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Association between microplastics and biofilm: a new perspective for monitoring microplastics in urban rivers

Associação entre microplásticos e biofilme: nova perspectiva para o monitoramento de microplásticos em rios urbanos

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ABSTRACT

Biofilm has an enormous capacity to accumulate pollutants, reflecting what happens for days in the water column of a river. However, there is a gap in using biofilm as a matrix for monitoring microplastics, especially in urban rivers. This study proposed using biofilms in environmental monitoring investigations of microplastic occurrence as a significant contribution to water and sediment analysis. To this end, a bibliographic review was carried out on databases regarding: monitoring microplastics in Brazilian rivers; and adsorption of emerging contaminants in microplastics associated with biofilms in fresh water. Additionally, the relevance of biofilms as bioaccumulators of pollution in their environment was highlighted. Based on the studies analyzed, it was observed that the evaluation of biofilms could broaden the view of microplastic pollution occurring within a water body, especially when compared to the analysis of water and sediment in the same period and environment.

Keywords: emerging contaminants; aquatic matrices; surface water; biofilm.

RESUMO

O biofilme tem enorme capacidade de acumulação de poluentes, refletindo o que acontece durante dias dentro da coluna d'água de um rio. No entanto, há uma lacuna quanto ao uso do biofilme como matriz de monitoramento de microplásticos, em especial em rios urbanos. Neste estudo foi proposto que esta matriz seja empregada nas investigações de monitoramento ambiental de ocorrência de microplásticos, como uma grande contribuição para as análises de água e sedimento. Para isto, realizou-se pesquisa bibliográfica em bases de dados sobre: monitoramento de microplásticos em rios brasileiros; e adsorção de contaminantes emergentes em microplásticos associados a biofilmes em água doce. Além disso, destacou-se a relevância do biofilme como bioacumulador da poluição ao seu entorno. Com base nos estudos analisados, observou-se que a avaliação do biofilme poderia ampliar a visão da poluição microplástica que ocorre dentro de um corpo hídrico, principalmente se comparada as análises de água e sedimento num mesmo período e ambiente.

Palavras-chave: contaminantes emergentes; matrizes aquáticas; água superficial; biofilme.

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Introduction

There is growing concern about emerging contaminants (ECs), which can affect water quality and cause potential public health and safety risks (Vargas-Berrones et al., 2020). Among the ECs are pharmaceuticals, hormones, sunscreens, personal care products and cosmetics, lipid regulators, synthetic hormones, alkylphenols, flame retardants, pesticides, drugs of abuse, and others (Montagner et al., 2017). In addition to those commonly investigated, microplastics have recently been classified as ECs (Richardson and Kimura, 2020; Montagner et al., 2021). These microplastics result from plastic pollution combined with poor solid waste management and are widely found in the environment in the size range of 1 to 5 mm (ISO, 2020). In light of this, this new class of ECs has been the subject of research in several countries precisely to elucidate the potential risks to living organisms and the levels of microplastic pollution in various environmental compartments (Montagner et al., 2021).

The problem of microplastic pollution in the environment extends beyond other classes of ECs, as microplastics can act as vectors for different chemical substances. The surface of plastics allows for the adsorption of heavy metals and other pollutants into the environment (Brennecke et al., 2016; Guan et al., 2022; Liu et al., 2022). Microplastics can be transported and release chemical substances along water bodies. Besides, they can carry other additives previously incorporated into their manufacturing process and transport other pollutants acquired through surface contact. Given the above, the concentration of contaminants in microplastics contaminants can be up to 10^5–10^6 times higher than that of the surrounding environment (Bradney et al., 2019; Li et al., 2020; Guan et al., 2022).

Global and national research on microplastics in the environment is primarily conducted in marine and estuarine waters (Sodré et al., 2023; Escrobot et al., 2024). As a result, there is a lack of studies and data on microplastics in freshwater systems (Lambert and Wagner, 2018; Li et al., 2018; Sodré et al., 2023), although some studies have already shown that the amount of microplastics in freshwaters is similar to that found in the marine environment (Peng et al., 2017; Li et al., 2018). In Brazil, the study of microplastics in urban freshwater environments (water and sediment) is still emerging. In addition, a literature review identified that, to date, no studies have integrated the assessment of microplastic pollution across different environmental matrices, such as comparing concentrations in water and sediment within the same study area. There is also a gap in both national and international research regarding the occurrence of microplastics, particularly biofilms in urban rivers.

Rivers have a complex and dynamic structure known as biofilms, which are fundamental to aquatic ecosystems. They consist of fungi, bacteria, algae, and protozoa, surrounded by a matrix of extracellular polysaccharides, lipids, and proteins. This matrix enables them to attach to and grow on organic and inorganic surfaces, such as rocks, sediments, garbage, wood, plastic, and glass (Sentenac et al., 2021). Biofilms are exposed to the nutrients and pollutants present in water, giving them a high capacity to absorb chemical substances into their matrix (Bechtold et al., 2012; Battin et al., 2016; Reichert et al., 2021).

Biofilms could serve as a promising matrix for studying microplastics in rivers, acting as bioaccumulators of these contaminants. In addition, they could become an important tool for integrated microplastic pollution monitoring alongside environmental matrices such as water and sediment. Therefore, studying this matrix could contribute to a deeper understanding of the dynamics of microplastics in rivers over time. Based on this, this research aimed to: (1) review microplastic monitoring studies in Brazilian rivers, focusing on the environmental matrices of surface water and sediment; (2) present existing studies on the adsorption of ECs on microplastics associated with biofilms in freshwater; (3) analyze the relevance of biofilm as a bioaccumulator of microplastics, highlighting its ability to reflect the dynamics of pollution over prolonged periods in rivers; and (4) propose a new methodological approach based on the use of artificial samplers and analysis of the biofilm matrix to quantify microplastics in urban rivers.

Methodology

A bibliographic review was conducted across five databases: Embase, Scielo, ScienceDirect, Scopus, and Web of Science. Keywords were used, linked by the Boolean operators "AND" and "OR". Article search was carried out until December 15, 2024. The keywords used were: ("biofilm" OR "plastisphere") AND ("microplastics" OR "plastic debris") AND ("adsorption") AND ("river"); ("biofilm" OR "plastisphere") AND ("microplastics" OR "plastic debris") AND ("adsorption") AND ("lake"). Research articles in peer-reviewed journals between 2017 and 2024 were considered, excluding review articles. At the end of the search, 72 articles were found (Embase=20; Scielo=0; ScienceDirect=13; Scopus=17; Web of Science=22). Mendeley® (Elsevier, online version) was used to manage and exclude duplicate articles, resulting in a total of 37 works (Figure 1).

With regard to research into microplastics in Brazilian rivers, a search was conducted in the aforementioned databases and on Google Scholar. Although significant studies have been carried out in lakes in the national context (Blettler et al., 2017; Lorenzi et al., 2020; Bertoldi et al., 2021; Silva and de Sousa, 2021; Silva-Cavalcanti et al., 2023; Queiroz et al., 2024), we chose to focus on studies conducted in surface water and river sediment. Only case studies or original articles that investigated the determination and occurrence of microplastics in Brazilian rivers were considered. The results did not include review articles, short notes, conference papers, or articles that only presented the development of analytical methodologies. However, bibliographic reviews were referenced throughout the text, as they are very important for constantly contextualizing the subject.

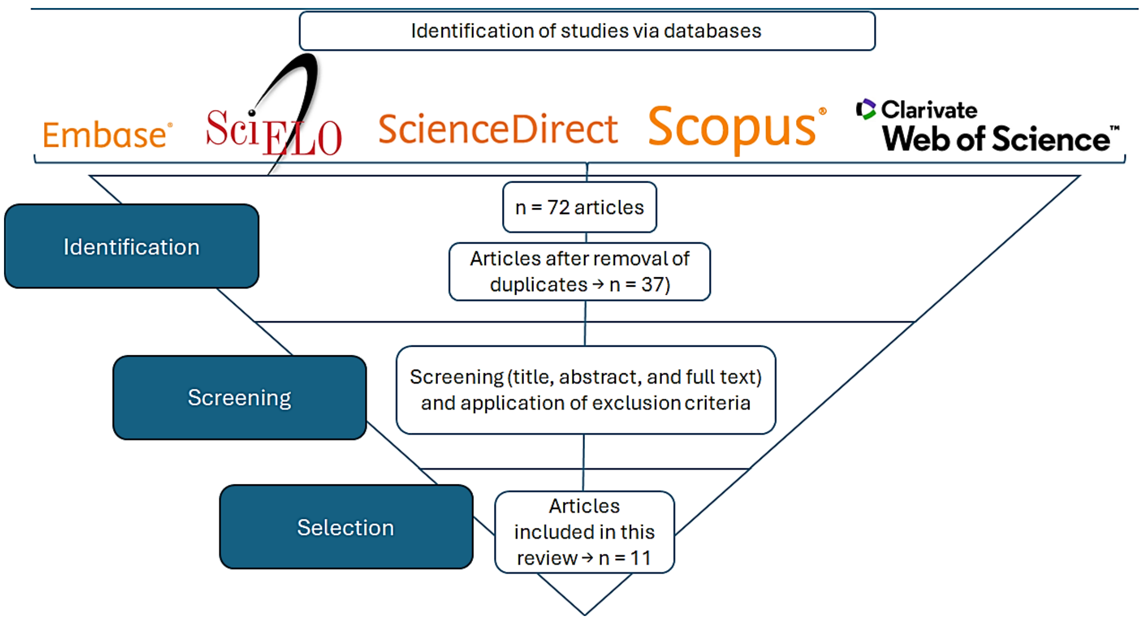


Figure 1 – Literature review procedure on emerging contaminants adsorbed onto microplastics associated with biofilms in rivers and lakes.

Occurrence of Microplastics In Brazilian Rivers

In recent years, freshwater environments (water and sediment) have gained increasing attention regarding microplastic characterization. This delayed focus highlights an inconsistency and a scientific gap, given that these environments are the main sources of the microplastics that reach the oceans (Montagner et al., 2021). Rivers, for example, contribute around 80% of the plastic that reaches the oceans, and the Amazon river—Brazil's largest river—is one of the main contributors to this pollution (Meijer et al., 2021). However, until 2020, only 8% of research focused on assessing microplastics in freshwater ecosystems (Montagner et al., 2021). Table 1 provides an overview of the incidence of microplastics in Brazilian rivers and the methods used to collect and analyze the samples.

A brief overview indicates distinct patterns of microplastic concentrations in water and sediment in the regions of Brazil. Figure 2 illustrates that microplastic investigations have been concentrated mainly in six states. In Rio Grande do Sul, high levels of microplastics were found in water, while in Amazonas, elevated levels were reported in both water and sediment. This reveals that these two geographically distinct regions, South and North, had the highest concentrations of plastic pollution than other states. In Pará (North) and Mato Grosso (Center-West), lower concentrations were observed, while in São Paulo (Southeast) and Rio de Janeiro (Southeast), there was significant variation in the results found by the surveys.

The most significant percentage of freshwater environment studies focused on analyzing surface water in rivers. Two studies stood out because they analyzed the same sampling area: Costa et al. (2022) and Costa et al. (2023). In both studies, microplastics were monitored in the Paraíba do Sul river basin (Rio de Janeiro) but different mesh sizes were used in the samplings. In 2022, a 50 µm mesh was used, resulting in a maximum value of 18.3 items m^{-3}, while in 2023, a 300 µm mesh was selected, obtaining a maximum value of 0.71 standard deviation (±) 0.25 items m^{-3}. This difference in mesh may have led to an underestimation of the results in the second study. Drabinski et al. (2023), who also chose a 300 µm mesh to collect samples from three rivers in Rio de Janeiro, reported an average of 651.5 items m^{-3}, with variations ranging from 3.6 to 51,166.5 items m^{-3}.

Other studies have also used nets with mesh sizes smaller than 300 µm. Faria et al. (2021) and Santos et al. (2024) adopted 68 µm nets, while Rico et al. (2023) selected 55 µm mesh. Faria et al. (2021) found a maximum value of 310 items m^{-3} in an urban tributary of the Cuiabá river (Mato Grosso). This value is not particularly significant compared to the findings of Rico et al. (2023), who recorded a maximum value of 74,550 items m^{-3} (Amazonas), and Santos et al. (2024), who reported up to 6,370 items m^{-3} (São Paulo). It is worth noting that these results reflect local pollution levels and are associated with the inadequate disposal of solid waste and sewage and the low rate of sewage treatment in the region.

The study by Bertoldi et al. (2023) demonstrated how rainfall and depth influence the distribution of microplastics in urban rivers. The research was conducted on the Guaíba river in Porto Alegre city, with surface water samples taken at different depths during both drought and rainy periods. The results indicated a positive correlation between high concentrations of microplastics and population density and depth at each sampling point. Most of the particles found were white-transparent (51%) and fragment-shaped (89%). In terms of composition, polyethylene and polypropylene accounted for 37 and 57% of the particles analyzed, respectively.

Table 1 – Occurrence of microplastics in Brazilian rivers and methods used to collect and analyze the samples.

Reference	Sampling	PC	CQ	Location study	Maximum quantification (items m^{-3})
Surface water					
Faria et al. (2021)	Plankton net, 68 µm mesh	Optical microscopy	NC	Two urban tributaries of the Cuiabá river (MT)	310
Ferraz et al. (2020)	1 L glass bottles	Fluorescent microscope	NC	Sinos river (RS)	940,000
Costa et al. (2022)	4 L glass bottles and plankton net, 50 µm mesh	Optical microscopy	µ-FTIR	Paraíba do Sul river basin (RJ)	18.3
Bertoldi et al. (2023)	zooplankton net, 60 µm mesh	Optical microscopy	µ-FTIR	Guaíba river (RS)	53.8
Drabinski et al. (2023)	Neuston net, 300 µm mesh	Optical microscopy	ATR-FTIR	Rivers: Macacu, Guapimirim, and Maracanã (RJ)	51,166.5
Costa et al. (2023)	Neuston net, 300 µm mesh	Optical microscopy	µ-FTIR	Paraíba do Sul river basin (RJ)	0.71
Oliveira et al. (2023)	Neuston net, 300 µm mesh	Optical microscopy	NC	Tapajós river (PA)	200.44
Rico et al. (2023)	Plankton net, 55 µm mesh	Optical microscopy	FTIR	Amazon river, three tributaries, and urban streams (AM)	74,550
Santos et al. (2024)	30 cm diameter net, 68 µm mesh	Optical microscopy	NIR-HSI combined with SIMCA and µ-FTIR	Atibaia river basin and Turvo/Grande river basin (SP)	6,370
Moraes et al. (2024)	10 L aluminum bucket and stainless-steel sieves with openings of 0.106 mm and 5.6 mm	Optical microscopy	ATR-FTIR	Tietê river (SP)	1,530
Sediment					
Gerolin et al. (2020)	Van Veen sampler (single collection at each point), 5–10 cm sediment layer	Optical microscopy	NC	Rivers: Negro, Solimões, and Amazonas (AM)	8,178
Toyama et al. (2021)	Corer sampler	Optical microscopy	NC	Água Branca stream basin (SP)	956
Cardoso Neto et al. (2023)	Rings volumetric stainless-steel measuring approximately 100 cm3 (depth 0–5 cm)	Optical microscopy	NC	Xingu river (PA)	246

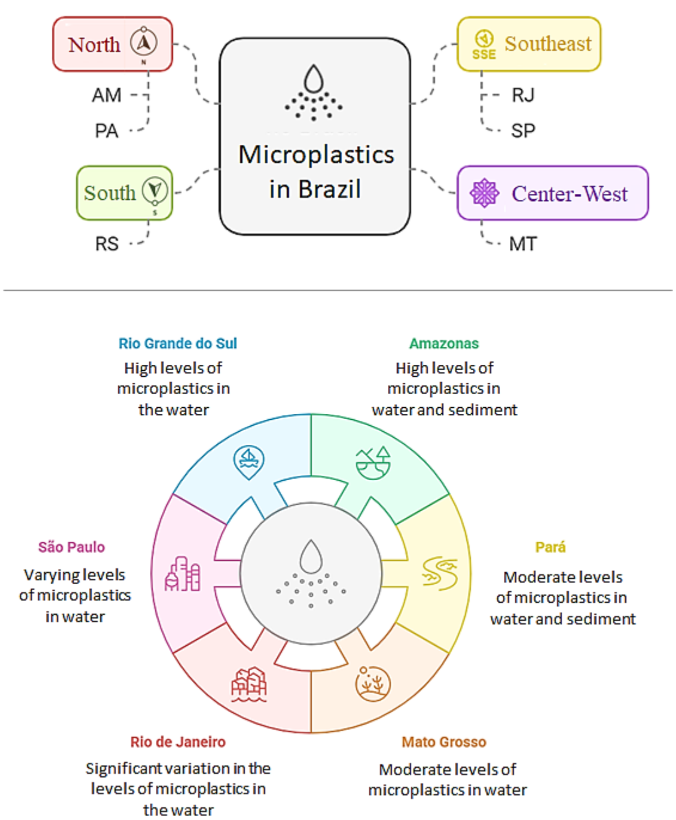
PC: physical characterization; CQ: chemical characterization; NC: not characterized; ATR: attenuated total reflectance; FTIR: Fourier transform infrared spectroscopy; µ-FTIR: Fourier transform infrared microspectroscopy; NIR-HSI: near-infrared hyperspectral imaging; SIMCA: soft independent modeling of class analogy; AM: Amazonas; RS: Rio Grande do Sul; MT: Mato Grosso; RJ: Rio de Janeiro; PA: Pará; SP: São Paulo.

In contrast to studies that focused solely on surface water, Moraes et al. (2024) reported the presence of microplastics and polychlorinated biphenyls (PCBs) adsorbed onto particles collected from the Tietê river (São Paulo). The concentrations of microplastics ranged from 6.67 to 1,530 items m^{-3}, with a predominance of polyethylene (PE, 58.17%) and polypropylene (PP, 23.53%). The most common forms found were fragments and fibers. The highest concentrations of PCBs were found in microplastics between 0.106 and 0.35 mm in size, ranging from 20.53 to 133.12 nanograms of PCBs per gram of microplastic.

The characterization of microplastics is divided into physical and chemical. Physical analysis, often conducted using optical microscopes (Table 1), is influenced by the subjectivity and experience of the observer, which can lead to overestimation or underestimation of the particles. For this reason, confirmation through chemical characterization is essential. Visual identification of microplastics remains a fundamental step in determining their morphological characteristics (size, shape, and texture), optical properties (color and reflectance), and physical and mechanical properties (flexibility, hardness, among others) (GESAMP, 2019; Lusher et al., 2020; Fernandes et al., 2022). This type of analysis helps identify potential sources of pollution and assess the degree of particle degradation.

The most established techniques for the chemical characterization of polymers are the spectroscopic methods. Fourier transform infrared spectroscopy (FTIR) and Fourier transform infrared microspectroscopy (µ-FTIR) are among the most widely used for microplastic identification (Blettler et al., 2017; Bertoldi et al., 2021; Silva and de Sousa, 2021; Costa et al., 2022; Costa et al., 2023; Drabinski et al., 2023; Rico et al., 2023; Souza et al., 2023; Santos et al., 2024). These techniques allow for the identification of the amount of light reflected, absorbed, or transmitted by the sample in an already defined spectral range. The results are then compared with infrared spectra stored in the equipment's libraries (Chen et al., 2020). Other techniques, such as near-infrared hyperspectral imaging (NIR-HIS), soft independent modeling of class analogy (SIMCA), Raman spectroscopy, micro-Raman spectroscopy, and hot needle testing, are also used.

As for the studies conducted on river sediments, none included chemical characterization, focusing solely on physical analysis. Gerolin et al. (2020) monitored three important rivers in the state of Amazonas—Negro river, Solimões river, and Amazonas river—and found values between 417 and 8,178 items kg^{-1} for particles from 0.063 to 5 mm and between 0 and 5,725 items kg^{-1} for particles from 0.063 to 1 mm. The highest concentrations of microplastics were observed at shallower sites (5–7 m). In comparison, Toyama et al. (2021) identified an average range of 94 to 956 items kg^{-1} in the Água Branca river basin (São Paulo), while Cardoso Neto et al. (2023) reported an average of 204.00±22.40 items kg^{-1} in the Xingu river (Pará).



Source: generated by Napkin AI on 01/15/2025.
AM: Amazonas; PA: Pará; RS: Rio Grande do Sul; RJ: Rio de Janeiro; SP: São Paulo; MT: Mato Grosso.
Figure 2 – Overview of the occurrence of microplastics in Brazilian rivers: states and contamination levels.

It should be noted that, to date, no national studies integrated the monitoring of microplastics in water and sediment within the same area and period. This gap prevents a more comprehensive, integrated assessment of these aquatic environments. In addition, the high standard deviations observed between minimum and maximum concentrations, as seen in the results of Drabinski et al. (2023), which ranged from 3.6 to more than 51,000 items m^{-3}, highlight the significant variability associated with the proximity of samples to pollution sources. Factors such as population density, intense urbanization, and inadequate solid waste management directly influence this variability and have been further evaluated and discussed in studies (Fahrenfeld et al., 2019; Mani and Burkhardt-Holm, 2020; Bertoldi et al., 2023; Drabinski et al., 2023).

Biofilm and Its Relationship With Microplastics

The biofilm is sensitive to the environment it is exposed to, and capable of absorbing and storing pollutants (Pu et al., 2019). As it represents the first level of the food chain, it can transfer pollutant loads to other trophic levels, justified by the organisms' bioaccumulation capacity (Dunck et al., 2019). Therefore, studying biofilm serves as a valuable tool for advancing our understanding of the aquatic ecosystem precisely because it is the base of the trophic web, is made up of sessile organisms, and has a rapid life cycle, i.e., it is the present representation of what occurs in the local environment (Zorzal-Almeida and Fernandes, 2021).

As it is a direct reflection of local pollution, biofilm can serve as an excellent matrix for investigating microplastics in freshwater environments. However, few studies explore the relationship between river biofilm and microplastic pollution, particularly regarding how biofilms may influence the association with other contaminants in the water. This area requires further research, as most of the work already carried out deals with the adsorption of metals on microplastics and how the biofilms present on their surfaces can affect the concentration of metals. Among the metals studied are silver, lead, cobalt, nickel, copper, zinc, and cadmium (Johansen et al., 2019; Kalčíková et al., 2020; Qi et al., 2021; Niu et al., 2022; Wu et al., 2022).

Table 2 provides an overview of the research conducted up to 2024 on quantifying ECs in microplastics, with a particular focus on studies dealing with biofilms. The investigations include identifying and quantifying contaminants in microplastics formed from different polymers and evaluating interactions between these contaminants and the biofilm formed on the microplastic surface.

As shown in Table 2, the majority of research has focused on quantifying the concentration of ECs in microplastics, with a secondary focus on the relationship between these pollutants and biofilms. In addition, some of the most recent studies are dedicated to exploring the adsorption capacity of microplastics. On the other hand, the studies by Ji et al. (2024) and Liu et al. (2024) specifically address how biofilms influence the adsorption dynamics of ECs on microplastics. Ji et al.

(2024) reported that the aging of microplastics, combined with the formation of biofilms, generates complex interactions that affect the adsorption of antibiotics. The ageing of microplastics introduces new surface functionalities, increasing their adsorption capacity, while biofilms can amplify or compete for binding sites, depending on their composition and thickness.

Table 2 – Research on emerging contaminants adsorbed on biofilm-associated microplastics in freshwater systems.

Authors (year)	Country	Micropollutants	Microplastics	Summary of the study
Magadini et al. (2020)	United States	Drugs (atenolol, sulfamethoxazole, and ibuprofen)	PET, HDPE, PVC, LDPE, PP	The adsorption of pharmaceuticals on eight types of materials (pellets of five types of polymers, small pieces of straws, fragments of bags, and glass beads) was investigated. The observations showed that extensive biofouling and biofilm formation in nutrient-enriched waters can significantly affect the adsorption of pharmaceuticals onto plastics.
Wang et al. (2021)	China	Antibiotic tetracycline (TC)	PE	The study investigated the adsorption of TC and copper (Cu(II)) on PE. Biofilm was formed on the microplastics exposed to fresh water and soil. Compared to virgin PE microplastics, the microplastics exposed to the environment showed more significant adsorption and stabilization capacity for Cu(II) and TC.
Hataley et al. (2022)	Canada	Microcystins	LDPE, PET, PVC, PP	The adsorption of four microcystin congeners to different commercially available plastic polymers was studied. In doing so, microplastics were tested regarding its influence on the partitioning of microcystins in freshwater lakes. In addition, biofilm's influence on microcystin sorption on microplastics and microplastics' aging was also investigated.
He et al. (2022)	China	Microcystin (MC-LR)	PS	The influence of PS microplastics on the behavior of MC-LR was studied. The results revealed that adsorption by PS- microplastics was the main process that led to a rapid reduction in aquatic concentrations of MC-LR. With the colonization of microorganisms on the PS- microplastics, the adhered biofilm altered the surface properties of the PS- microplastics, which increased the bioabsorption of MC-LR.
José and Jordao (2022)	Portugal	Polycyclic aromatic hydrocarbons (PAHs), benzo(a)pyrene (BaP), and pyrene (Pyr)	PET, HDPE, LDPE, PP, PS	The ability of some types of microplastics to adsorb BaP and Pyr in fresh water after 3 and 30 days was investigated. LDPE was the best surface for biofilm formation by bacteria, followed by HDPE and PS.
Kiki et al. (2022)	China	Bisphenol analogues (BPA, BPS, BPE, BPB, BPF, BPAF) and parabens (propylparaben, benzylparaben)	PE, PVC, PA	The influence of biofilms on the alteration of the surface of microplastics under study, structural change, and adsorption of organic micropollutants was evaluated. Biofouling significantly modified the intrinsic properties of the microplastics, leading to an increase in PE and PVC adsorption capacity by factors of 3.04–6.72 and 2.14–8.72, respectively.
Wang et al. (2022)	China	Antibiotics and antibiotic resistance genes (ARGs)	PLA, PVC	The degradation capacity of TC was compared between PLA and PVC microplastics and quartzite. Compared to the quartzite biofilm, the microorganisms in the plastisphere carried more ARGs.
Zhang et al. (2022)	China	Pesticides, hormones, antibiotics, drugs	PVC, PVC, PP	The effect of biofilms on microplastics on the adsorption of ECs was investigated employing field-laboratory exposure experiments. Three types of microplastics were naturally colonized with lake biofilms.
He et al. (2023)	China	Antibiotics	PVC, PA, HDPE	The formation of biofilms on three different microplastics was studied. From this, it was observed how the chemical structure, hydrophobicity, and other properties of the microplastics affected the microbial biomass and community composition. Potential pathogens were found in all biofilms formed on the three microplastics.
Ji et al. (2024)	China	Antibiotics: tetracycline hydrochloride (TC-HCl) and cephalexin (CFX)	PE	The adsorption of TC-HCl and CFX on PE was investigated: virgin, aged, virgin with surface biofilm, and aged with surface biofilm. It was observed that aging and biofilm formation alter the physicochemical properties of microplastics, influencing their adsorption capacity.
Liu et al. (2024)	China	Perfluoroalkylated and polyfluoroalkyl substances (PFASs)	PE, PVC	The dynamics of adsorption and desorption of PFASs on PVC and PE microplastics were studied, taking into account the presence of biofilms. The microplastics were aged *in situ* in lake water. The research sought to understand the role of biofilms in the interaction between microplastics and PFASs.

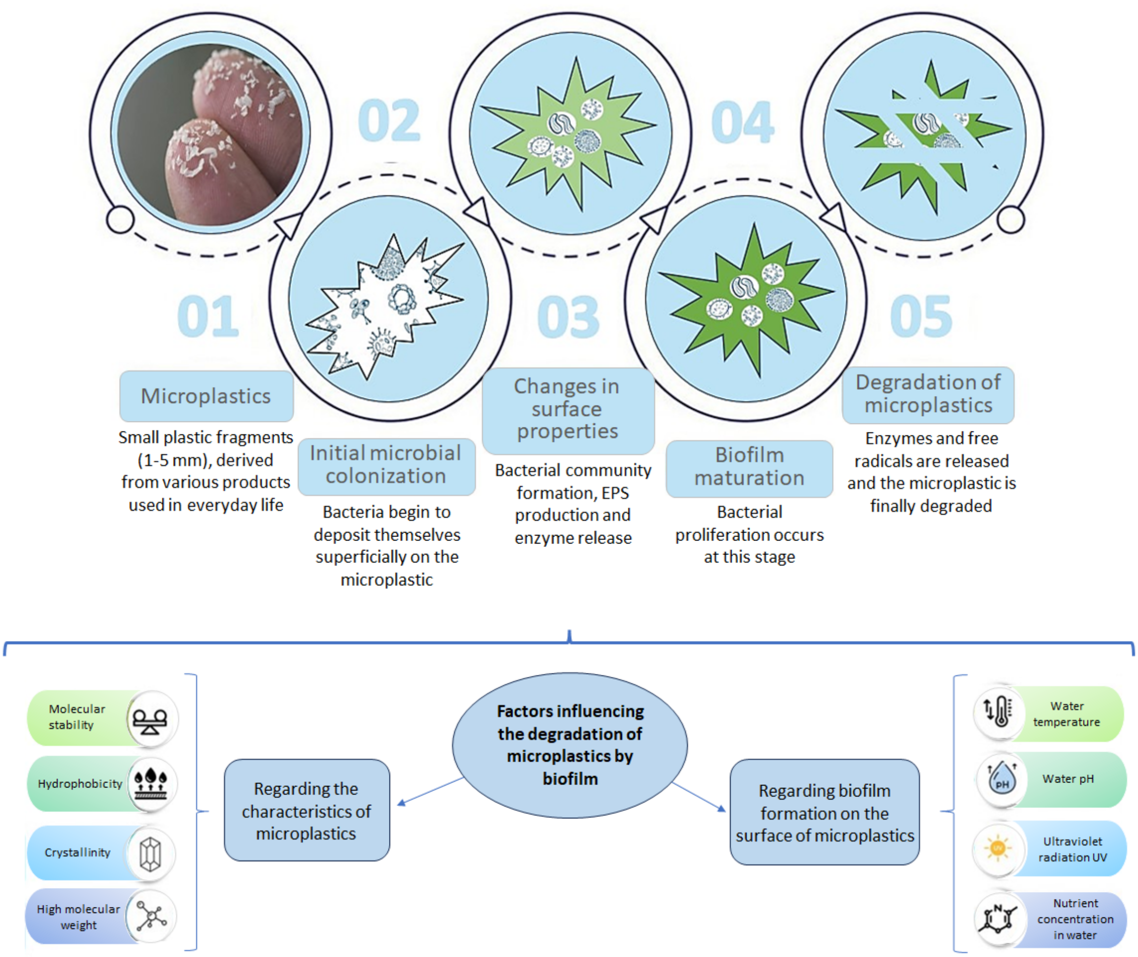
ARGs: antibiotic resistance genes; PLA: polylactic acid; PVC: polyvinyl chloride; PE: polyethylene; PA: polyamide; PET: polyethylene terephthalate; HDPE: high density polyethylene; LDPE: low density polyethylene; PP: polypropylene; PS: polystyrene; TC: tetracycline; TC-HCl: tetracycline hydrochloride; MC-LR: microcystin; PAHs: polycyclic aromatic hydrocarbons; BaP: benzo(a)pyrene, Pyr: pyrene; CFX: cephalexin; PFASs: polyfluoroalkyl substances.

Liu et al. (2024) demonstrated that the morphological characteristics of microplastics influence the distribution of long-chain per- and polyfluoroalkyl substances (PFASs) in water. The presence of hexafluoropropylene oxide dimeric acid (HFPO-DA) and perfluoro hexanoic acid (PFHxA) in the sediments was directly associated with the concentration and size of microplastics. The experiments revealed that the adsorption between microplastics and HFPO-DA intensifies the accumulation of this compound in the sediments. Moreover, the formation of biofilms on the surface of microplastics further accelerates this process. According to the authors, these findings provide a new perspective on the joint behavior of ECs in aquatic environments, highlighting the importance of considering the interactions between biofilms, microplastics, and contaminants when assessing ecological risks.

The microplastics in aquatic ecosystems undergo physical, chemical, and biological processes that alter their properties and influence their interaction with contaminants and organisms. Environmental exposure leads to the formation of the eco-corona, an initial layer composed of biomolecules and microorganisms adsorbed on the surface of the microplastics, which modifies their physicochemical properties (Galloway et al., 2017; Alimi et al., 2018). This eco-corona plays an important role in the adsorption of chemical contaminants and bioavailability to aquatic organisms (Hartmann et al., 2017; Wang et al., 2021; Yao et al., 2023).

In addition, eco-corona serves as a precursor for the formation of biofilms, which are more structured formations. Different microorganisms, such as bacteria, fungi, algae, archaea, protozoa, and protists, colonize the surface of microplastics, forming the biofilm (Zettler et al., 2013; Flemming, 2020; Guan et al., 2020). This colonization is facilitated by the hydrophobic nature of plastics, creating a favorable environment for microbial adhesion (Amaral-Zettler et al., 2020; Niu et al., 2022).

Biofilm formation on microplastics progresses through several stages that culminate in the biodegradation of the microplastic surface. First, initial colonization occurs, followed by the maturation of the biofilm, production of extracellular polymeric substances and, finally, the release of enzymes and free radicals that degrade the microplastics surface (Sun et al., 2023) (Figure 3).



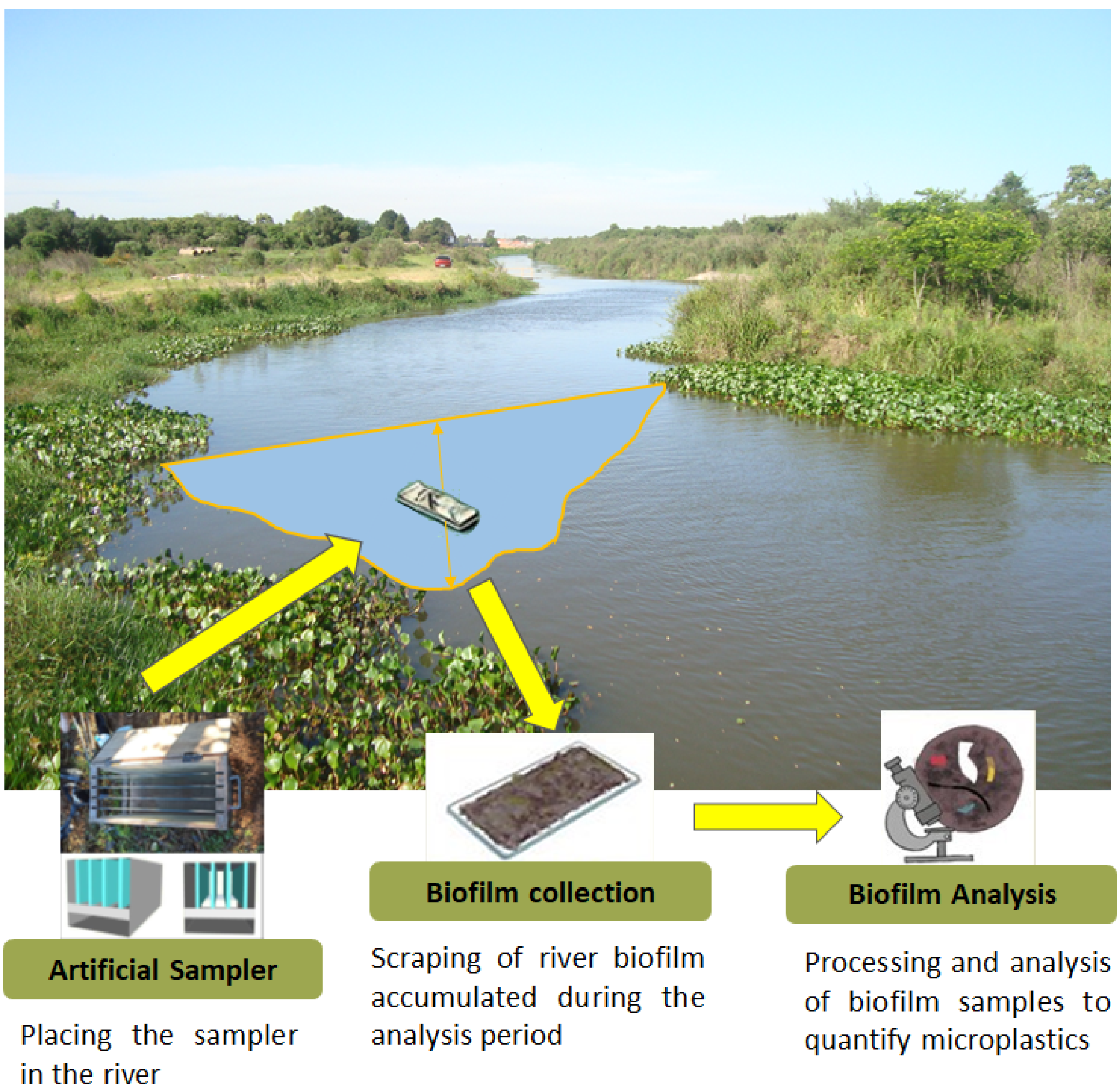
EPS: extracellular polymeric substance.

Figure 3 – Steps involved in the formation of biofilms, subsequent biodegradation of microplastic surfaces, and factors influencing degradation.

Factors influencing biodegradation include the characteristics of microplastics (such as molecular stability, hydrophobicity, crystallinity, and molecular weight) and environmental conditions such as temperature, pH, ultraviolet radiation, and nutrient availability. Amorphous plastic regions are more susceptible to microbial attack (Khoironi et al., 2020; Sun et al., 2023). Abiotic factors, such as ultraviolet radiation, destabilize the structure of microplastics, facilitating biodegradation (Zhang et al., 2021; Sun et al., 2023). Furthermore, aging processes, such as photothermal oxidation, mechanical degradation, and fragmentation, contribute to reducing the size of microplastics, increasing their surface area and adsorptive capacity for contaminants (Song et al., 2017; Guan et al., 2022; Lang et al., 2020).

Biofilm as a Bioaccumulator of Microplastics

Scientific research has only recently focused on biofilms as bioaccumulators. Most river studies assessed surface water (Table 1). To date, there is no research on integrated monitoring in the aquatic environment that seeks to evaluate the main differences in the results of the occurrence of microplastics in water and sediment. Studying these matrices together would make it possible to allow for the categorization of pollution levels' heterogeneity since, often, what is not found in water can be found in sediment. This approach is essential because sediment analysis reflects the contamination accumulated over time and highlights the possibility of these compounds being released into the water column (Biamont-Rojas et al., 2022). Similarly, river biofilm can act as a temporal record, showing pollutants that have passed through surface water at specific intervals.



Source: adapted from Reichert et al. (2021).

Figure 4 – Biofilm as an environmental matrix for monitoring microplastic pollution in rivers: artificial sampler, collection of the glass plate containing river biofilm, and processing and analysis of the biofilm sample for the quantification of microplastics.

The biofilm formation time can be calculated using artificial samplers. These devices allow for growth and subsequent collection at defined intervals, as the process of biomass formation begins when they are placed in water. Thus, selecting artificial substrates is crucial to control the incubation period, as demonstrated by Moschini-Carlos et al. (2000). It should be noted that, depending on the river width and the research objectives, multiple samplers can be used to obtain results that are more representative of reality. Figure 4 shows an example of an artificial sampler used in studies of river biofilms.

The sampler model in Figure 4 is made of wood and metal, supporting four glass plates inside. Glass is the substrate chosen for biofilm formation in this example. The sampler is fixed to the riverbed with metal rods and placed in the flow direction of the water body so that the water passes between the glass plates and the contaminants accumulate in the biofilm. Calculating the flow rate of the water passing through this is also possible.

Other artificial substrates for collecting biofilm include glass tiles and slate tiles (Andrus et al., 2013; Osorio et al., 2015). In the research by Reichert et al. (2021), a sampler with glass plates was used to investigate antibiotic-resistant bacteria. In the analysis of water, sediment, and biofilm from the Kraichbach river, in Germany, antibiotic resistance genes (ARGs) and genetic markers for facultative pathogenic bacteria (FPB) were investigated. The results showed that the highest concentration of ARGs and FPB was found in the biofilm. This indicated that the biofilm acted as an excellent bioaccumulator of these genes and more accurately represented the presence of these contaminants in the watershed relative to water and sediment.

In the research conducted by Marques et al. (2024), glass plates were also used as artificial substrates. The authors evaluated the biofilm's potential for accumulating ultraviolet filters. In this way, a comparison was made between the analysis of water and biofilm from the same study area. The results showed maximum concentrations of 5.85 $\mu g\ L^{-1}$ of benzophenone-1 in the water and 1,907.40 $\mu g\ kg^{-1}$ of benzophenone-3 in the biofilm. The biofilm offered a broader view of anthropogenic impacts over time an stood out as an environmental monitoring tool since water only reveals the concentration at the time of collection.

The aforementioned studies demonstrated that biofilm acts as an efficient bioaccumulator of contaminants, with concentrations significantly higher than those found in water and sediment. Artificial samplers have proven to be accessible and effective tools for monitoring pollution in rivers, facilitating the collection and analysis of biofilms. By integrating variables such as formation time and flow rate, biofilm studies offer a more comprehensive perspective of environmental contamination than isolated analyses of water or sediment. As a result, biofilm emerges as a promising environmental matrix for monitoring microplastics in urban waterways, especially in stretches where microplastic levels in the water are low. Its ability to accumulate contaminants over time allows for a more accurate assessment of prolonged environmental exposure.

Research on microplastics in biofilms in conjunction with ECs represents a new scientific approach to understanding environmental impacts in aquatic ecosystems. Biofilm can serve as an integrated matrix for evaluating synergies and patterns of co-occurrence between different pollutants. Studies that combine the analysis of ECs with microplastics can provide a deeper insight into anthropogenic pressures on aquatic environments. This research field can not only enhance our understanding of the mechanisms of accumulation and interaction in the biofilm but also support the development of more effective strategies for monitoring and mitigating pollution in rivers and other bodies of water.

Conclusions

The research conducted so far highlights the importance of continuous environmental monitoring, both for the scientific growth of the subject in question and for the need for more comprehensive studies on the occurrence of microplastics in Brazilian rivers. Since Brazil is a country of continental dimensions and with different hydrological and socio-environmental realities, specific to each region, further research is crucial. The literature review showed that an integrated study of the environmental matrices of water and sediment would greatly contribute to a better understanding of the behavior of microplastics in water bodies. In addition, the use of biofilm as an additional matrix for comparing results would add even more to environmental monitoring, precisely because of its great capacity for accumulation. It would also make it possible to investigate microplastics together with other emerging contaminants. Artificial samplers have proven to be a valuable tool for new perspectives in the study of plastic pollution, not only in terms of adsorption but also in relation to bioaccumulation and biodegradation. Considering the importance of scientific exploration of the subject, biofilm could be studied in future work with the aim of identifying spatio-temporal patterns of contamination. Based on these observations, the study of biofilm could provide valuable insights for the development of public policies aimed at managing water resources.

Authors' Contributions

Chaves, J.R.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review & editing. **Nawate**, B. A. L.: formal analysis, investigation, methodology, visualization, writing – original draft, writing – review & editing. **Modkovski**, T.A.: investigation, writing – original draft, writing – review & editing. **Leite**, L.T.: investigation, visualization, writing – original draft, writing – review & editing. **Martins**, L.R.R: conceptualization, funding acquisition, resources, programs, validation, writing – original draft, writing – review & editing. **Knapik**, H.G.: conceptualization, funding acquisition, resources, programs, validation, writing – original draft, writing – review & editing. **Azevedo**, J.C.R.: conceptualization, funding acquisition, resources, programs, supervision, validation, writing – original draft, writing – review & editing.

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