particles, the greater the chances of their introduction into organisms and, therefore, the greater the possible interferences (TRIEBSKORN et al., 2019).

There is a greater predominance of studies on this pollutant in marine environments compared to research in freshwater ecosystems (WONG et al., 2020). Only 32% of articles on MPs in the UK in 2019 dealt with freshwater bodies (MENG; KELLY and WRIGHT, 2020). Lately, there has been a trend towards expanding research on MPs in rivers, as their presence will design the path for this pollutant into marine environments (MENDOZA and BALCER, 2019; LI; BUSQUETS and CAMPOS, 2020; SARIJAN et al., 2020).

Several authors point out that there is no standardization in the methodologies for collecting and analyzing MPs. Thus, the information is dispersed in the literature, requiring studies that can unite them to obtain a current scenario of MPs pollution (LI; LIU and CHEN, 2018; MENDOZA and BALCER, 2019; PICO; ALFARHAN and BARCELO, 2019; BOYLE and ÖRMECI, 2020; SZYMAŃSKA and OBOLEWSKI, 2020; SARIJAN et al., 2020; WONG et al., 2020). Therefore, the objective of the present work was to elaborate an overview of the main aspects related to the contamination of freshwater bodies by MPs. An exploratory and descriptive study was carried out using scientific articles from the Web of Science database and RStudio software to prepare bibliometrics. The research has a structured scope in information about the characterization of MPs, their sources in freshwater environments and their impacts.

1.1 Materials and methods

In this study, a literature review on microplastics (MPs) in freshwater was conducted in order to provide an overview of the characterization, sources, and impacts of this pollutant and to systematize the available information. The Web of Science database was used for this purpose. For the article search, the keywords “microplastic” (or “microplastics”) and “freshwater” were used in the title search of works published between January 2015 and May 2023 (as a significant presence of articles on MPs in freshwater began in 2015), resulting in 331 documents. From this total, 79 articles were selected for the present review. Before the full analysis of the selected papers, their objectives were examined to assess their contribution to this research. A bibliometric analysis was also conducted using the Bibliometrix package (Aria and Cuccurullo, 2017) in RStudio to map the topic of MPs in freshwater between 2015 and 2023.

1.2 Bibliometric analyses

A unique search in the title field was done for the words "microplastic" or "microplastics" and using the connective "and" to add the word "freshwater" in the Web of Science database, from January 2015 to June 2023. It resulted in 331 documents, comprising 263 research articles, 58 reviews, 4 meeting abstracts, 3 editorial materials, and 2 corrections. These data were selected and exported to obtain bibliometric information from the R Studio software with the Bibliometrix tool (Table 1).

Table 1: Main information from the bibliometric analysis.

Description	Results
Period	2015 to 2023
Sources	96
Documents	331
Average of citations per document	50
Type of document	
Articles	263
Corrections	2

Editorial materials	3
Meeting abstracts	4
Reviews	58
Documents content	
Keywords	962
Authors	
Numbers of authors	1405
Authors of single-authored articles	5
Authors collaboration	
Co-authors per document	5.3

Since 2015, there has been an increase in the number of published works on this topic. The year with the highest number of published works was 2022. Despite the small number of authors working on the subject, the average number of citations per document indicates that the scientific community has been promoting an intense debate on the subject. A factor also highlighted by the large number of works published in 2022 (Figure 1).

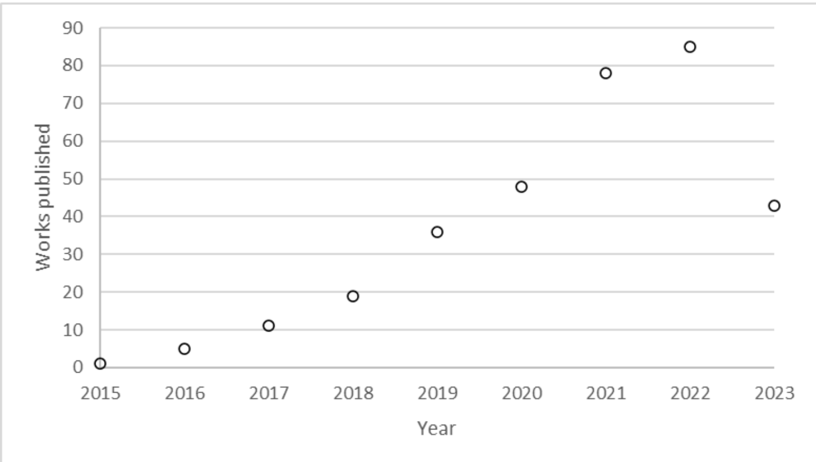

Figure 1: Works published per year with the theme of MPs in freshwater, from January 2015 to June 2023.

From 2015 to 2023, the publication of works on MPs in freshwater had the highest number of publications in China (321), Germany (107) and the United States (77). In Brazil, the number of publications in the same period was fifty-two (Figure 2).

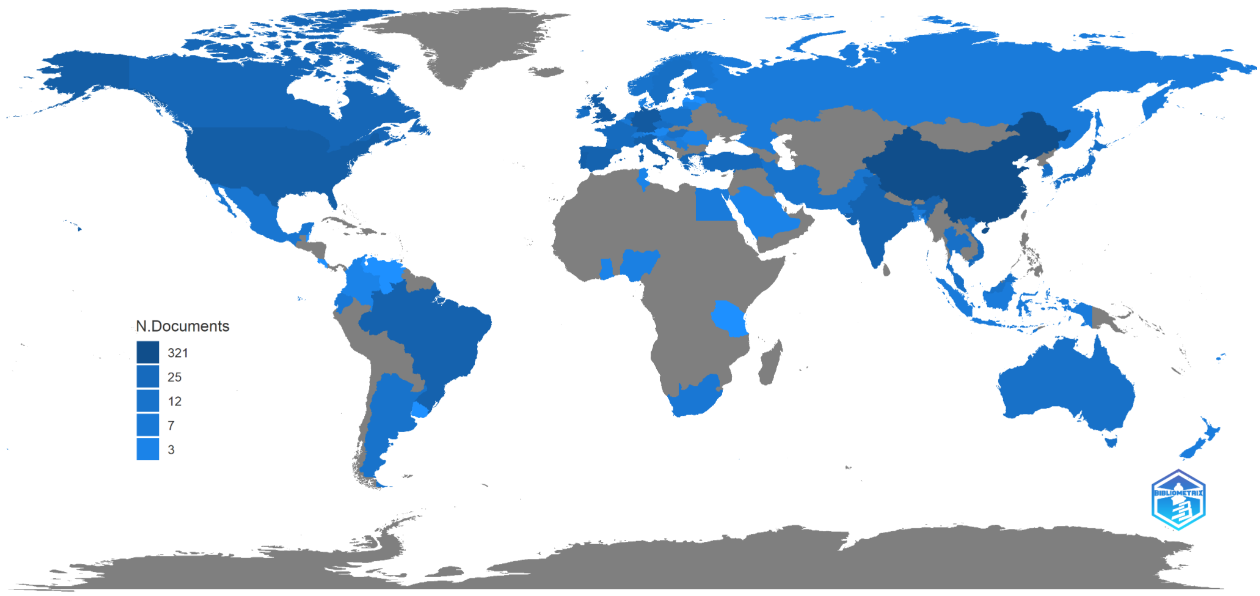

Figure 2: Publications of papers on MPs in freshwater from 2015 to 2023 by country.

2 CHARACTERIZATION OF MPS

MPs are characterized by having dimensions smaller than five millimeters (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; DOMOGALLA-URBANSKY et al., 2018; LI; LIU and CHEN, 2018; RODRIGUES et al., 2018; ERDOGAN, 2020). Some works show the predominance of particles smaller than 2 mm (WANG et al., 2019), 1 mm (KARUPPASAMY et al., 2021; SUN et al., 2021) and 0.5 mm (KASAMESIRI et al., 2021).

The daily release of MPs can reach millions of particles (PICO; ALFARHAN and BARCELO, 2019). In the literature, values of up to 14,210 items per cubic meter (items/m³) were found for bodies of water (WANG et al., 2019) (Table 2) and up to 24 items per gastrointestinal tract sample of Tilapia (*Oreochromis niloticus*) (MARTINEZ-TAVERA et al., 2021) (Table 3).

Table 2: Number of MPs per body of water found in the literature.

Year	Authors	Quantitative	Body of water	Country	Continent
2021	STRADY et al.	0,35–2522 items/m³	Surface water	Vietnam	Asia
	AJAY et al.	2-64 items/L	Lake	India	Asia
	ZHANG et al.	67,5±65,6 items/m³	River	China	Asia
	KARUPPASAMY et al.	13–54 items/km²	Lake	India	Asia
	BERTOLDI et al.	11,9–61,2 items/m³	Lake	Brazil	South America
	GARCIA et al.	0,87±1,24 items/m³	River	France	Europe

2020	GONZÁLEZ-PLEITER et al.	0,47-1,43 items/10^3 m^3	Stream	-	Antarctica
	ERDOGAN	233 items/m^3	Lake	Turkey	Europe/Asia
	NAN et al.	0,40±0,27 items/L	River	Australia	Oceania
2019	EHLERS; MANZ; KOOP	0,003±0,001 items/ml	Stream	Germany	Europe
	WANG et al.	1760 to 10120 items/m^3	Lake	China	Asia
2018	RODRIGUES et al.	59-193 and 71-1265 items/m^3	River	Portugal	Europe

Table 3: Quantity of MPs by freshwater organisms found in the literature.

	Authors	Quantitative (items/individual)	Organism	Country	Continent
2021	ZHANG *et al.*	0,6±0,6	Wild fish	China	Asia
	MARTINEZ-TAVERA *et al.*	24	*Oreochromis niloticus* (Tilapia)	México	North America
	SUN *et al.*	18 and 14	*Oreochromis niloticus* (Tilapia) e *Cirrhinus molitorella* (Mud Carp)	China	Asia
	KASAMESIRI *et al.*	2,92±1,30	14 fish species	Thailand	Asia
	GARCIA *et al.*	0.02±0,15 and 0,13±0,42	Macroinvertebrates and fish, respectively	France	Europe
2020	KUSMIEREK; POPIOLEK,	1.15±1,65 and 1,18±1,89	*Gobio gobio* (Gudgeon) and *Rutilus rutilus*, respectively	Poland	Europe
	NAN *et al.*	0,52±0,55	*Paratya australiensis* (Shrimp)	Australia	Oceania
	WARDLAW; PROSSER	0-7	*Lasmigona costata* (mussels)	Canada	South America
2019	EHLERS; MANZ; KOOP	1,14±0,28	*caddisfly larval cases Lepidostoma basale*	Germany	Europe
2017	PAZOS *et al.*	19,3	11 fish species	Argentina	South America

The comparative analysis of MP quantities, especially in water samples, is often hampered by the lack of standardization in the expression of results. Therefore, it is recommended that water samples be treated in number of items per liter (nº/L or items/L, the latter most used) or items per cubic meter (items/m^3). To express the results by area, it is suggested to prioritize the number of MPs found per square meters (items/m^2) (MENDOZA and BALCER, 2019).

Most research carry out visual inspection for quantification, without characterizing the polymers (PICO; ALFARHAN and BARCELO, 2019), which is an extremely important factor, as the characteristics of the polymers will determine the distribution along the water column (MENG; KELLY and WRIGHT, 2020). The main polymers that make up MPs are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) (LI; BUSQUETS and CAMPOS, 2020) and polyvinyl chloride (PVC) (MILOLOŽA et al., 2021) (Figure 3), which are the most used in industrial activities (LAGARDE et al., 2016).

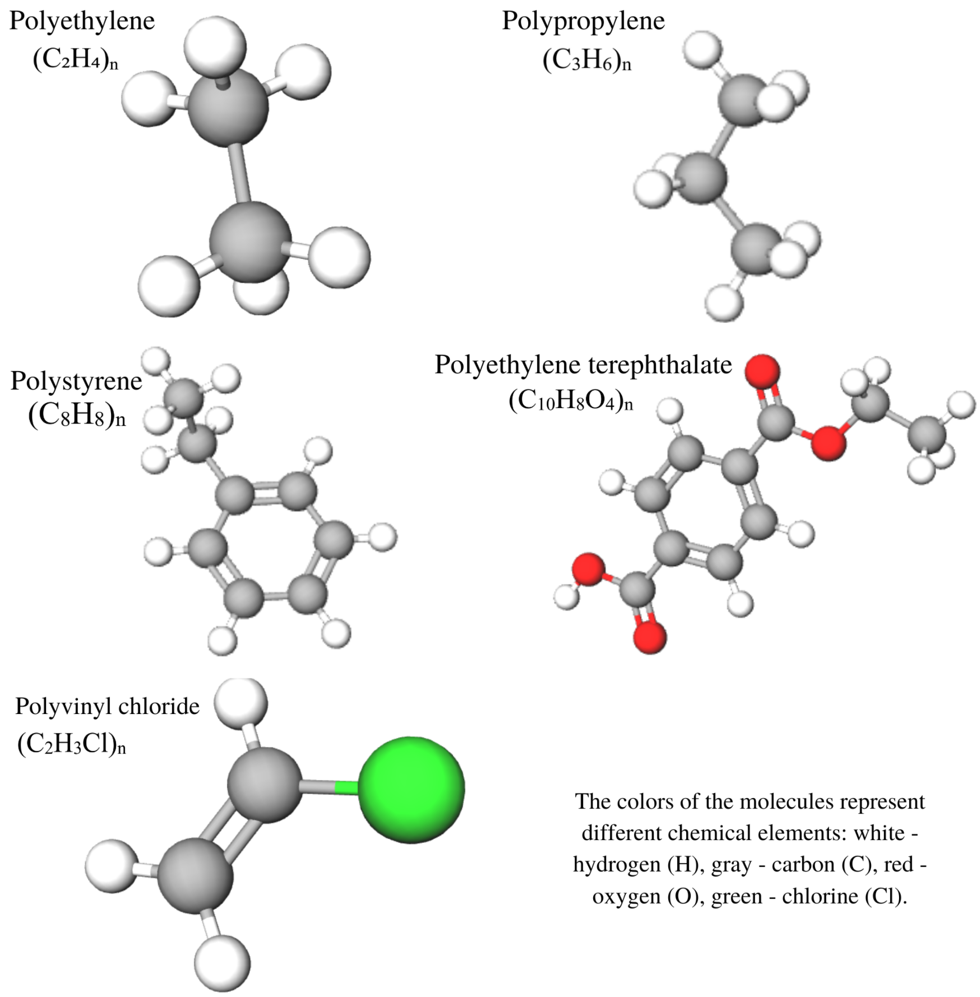

Figure 3: Molecular structure of the main constituent polymers of Mps.

The ones most commonly found in water are PP and PE (RODRIGUES et al., 2018; WANG et al., 2019; CERA; CESARINI and SCALICI, 2020; ERDOGAN, 2020; BERTOLDI et al., 2021; AJAY et al., 2021; ZHANG et al., 2021) and in the biota they are PE (WEBER; JECKEL and WAGNER, 2020; ZHANG et al., 2021), PET (CERA; CESARINI and SCALICI, 2020) and PP (WARDLAW and PROSSER, 2020). PE is used in a variety of products and often seen in the works. PP is less degradable, being degraded only by strong oxidants and is prone to the adherence of microorganisms to its surface (MILOLOŽA et al., 2021). PP and PE have wide applicability in the industry (LAGARDE et al., 2016). With high resistance to degradation, PVC is used in construction and the manufacture of packaging (MILOLOŽA et al., 2021). PS is a hydrophobic polymer of synthetic origin, with high molecular weight and, therefore, the MPs constituted by these present great complexity for degradation and metabolism (ZHANG et al., 2021). PET is used to manufacture food packaging (MILOLOŽA et al., 2021).

Regarding their format, MPs are classified into fragments, filaments, pellets, fibers, among others (MENDOZA and BALCER, 2019) (Figure 4). Of the formats mentioned, fibers are most frequently found in fresh water (PAZOS et al., 2017; WANG et al., 2019; MENDOZA and BALCER, 2019; ERDOGAN, 2020; NAN et al., 2020; WARDLAW and PROSSER, 2020; KASAMESIRI et al., 2021; STRADY et al., 2021; ZHANG et al., 2021; KUŚMIEREK and POPIOłEK, 2022) with records of MP fibers even in Antarctica (GONZÁLEZ-PLEITER et al., 2020).

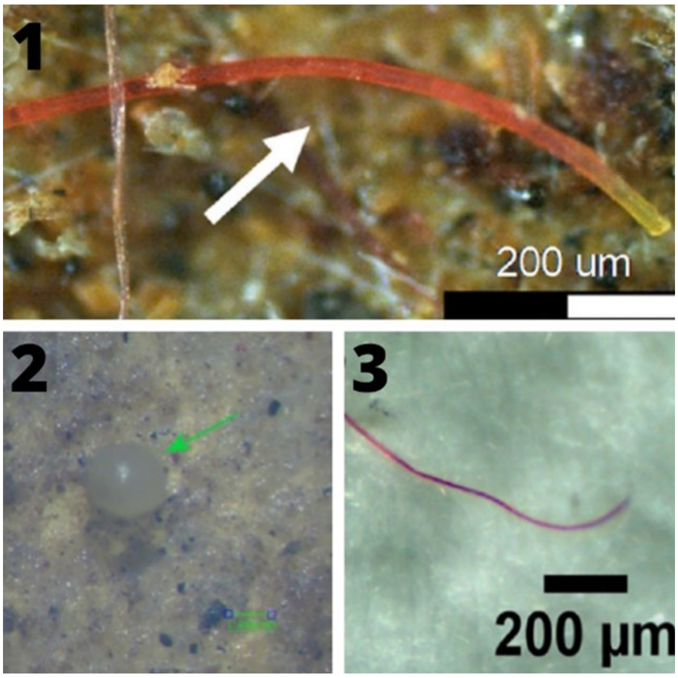

Figure 4: Main formats presented by MPs.
Sources: (1) MP in fragment format (BERTOLDI et al., 2021); (2) pellet (SUN et al., 2021); (3) fiber (GONZÁLEZ-PLEITER et al., 2020).

The fibers are elongated and thick lines. The fragments are irregular, hard or flexible particles (STRADY et al., 2021) found in large numbers in freshwater fish, such as Tilapia, Mud Carp (SUN et al., 2021), macroinvertebrates (GARCIA et al., 2021) and moluscs (BOTELHO et al., 2023).

Regarding the coloration of MPs, both in water and in the biota, the most commonly found are white (BERTOLDI et al., 2021; GARCIA et al., 2021; KARUPPASAMY et al., 2021; SUN et al., 2021), blue (NAN et al., 2020; ERDOGAN, 2020; KASAMESIRI et al., 2021) and black (WANG et al., 2019; GARCIA et al., 2021; MARTINEZ-TAVERA et al., 2021). Black MPs in water are more difficult to quantify, with a risk of underestimation, as most of the works employ visual inspection (LI; LIU and CHEN, 2018; BERTOLDI et al., 2021).

Another point is the long time these particles remain in bodies of water, a factor evidenced by the high oxidation and smaller sizes of MPs (BERTOLDI et al., 2021). Degradation also changes their surface characteristics (HOSSAIN et al., 2018).

Regarding their density, the most common MPs are those with low densities. PP and PE with 0.92 and 0.90-0.97 g/cm³, respectively (BERTOLDI et al., 2021). Higher density polymers, such as PET (1.38 g/cm³), are found in the deepest parts of bodies of water or in sediments, which are more ingested by fish (GARCIA et al., 2021). In a study that analyzed the presence of MPs in a rainwater treatment pond, it was demonstrated that most floating MPs are made up of PP (MOLAZADEH et al., 2023). Other characteristics related to hydrophobicity, surface morphology and roughness of MPs are important to be evaluated as they affect their colonization by biofilms (MIAO et al., 2021).

As the characteristics of MPs are directly related to the means of entry and the distance from the source of contamination (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015), it can be stated that the discussion about the means of entry of MPs into bodies of water is relevant to understanding their dynamics in freshwater environments.

3 SOURCES OF MPS

Urban areas are important sources of MPs to bodies of water and several studies point to the link between MP contamination and large population numbers and high urbanization (RODRIGUES et al., 2018; WARDLAW and PROSSER, 2020; WONG et al., 2020; AJAY et al., 2021; MARTINEZ-TAVERA et al., 2021; ZHANG et al., 2021).

The exposed factor is considered as one of the reasons when selecting areas for analysis in the works, in addition to high rates of industrialization, presence of effluent treatment plants (ETPs) and activities involving tourism (RODRIGUES et al., 2018; AJAY et al., 2021). The spatial distribution of MPs and their characteristics are directly related to human activities (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015).

In this sense, the disposal of plastic waste in bodies of water or in their vicinity is one of the ways that MPs end up present in the water (RODRIGUES et al., 2018; ERDOĞAN, 2020; AJAY et al., 2021). The entry of MPs into bodies of water is classified into two sources: primary and secondary. The primary source is when pellets, mainly, and fragments are directly inserted into the compartments through domestic and industrial effluents. The presence of MPs in domestic effluents is due to plastic particles, which are usually used in the production of cosmetics and personal hygiene products such as toothpaste. The degradation of larger plastics due to Sun exposure, wind currents or water flows is characterized as a secondary source of MPs in environments (JEMEC et al., 2016; LAGARDE et al., 2016; WANG et al., 2019; WONG et al., 2020; ERDOGAN, 2020; KASAMESIRI et al., 2021).

Regarding domestic effluents, both raw disposal and effluents from ETPs and WTPs (Water Treatment Plants) are considered the most significant means of entry of MPs into bodies of water (LI; LIU and CHEN, 2018; RODRIGUES et al., 2018; WANG et al., 2019; WARDLAW and PROSSER, 2020; WONG et al., 2020; SARIJAN et al., 2020; STRADY et al., 2021; ZHANG et al., 2021; METCALF et al., 2023). Some MPs from this source of contamination are classified as synthetic fibers, which originate from the washing of clothes (PAZOS et al., 2017; WANG et al., 2019; ERDOĞAN, 2020; KUŚMIEREK and POPIOłEK, 2022).

The contribution of ETPs to the presence of MPs in the water, when MPs are made of PVC, may even come from the plumbing material used (DOMOGALLA-URBANSKY et al., 2018). Characterizing itself as a significant source, a higher incidence of MPs has already been analyzed and found in the intestinal content of fish near the effluent discharge areas (PAZOS et al., 2017).

In relation to fishing, this activity is extensively characterized as a means of entry of MPs into the water (KASAMESIRI et al., 2021; KARUPPASAMY et al., 2021; SUN et al., 2021), mainly due to the decomposition of materials used in this activity (KARUPPASAMY et al., 2021). There is also an association between the presence of MP fragments in bodies of water and boat paint (AJAY et al., 2021).

Industrial activity is an important source of impact. Industry potentially contributes to the pollution of bodies of water by MPs (RODRIGUES et al., 2018; SARIJAN et al., 2020; MARTINEZ-TAVERA et al., 2021; SUN et al., 2021), with one of the examples being the textile industry, which raises the level of PE in the water (PARKER et al., 2021). Furthermore, if toxic compounds are used in the production of plastics, they are released into aquatic environments when in the form of MPs (KIM et al., 2022).

Atmospheric currents also act in the transport of MPs. Thus, air pollution is also identified as a source of MPs in bodies of water. As there are currently few works, more of them are needed as this topic in atmospheric sciences is recent and still carries insufficient data (GONZÁLEZ-PLEITER et al., 2020; WONG et al., 2020). Research that detected the presence of MPs in protected areas, far from the influences of human activities (100 km away from areas with tourists), bring the weather conditions associated with winds as a means of transporting MP particles into bodies of water (ERDOĞAN, 2020; GONZÁLEZ-PLEITER et al., 2020).

Agriculture is an anthropic activity with a significant polluting impact regarding MPs. The contribution to the quantity of MPs in bodies of water by agriculture is given (WANG et al., 2019; SUN et al., 2021), among other, using techniques such as mulching (WANG et al., 2019). A technique that consists of covering the soil with plastic film to reduce limiting factors, such as water scarcity and low temperatures, in rice crops (WU et al., 2001). This technique provides gains in the growth and production of crops, but with the various impacts related to contamination by plastics, its use has been questioned (GAO et al., 2019).

It has also been pointed out, in addition to these means of entry, the accidental releases and extreme events such as storms and floods (SARIJAN et al., 2020; WONG et al., 2020), and the presence of ports and vessels (ZHANG et al., 2021). Less common means of entry of MPs into freshwater bodies that also cited in the literature are related to animal excrement or the decomposition of organisms, mainly in protected areas and/or near river mouths (GONZÁLEZ-PLEITER et al., 2020).

Not only the means of entry are expressed in the literature, but also the transport dynamics of MPs in water. It is proposed that freshwater bodies and small rivers act as carriers of MPs (RODRIGUES et al., 2018) both for larger rivers and for saline water ecosystems (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; KUŚMIEREK and POPIOŁEK, 2022). In this context, nature-based strategies, as discussed by Silva Junior et al. (2024), can help mitigate the spread of contaminants by promoting the natural retention and treatment of water in adapted landscapes.

In summary, the most relevant sources of MP contamination in bodies of water are the dumping of domestic effluents, industrial activities, fishing, agriculture, the direct disposal of solid waste, and atmospheric pollution. Despite this, many systematic monitoring programs still do not analyze the presence of MPs in environmental compartments (CINTRA et al., 2020; COSTA et al., 2020; COSTA et al., 2021). It is noteworthy that even areas with high protection and without the direct influence of human activities are likely to be contaminated by MPs, owing to their different types of sources and the long distances over which these particles can be carried (GONZÁLEZ-PLEITER et al., 2020). The relationship between the structure and conservation status of vegetation in natural environments can also influence pollutant retention, the quality of water bodies, and their spatial and temporal variations (GELLI et al., 2023; COSTA et al., 2023).

4 IMPACTS OF MPS ON FRESHWATER ECOSYSTEMS

Several authors highlight the need for greater knowledge regarding the impacts of MPs on the quality of bodies of water, fauna and flora, and human health, as current knowledge is limited (LI; MARTINS and GUILHERMINO, 2018; WANG et al., 2019; BUSQUETS and CAMPOS, 2020; MENG; KELLY and WRIGHT, 2020; SARIJAN et al., 2020; SZYMAŃSKA and OBOLEWSKI, 2020; WONG et al., 2020; PARKER et al., 2021; CHEN et al., 2021;).

Not only is knowledge about the impacts low, but over time there is an increase in environmental compartments with the presence of these particles, due to their large dispersion. This factor is emphasized by the results obtained by research in Antarctica, where significant numbers of MPs were found in protected areas, with no activities characteristic of urbanized locations nearby (GONZÁLEZ-PLEITER et al., 2020).

Regarding the impacts on the dynamics present in freshwater bodies, it was found that the association between MPs and biofilms, mainly due to the adherence of microorganisms on the surface of the polymers, has consequences for the nitrogen cycle, a factor evidenced by the calculation of the balance of mass. In addition to nitrogen, another parameter that was considered for the analysis was phosphorus, as the effects of sorption and transformation of this nutrient by microorganisms were verified (CHEN et al., 2020).

The association between MPs and biofilms, mainly by bacteria, will depend on the physicochemical aspects of the MPs and on the physiological characteristics of the bacteria. Recent research has presented high potential results for this association, with the aim of understanding the colonization of MPs by bacteria of the species *Acinetobacter calcoaceticus*, *Burkholderia cepacia* and *Escherichia coli* (the latter used as a bioindicator of contamination of bodies of water by domestic effluents) (HOSSAIN et al., 2018). Recent research found that pathogens present in effluents can remain on the surface of PMs for 25 days, which facilitates the transport of these microorganisms (METCALF et al., 2023). On effects, the colonization of MPs by biofilms in work showed that, when compared to an inert substrate, the amount of organic matter is reduced (MIAO et al., 2021).

Besides bacteria, it is important to verify the impacts on other organisms, since the presence of MPs in bodies of water will lead to accidental ingestion (EERKES-MEDRANO;

THOMPSON and ALDRIDGE, 2015). That is, from the moment MPs are found in the water or even in the sediment, there is a great chance that they are also present in organisms (WONG et al., 2020), promoting damage to their metabolism (CERA; CESARINI; SCALICI, 2020; SZYMAŃSKA and OBOLEWSKI, 2020; ZHANG et al., 2021). Furthermore, MPs in bodies of water tend to be carried by currents and reach other areas, remaining in the water column or being deposited in sediments. A mechanism was identified that demonstrates a trend of displacement of PMs from the water column to the sediments, meaning the possibility of permanent incorporation of these elements in the sediment, according to the hydrodynamics and properties of the sediment (MOLAZADEH et al., 2023).

On the permanence of MPs in environmental compartments, when captured by animals, such as fish, they persist for longer in a given region, contributing to the interference in the dynamics of the biosphere (NAN et al., 2020). As organisms are susceptible to accidentally ingesting MPs, several recent studies show impacts of MPs on the biota present in freshwater (JEMEC et al., 2016; PAZOS et al., 2017; STRAUB; HIRSCH and BURKHARDT-HOLM, 2017; MARTINS and GUILHERMINO, 2018; OLIVEIRA et al., 2018; GUIMARÃES; WANG et al., 2019; CHARLIE-SILVA and MALAF, 2021; WEBER; JECKEL and WAGNER, 2020).

Impacts on the antioxidant activity of mussels (*Dreissena polymorpha*) were found and the greater the amounts of MPs, the greater the stress that was presented (WEBER; JECKEL and WAGNER, 2020). Another bivalve which showed damage due to the presence of MPs was the species *Corbicula fluminea*. This bivalve exhibited oxidative damage to lipids and neurotoxicity from the ingestion of MPs, and a period of six (6) days for recovery from the effects was not sufficient (OLIVEIRA et al., 2018).

Another species that presented recovery difficulties after exposure to MPs was *Daphnia magna*, a planktonic crustacean (JEMEC et al., 2016; MARTINS and GUILHERMINO, 2018). The crustaceans of the species *Daphnia magna*, in addition to the adversities to complete their recovery, showed damage in growth and reproduction, with population reduction in the following generation and the extinction of the descendants of the second generation (MARTINS and GUILHERMINO, 2018). In this species, a significant increase in mortality was also observed in individuals that had not had food prior to their exposure to MPs (JEMEC et al., 2016). Another species of crustacean that showed damage after exposure was the species *Gammarus fossarum* (amphipod). It showed a decrease in assimilation efficiency and wet weight, which resulted from the digestive restriction caused by the ingestion of MPs, both biodegradable and derived from petroleum (STRAUB; HIRSCH and BURKHARDT-HOLM, 2017).

Although reduced, there are already reports in the literature of the effects on fish with exposure to MPs (PARKER et al., 2021), mainly on fish found near areas with a high degree of urbanization (SARIJAN et al., 2020). It was found that the presence of MPs in the intestine of fish is not cumulative, but related to the environment, so the quantity of these particles in the intestines would be a way to indirectly measure the presence of MPs in the water (PAZOS et al., 2017). Among the damages to fish that ingested MPs are neurotoxic and cytotoxic damages, observed in the species Danio rerio (GUIMARÃES; CHARLIE-SILVA and MALAF, 2021; KALOYIANNI et al., 2021).

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Other organisms are also affected by the exposure to MPs, such as algae. The currently available literature describes the effects of this exposure, with the analyses being constructed by four (4) main factors: growth, photosynthesis, pigmentation and enzymatic activity, and oxidative stress (RANI-BORGES; MOSCHINI-CARLOS and POMPÊO, 2019). Harmful effects were observed in algae of the species *Microcystis aeruginosa*, where the exposure promoted growth restriction, a decrease in photosynthetic pigments and, consequently, photosynthesis was drastically reduced (WANG et al., 2019; SÁNCHEZ-FORTUN et al., 2021).

MPs also affect insects that have part of their life cycle in the water, such as *Lepidostoma basale*, where it was found that individuals of this species ingested the MPs from polymers which are most commonly found in the water (EHLERS; MANZ and KOOP, 2019). The association between biofilms and MPs (CHEN et al., 2020) can place MPs formed by low-density polymers in the sediments, thus becoming available for ingestion by organisms of species such as *Lepidostoma basale* (EHLERS; MANZ and KOOP, 2019).

Regarding the deposition of MPs in the sediments, it was verified that the association between MPs and microalgae of the species *Chlamydomonas reinhardtii* forms heteroaggregates where it is possible that the MPs previously present in the water are directed to the sediments, because of the increase in density (LAGARDE et al., 2016).

The aspect that should be highlighted concerns conditions that culminate in greater ease for the ingestion of MPs by organisms. Thus, it has already been verified in the literature that fibers are the most common form of MP found in freshwater ecosystems, and due to their high quantities in the waters, these are easily ingested by macroinvertebrates (NAN et al., 2020).

On the other hand, some organisms do not exhibit damage to their metabolism because of accidental ingestion of MPs. The aquatic worm *Allonais inaequalis* is an example of resistance to MP contamination. This characteristic makes it a potential organism for future studies with long exposure periods and different formats and types of MP polymers (CASTRO et al., 2020). Another organism that did not present deleterious effects with the high ingestion of MPs were bivalves of the species *Unio pictorum*, which were exposed to effluents from ETPs, despite the potential for absorption and increase in the level for periods of high exposure (DOMOGALLA-URBANSKY et al., 2018).

Not only associations between MPs and organisms are present in the literature, but associations between MPs and substances such as drugs (VERDÚ et al., 2021; ZHANG et al., 2021; WU et al., 2022; TUMWESIGYE et al., 2023) and metals (OLIVEIRA et al., 2018; WANG et al., 2019; DONG et al., 2021; TUMWESIGYE et al., 2023) are also verified in research. The presence of these relationships in the literature happens because MPs can act as carriers of contaminants (LI; LIU and CHEN, 2018) according to the characteristics of MP polymers, such as the presence of polar groups (VERDÚ et al., 2021), and the individual and combined effects of MPs with other pollutants can lead to different situations in freshwater environments (WANG et al., 2019).

In the case of drugs, it was detected that MPs can increase the bioaccumulation and affect the metabolism of the antibiotic roxithromycin in fish of the species *Oreochromis niloticus* (ZHANG et al., 2021). The microalgae *Anabaena sp.*, considered as an organism belonging to the base of the trophic chain, showed effects on its growth and chlorophyll-a content with the exposure of MPs with triclosan (antiseptic) (VERDÚ et al., 2021). Another microalgae that was affected was *Chlorella vulgaris*, used in the degradation of the antibiotic levofloxacin, which had its growth inhibited as well as drug assimilation (WU et al., 2022).

Regarding trace elements, metallic elements adsorbed on the surface of MPs were detected, these being iron (Fe), calcium (Ca) and zinc (Zn). The presence of these elements associated with MPs can increase the pollution of bodies of water (WANG et al., 2019). Bivalves of the *Corbicula fluminea* species showed damage to lipids with the ingestion of a mixture of MPs and mercury (Hg) (OLIVEIRA et al., 2018).

Algae of the *Microcystis aeruginosa* species had effects on antioxidant enzyme activity and cell damage with exposure to lead-containing MPs (Pb) (WANG et al., 2019).The species *Chlamydomonas reinhardtii*, an important microalgae for the purification of water contaminated with arsenic (As), showed a decrease in photosynthesis, respiration, and growth in the presence of MP combined with Arsenic. The species also had its pollutant retention capacity reduced (DONG et al., 2021). Negative effects were detected in *Danio rerio, Daphnia magna* and *Chlamydomonas reinhardtii* when in the presence of leachate with tennis sole fragments. This effect was associated with the presence of toxic compounds in this leachate, such as benzothiazole, carbon disulfide, ethyl acetate, methyl salicylate and p-xylene (KIM et al., 2022).

Although knowledge about the impacts on human health is limited (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; SARIJAN et al., 2020), this concern is pertinent and originates from the possible problems arising from the accidental ingestion of MPs when consuming water and/or fish and seafood (EERKES-MEDRANO; THOMPSON and ALDRIDGE, 2015; SZYMAŃSKA and OBOLEWSKI, 2020). Regarding the effects on the biota, these are still minimal, but with critical findings of toxic impacts for organisms (SARIJAN et al., 2020; CHEN et al., 2021; TUMWESIGYE et al., 2023). In general, this panorama points to evidence of negative effects both for the ecosystem and for humans (MARTINS and GUILHERMINO, 2018; OLIVEIRA et al., 2018; TUMWESIGYE et al., 2023). Another point to be considered is that in the associations that occur between MPs and other contaminants (the former functioning as a means of transport for the latter), some harmful effects on human health by pollutants are already known in the literature (LI; LIU and CHEN, 2018; TUMWESIGYE et al., 2023). The adoption of innovative approaches to estimate water quality, such as the use of machine learning techniques, has already been successfully employed for water quality assessment (COSTA et al., 2024), and can be adapted to evaluate and predict the presence of microplastics.

5 FINAL CONSIDERATIONS

Several authors point to the need for greater knowledge about the impacts of MPs on the quality of bodies of water, fauna and flora, and human health, as current knowledge is limited. Concerns about the presence of MPs in freshwater bodies have aroused interest in research, a factor confirmed in the bibliometric analysis by the increase in the amount of research which has been carried out over time.

The characterization of MPs in the aspects presented in the literature (dimension, constituent polymers, color, and shape) is well-defined and is widely discussed in the works. The exception being the density parameter that has yet to be properly explored, making it difficult to characterize this aspect and even to understand the dynamics of MPs in freshwater bodies. Regarding this dynamic, it is important to highlight that the characterization of MP sources in these environments still lacks specific methodologies for their identification. This makes it more complex to carry out diagnoses aiming to regulate the quality of bodies of water impacted by this pollutant.

Another gap in the literature concerns the effects on human health with the ingestion of MPs. Despite recent studies confirming the presence of MPs in human tissues, knowledge about their effects on human health does not exist and only assumptions are made according to the theoretical knowledge of other components and their effects on the health of organisms. The impacts on the biota, although not numerous, are already reported in research, through neuro and cytotoxic effects, bringing serious implications to the metabolism of the species studied.

It is still necessary for research to advance to fill the gaps observed in the characterization, in the identification of sources and their impacts, so that a more complete panorama is achieved for future studies and actions for the conservation and preservation of these environments, resulting in the minimization of the impacts of this emerging pollutant.

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