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From source to mouth: an integrated assessment of microplastics in the Sinos River, Southern Brazil, using SEM-EDS analysis and atmospheric modeling

Da nascente à foz: avaliação integrada de microplásticos no Rio dos Sinos, Sul do Brasil, utilizando análise de MEV-EDS e modelagem atmosférica

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ABSTRACT

Plastic waste is one of the main causes of the deterioration of freshwater ecosystems. Once in the environment, microplastics (MPs) have harmful effects on living organisms and pose risks to human health. This study used an integrated approach to assess the presence of microplastics in surface water and sediment samples from three sites along the Sinos River in the State of Rio Grande do Sul, Brazil. Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS) were employed for characterization, and a Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was proposed to understand atmospheric influences. Microplastics were found in all samples and sites, including the river's source. Fibers were predominant, and particle sizes ranged from 67 µm to 4.2 mm. A total of 109 particles were recovered from the water samples (12±4 L^{-1} particles), and 21 from the sediment samples (2±2 100 g^{-1} particles). SEM analysis revealed surface cracking, and EDS confirmed the prevalence of carbon and oxygen in the particles. Based on the atmospheric model, the trajectories of air masses prior to sampling at the highest site demonstrate that MPs can be transported from other locations. Our study reports microplastic contamination in Caraá for the first time, provides insights for future studies on the atmospheric transport and deposition of microplastics in countryside regions, and highlights the urgent need to include these pollutants in environmental quality assessments of this important hydrographic basin.

Keywords: HYSPLIT; plastic pollution; SEM/EDS; Rio Grande do Sul; Caraá; Parobé; Sapucaia do Sul.

RESUMO

Resíduos plásticos são uma das principais causas da deterioração dos ecossistemas de água doce. Uma vez no meio ambiente, os microplásticos (MPs) têm efeitos nocivos sobre os organismos vivos e representam riscos à saúde humana. Este estudo utilizou uma abordagem integrada para avaliar a presença de microplásticos em amostras de águas superficiais e sedimentos de três pontos ao longo do Rio dos Sinos, no estado do Rio Grande do Sul, Brasil. Microscopia Eletrônica de Varredura (MEV) e Espectroscopia de Dispersão de Energia (EDS) foram empregadas para a caracterização, e um modelo Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) foi proposto para compreender influências atmosféricas. Microplásticos foram encontrados em todas as amostras e pontos, incluindo a nascente do rio. Fibras foram predominantes, e os tamanhos das partículas variaram de 67 µm a 4,2 mm. O total de 109 partículas foi recuperado das amostras de água (12±4 L^{-1} partículas) e 21 das amostras de sedimentos (2±2 100 g^{-1} partículas). A análise por MEV revelou fissuras na superfície, e o EDS confirmou a prevalência de carbono e oxigênio nas partículas. Com base no modelo atmosférico, as trajetórias das massas de ar antes da amostragem no ponto mais alto demonstram que os MPs podem ser transportados de outros locais. Nosso estudo reporta, pela primeira vez, a contaminação por microplásticos em Caraá, fornece subsídios para estudos futuros sobre o transporte atmosférico e a deposição de microplásticos em regiões rurais e destaca a necessidade urgente de incluir esses poluentes nas avaliações de qualidade ambiental desta importante bacia hidrográfica.

Palavras-chave: HYSPLIT; poluição plástica; MEV/EDS; Rio Grande do Sul, Caraá, Parobé, Sapucaia do Sul.

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Introduction

The intensification of anthropic activities is one of the major factors responsible for the pollution of the aquatic ecosystem. Besides visual pollution, the inadequate disposal of solid waste in the environment causes several impacts, since litter can reach watercourses, and the dependence on finite resources for plastics production, along with current patterns of use, are generating global waste management problems (Lebreton and Andrady, 2019; Khan et al., 2025).

Plastic waste is introduced into the aquatic environment in larger items, degraded by ultraviolet (UV) radiation or broken down by mechanical forces and other biological processes into small secondary particles (Browne et al., 2007). In contrast, particles lost during transport or in the post-production of plastic products are considered primary sources (Hidalgo-Ruz et al., 2012). Microplastics (MPs) are currently defined as solid plastic particles of 5 mm in size (Hartmann et al., 2019). They have reached global levels and the retention downstream of a water body is extremely difficult, requiring upstream intervention to prevent and reduce them before entering coastal and oceanic areas, since rivers are one of the main sources of marine microplastics (Yao et al., 2020; UNEP, 2021).

Scientific concern for rivers resulted in numerous publications (Wong et al., 2020; Leterme et al., 2023; Moraes et al., 2024; Islam et al., 2025), and studies have shown that MPs occur or are more easily found near densely populated areas. Sediments are indicated as a long-term deposit for MPs (Bel Hassen et al., 2025). It is estimated that approximately 80% of ocean plastics originate from land-based sources and without meaningful action, emissions are projected to nearly triple by 2040 (UNEP, 2021), posing risk to ecosystem services and human health (Harris et al., 2021).

Studies reporting plastic fragments including pellets (≤5 mm) in Brazilian ecosystems date to the early 2000s (Ivar do Sul et al., 2009). A notable increase in the number of publications occurred in 2015, reflecting the advancement of MPs research on a global scale from 2013 (Barboza and Gimenez, 2015). More extensive investigations have been conducted in the Northeast and Southeast coast areas, mainly in the states of Pernambuco and São Paulo (Castro et al., 2018). Although Brazil is the country with the largest number of scientific publications on the occurrence of microplastics in aquatic systems in Latin America and the Caribbean (Orona-Návar et al., 2022), studies concerning atmospheric MPs are limited and rarely developed in countryside locations or rural areas (Ferraz et al., 2024).

Over the decade, an increasing number of techniques have been developed to detect, identify, separate, and characterize MPs in aquatic environments (Cai et al., 2025), and post-laboratory processes include physical identification under a microscope, and characterization of the chemical composition from isolated particles where Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy are widely used (Primpke et al., 2020). Nevertheless, they do not provide a detailed morphological image of the surface of the materials, which is important to infer about weathering mechanisms (Gniadek and Dąbrowska, 2019; Zhang, 2026).

The use of Scanning Electron Microscopy (SEM) added to Energy Dispersive X-Ray Spectroscopy (EDS/EDX) is efficient to overcome these disadvantages, since knowing the elemental composition of a particle is useful for identifying carbon-dominant plastics over other interfering materials (Gniadek and Dąbrowska, 2019), given that carbon (C) and oxygen (O), are predominant components in MPs (Kundu et al., 2026). Therefore, combining more than one technique to chemically verify microplastics in water and sediment samples is highly indicated.

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model has been used to analyze the potential source of atmospheric MPs (Brahney et al., 2020; Wang et al., 2021; Ward et al., 2024; Liu et al., 2025). Once in the atmosphere, the behavior of microplastics is significantly influenced by weather conditions and the physical properties of the particles (Liu et al., 2025). Also, MPs can be transported by wind over long distances and deposited even in remote, sparsely inhabited areas such as mountainous regions (Allen et al. 2019; Ward et al., 2024), representing an additional source of contamination in terrestrial and aquatic ecosystems (Chen et al., 2020).

In order to contribute to the knowledge about microplastic contamination in an unstudied region and fill this regional gap for the State of Rio Grande do Sul and the Vale dos Sinos Region, Southern Brazil, our study employs an integrated methodological approach to assess microplastics recovered from surface water and sediment samples in the Sinos River Basin, discusses the applicability of SEM-EDS analysis for characterization, as well as presenting a HYSPLYT model to identify the source routes of air masses and explore the potential transport of atmospheric microplastics found in the river's source, Caraá. Thus, being the first to report contamination in this area and serving as a valuable reference for the region, it offers significant contributions concerning the sources, transport processes, and management strategies for MPs in freshwater environments.

Material and Methods

Study area

The Sinos River Basin (SRB) is located in the northeastern region of the State of Rio Grande do Sul (29°20' to 30°10'S and 50°15' to 51°20'W), which comprises 30 municipalities, and represents approximately 1.3% of the state. It covers a densely populated urban area where the industrial production is highly diversified and includes the leather-footwear, food, petrochemical, metallurgical, steel, and timber sectors. Agriculture also thrives in many regions of the basin (Konzen et al., 2015; ComiteSinos, 2026). One of the main water bodies of the SRB is the Sinos River (SR), with 190 km in length from the source in

Caraá to the mouth in the municipality of Canoas (Figueiredo et al., 2010; ComiteSinos, 2026). Degradation causes are the discharging of untreated domestic and industrial effluents in urbanized areas, eutrophication, erosion, and destruction of riparian forests in agricultural areas (Figueiredo et al., 2010; Ortega et al., 2020).

The river is subdivided into three distinct stretches in terms of water dynamics, defined by the bottom slope. The upper section (from Caraá to Rolante) has a high declivity, considerable riparian vegetation, and small wetlands. This area exhibits low population density a predominantly rural population, with primary economic activities including rice and sugar cane cultivation and livestock. The middle section (between the cities of Taquara and Sapiranga) has medium declivity, and this region presents both rural and urban characteristics. Finally, the lower section (from Campo Bom to Canoas) presents a gentle declivity until the Jacuí Delta, with higher population density and more intense industrial activities (Konzen et al., 2015; ComiteSinos, 2026).

These three stretches have already been studied (Bianchi et al., 2017; Cassanegro and Droste, 2017; Alves et al., 2018; Dalzochio et al., 2018), and a standardization regarding environmental data collection is well established.

Sites

Caraá (29°42'27.9"S and 50°17'28.7"W) represents the upper section, is located near the source of the SR. It has a population of 7,394 (IBGE, 2022), and agricultural activities are predominant. The city is a tourist destination, receiving a considerable number of visitors annually. Parobé (29°41'12.2"S and 50°51'01.0"W), situated in the middle section, has an estimated population of 52,058 (IBGE, 2022), presents a larger width of the riverbed, and is located downstream of the three largest contributors to the SR. With houses near the river, the area is used for bathing and leisure. Sapucaia do Sul, (29°47'52.6"S and 51°11'25.7"W), representing the lower section, is in a region with strong anthropogenic, domestic, and industrial activities. The municipality has 132,107 inhabitants (IBGE, 2022), and at this location the riverbed is wide, the riparian forest is almost non-existent, and the area is used for bathing, leisure, and artisanal fishing.

In the last five years, the population of the three cities has decreased compared to the data available when this study was conducted (2020). Nevertheless, Sapucaia do Sul is one of the municipalities with the highest percentage of its population living in urban areas (99.7%) in the state. All of the site's locations are shown in Figure 1.

Sampling and laboratory procedures

In August 2019 and along the riverbank, surface water samples were collected directly with clean polypropylene buckets (30 L in total), and sediment samples (~0.15 m depth in 0.45 m^2 (Quadrat Sampling adapted from Peng et al., 2018) were also transferred to clean buckets using a metal shovel (~10 kg in total). This procedure was performed once at each site (Masura et al., 2015), and all composite samples were carefully transported and stored.

For water samples, 1 L was first placed in glass beakers, in triplicate, and 100 mL of potassium hydroxide (KOH) 10% was added for organic matter (OM) removal. A manual stirring was performed. After 24 hours, the entire content was vacuum filtered using Millipore™ cellulose acetate membranes (filters), with a porosity of 0.45 µm and a diameter of 47 mm. After filtration, the filters were placed in Petri dishes and stored at a controlled temperature (22°C) for further analysis.

For sediment samples, 1 kg was placed in an aluminum mold, in triplicate, and manually sorted to remove coarse, then oven dried at 40°C for 24 hours (Antunes et al., 2018). Subsequently, a new screening was performed, and 100 g of each sample were transferred to glass beakers and filled with 1 L of distilled water. Similarly, 100 mL of KOH were added since samples visually showed high biological content, an alkaline treatment was used for faster digestion (Bessa et al., 2019) and after 24 hours, a density separation with 140 g L^{-1} of NaCl, followed by automatic stirring for 5 minutes. Twenty-four hours later, 100 mL of each beaker was filtrated. Saturated sodium chloride is a widely used solution due to its availability, low-cost and eco-friendly properties; however, it has a density of less than 1.20 g/cm^3 (Cai et al., 2025), therefore, for high-density microplastics such as polyethylene terephthalate

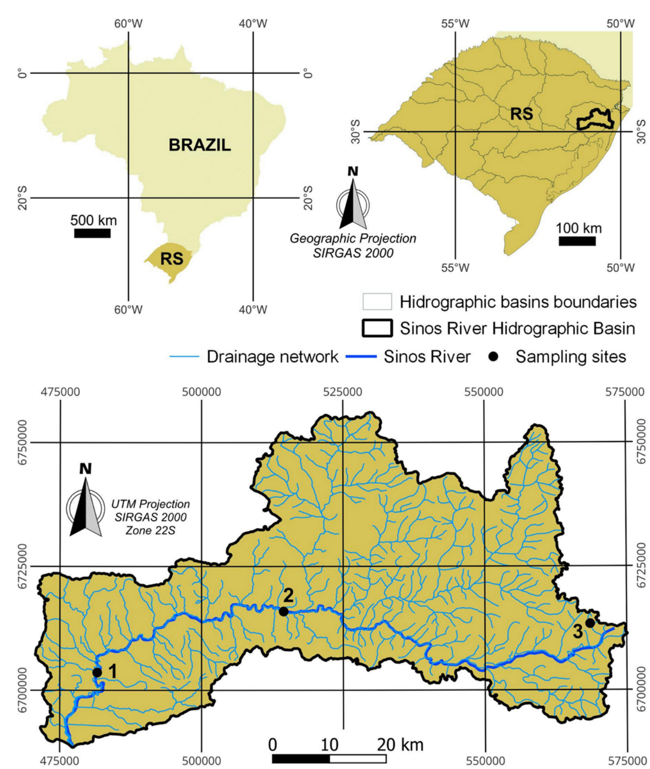


Figure 1 – Sampling sites of surface water and sediment along the Sinos River: Caraá (1), Parobé (2), and Sapucaia do Sul (3).

(PET) and polyvinyl chloride (PVC), additional separation methods should be considered at this stage. Prior to filtration, visible particles (>5 mm) and other suspended organic materials were removed using a metal spatula. The same post-filtration procedures for water samples were applied.

External contamination control

The buckets containing the samples remained sealed to avoid external contamination and were only opened at the beginning of the experiments, when access to the laboratory was allowed in accordance with the restrictions imposed by the SARS-CoV-2 pandemic (August 2020). Precautions were taken in all steps of the laboratory procedures, such as cotton clothing and the use of clean glassware and metal utensils. All processes occurred in a flow chamber, and blanks were used during the experiments. In addition, 12 Petri dishes with clean filters were randomly placed in the laboratory during this period. A small sample from the buckets (lids and the recipients) and all filters were observed under a stereomicroscope and no similar particles were found in samples that could have come from the buckets or external air.

Physical analysis

Filters were observed under an optical stereomicroscope, and all particles were photographed, counted, and classified according to their shape/type and color (Frias et al., 2018). The scale was set automatically according to magnification, and particle sizes were obtained using ImageJ Software (version 1.35e).

Morphological analysis and chemical characterization

Surface and elementary morphological analyses were performed by SEM using an electron beam acceleration voltage of 10 and 20 kV, with an EDS accessory. Six visible microparticles were randomly removed from the filters for characterization. It was not possible to remove any fragments due to their small sizes (67–763 μm), so four (4) fibers, one (1) filament, and one (1) film were transferred to a conductive carbon adhesive, mounted on a copper plate and vacuum metalized with gold (Au) for 3 minutes (standard Sputtering procedure). From the EDS spectra, particle content inferences followed the presence and difference between the carbon (C) and oxygen (O) peaks, the atomic percentage of these two elements, and the composition of all detected elements (Silva et al., 2018; Gniadek and Dąbrowska, 2019).

Atmospheric modeling

Developed by the Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Administration (NOAA) of the United States of America, HYSPLIT is a complete system for calculating simple air parcel trajectories, complex transport, dispersion, chemical transformation, and deposition simulations (Stein et al., 2015). Features of the HYSPLIT model include a backward option for tracing air mass trajectories (available at (https://www.ready.noaa.gov/hypub-bin/trajtype.pl). The model was generated using the trajectory frequency calculation with the following settings: reanalysis database, backward trajectories, latitude-longitude coordinates, 500-meter altitude, a maximum of 48 hours of modelling starting from the sampling date, and eight trajectories.

Statistical analysis

A cluster analysis was applied based on the agglomerative hierarchical, Euclidean squared method in order to demonstrate the similarities and dissimilarities between sites from water and sediment samples. The data were processed using IBM Statistical Package for the Social Sciences (SPSS) Statistics (version 22), and the dendrograms can be consulted in the Supplementary Material.

Results and Discussion

Microplastics were found in all samples and sites. Analyzed particle sizes ranged from 67 μm–4.2 mm. Photomicrographs of some particles in water and sediment samples are shown in Figure 2.

Surface water and sediment

In surface water samples, 109 particles were found in total (12±4 items L^{-1}). Site 1, Caraá, had the highest number (50), Parobé (32), and Sapucaia do Sul (27). The most frequent types were fibers (84), followed by films (9), fragments (9), and filaments (7). In sediment samples, 21 particles in total (2±2 items 100 g^{-1} dry weight) were found. Site 3, Sapucaia do Sul, showed the highest number (13), Parobé (4), and Caraá (4). Fibers (10) were the most frequent type, followed by films (8) and fragments (3).

The predominant colors were blue (44), transparent (29), and black (29); also, pink, red, green, and multicolor for particles in water samples. For sediment, green (9), blue (6), transparent, black, and pink particles were found.

Fibers in surface water samples are placed among the most prevalent types of microplastic debris observed in the natural environment (Jiang et al., 2019; Olivatto et al., 2024; Khan et al., 2025). Similarly, in sediments, fibers are commonly found (Alam et al., 2019; Islam et al., 2025). Transparent, blue, and black fibers are usually found in surface water and sediment in freshwater ecosystems (Rodrigues et al., 2018; Jiang et al., 2019; Trindade et al., 2023). Some fibers considered transparent had color residue, confirming that they were industrially processed (Dris et al., 2018). Colored microplastics can lose pigmentation and become transparent, fading when exposed to ultraviolet light and other weather conditions (Wong et al., 2020; Bertoldi et al., 2021).

The small number of microparticles recovered from sediments in our study is related to the filtration of only 100 mL of the one-liter (1 L) dilution, influenced by the insufficient removal of OM from the samples, as seen on the different surfaces of the filters in Figure 2d-e. This may have led to an underestimation of contamination in these samples. Inadequate removal of organic content can limit the amount of sample available for processing and the accuracy of particle counts (Lavoy and Crossman, 2021). Apetogbor et al. (2023) used NaCl and KOH to extract microplastics from surface water and sediments. The authors evaluated the effectiveness of the protocol by filtering known quantities of fibers and reported an efficiency rate of 95%. Adopting this process can ensure data reliability, help overcome the challenges posed by OM in samples, and reduce the risk of underestimation.

Although bulk sampling offers benefits, e.g. easy to operate and known sampling volumes, its representativeness is limited due to the small volume capacity (Cai et al., 2025). Also, different methods of digesting OM present advantages and drawbacks. Depending on the chemicals used, the digestion protocol can affect polymers, consequently influencing results (Hurley et al., 2018; Pfohl et al., 2021) and alkaline solutions, such as KOH, may degrade microplastics (Ghosal et al., 2018). Enzymatic digestion, for example, is a gentle method that is relatively efficient. However, this method is still used on a small scale due to its high cost (Cai et al., 2025).

The lack of standardized protocols in MPs research has led to significant variability in the quantitative presentation of data in Brazil and in the world (Castro et al., 2018; Orona-Návar et al., 2022). In a recent review on microplastics in Brazilian sediments in coastal and marine areas, Zanetti et al. (2025) showed that depending on the methodological approach and the research objectives and hypotheses, concentrations are expressed in different units, and for the authors, it is still necessary to standardize the units to establish comparisons between studies.

Scanning electron microscopy coupled with energy dispersive spectroscopy

Visual analysis of the particles allows quick results, but it is crucial that different methodologies be employed to confirm their polymeric content. In our study, we present SEM-EDS analysis as a complementary methodology that, whenever possible, should accompany other techniques. Since it is expensive and time-consuming with laborious sample preparation steps, the number of particles that can be analyzed in a given period of time is limited (Silva et al., 2018). Additionally, it relies on elemental composition and requires spectroscopic data support to distinguish polymers with similar profiles (Omole et al., 2026).

Figure 3 shows images obtained by stereomicroscopy and electron microscopy of a blue fiber and a green film.

One of the characteristics used to screen MPs with electron microscopy is surface texture. Caused by environmental exposure, it often reveals crack characteristics, implying polymer aging, mechanical and oxidative wear on the plastic surface. However, the primary degradation aspects exhibited on most microplastics are also fissures and deep fractures (Gniadek and Dąbrowska, 2019). Some of these cracks are observed in the microplastics recovered, as shown in Figure 4.

Kundu et al. (2026) used SEM-EDS to characterize the surface morphology of microplastics identified in raw and packaged milk. The SEM images revealed hollow and porous structures, cavities, worn edges, and surface fissures on the particles. These findings indicate that environmental aging or fragmentation processes may have altered the shape of the MPs prior to contamination.

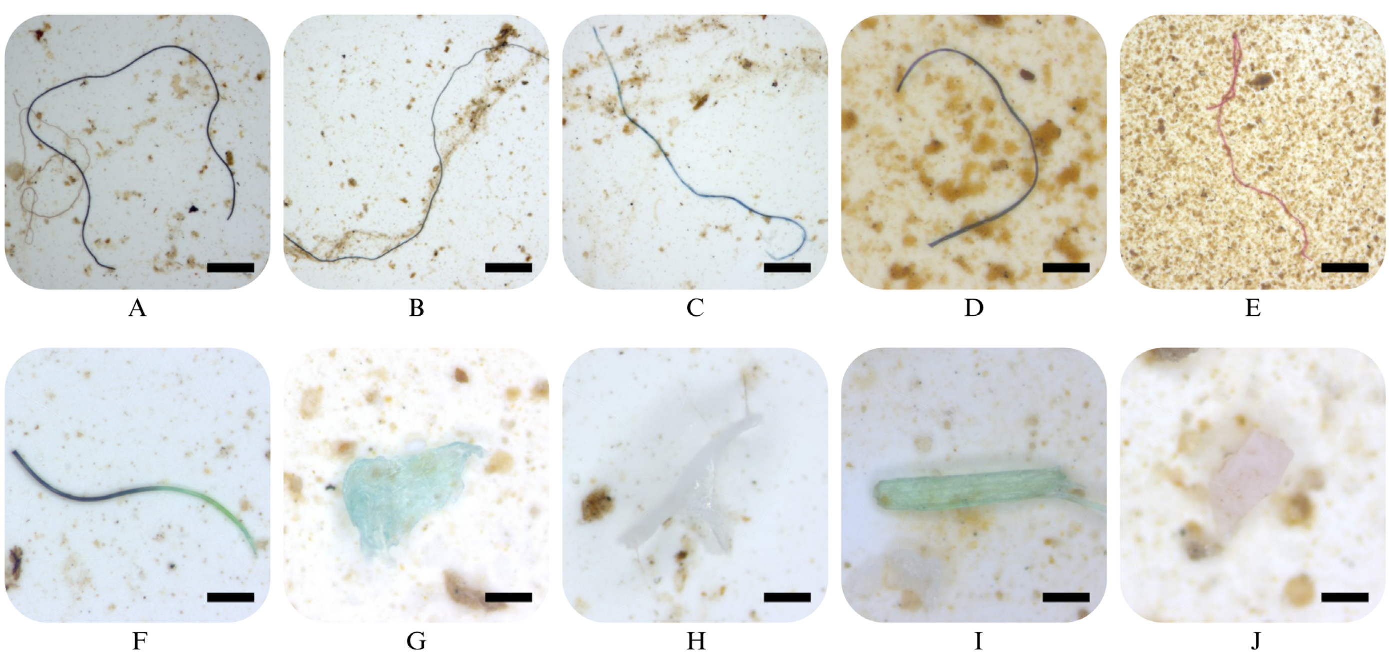


Figure 2 – Photomicrographs of microparticles found in water and sediment samples from the Sinos River: (A and B) black filaments, (C and D) blue fibers; (E) red fiber, (F) blue and green fiber, (G and H) green and transparent films, and (I and J) green and pink fragments. Scale bar of 200 µ.

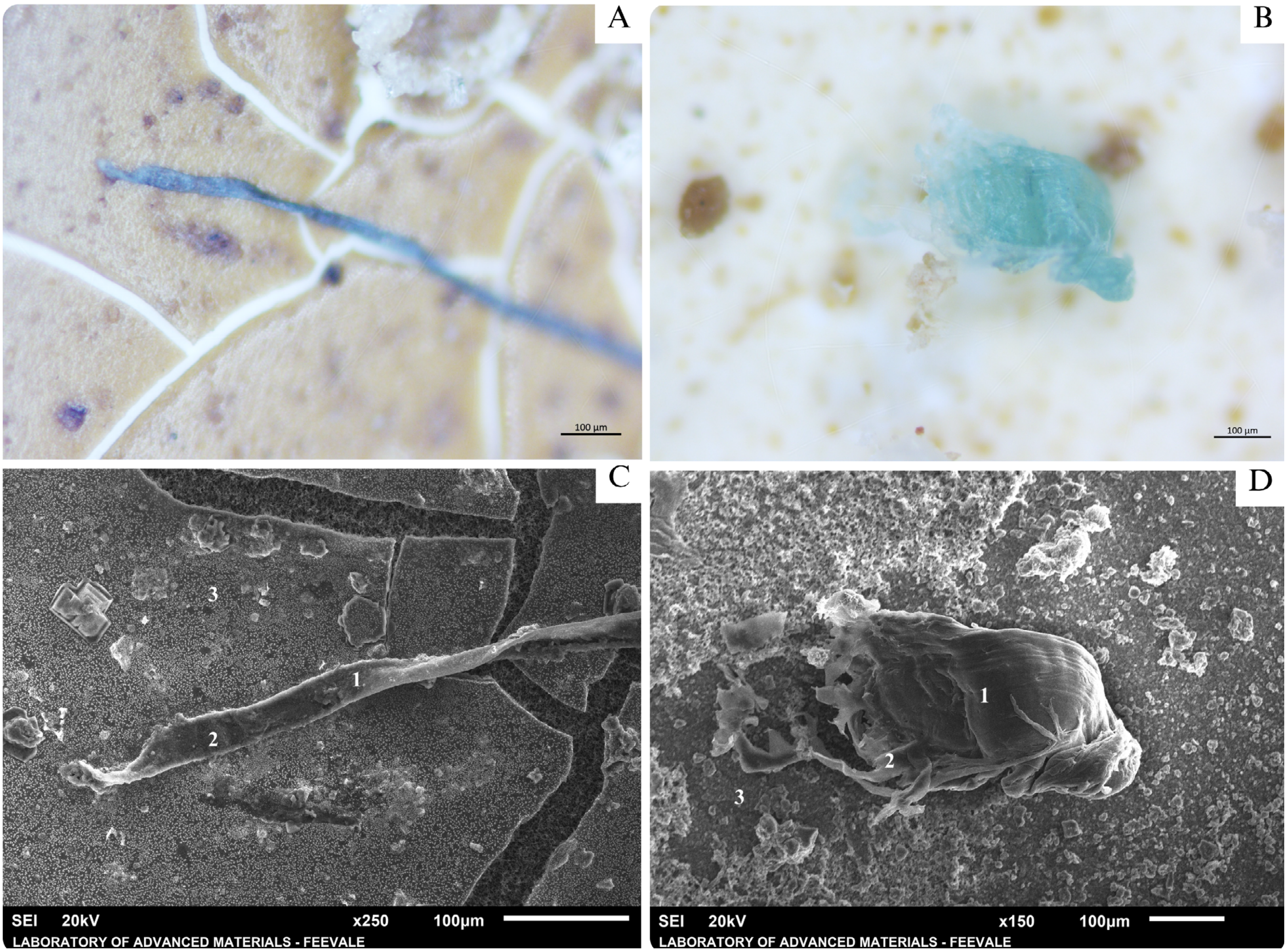


Figure 3 – (A and B) Stereomicroscopy and (C and D) Scanning Electron Microscopy (SEM) from a blue fiber and a green film found in water and sediment samples.

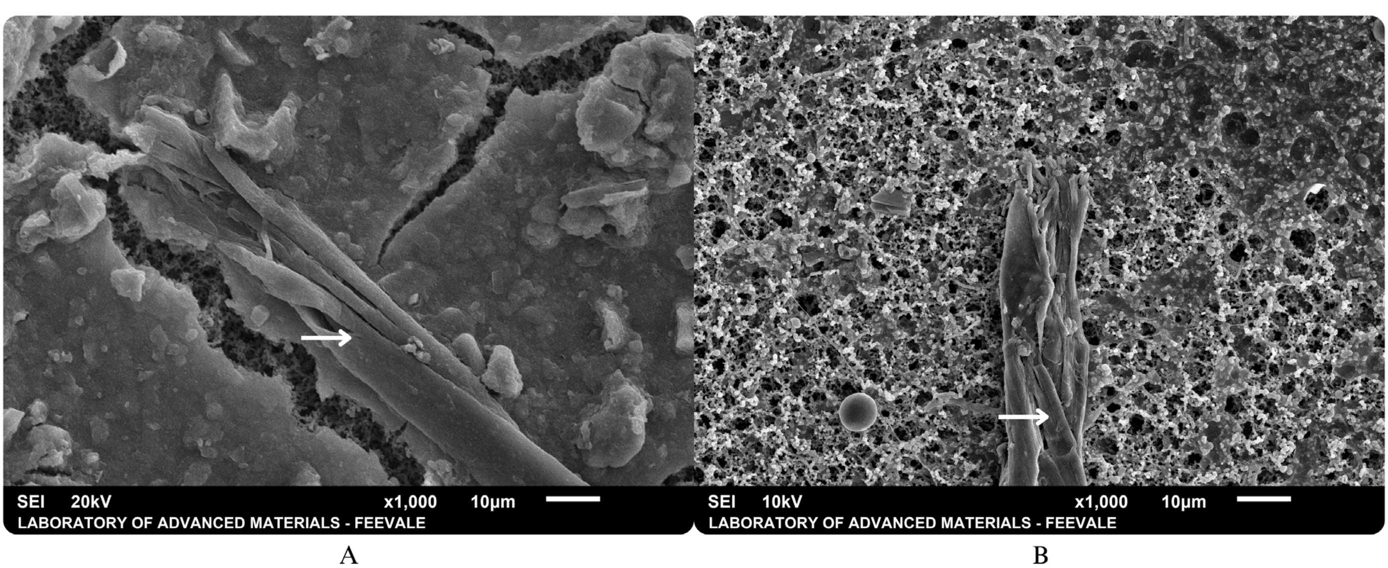


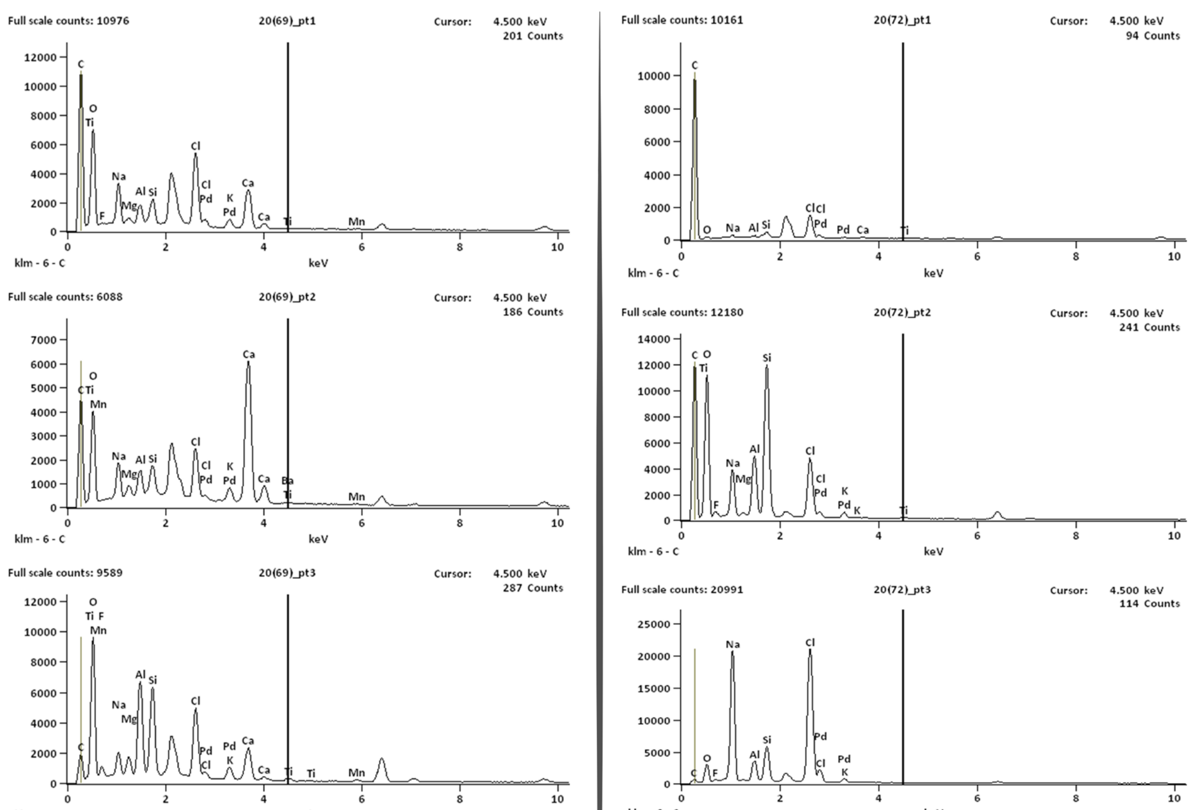
Figure 4 – Micrographs of two fiber ends isolated from the samples: (A and B) fibers with cracks. 1000x.

In most of them, especially the longer and narrower fibers, the ends appeared to be damaged, and frayed, while others were crushed to the filter, impairing the distinction in the images (due to the organic content), unlike rigid fibers and with slightly rounded, straighter, or fuller ends. Other SEM images are available in the Supplementary Material. More studies are necessary for better comprehension, not only in fibers, as these observations are useful for understanding plastic degradation in the environment.

All particles considered to be plastic presented high carbon peaks. The EDS spectra and the atomic percentage values of C and O are presented in Figure 5.

Commonly, blue fibers can be composed of either cotton or polyacrylic (Dyachenko et al., 2017). Therefore, further analysis using micro-Fourier transform infrared (µ-FTIR) or Raman spectroscopy is required for definitive plastic identification (Gniadek and Dąbrowska, 2019). Since these pieces of equipment were not available to analyze the particles found in the present study, EDS provided qualitative and quantitative information about the composition of the sample, being useful for the distinction of organic materials (rich in Ca, Mg, Sr), inorganic materials (minerals, salts), and MPs, rich in C, Cl, S and Ti (Dąbrowska et al., 2022; Omole et al., 2026). Kundu et al. (2026) also found in the EDS analysis that MPs predominantly contained C and oxygen O, trace amounts of silicon (Si), calcium (Ca), phosphorus (P), and iron (Fe).

In addition to the fibers presenting a strong C peak, some particles that visually appeared to be plastic may not present this sign, reinforcing that cellulose fibers, for instance, may also show similar results (Blair et al., 2019). The elements present in the spectra obtained could have come from additives; the biological content that remained on the surface of the particles; chemicals used in the wastewater treatment, or even from the OM



Atom (%)	C	O
pt1	47.46	40.15
pt2	33.71	46.39
pt3	16.66	54.69

A

Atom (%)	C	O
pt1	93.22	2.60
pt2	45.33	40.00
pt3	12.81	24.54

B

Figure 5 – Energy Dispersive Spectroscopy (EDS) spectra and atomic percentage values of C and O from isolated (A) blue fiber and (B) green film.

removal and density separation steps, due to the presence of K, Na and Cl in the spectra. See the Supplementary Material for more EDS results.

Sources of the fibers in sites 2 and 3 include washing processes, transport to the natural environment via effluent discharges and through rainwater runoff (Piñon-Colin et al., 2020; Cai et al., 2025) as well as atmospheric air, and the presence of microplastics in site 1, for both water and sediment samples could be originated from this phenomenon (Dris et al., 2016; González-Pleiter et al., 2021). Many Brazilian cities still release effluents into water bodies without prior treatment. According to the National Sanitation Information System (SNIS, 2022), only 52.2% of the total wastewater generated is treated, reflecting a lack of proper treatment, flooding in storm sewers, and inadequate control of solid waste. Notably, the country has not adopted strict measures to prevent synthetic polymers and other types of waste from reaching natural areas (Azevedo-Santos et al., 2020; Sodré et al., 2023).

Substantial amounts of microplastics were recorded in Guaíba Lake, located in the metropolitan region of Porto Alegre (Bertoldi et al., 2021), and the MPs abundance per sample varied in a range of 11.9±0.6 to 61.2±6.1 items m^{-3}. The lake receives water contribution from the SR, and historically, the release of domestic wastewater without proper treatment is placed among the main sources of pollution. In the most recent Surface Water Quality Report (Rio Grande do Sul, 2019), a new assessment considering historical monitoring data showed that the Sinos water quality has been decreasing over the years. The report suggests that concentrations of metals, pesticides, and ecotoxicity tests in water and sediment would help detect other degrees of quality in the river, but the document does not address microplastics as a potential contamination.

Although urban centers may be the initial source, plastics accumulate in the atmosphere for longer periods, are transported over longer distances and deposited under favorable conditions such as slower air masses or mountain intersections (Allen et al., 2019; Brahney et al., 2020; Ward et al., 2024). To explore the hypothesis that deposition of atmospheric MPs may have occurred in site 1, a HYSPLIT model was designed to observe the air masses 48 hours prior to sampling.

Caraá is located in a mountainous region where the most intense winds occur in the second half of the year, and the wind regime is characterized by the predominance of winds coming from the Northeast (NE) quadrant, both in terms of frequency of occurrence and direction of origin (Rio Grande do Sul, 2010). This site integrates an Environmental Protection Area (APA) classified as a Sustainable Use Conservation Unit, created by Decree No. 076/98 on September 25, 1998, whose Management Plan aims to preserve and improve the biological and ecological characteristics of the area's water systems, such as protecting the sources of the Sinos River and its tributaries.

It is possible to verify that the direction of the trajectories was predominantly N and SW (Figure 6). In this case, the air masses could have transported microplastics from other regions and even other

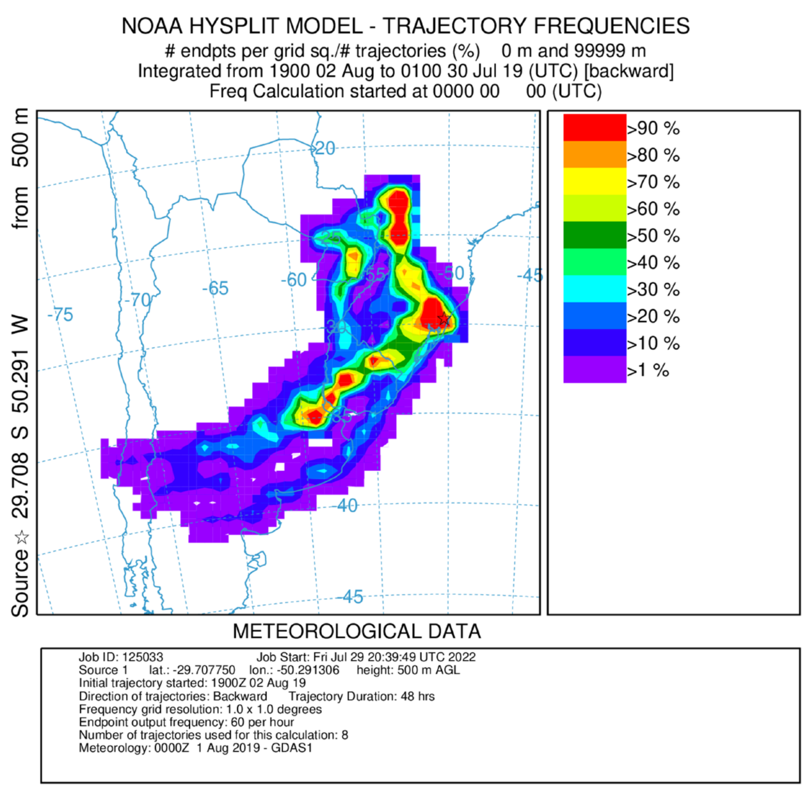


Figure 6 – Trajectories of the air masses obtained from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model calculated for Caraá (site 1).

States (González-Pleiter et al., 2021). Therefore, the absence of studies assessing the presence of MPs due to transport and deposition in the region studied is highlighted.

A recent study conducted by Pletsch et al. (2025) assessed atmospheric pollution in the Region of Hortênsias (municipalities of Canela and Gramado) in Rio Grande do Sul state, and demonstrated, by SEM-EDS analysis, the presence of particles with polymeric material characteristics, similar to the particles found in our study, when compared with other types of atmospheric particles from known sources, such as vehicle soot and fly ash. However, when analyzing microplastic dispersion, polymer type alone is not a sufficient trace to identify emission sources, since little is known about the displacement dynamics and fate of atmospheric microplastics (Wright et al., 2020).

Conclusion

The presence of microplastics, primarily fibers, in surface water and sediment samples at all sites demonstrates widespread contamination throughout the Sinos River Basin, including areas with minimal human impact. Considering that the Sinos River is more than 190 km long with numerous tributaries, favorable atmospheric conditions are serving as an additional input, therefore potentially extending this contamination beyond the basin's limits.

In microplastics characterization, combining SEM and EDS as complementary methodologies allows for detailed morphology visualization, contributes to inferences about degradation processes, and enables differentiation of synthetic particles. Characteristics such as surface cracks and the predominance of carbon and oxygen were observed and confirmed, respectively, in the analyzed particles.

In our study, a hypothesis was proposed to understand the source of particles in Caraá, a region considered more preserved as it does not receive major anthropogenic influences. Based on the HYSPLIT model, the direction of the trajectories prior to sampling indicates that air masses from other locations transported MPs to this area.

The limitations of this study mainly refer to the sampling volume and pre-filtration aspects. Only one sample was collected at each site, and applying an alternative digestion treatment could have improved the removal of OM from the sediments. Although considerable progress has been made in microplastics research, challenges remain, and choosing the optimal protocol based on sample conditions is important to avoid underestimation.

The environmental implications of these contaminants encompass a broad range of biological groups, extending to complex ecological levels. This includes physical and chemical interactions, as well as impacts on biodiversity and human health. Microplastics have been detected in potable drinking water and to date, current technologies are not capable of safely removing them. In this regard, it is imperative to implement updated regulatory guidelines concerning water quality parameters.

Further studies will contribute to a more in-depth diagnosis and establishment of sources, transport, and fate of microplastics in the basin. Measuring variables such as affluent inputs and atmospheric deposition over time, alongside strategies to effectively control and mitigate the impacts, is essential. Despite supplying more than one million inhabitants, the Sinos River is classified as one of the most polluted rivers in Brazil. Thus, this additional pollution requires urgent attention.

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