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Urban River Microplastics as Vectors for Pharmaceutical Contaminants in a Savannah Region (Caatinga Biome)

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Abstract

The study investigates the presence of emerging contaminants in a river within a watershed located in the Brazilian semiarid region, specifically within the Caatinga biome, emphasizing the importance of environmental monitoring in areas that have historically been underrepresented in scientific research. The analysis focused on the associations between microplastics and pharmaceutical compounds, demonstrating that the discharge of untreated domestic effluents and the low efficiency of sanitation systems increase water resource contamination and threaten water security. The interdependence between these variables underscores the need for integrated public policies for waste management, complemented by environmental education strategies and technological innovations. The work makes an unprecedented contribution to expanding knowledge about emerging pollutants in semiarid environments, highlighting the urgency of holistic approaches, continuous monitoring, and strengthening environmental governance to ensure the sustainability and resilience of ecosystems like the Caatinga in the face of the challenges posed by global environmental change, urban growth, and those outlined in the Sustainable Development Goals.

Keywords: emerging pollutants; drug residues; μ-Raman spectroscopy; sanitation; water resources; SDG

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1. Introduction

Plastic production and consumption continue to increase globally, and ineffective waste management sustains high inputs of this type of debris into aquatic environments [1,2]. In rivers and reservoirs, the progressive fragmentation of larger items and the direct release of industrial pellets and synthetic fibers generate microplastics (MP; <5 mm), which have become ubiquitous in freshwater systems [3,4].

Freshwater environments are particularly relevant because they integrate multiple land-based sources (urban runoff, wastewater discharges, and diffuse inputs from agriculture and informal dumping) and act as conduits transporting plastic particles downstream [5,6]. Once present, MP exhibit heterogeneous transport and residence times driven by particle size, density, biofouling, and hydrodynamics, resulting in complex spatial patterns and variable exposure for aquatic organisms and water users [4,7].

Beyond their physical presence, MP are increasingly viewed as reactive surfaces capable of concentrating chemicals from surrounding waters and subsequently mediating their transport and bioavailability [8]. Sorption is controlled by polymer type, crystallinity, surface area, additive content, and the environmental matrix, which collectively modulate a range of key variables (e.g., pH, dissolved organic matter, salinity, and sunlight exposure), and is frequently enhanced as particles weather and develop oxygen-containing functional groups and higher surface roughness [9].

This "vector effect" is well-documented for hydrophobic organic contaminants and metals, but it is also relevant to pharmaceuticals, an essential class of emerging contaminants in surface waters [8,10–14]. Model-supported reinterpretations indicate that the magnitude and direction of MP-mediated chemical transfer depend on concentration gradients and exposure pathways, rather than on plastic presence per se [15].

Nevertheless, growing experimental evidence shows that weathered MP can substantially increase the adsorption of commonly used drugs, strengthening the plausibility of MP-assisted transport in freshwater [16–18]. Recent syntheses similarly highlight pharmaceuticals among the contaminant groups reported on MP surfaces in freshwater and identify a need for more field-based evidence linking MP occurrence with these residues under realistic environmental conditions [14,19].

Addressing this niche requires analytical approaches that can reliably characterize MP and screen co-occurring chemical signatures at environmentally relevant sizes. In this context, μ-Raman spectroscopy (and μ-Raman microscopy) stands out as a fundamental tool for identifying MP and contaminants adsorbed on their surfaces. Based on inelastic light scattering, this non-destructive technique yields molecular "fingerprints" that enable detailed characterization of synthetic polymers and organic compounds [20–23].

Given the widespread occurrence of MP in diverse environments, including freshwater systems, μ-Raman has become essential for supporting environmental and human-health risk assessments [24–27]. The non-destructive method allows discrimination among polymer types and identification of associated contaminants, such as additives and pharmaceutical residues [28–30].

When coupled with microscopy and particle imaging, it enables particle-by-particle characterization at high spatial resolution, including very small MP (<20 μm) that are often underrepresented by bulk approaches, and provides information on composition, potential origin, and exposure to pollutants even in complex matrices with high organic loads, such as urban rivers [28,31–33]. Consequently, μ-Raman microscopy is an indispensable resource for advancing understanding of MP as pollutant vectors in aquatic ecosystems [27].

The semiarid Northeast of Brazil provides a particularly relevant setting for investigating microplastics–pharmaceutical interactions, because recurrent droughts and intermittent river regimes intensify pressures on surface-water availability and quality, thereby increasing the need for robust monitoring of multiple stressors [34,35]. In Caatinga river systems, the presence and dynamics of MPs warrant urgent attention, given that the sorption capacity of plastic particles can facilitate the retention and transport of harmful substances, potentially compromising water security, affecting aquatic ecosystems, and threatening water uses for supply and irrigation [36,37]. Understanding whether MP and pharmaceuticals co-occur in these freshwater environments, and the extent to which MP may act as carriers,

can therefore inform risk assessment and mitigation strategies aligned with the sustainable development agendas [38].

Accordingly, this study applies μ-Raman microscopy to identify MP particles and pharmaceutical compounds in surface-water samples collected along a river reach in the semiarid Northeast of Brazil (within the Caatinga biome, which remains comparatively understudied with respect to this problem) and to explore their potential co-occurrence. More broadly, monitoring MP using techniques such as μ-Raman spectroscopy can support the sustainable management of water resources and the formulation of evidence-based public policies [39,40], reinforcing progress toward the Sustainable Development Goals, particularly SDGs 6, 12, 14, 15, 3, and 9 [38].

2. Methodological Approach

2.1. Study Area and Fieldwork Sample Points

Sampling was carried out at two sites (P1 and P2) along a 16-km reach of the Granjeiro River (GR) within the Caatinga, a Brazilian savannah biome that covers approximately 10% of the national territory. Characterized by high biodiversity and strong adaptation to semi-arid conditions, the Caatinga plays a key role in climate regulation, hydrological cycling, and the maintenance of natural resources [41,42]. The GR watershed drains ~12,865 km^2 and crosses the urban areas of Crato and Juazeiro do Norte, where it receives substantial domestic and industrial effluent inputs from a combined population of approximately 417,170 "https://www.ibge.gov.br/ (accessed on 7 August 2025)" across both municipalities [43,44] (Figure 1).

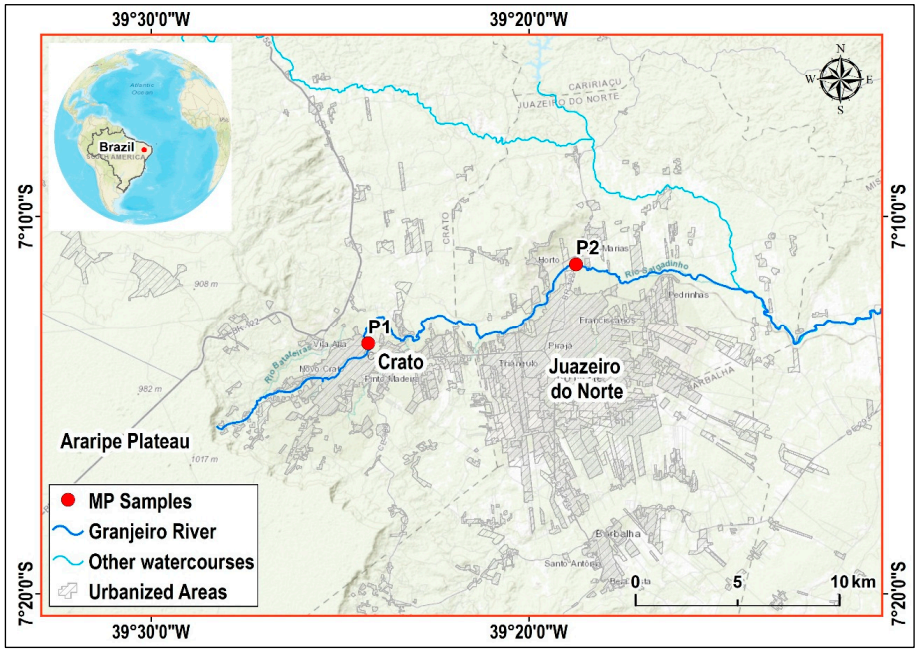

Figure 1. Microplastic (MP) sample collection points in the aquatic environment of the semiarid northeastern region of Brazil.

The Granjeiro River becomes channelized shortly downstream from its headwaters, modifying its flow dynamics and increasing public access to the channel bed and margins, encouraging the direct and irregular disposal of solid waste and the entry of sewage through clandestine connections of domestic effluents into the drainage network. The surrounding urban region sustains intense activities, including religious tourism, and productive sectors such as jewelry and footwear manufacturing, aluminum goods production, and plastic recycling, and it also includes the legacy of a deactivated dump and two sanitary landfills

currently in operation [45,46]. Juazeiro do Norte is additionally ranked among Brazil's ten worst municipalities for both total and urban sewerage service coverage in the 2025 national sanitation ranking [47].

The semiarid regional climate is marked by mean temperatures of 24–26 °C and irregular precipitation controlled by atmospheric systems such as Upper Air Cyclonic Vortices and the Intertropical Convergence Zone [48,49]. From a hydrological perspective, the area is distinguished by the dominance of intermittent rivers and strong reliance on sedimentary aquifers associated with the Araripe Plateau (AP) [50]. Local geodiversity encompasses the AP and the Cariri Valley, both recognized for their hydrogeological relevance [51]. Framing the study area within the Araripe Geopark—the first UNESCO-recognized geopark in Brazil "https://www.unesco.org/en/iggp/geoparks?hub=67817#full-list-of-unesco-global-geoparks (accessed on 7 August 2025)", further underscores the need for integrated environmental management [52–55].

2.2. Polymer Treatment and μ-Raman Characterization

Sample treatment and characterization included: (i) evaporation; (ii) removal of organic matter; (iii) density separation; (iv) filtration; (v) counting; (vi) MP characterization. Water samples (100 mL) were evaporated in covered porcelain dishes using the bain-marie method (60 °C). Subsequently, 20 mL of a 0.05 M $FeSO_4$ solution (reaction catalyst) and 30% hydrogen peroxide (H_2O_2) were added, waiting 24 h to remove the organic matter present, given the low sewage treatment rate in the region [56–58]. Subsequently, MP flotation was performed by density separation using approximately 6 g of NaCl per 20 mL of sample. They were then vacuum filtered with 0.45 μm glass microfiber filters [56–58]. Finally, the filters were dried in desiccators at room temperature, and subsequently, the MP were counted and identified using an optical microscope (20× to 100×) with a light source (Figure 2).

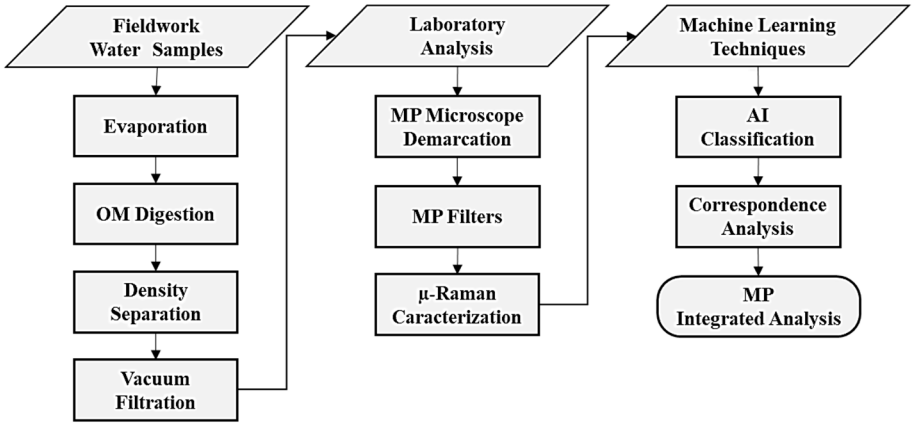

Figure 2. A flowchart summarizing the step method used in this research.

The polymeric characterization of MP and associated substances is performed by acquiring μ-Raman spectra with a labRAM HR Evolution (HORIBA) instrument equipped with lasers at different wavelengths (473, 532, 633, and 785 nm) and a 50× long-range objective (NA = 0.55). The materials are initially tested at various power levels to obtain optimal spectra without damaging the samples, prioritizing the observation of the polymer identification region (fingerprint), which is located near 1600 cm^{-1}. The spectral range adopted in the definitive measurements goes from 200 to 3200 cm^{-1}, covering the polymer fingerprint region and the C-H bond stretching (2800–3100 cm^{-1}), which indicates alkanes, alkenes, and alkynes [28,59–61]. Additional adjustments, such as integration time, number

of accumulations, and slit diameter, are made to optimize the signal-to-noise ratio and avoid sensor saturation (Figure 2).

2.3. Learning Integrated Analysis

After acquisition, the spectra are corrected for baseline and cosmic-ray noise using a Matlab® routine (version R2017b). Finally, the spectra are compared with the Knowitall® software v2024.1 database for polymer identification, complemented by images obtained with the µ-Raman system coupled to microscopy.

Given the nature of the data, we employed exploratory multivariate correspondence analysis (CA). This algorithm was chosen based on its simplicity and effectiveness to examine qualitative variables, also known as latent or categorical variables, which cannot be measured directly but can be categorized or counted [62,63]. CA examines associations between variables of interest using the chi-square test (χ^2; p-value < 0.05). Adjusted standardized residuals (ASR) assess the dependent relationships between each variable based on the critical reference value of the standard normal curve at the 5% significance level. Thus, if the ASR value in a cell is greater than or equal to 1.96, there are significant dependent relationships [62,64,65]. All statistical analyses were performed using Python in Spyder v. 6.0.7 software (Figure 2).

3. Results

3.1. Absorbed Drugs

Table 1 highlights the leading pharmaceuticals found at the sampled sites and their applications/uses, according to established references. The polymer 5-Vinyl-2-norbornene (5VNB), present in synthetic rubbers and epoxy resins, appears alongside 6-Amino-3-bromo-2-methylpyridine (ABMP), a chemical precursor derived from pyridine, relevant to pharmaceutical synthesis [66–68]. Poly(phenylene sulfide) (PPS), valued for its high strength in energy and electronics applications, adsorbs acetamide (ACM), a diuretic, indicating the role of these MP as vectors for specific drugs [69–74]. Carboxymethylated cellulose sodium salt (CMC), widely used for its thickening and stabilizing properties in pharmaceutical formulations [75], was found with gatifloxacin (GFLX), a broad-spectrum antibiotic [76–78].

Polyethylene terephthalate (PET), prevalent in aquatic environments due to irregular disposal, mainly of packaging, appears together with Norketamine HCl (NK, an antidepressant), 3,7,8,2′-Tetrahydroxyflavone (THF, an antioxidant), and 5-Nitroisatin (5NI, an antibiotic), as well as All-Trans Retinoic Acid (ATRA, a dermatological and oncological medication). Demonstrating the versatility of MP in transporting both simple and highly complex pharmaceutical compounds [79–90] (Table 1).

In the same Table 1, Tetraethylsilane (TES), used mainly in the electronics industry as a precursor for silicon thin films, appears adsorbed to ATRA, showing that different polymeric matrices can serve as supports for bioactive substances [89–92]. Polystyrene sulfonate (PSS), a superplasticizer, was found in combination with both ATRA and 1,3,7-trimethylxanthine (CAF), also known as caffeine, a central nervous system stimulant. At the same time, polysulfone (PSU) was observed with 5NI, demonstrating the diversity of interactions between polymers and drugs in aquatic environments [89,90,93–96].

Table 1. Characterization of polymers and pharmaceuticals associated with microplastics (MP) in the aquatic environment of the semiarid northeastern region of Brazil. Poly(ethylene terephthalate), Polyester Film 3000 Series, and Polyester Film are all names for products made from the same base polymer: polyethylene terephthalate (PET), and they share the same Chemical Abstracts Service (CAS) number.

Sample	Polymer	PolymerCAS	PolymerCod	Pharm	PharmCAS	PharmCod	PharmType
P1	5-Vinyl-2-Norbornene	3048-64-4	5VNB	6-Amino-3-bromo-2-methylpyridine	42753-71-9	ABMP	Chemical Precursor
P1	Poly(phenylene sulfide)	25212-74-2	PPS	Acetamide	60-35-5	ACM	Diuretic
P1	Cellulose, Carboxymethyl, Sodium Salt	9004-32-4	CMC	Gatifloxacin	112811-59-3	GFLX	Antibiotic
P1	Poly(ethylene terephthalate)	25038-59-9	PET	Norketamine HCl	79499-59-5	NK	Antidepressant
P1	Poly(ethylene terephthalate)	25038-59-9	PET	3,7,8,2′-Tetrahydroxyflavone	438001-91-3	THF	Antioxidant
P1	Poly(phenylene sulfide)	25212-74-2	PPS	All-Trans-Retinoic Acid	302-79-4	ATRA	Dermatological-Oncological
P1	Tetraethylsilane	631-36-7	TES	All-Trans-Retinoic Acid	302-79-4	ATRA	Dermatological-Oncological
P1	Tetraethylsilane	631-36-7	TES	All-Trans-Retinoic Acid	302-79-4	ATRA	Dermatological-Oncological
P1	Polystyrene sulfonate	9080-79-9	PSS	All-Trans-Retinoic Acid	302-79-4	ATRA	Dermatological-Oncological
P1	Polystyrene sulfonate	9080-79-9	PSS	1,3,7-Trimethylxanthine	58-08-2	CAF	CNS Stimulant
P1	Tetraethylsilane	631-36-7	TES	All-Trans-Retinoic Acid	302-79-4	ATRA	Dermatological-Oncological
P2	Polysulfone	25135-51-7	PSU	5-Nitroisatin	0611-09-06	5NI	Antibiotic
P2	2-Acetyl-5-norbornene, mixture of endo and exo	5063-03-06	ANE	AG-494	133550-35-3	AG-494	Inhibitor
P2	Poly(ethylene terephthalate)	25038-59-9	PET	5-Nitroisatin	0611-09-06	5NI	Antibiotic
P2	Polyester Film 3000 Series	25038-59-9	PFS3K	5-Nitroisatin	0611-09-06	5NI	Antibiotic
P2	Polyester Film	25038-59-9	PF	5-Nitroisatin	0611-09-06	5NI	Antibiotic
P2	Poly(ethylene terephthalate)	25038-59-9	PET	5-Nitroisatin	0611-09-06	5NI	Antibiotic

3.2. Analysis of Associations and Relationships

The CA reveals a statistically significant association between the collection points, the types of polymers identified, and the pharmaceutical residues adsorbed on the MP (χ^2 = 105.000; p = 0.03194). This result indicates that the observed associations between polymers and drugs are not random, reflecting specific adsorption relationships in the urban aquatic environment of this semiarid Northeast region. The perceptual map in Figure 3 identifies the following dependent relationships, with strong intensity (i.e., they presented a significant result) in P1 between: (i) polymer 5VNB and the drug ABMP (ASR = 4.01); (ii) polymer CMC and GFLX (ASR = 4.01); (iii) PET with NK (ASR = 2.67)

and with THF (ASR = 2.67); (iv) PPS and the antibiotic ACM (ASR = 2.67) and caffeine CAF (ASR = 2.67); (v) TES with ATRA (ASR = 2.31), widely used in dermatological and oncological treatments. Similarly, at point P2, we found that the polymer ANE has a strong dependence relationship with the drug AG-494 (ASR = 4.01), a pharmacological inhibitor. For the other polymers at the same collection point (P2), no statistically significant dependence relationships were found between the polymers and the drugs (ASR < 1.96).

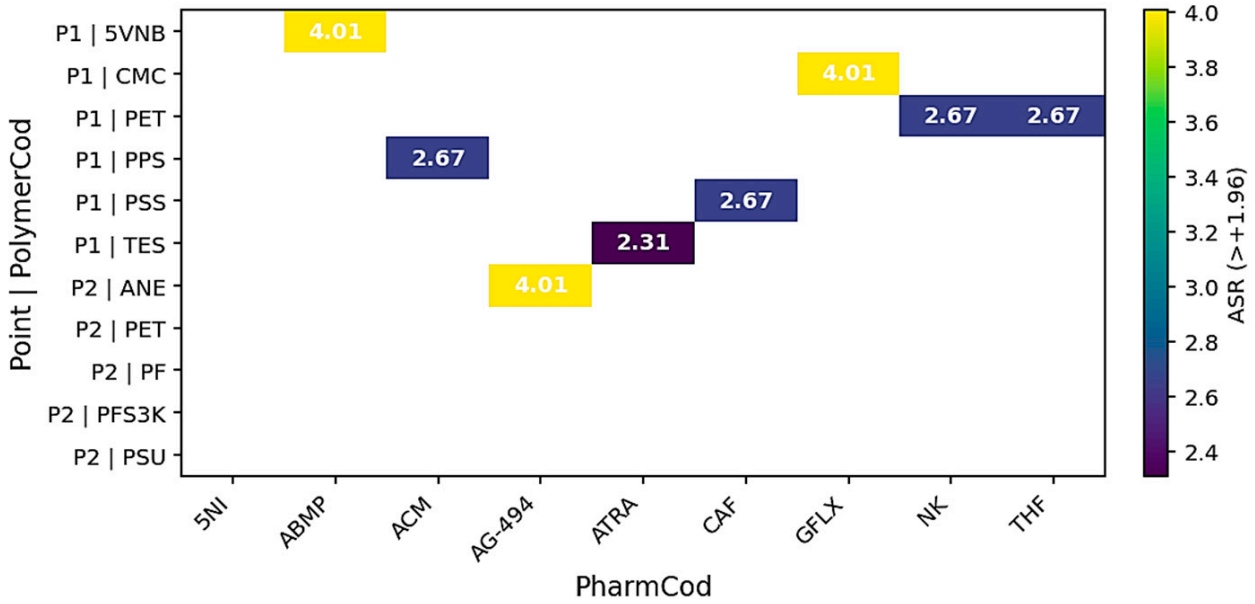

Figure 3. Perceptual maps showing the standardized adjusted residual (ASR) values between collection points, types of polymers identified, and pharmaceutical residues adsorbed on microplastics (MP). The colored cells indicate significant relationships between variables (+1.96 ≤ good ASR). The acronyms for the X and Y axes can be found in Table 1 (PolymerCod and PharmCod).

4. Discussion

4.1. Pharmaceutical Vector Mechanisms

The role of MP as vectors of pharmaceutical contaminants has gained prominence due to their increasing presence in urban and natural aquatic environments [29,30,97,98]. MP not only act as physical substrates but also as transporters (by adsorption) of different pharmaceutical residues, such as antibiotics, antidepressants, antioxidants, chemical precursors, and dermatological-oncological drugs, increasing environmental and human health risks [99–109].

Since certain polymers can act as preferred carriers for specific contaminants in the aquatic environment [110–112], we can consider them as true "Trojan Horses" [113]. Adsorption processes on MP can occur via various physicochemical mechanisms that depend on the polymer properties, contaminant characteristics, and environmental conditions [14]. Among them are hydrophobicity and hydrophilicity, surface charge, and functional groups [114], which are associated with partition mechanisms, intermolecular hydrogen bonds, and electrostatic and aromatic stacking (ring–ring) interactions that influence and govern the adsorption of pharmaceutical products to these materials [115].

In this case, adsorption is favored by the environmental aging of the polymers, which modifies their surface properties such as polarity and morphology, making them rougher and selectively modulating their affinity for different classes of drugs. This ultimately increases their capacity to transport harmful substances [110,111,116], consequently making them even more efficient in capturing contaminants by increasing their affinity for organic

compounds and heavy metals [30,97,117]. Furthermore, environmental factors such as pH and salinity also alter the intensity and selectivity of adsorption [8,14,118].

4.2. Polymer–Drug Interactions

Results from several compiled studies point to the predominance of hydrophobic interactions for antibiotics, aromatic hydrocarbons, and chemicals acting as endocrine disruptors, as well as the relevance of aromatic stacking interactions in polymers such as polystyrene and electrostatic interactions in systems where there is a difference in charges between contaminants and PM [118].

Among the polymers found in the present study, PSS is characterized as a non-polar, non-biodegradable aromatic polymer with delocalized aromatic electron systems and an amorphous structure, properties that contribute to its high adsorption capacity [115]. PET, in turn, exhibits high adsorption capacity, attributed to its greater diffusivity, resulting from the high free volume, greater flexibility, and mobility of its polymer chain, which favor the rapid diffusion of organic compounds in its matrix [119].

Regarding the drugs absorbed by the MP found, they represent an unprecedented survey for this type of environment (Caatinga biome urban river) [120,121]. Among the critical polymer-drug pairs identified in the GR studied area, the following stood out: 5VNB associated with a chemical precursor (ABMP), CMC with an antibiotic (GFLX), PET with an antidepressant (NK) and antioxidant (THF), PPS with acetamide (diuretic), PSS with caffeine (central nervous system stimulant), and TES with a dermatological-oncological drug (ATRA).

To make matters worse, the literature points out that such complex interactions between MP and pharmaceutical-drug residues are also a concern due to the possibility of synergistic effects, since the joint transport of these substances can intensify exposure to mixtures of contaminants with potential adverse effects that are still poorly understood [30,96]. Furthermore, the association between MP and these residues can raise the environmental persistence of these contaminants, increasing the ecotoxicological risk, and facilitate bioaccumulation and biomagnification processes along the trophic chain, expanding the risk of exposure for aquatic organisms and human populations [30,103,104,122], especially in regions that lack efficient sewage treatment systems [103,104].

Considering also the aforementioned environmental conditions of the aquatic environment and the availability of aromatic rings, hydroxyls and carbonyls present in all drugs with statistical significance observed (see "Data Availability Statement" to Supplementary Materials for chemical structures), we understand that the occurrence of these substances with the respective MP is chemically possible, and that the water quality conditions added to the degree of polymer degradation define the favorable scenario for interaction between them [9,14,16,123,124].

This fact was previously noted by Kalaronis et al. (2024) [17] when investigating the adsorption of a mixture of seven drugs (Diclofenac, Ketoprofen, Valsartan, Indomethacin, Trimethoprim, Isoniazid, and Metronidazole) on virgin and aged polylactic diacid MP, it was found that adsorption can occur simultaneously for all compounds analyzed, despite the differences in their physicochemical Properties [12,16].

In our study, the statistically significant associations between the collection points, types of polymers identified, and drugs adsorbed on the MP show that the observed relationships are not random, but rather the result of specific physicochemical interactions between the polymeric surfaces and certain pharmaceutical contaminants [97,125,126]. Of particular note are polymers that are statistically associated with specific drugs (X^2 test) and dependently related to them (ASR analysis). This can be considered the most essential and innovative result of the work, especially for the region studied [39,40].

4.3. Ecotoxicological Risks and Modeling

Recent studies have demonstrated that the accumulation of contaminants, such as antibiotics adsorbed by MP, can promote bacterial resistance in the environment, exacerbating one of the primary challenges to contemporary public health [76,77,127]. Furthermore, it can result in toxic effects, endocrine disruptions, and sublethal impacts that compromise biodiversity and food security [112,128]. Here, computational chemistry emerges as a possibility for understanding the molecular interactions between molecular molecules and drugs, through tools such as modeling, mainly molecular dynamics simulation (SDM), since this technique allows the energetic evaluation of the interactions by mapping the preferential adsorption sites and the influence of environmental variables such as pH, temperature, presence of ions, including non-binding interactions such as van der Waals forces, electrostatic attractions and hydrogen bonds [129,130].

The presence of compounds such as antidepressants, antioxidants, and oncological drugs can interfere with the physiological processes of aquatic organisms, impacting biodiversity and related ecosystem services [85,89,90]. It is therefore evident how the chemical diversity of MP broadens the spectrum of adsorbed molecules and, consequently, the ecological and toxicological risk for the entire environment exposed to them [4,37,112,131–133].

Environmental management in semiarid regions, such as this watershed located in the Caatinga biome, faces complex challenges due to low sanitation rates, high domestic and industrial sewage loads, and the increasing use of pharmaceuticals [47]. Inefficient waste treatment and disposal exacerbate water pollution, increasing risks to environmental and human health [38,44,128]. Plastic recycling in Brazil is still incipient compared to developed countries, resulting in the accumulation of this type of waste and its fragmentation into MP, which, as already noted, act as adsorbents and vectors for pollutant transport [117,134]. Furthermore, emerging pollutants, such as MP themselves, pharmaceuticals, and organic and inorganic contaminants, have been detected in different environmental sample sets (matrices), including in low-population-density regions, where public policies for waste management and sanitation are historically insufficient [103,104,135].

In the Caatinga region, the relevance of this topic is even greater, considering the region's history of scientific neglect and underinvestment in water infrastructure [41,128]. Semi-arid environments are particularly vulnerable to environmental degradation due to water scarcity, climate variability, and low ecosystem resilience [34,35,42,136–138]. Recent studies demonstrate that, in addition to diffuse pollution, there is a lack of systematic monitoring and interdisciplinary approaches that integrate public health, geosciences, and environmental policies to address the challenges posed by emerging pollution [43,44]. Thus, the adoption of innovative technologies for monitoring contaminants, associated with community participation and environmental education, has become a fundamental part of supporting mitigation and conservation strategies [38,44].

4.4. Monitoring, Methods, and Governance

Regarding the analysis method: consolidated as a sensitive and non-destructive tool for the identification of MP and contaminants adsorbed in environmental matrices, μ-Raman spectroscopy has been widely used due to its high molecular selectivity and in situ analysis capability [22,25,28]. Its application enables not only the detection and differentiation of different polymers but also the characterization of organic and inorganic contaminants associated with the particles, thereby facilitating bioaccumulation investigations and source tracking [31,134].

Furthermore, controlled laboratory experiments have enabled analysis of pollutant adsorption behavior and the interactions of different types of plastics with these drugs,

revealing relevant mechanisms and dynamics. However, such approaches have significant limitations in faithfully reproducing the complex environmental conditions [129,139].

That said, it is essential to highlight its limitations, especially in complex matrices, in which there is significant interference from organic matter, minerals, or biofilms, making it challenging to obtain high-quality spectra and, consequently, the accurate identification of specific polymers, such as polyethylene and polypropylene [28,33]. Furthermore, the detection of MP smaller than 10 µm still faces technical challenges related to both sample preparation and spectral resolution, as well as Raman signal intensity [22,58]. Therefore, although it is a powerful tool, the effectiveness of µ-Raman spectroscopy depends on the refinement of preparation and analysis techniques, as well as integration with other spectroscopic methods to overcome these limitations presented by complex environments [22,25,28].

All these challenges are intrinsically linked to the achievement of the Sustainable Development Goals (SDGs), especially SDGs 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), 14 (Life Below Water), 15 (Life on Land) and which demand the integration of science, environmental health and water governance [38,44]. Therefore, the articulation of effective public policies, based on scientific data and interdisciplinary approaches, is essential to guarantee water security, promote environmental justice, and ensure the sustainability of Caatinga ecosystems in the face of contemporary anthropogenic pressures [38,103,104,117,128,134].

5. Conclusions

This study, in an unprecedented manner, highlights the complexity and severity of the challenges posed by contamination of urban aquatic environments, particularly in the Caatinga region, a semiarid biome that has been relatively understudied, especially from the perspective of emerging pollutants. The results demonstrate that, in addition to the already well-known problem of improper domestic sewage disposal, there is a worrying overlap between solid waste, particularly MP, and chemical pollutants such as pharmaceutical residues, increasing risks to environmental health and regional water security.

Among the main findings, we identified a significant relationship between the presence of MP (considering certain polymer classes) and the use of certain medications used continuously and intensively by the population. This relationship suggests that, in addition to sharing the same entry routes into the aquatic environment, these pollutants can interact synergistically, altering dispersion and bioavailability patterns. This reinforces that MP acts as a vector for the transport of pharmaceutical residues, promoting both the adhesion of molecules and the increased persistence of these compounds in the environment. This process also increases the exposure of aquatic organisms to complex mixtures of contaminants, which can cause cumulative toxic effects, endocrine changes, and ecosystem impacts that are still poorly understood.

In this sense, low sanitation rates, as described, and inefficient solid waste management exacerbate water contamination. Improperly disposed of plastic waste eventually fragments into MP, increasing the pollutant load in the aquatic environment. Data analysis indicates a pressing need for public policies that promote the integration of solid and liquid waste management, including strengthening selective collection systems, encouraging recycling, and investing in basic sanitation.

Furthermore, the study highlights the urgency of continuous and systematic environmental monitoring to track the evolution of MP pollution and pharmaceutical residues over time. The adoption of more sensitive analytical methodologies and the integration of

interdisciplinary approaches, involving areas such as environmental chemistry (i.e., non-destructive analysis), ecotoxicology, public health, geosciences, and statistical models, are crucial for improving the understanding of environmental impacts and supporting effective management and conservation actions. In addition, planning new collections along the river course, including bottom sediment, at different times of the year to assess whether there is temporal variation in the distribution of these PMs and adsorbed pharmaceuticals, and encouraging the use of machine learning techniques for statistical analyses.

In the context of the SDGs, the research underscores the importance of promoting universal access to drinking water and sanitation, encouraging responsible consumption and production practices, and fostering innovations in urban infrastructure. Contamination by MP and pharmaceutical residues poses a direct threat to achieving the SDGs, particularly to human health (SDG 3), water quality (SDG 6), aquatic biodiversity (SDG 14), and the resilience of cities (SDG 11) amid contemporary environmental challenges.

Finally, the article contributes to advancing scientific knowledge on emerging pollution in semiarid regions, opening new perspectives for future research that investigate not only the distribution and mechanisms of interaction between MP and pharmaceuticals, but also the long-term impacts on the ecosystem and human health. Therefore, we recommend intensifying collection efforts, environmental education strategies for proper medicine disposal (e.g., pharmacy take-back for subsequent incineration), and technological innovations, engaging public officials, and strengthening cooperation between universities, research institutes, environmental agencies, and civil society as fundamental ways to address the challenges posed by emerging pollution and ensure the sustainability of the Caatinga's natural resources.

Supplementary Materials: The following supporting information can be downloaded at: https://doi.org/10.5281/zenodo.17967343 (accessed on 18 December 2025).

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