Brief Report

First evidence of microplastic contamination in the tissue and skeletons of the keystone reef-building coral *Siderastrea stellata* in coastal reefs

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Abstract
Most studies on microplastics (MPs) in corals have relied on aquarium experiments, with limited field-based data available for many reef regions. This highlights a gap in in situ studies of microplastics in keystone corals, particularly along the tropical southwest Atlantic coast. Therefore, establishing a database on microplastics in corals is essential for effective monitoring. Our short communication presents the identification of MPs in the major reef-building coral *Siderastrea stellata* Verrill, 1868, in a Southwestern Atlantic coastal reef, and is therefore a pilot study of microplastics in inshore reef corals. Raman spectroscopy was used to analyze the composition of each microplastic captured in two intertidal reefs. We detected MPs in both the tissue and carbonate skeleton on coastal reefs. The predominant form was filamentous, with polystyrene being the most common MPs. The observed colors were primarily transparent, with some black and blue fragments. Notably, we provide the first field-based record of microplastics in coral skeletons in the SW Atlantic Ocean. These results highlight the importance of studying microplastics in coral reefs, supporting the hypothesis that these ecologically significant areas are global sinks for plastic pollution.

Keywords Plastic pollution · Coral reefs · Scleractinia · Polystyrene

1 Introduction

Reef-building corals secrete a calcium carbonate skeleton ($CaCO_3$) [56], which is crucial for long-term reef growth. This biogenic process supports the formation of a three-dimensional reef habitat, essential for the structure and functioning of reef ecosystems [21, 57]. However, coral reefs, often located near coastal regions, face increasing threats from activities such as tourism, urbanization, and fishing [19, 22, 28]. Their proximity to human settlements and unique three-dimensional structures facilitate the accumulation of plastics, including macro- and microplastics, within reef environments such as water, sediments, and corals [22, 51]. Rivers, a significant source of microplastic pollution, further exacerbate this issue, with contamination levels closely tied to urbanization in surrounding reef areas [19, 28].

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Most of our knowledge about microplastics (MPs) in corals comes from laboratory experiments in aquariums. Coral interactions with MPs can occur through ingestion, exposure, or adhesion [13, 22]. The potential impacts of these interactions include diseases induced by MPs [1, 14], contamination by elements absorbed by MPs, reduced efficiency in coral symbiosis with zooxanthellae, energy deficits, alterations in growth, respiratory, and reproductive processes, induction of bleaching, excess mucus production, and oxidative DNA damage, which weakens coral defense systems [13, 22]. In summary, MPs have numerous negative consequences for reef-building corals, directly and indirectly affecting the entire reef ecosystem [54].

MPs have predominantly been detected in reef sediments [7, 9] and coral reef waters [23, 37]. In contrast, relatively few studies have identified MPs within reef-building corals [20, 29, 32]. Most of these research studies have focused on reefs in the Caribbean and Indo-Pacific regions, which are key biodiversity hotspots [40, 54]. Current findings suggest that coral reefs may function as sinks for MPs, trapping these particles within their ecosystems [13, 42, 47]. The proximity to urban areas facilitates human interaction through fishing and tourism, making the selected sites suitable for studying microplastics in corals inhabiting marginal tropical reefs under urbanization pressure [35]. Further research into MP accumulation in reef-building corals is crucial for understanding the broader impacts of plastic pollution on marine environments.

One of the least studied reef regions is the Southwest Atlantic, where MPs on coral tissues—whether ingested or adhered to the coral surface—have, to date, been studied only on oceanic islands [41]. Among the corals in this region, *Siderastrea stellata* Verrill, 1868, stands out as a key reef builder and one of the most widely distributed species in the Southwestern Atlantic Ocean [10, 30]. Its resilience to high sedimentation and turbidity allows it to dominate most reef habitats in the area [2, 18, 30]. Despite the ecological importance of this species, research on MPs in Southwestern Atlantic coastal reefs remains scarce. We identified two main gaps in the literature. The first is the lack of field-based studies of MPs in corals off the coast of the tropical Southwestern Atlantic. In addition, throughout this extensive region there have never been studies (either on the coast or on the islands) on the skeletons of these important reef builders. Based on this, we sought novel research to analyze these gaps. This short communication addresses this gap by analyzing MPs in the skeleton and tissue of *S. stellata* from coastal reefs. It therefore aims to present a pilot study of MPs in corals from Southwest Atlantic coastal reefs. In addition to being the first study on coastal reefs, it is also the first to analyze MPs in the skeleton of South Atlantic corals. Furthermore, this study contributes to scientific knowledge by paving the way for research on the development of standardized methodologies for identifying MPs in the skeleton and tissues of inshore Southwest Atlantic corals.

2 Material and methods

The equatorial coast of the Southwestern Atlantic (Ceará, Brazil) encompasses diverse tropical habitats, including intertidal, shallow, and mesophotic reefs, where *S. stellata* is the dominant reef-building species [12, 38, 39]. This low-latitude region is characterized by a semi-arid climate, with rainfall concentrated in the first half of the year [3, 39, 46]. Intertidal reefs experience seasonal variations in water temperature (25–33.5 °C) and high salinity (35–43.2) due to the mesotidal regime [2, 3, 12]. Additionally, high sedimentation and turbidity contribute to low coral species diversity and significant endemism in this reef area [11].

The study area includes the intertidal reefs at Fortaleza city (3°43′6″ S, 38°32′34″ W) and Paracuru beach (3°41′5″ S, 39°02′46″ W) (Fig. 1). These reefs share geomorphological similarities, being composed of sandstone with a gentle slope toward the sea (maximum 2°) and exposed to waves, low tides, and winds [38]. However, they differ significantly in their levels of urbanization [5, 39]. Fortaleza, the capital of Ceará state, is the most densely populated city in Brazil, with approximately 8655 inhabitants per square kilometer [24]. In contrast, the reefs at Paracuru beach, located 90 km from Fortaleza, experience considerably less human pressure, with a population density of only 116.58 inhabitants per square kilometer [25, 39]. This makes Fortaleza's population density 74 times higher than that of Paracuru. Despite these differences, both regions host diverse intertidal habitats. Paracuru's reefs, stretching along 3 km of coastline, are characterized by tide pools that support significant biodiversity, including mollusks, crustaceans, corals, and macroalgae [5, 39].

Two regions of intertidal reefs were selected for sampling, differing in their proximity to urban centers. Sampling in these areas was done randomly, with efforts to match the size of the samples using metric measurements. The same procedures were followed for field storage, transport, and laboratory storage of samples from both reef regions. As this was a pilot survey, only one coral colony was collected from each intertidal reef. Samples were collected during low tide in the dry season of 2022 from the Fortaleza and Paracuru reefs (Fig. 1a) at depths of less than 2 m. In each area, a

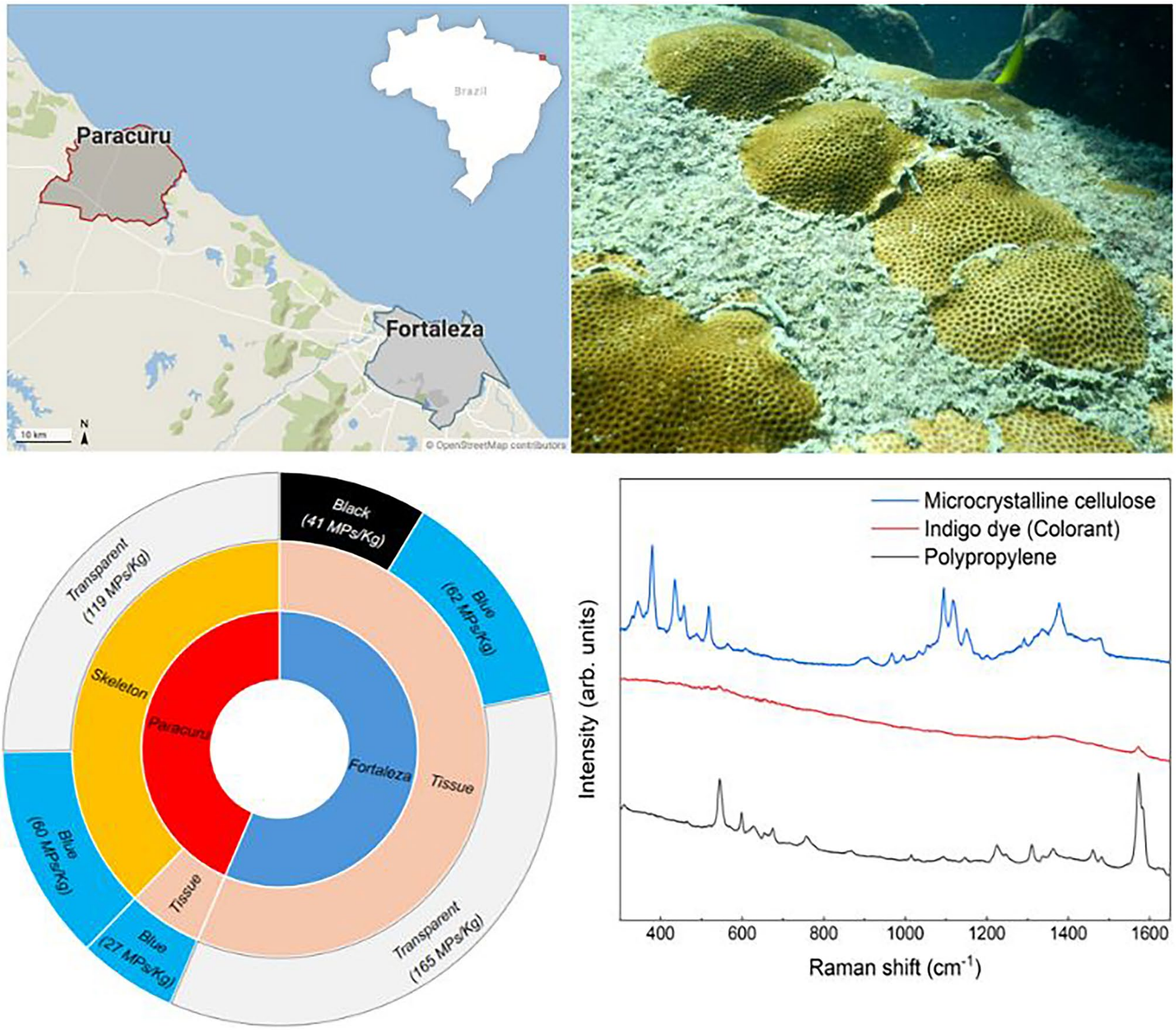

Fig. 1 **a** Map of coral sampling on Fortaleza (blue color) and Paracuru (red color) on Southwestern Atlantic (Ceará, Brazil); **b** colonies of incrustant coral *Siderastrea stellata* (author: Caroline Feitosa); **c** sunburst chart of microplastics concentration and colors observed on coral skeleton and tissues from Paracuru (green) and Fortaleza (red); **d** Raman spectrum of microplastics observed in corals.

colony of the coral *S. stellata* (Fig. 1b) was extracted using a chisel and sledgehammer. The samples were rinsed with distilled water in the field and stored in 250 mL glass jars. Due to the narrow jar openings, the coral colonies were broken into smaller pieces for storage. Details on sample quality control, tissue digestion, carbonate skeleton dissolution, MPs separation using the Microplastic Extraction System (MES), and particle analysis via Raman Spectroscopy are provided in the Supplementary Material.

To prevent microplastic contamination, distilled water used for washing the samples was transported from the laboratory in a spouted container, and the storage bottle was only opened during sample storage. Additional measures to minimize cross-contamination included: wearing cotton lab coats during analysis; using predominantly metal or glass materials for sample processing; opening samples only once for microplastic (MP) counting; and avoiding the use of air conditioning in the analysis room.

The samples were stored and processed as follows: they were packed in a −80 °C freezer, placed in a freeze-dryer for at least 24 h to remove all water, and weighed in a previously cleaned petri dish [15]. To remove MPs from the coral tissue, the samples were immersed in a 35% hydrogen peroxide (H_2O_2) solution under heat (of up 60 °C) for 2 h [15, 20, 49]. The coral skeleton, now free of tissue, was then removed from the beaker using metal tweezers, washed with distilled water, and transferred to a second beaker covered with aluminum foil.

The solution of hydrogen peroxide, distilled water, and coral tissue was first sieved through a 2 mm steel sieve to remove any particles that could clog the MES. The solution was then filtered through a 65 µm mesh in the MES. The coral skeleton, once again free of tissue, was removed, washed, and transferred to a new beaker. Next, the skeleton was immersed in a 5.5% hydrochloric acid (HCl) solution for 18 h (room temperature). The entire sieving process, previously carried out to extract microplastics from the tissue, was then repeated for the skeleton [15, 49]. A saturated solution of sodium chloride (NaCl) (337 g/L) was used for the density separation process

MPs were counted and identified by color using a Leica EC3 high-resolution digital camera attached to a Greenough stereomicroscope (model S8 APO, Leica) with 8× magnification [36]. The "zigzag" counting method described by Peng et al. [37] was adapted for use with the stereomicroscope. For chemical identification, Raman spectroscopy was employed to analyze each microplastic (see Supplemental Material for further details).

3 Results

The concentration of MPs in the coral tissue was 267 MPs/kg in Fortaleza and 27 MPs/kg in Paracuru. In the skeleton, MPs were found only in the Paracuru sample, with a concentration of 179 MPs/kg. A total of 31 MPs, microparticles that have not yet been through the process of identification of their chemical composition, were identified in the coral samples, with the highest number observed in the sample from Fortaleza. The detected MPs included black (4), blue (9), and transparent (18) particles, with filaments being the predominant shape (Supplementary Material; Table S1 and Figure S1).

In terms of distribution, 26 MPs were found in the coral tissue from Fortaleza, while Paracuru samples contained 2 MPs in the tissue and 3 MPs in the skeleton. Notably, no MPs were observed in the skeleton of the coral from Fortaleza. The filament shape was common to both regions. Color differences were also noted, with black, transparent, and blue particles present in Fortaleza, whereas only blue and transparent MPs were observed in Paracuru. Of the 31 suspected MPs observed, only four could be identified by their chemical composition. The spectra observed in the tissue of coral collected from the Fortaleza reef indicated the presence of polypropylene (PP) and microcrystalline cellulose (Fig. 1d). Similarly, microcrystalline cellulose was detected in the coral tissue from Paracuru. In the skeleton, the identification of a filament was hindered by the presence of dye, which obscured the polymer bands. However, the detection of dye suggests the filament is an artificial material (Fig. 1). Similarly, the dye present in stained samples from the tissue made it challenging to identify polymer bands, with most of the observed peaks corresponding to the dye. It is important to note that, although Raman spectroscopy favors the identification of particles smaller than 10 µm, it has several limitations: a long analysis time, the potential for sample destruction depending on the duration and intensity of the laser, and the possibility of dye interference [16].

4 Discussion

Research on MPs in corals has predominantly focused on the Indo-Pacific and Caribbean regions. In comparison, studies addressing MPs in corals are less common than those investigating sediments and water in reef environments [47]. Furthermore, most existing studies are based on laboratory experiments rather than in situ analysis, underscoring the lack of research on MPs in corals from Southwestern Atlantic coastal reefs. Notably, the investigation of MPs in coral skeletons, as demonstrated in our study, remains particularly scarce.

Our findings suggest that the presence of MPs in the tissue and skeleton of *S. stellata*, can be attributed to the proximity of the coastal reefs to urban centers and their accessibility for fishing and tourism activities in intertidal zones. Similar intertidal environments—such as mangroves [35], beaches, wetlands [55], kelp beds [27], and estuaries [34]—are also potential hotspots for MPs accumulation. Although our sample size is small, this study detected microplastics in coastal reefs, likely driven by urban pollution associated with the city's significant economic activities and the close integration of reef ecosystems within urban areas [4]. Mismanagement of stormwater drainage systems and activities related to ports, fishing, tourism, industry, and oil are potential sources of microplastic pollution along the Ceará coast [6, 36, 53].

Although PP was found on coral surfaces, it is not the most frequently observed plastic type [31, 47]. As a low-density polymer, PP is commonly found in the water column [17, 50]. In addition to MPs, cellulose microfibers are also prevalent in reef environments [33]. These fibers primarily originate from clothing and enter the marine environment through wastewater effluents during washing [44, 48]. Unlike MPs, which are petroleum-based polymers, cellulose microfibers are derived from plant material [33]. However, the concern surrounding cellulose microfibers lies not in the fibers themselves but in the commercial additives and dyes attached to them, which may pose environmental risks [43].

Considering the presence of microplastics (MPs) in coral skeletons, the studies by Reichert et al. (2022) and Chen et al. [8] report this occurrence in experimental settings and discuss associated damage such as coral necrosis, impaired growth, and increased mucus production. Although we were unable to chemically identify the microparticle found in the skeleton of the coral from, we cannot rule out the possibility that corals in the southwest Atlantic already incorporate MPs into their carbonate structure. Beyond the harm to the organism itself, the entrapment of MPs in coral skeletons may prolong the presence of these contaminants in the ecosystem and facilitate their recycling through food webs via erosion and bioerosion [8]. This highlights the urgent need for long-term monitoring of this contaminant in reef ecosystems.

Rani-Borges et al. [41] reported the presence of MPs adhered to the surface and within the tissue of scleractinian coral species such as *Favia gravida*, *Mussismilia hispida*, *Montastrea cavernosa*, and *Siderastrea stellata*, in Brazilian oceanic islands. Among these, *Siderastrea stellata* Verrill, 1868, exhibited the second-highest concentration of MPs in its tissue, with fibers being the most abundant form. Similar plastic structures were identified in the skeletons of coral species such as *Montipora capricornis* and *Seriatopora hystrix* [20], as well as *Montipora turgescens*, *Favia speciosa*, and *Favite abdita* [15], which are prevalent in the Indo-Pacific region. In our research, fibers are categorized as filaments—thin, elongated structures. Such particles have also been documented in other sessile structures within biogenic habitats, including macroalgae and seagrasses [45]. The shapes and colors observed in our study have been previously reported in coral reef species from both the Pacific [32, 49] and South Atlantic regions [41]. MPs are a major stressor for corals, and their effects on these animals are unpredictable. The timing and form of the coral/MP response—such as increased mucus production, bleaching, or increased metabolic activity—depend on factors such as species, exposure duration, and MP concentration [52]. Furthermore, the incorporation of MPs into the coral skeleton means that these synthetic particles remain in the reef environment even after the coral dies [26].

Although our sample size is small, limiting statistical comparisons, this pilot study detected MPs in urban coastal reefs, likely driven by urban pollution associated with the city's significant economic activities and the close integration of reef ecosystems with urban areas [4]. Mismanagement of stormwater drainage systems and activities related to ports, fishing, tourism, industry, and oil are potential sources of microplastic pollution along the Ceará coast [6, 36, 53].

5 Conclusions and final recommendations

While this study documents the presence of microplastic particles in coral skeletons, further sampling and long-term studies are required to better understand the prevalence and distribution of MPs in both the skeleton and tissue of corals along the South Atlantic coasts (e.g., Brazil and Africa). Employing additional analytical techniques (e.g., Fourier-transform infrared spectroscopy, FTIR) would enhance the characterization of the chemical structure of these particles. Improving methodologies for weighing coral fragments, digesting tissue, and dissolving skeletons would also facilitate a more comprehensive understanding of the impacts of MPs on reef ecosystems.

Although this pilot study aims to encourage future research, several recommendations are made. For future studies on this topic, a larger sample size and broader SW Atlantic reef survey areas are recommended to enable statistical analysis of the microplastic data. Also we suggest considering environmental variability, coral species and coral health for more comparisons. As many samples were discarded due to challenges in chemical identification, it is also recommended that multiple methods be used to analyze the composition of MPs in corals. Additionally, a storage method is needed that allows for repeated chemical analysis of coral samples.

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Data availability The data of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate The submitted work is original and not have been published elsewhere in any form or language. All authors agree with the submission.

Competing interests The authors declare no competing interests.

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