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No escape from microplastics: Contamination of reef manta ray feeding areas in a remote, protected archipelago

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Abstract

Remote islands receive plastic debris from elsewhere, ranging from microplastics (>5 mm) to macroplastics, which can further breakdown into microplastics. The ingestion of microplastics by marine species has been linked to decreased fitness. Reef manta rays, *Mobula alfredi*, are liable to ingest microplastics due to their filter-feeding strategy and habitat overlap with plastic hotspots. Their population is in decline due to unsustainable fishing pressures and a slow life history, with potential additional demographic pressure from plastic pollution. This study investigates the concentration and characteristics of microplastics in the top 0.5 m of the water column in reef manta rays feeding areas around the Chagos Archipelago, a large remote marine protected area that is highly contaminated by macroplastic debris. Across all samples, a mean of 1.1 microparticle/m^3 was found, the majority of which were blue and black fibers. Half of the particles were confirmed as synthetic (53.6%, $n = 305$ out of 569 Fourier transform infrared spectroscopy'd particles), with the main synthetic polymers being polyester (21.1%), polypropylene (8.8%) and nylon (4.6%). Egmont Atoll, an International Union for Conservation of Nature "Important Shark and Ray Area" for its importance to reef manta rays, was the most contaminated atoll around the archipelago (1.6 microparticle/m^3). Continued regular beach cleans in important areas for biodiversity are recommended, as well as implementing new methods to reduce local input of microplastics, such as washing machine filters, and ultimately a global continued effort to reduce plastic usage and improve its disposal.

KEYWORDS

elasmobranch, filter-feeder, island conservation, marine pollution, marine protected area, microplastic

1 | INTRODUCTION

Islands are disproportionately affected by plastic pollution, which often originates from elsewhere (Filho et al., 2019; Lavers & Bond, 2017). Macro- and microplastic debris (plastic particles <5 mm in length; Thompson et al., 2004) can travel long distances in the ocean, pushed by waves and currents (van Sebille et al., 2020), which leads them to accumulate in large quantities in remote areas over time (Galgani et al., 2021). These plastic debris affect the island ecosystems (Barnes et al., 2018; Garrard et al., 2024; Jones et al., 2021). Many marine species can ingest plastic debris (Kühn & van Franeker, 2020), with potential impacts ranging from injury to the digestive system and starvation (Senko et al., 2020), to metabolic and reproductive disruption and behavioral modification from the leaching of toxic plastic chemicals (Hale et al., 2020). Cleanup of plastic debris in remote islands is difficult and cost-prohibitive (Burt et al., 2020), meaning the larger plastic items are left to break down into microplastics (Andrady, 2017), adding to the ever-increasing standing stock of debris in remote islands (Galgani et al., 2021). Due to their fragmentation, plastic debris items in the ocean and indeed in organisms are getting smaller (Lebreton et al., 2019; Lindeque et al., 2020; Ryan, 2008). The effects of microplastic ingestion on ecosystems are complex and depend on their concentration, size, shape, and polymer (Bucci et al., 2020). It is therefore important to quantify and characterize microplastic contamination of remote islands to understand the risk of microplastic ingestion to the vulnerable species they support, including marine megafauna that are likely to ingest microplastics (López-Martínez et al., 2021; Omeyer et al., 2023; Senko et al., 2020).

Large filter-feeders are particularly susceptible to microplastic ingestion due to their feeding strategy (Covernton et al., 2021; Di Beneditto & Awabdi, 2014), high prey biomass consumption (Kahane-Rapport et al., 2022), and their utilization of areas of high plastic contamination (Germanov et al., 2018; Guerrini et al., 2019). For example, baleen plates, the filtering mechanism of baleen whales, are likely to trap buoyant polymers directly from the water, particularly fragments and fibers, which risk clogging or damaging the filters (Werth et al., 2024). Trophic transfer also plays an important role in the uptake of microplastics by filter-feeders via their zooplanktonic prey that also ingests plastic (Zantis et al., 2022). As a result, microplastic particles have been found in the digestive systems of many filter-feeding megafauna species, including baleen whales (Besseling et al., 2015; Zantis et al., 2022) and elasmobranchs, such as whale sharks (*Rhincodon typus*; Abreo et al., 2019; Haetrakul et al., 2009). Although in large long-lived species, the negative impacts of plastic ingestion are harder to detect, they may accumulate over time (Alves et al., 2022; Senko et al., 2020). The direct and indirect microplastic ingestion routes for filter-feeders suggest that higher concentrations of microplastics in their feeding areas increase their chance of plastic ingestion via both routes.

Reef manta rays (*M. alfredi*) are large filter-feeding elasmobranchs that are susceptible to microplastic ingestion (Germanov et al., 2018, 2019). Reef manta rays forage on zooplankton from the surface to mesopelagic depths (Braun et al., 2014; Peel et al., 2020; Stewart et al., 2018) throughout which microplastics can occur (Boerger et al., 2010; Bond et al., 2018; van Sebille et al., 2012). Microplastic particles were found in Indonesian reef manta ray feeding areas (Argeswara et al., 2021), as well as in their egested material, showing that they ingest microplastic (Germanov et al., 2019). Due to widespread overexploitation leading to population declines, the species are listed as Vulnerable to Extinction on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Dulvy et al., 2021; Marshall et al., 2022; Pacoureau et al., 2021). Their recovery is impeded by their conservative life-history traits, such as slow growth, late maturation, and low fecundity (Couturier et al., 2012). Therefore, it is important to understand their exposure to sub-lethal threats of plastic ingestion, which may impact fitness at an individual and population level (Germanov et al., 2018; Law, 2017) and hinder their resilience to other pressing anthropogenic threats.

The Chagos Archipelago, situated in the central Indian Ocean, is made up of seven atolls, several large, submerged banks, and 58 low-lying islands, which are currently uninhabited, except for a military base on Diego Garcia (Sheppard et al., 2012). The entire region is within one of the world's largest no-take marine protected areas (MPAs; 640,000 km^2) (Hays et al., 2020). Despite the archipelago being remote and mainly uninhabited, large quantities of plastic debris that mostly originate from elsewhere have been found on its beaches (Hoare et al., 2022; Savage et al., 2024). Additionally, the archipelago supports a resident reef manta ray population (Andrzejaczek et al., 2020; Harris et al., 2021, 2023, 2024) that regularly forages in nearshore environments (Harris et al., 2023), which are generally areas of high exposure to microplastics globally (Compa et al., 2019; Onink et al., 2021).

This study aims to understand the exposure of the Chagos Archipelago reef manta ray population to microplastic contamination, which we expect to be comparable to the Maldives, a similar geographical location, and lower than Indonesia, a highly populated archipelago that emits large quantities of plastic into the marine environment (Mai et al., 2023). Firstly, we compare the concentrations and characteristics (type, color, and polymer) of microparticles in reef manta ray known feeding and non-feeding areas. We expect to see more microparticles in feeding areas and a positive correlation between quantities of microplastic and zooplankton, due to their accumulation processes being both governed in part by oceanographic processes (Fossi et al., 2016; Haury et al., 1990; van Sebille et al., 2020). Secondly, we compare quantities and types of microparticles between Diego Garcia, the only currently inhabited atoll, and the uninhabited atolls (Egmont Atoll in the south of the archipelago, and Peros Banhos, Salomon, and Great Chagos Bank, in the north), where we expect to find lower contamination than Diego Garcia.

This research is the first study to investigate water microplastic contamination of the Chagos Archipelago, offering a first step in understanding the potential risks microplastics pose to the local reef manta rays.

2 | METHODS

2.1 | Study area

The Chagos Archipelago has five emergent atolls: Diego Garcia and Egmont Atolls, which both have semi-enclosed shallow lagoons; Peros Banhos and Salomon Atolls, which are large circular atolls; and the Great Chagos Bank, which is the largest living coral atoll structure in the world. Egmont and Salomon Atolls have recently been designated an IUCN Important Shark and Ray Area (ISRA) following their recognition as essential habitats for reef manta rays and other threatened elasmobranchs (International Union for Conservation of Nature Species Survival Commission [IUCN SSC] Shark Specialist Group, 2023a, 2023b).

2.2 | Field sampling

Following the marine surface microplastic sampling method of Germanov et al. (2019), specifically developed for sampling filter-feeding elasmobranch foraging habitat, a circular mouthed net with a hard cod-end (mesh size of 200 μm, 0.5 m diameter mouth × 1.5 m in length) was trawled sub-surface in the upper 0.5 m of the water column (representative of where typically manta rays feed; Couturier et al., 2012). The net was weighted to ensure the whole mouth of the net was always submerged.

Fieldwork was conducted in June and July 2022 at Diego Garcia Atoll and in January 2024 at Egmont, Salomon, Peros Banhos, Great Chagos Bank, and Diego Garcia Atolls (Figure 1). A total of 61 sea surface trawls were conducted: 34 around Diego Garcia (combining those done in 2022 and 2024), 12 around Egmont, three in the Great Chagos Bank, six around Peros Banhos, and six around Salomon Atoll, equating to 30 samples in reef manta ray feeding (Harris et al., 2021, 2023, 2024) and 31 in non-feeding areas. Due to the vast size of the Great Chagos Bank and logistical constraints, only one reef manta ray feeding area could be sampled around this atoll. At each site, three 10-min trawls were conducted outside of the boat's wake and in Beaufort wind scale conditions of ≤4 to limit the mixing of the particles in the upper layer of water (Reisser et al., 2015). At the end of each trawl, the net contents were rinsed into the cod-end with a backwash of filtered seawater (filter size of 30 μm) and decanted into a 100 mL glass jar. The contents of these jars were preserved in a 4% formaldehyde/seawater solution and transported back to the laboratory at Royal Holloway University of London.

2.3 | Laboratory processing

Following Germanov et al. (2019), the samples were decanted into a graduated cylinder and left overnight. The settled volume of plankton was then recorded to the closest milliliter. The overnight settling allowed the plastic particles with a lower density than seawater to separate from the organic matter gravimetrically (the organic matter and non-buoyant plastic settles on the bottom while the buoyant plastic floats; Lusher, Munno, et al., 2020). The content of the cylinder was then filtered using a vacuum pump onto pre-weighed 10 μm filters (Whatman Cyclopore). The filters were dried at 60°C in a drying oven for 6 h and weighed with scales of 0.1 mg accuracy to record the dry weight of the plankton.

Using a dissection microscope with magnification ×16 (Leica EZ4E), the content of each filter was thoroughly scanned visually. The buoyant plastic particles were collected on the first filter (corresponding to the top layer of the settled sample), and the organic material on the subsequent filters was thoroughly examined to find the non-buoyant particles. Any particles found were transferred to a clean qualitative filter paper (Whatman No. 1), counted, and categorized into types and colors. The types of particles followed the categories in Germanov et al. (2019): "fiber" (long string-like shape), "tangle" (tangle of fibers), "film" (see through flexible and thin shape), "fragment" (hard irregular shape), "foam" (compressed under pressure), and "soft fragment" (irregular

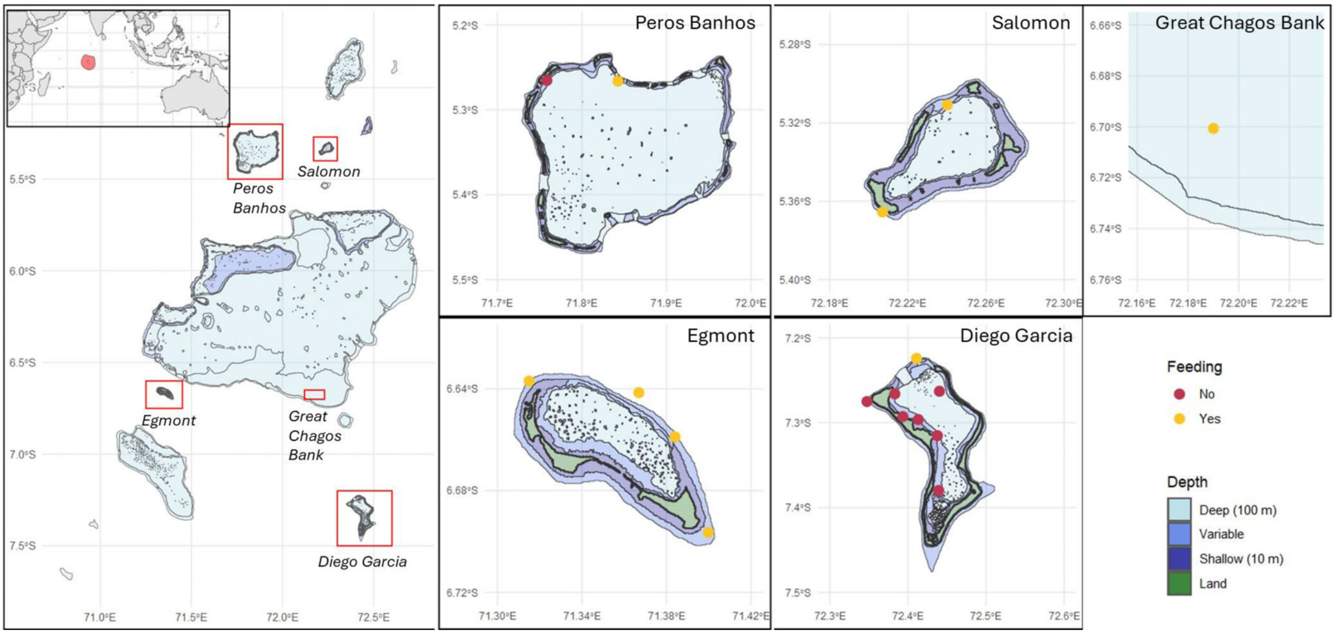

FIGURE 1 Map of the Chagos Archipelago highlighting sampling sites at each atoll (Peros Banhos, Salomon, Great Chagos Bank, Egmont, and Diego Garcia Atolls). Sample locations (one point per triplicate sample) are colored by whether they are manta ray feeding locations (in yellow) or non-feeding locations (in red).

but flexible shape). We refer to the particles as microparticles until they have been confirmed as a microplastic subsequently in the analysis (Lusher, Bråte, et al., 2020).

2.4 | Fourier transform infrared spectroscopy

For each sample, 10% of each particle category (e.g., blue fiber) was examined under Fourier transform infrared spectroscopy (FTIR, as recommended by Lusher, Bråte, et al., 2020) to identify their polymer composition. Particles from each sample were chosen at random and examined in transmission using a Thermo Nicolet iN10mx FTIR spectroscopy microscope with a LN2-cooled MCT/A (mercury cadmium tellurium) detector and a KBr beamsplitter. Spectra were collected from 675 to 4000 cm^{-1}, with 16 scans and a spectral resolution of 4 cm^{-1}. Background spectra were taken before each particle scan. The aperture was set to capture a region of the microparticle, with typical dimensions of 30–100 × 100μm. Samples were clamped in a diamond cell to ensure uniform thickness. The OMNIC™ HR Comprehensive Forensic FTIR Collection database was used to compare our spectra and identify polymers. Spectra were overlaid with the reference spectra and visually inspected to confirm matching peaks, with a minimum match of 70%, as recommended by the literature (Concato et al., 2023). All particles were classified into three categories based on the identified polymers: natural (cellulose, cotton, and other organic material), synthetic (any plastic polymer, including additives) following Lusher, Bråte, et al. (2020), and semi-synthetic (viscose and rayon, as modified natural particles).

2.5 | Contamination control

To mitigate contamination, the guidelines of Lusher et al. (2017) were followed. In the field, all glass jars and lids were rinsed three times with tap water filtered through a 30 μm mesh. Additionally, the net was flushed through without a cod-end at the start and in between each sample. Given the difficulties in restricting clothing to cotton during fieldwork, atmospheric controls (= boat atmospheric controls) were collected by exposing a moistened filter paper in a Petri dish during each trawl to quantify airborne contamination. These were later examined microscopically to isolate all microparticles. Procedural blanks were also prepared at each sampling location by treating filtered water with the same protocol as the samples. In the laboratory, cotton clothing and lab coats were worn throughout sample processing, with all filtering conducted under a laminar flow hood (ESCO Class II Biohazard Safety Cabinet, average inflow 0.67 m/s, average downflow 0.36 m/s). Microscopy was performed outside the laminar flow hood, so atmospheric controls (= laboratory atmospheric controls) were collected by exposing a moistened filter paper in a Petri dish to quantify airborne contamination during this process. Average contamination per sample was calculated as the sum of the average contamination in the boat and lab atmospheric controls and the procedural blanks (total contamination per sample = average boat atmospheric control + average laboratory atmospheric control + average procedural blank). These values were also broken down by particle type (fibers and fragments) and by color (e.g., blue fiber, etc.).

2.6 | Statistical analyses

2.6.1 | Particle concentration and characteristics

Descriptive statistics were used to illustrate the concentrations of particles found in the samples and their characteristics (particle type, color, polymer, and natural/synthetic/semi-synthetic origin). The mean number of particles per cubic meter (number of particles in each trawl divided by the volume filtered by the net in each trawl) was calculated for comparability with other similar studies, as well as percentage breakdown by particle type and color. These values were adjusted to account for the average contamination by deducting the overall average contamination from the overall mean number of particles (and same for the means by type and color). Quantities of synthetic/semi-synthetic/natural particles were compared using a chi-squared test and subsequent pairwise comparisons. Using the overall average particle concentration, the theoretical plastic ingestion rate for reef manta rays was calculated using their estimated filtration volume (86.4 m^3/h; Paig-Tran et al., 2013).

2.6.2 | Relationship between microparticle concentration and plankton quantities

The relationships between the log-transformed number of microparticles per sample (calculated as the number of particles in a sample divided by the sample volume) and the log-transformed (1) plankton settled volume per cubic meter and (2) plankton dried weight per cubic meter were explored using Spearman correlation tests, due to a non-normal distribution of the data and small sample sizes. The variables were log-transformed to improve the robustness of the analysis by removing the zero-bounding. These relationships were explored across all sites and for each individual atoll (except the Great Chagos Bank Atoll, which only had three sample points).

2.6.3 | Geographical variation in particle concentrations and characteristics

A generalized linear model (GLM) with a Gaussian error distribution was fitted to the data to assess whether the log-transformed concentration of particles in a sample was influenced by the sample location being a feeding or non-feeding area for reef manta ray and the geography of the sample location. The log transformation of the response variable was to ensure a normal distribution of the model residuals and to remove the zero-bounding of the variable, thereby improving the robustness of the analysis by putting the response variable on a continuous unbounded scale for the correlation analysis. The geography of the sample location was defined as either North (Salomon, Peros Banhos, and Great Chagos Bank Atolls), Southern-uninhabited (Egmont Atoll), or Southern-inhabited (Diego Garcia Atoll). The model was offset by the average concentration of particles from the atmospheric boat and laboratory controls and procedural blanks per sample.

Finally, the natural/synthetic/semi-synthetic origin of the particles and the top 11 polymers were compared between inhabited atolls (Diego Garcia) and uninhabited atolls (all the others) using a chi-squared test.

All statistical analyses were carried out in R Version 4.2.2.

3 | RESULTS

3.1 | Contamination removal

A mean of 5.1 particles was found in the boat atmospheric controls, 5.3 particles in the lab atmospheric controls, and 9.0 particles in the procedural blanks, equating to a total of 19.4 particles on average per sample (corresponding to means of 0.3 non-fibers and 19.1 fibers). A further breakdown of types and colors of particles in each type of blank is given in Table S1 (for boat atmospheric controls), Table S2 (for laboratory atmospheric controls), Table S3 for procedural blanks, and Table S4 for quantities by type and color. These quantities were removed from the raw particle concentration averages in the following section.

3.2 | Microparticle concentrations and characteristics

A total of 61 trawls were conducted (34 around Diego Garcia, 12 around Egmont, three around Great Chagos Bank, six around Peros Banhos, and six around Salomon

Atolls). A mean volume of 43,019.8 L (range—3351.6–89,023.2 L) was filtered per trawl. Once contamination was removed, a mean of 45.5 particles (35.6 fibers and 9.9 non-fibers) per trawl were isolated, equating to a mean of 1.1 microparticle (0.9 fiber and 0.2 non-fibers)/m^3 over the whole archipelago.

Overall, 78.2% of the particles in the trawls were fibers, 10.5% were fragments, 4.4% were tangles, 3.3% were soft fragments, and 2.6% were films. The last 1% of particles consisted of "fluff," "foam," "paper," and "bubble wrap." Blue fibers were the most prevalent type of particle (32.1% of all particles isolated), followed by black fibers (18.7%), clear fibers (18.5%), and red fibers (4.4%) (Figure 2).

FTIR analysis was performed on 569 (20.5%) of all particles. For all sample sites combined, there were significantly more synthetic particles ($n = 305$; 53.6% of particles examined under FTIR spectroscopy) than natural particles ($n = 168$; 29.5%) or semi-synthetic particles ($n = 87$; 15.3%) ($\chi^2 = 130.1$, df $= 2$, $p < .01$, and $p < .001$ in all pairwise combinations: natural/synthetic, natural/semi-synthetic, and semi-synthetic/synthetic). There were also nine unknowns (1.6%). Finally, a total of 57 polymers were identified, with the top five synthetic polymers being polyester (21.1% of particles examined under FTIR spectroscopy), polypropylene (8.8%), nylon (4.6%), polyethylene (3.7%), polyvinylchloride (2.8%), and polymethyl acrylate (1.6%).

Using an estimated water filtration rate for feeding reef manta rays of 86.4/m^3 h (Paig-Tran et al., 2013) and based on the particle abundance observed in samples (1.1 particles/m^3), reef manta rays could potentially be ingesting an average of 95 microparticles/h of feeding, with just over half of them being synthetic polymers.

3.3 | Relationship between microparticle concentration and plankton quantities

There was no relationship between the concentrations of microparticles and settled volume of plankton per cubic meter ($p > .2$), nor between the concentration of microparticles and dried weight of plankton per cubic meter ($p > .3$) (Figure 3). These results are reflected around Diego Garcia (Figure S1), Egmont (Figure S2), and Peros Banhos Atolls (Figure S3). Around Salomon Atoll, a significant positive relationship was observed between the number of microparticles and the amount of plankton (Figure S4).

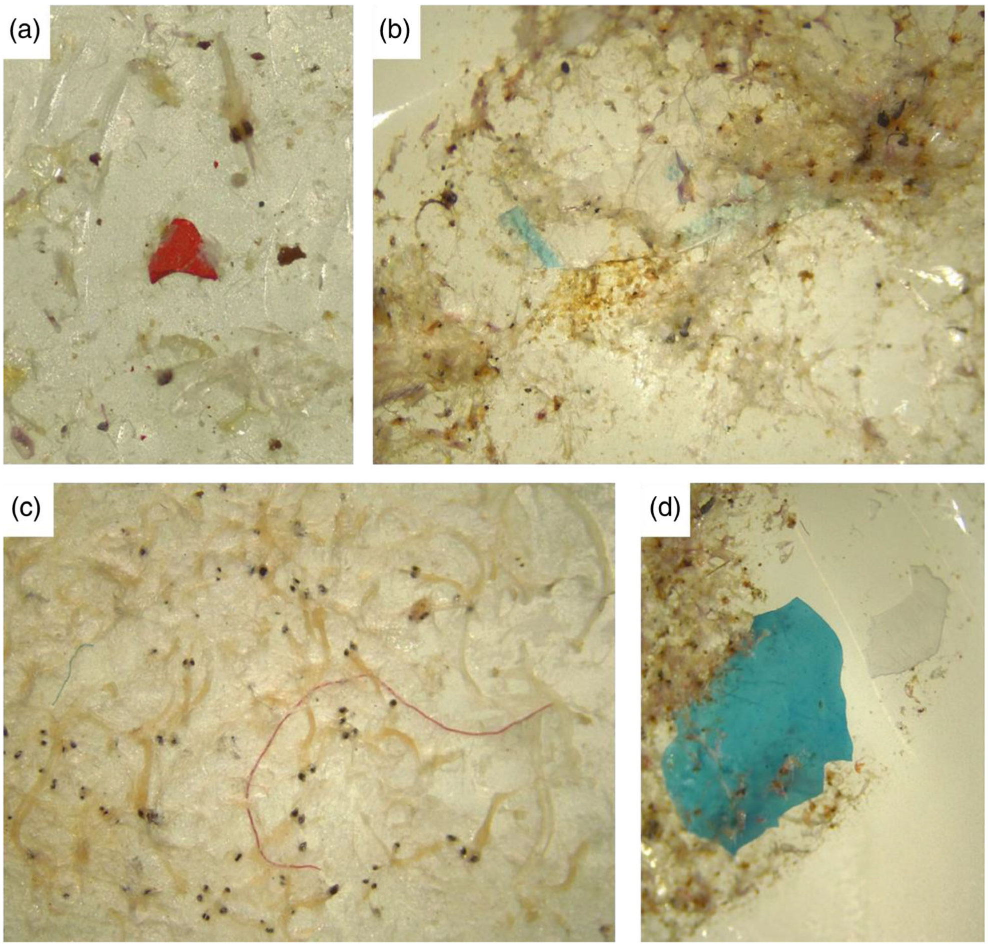

FIGURE 2 Microscope pictures at zoom ×16 showing a red fragment (a), a blue and clear film (b), a red and a blue fiber (c), and a clear and a blue film (d).

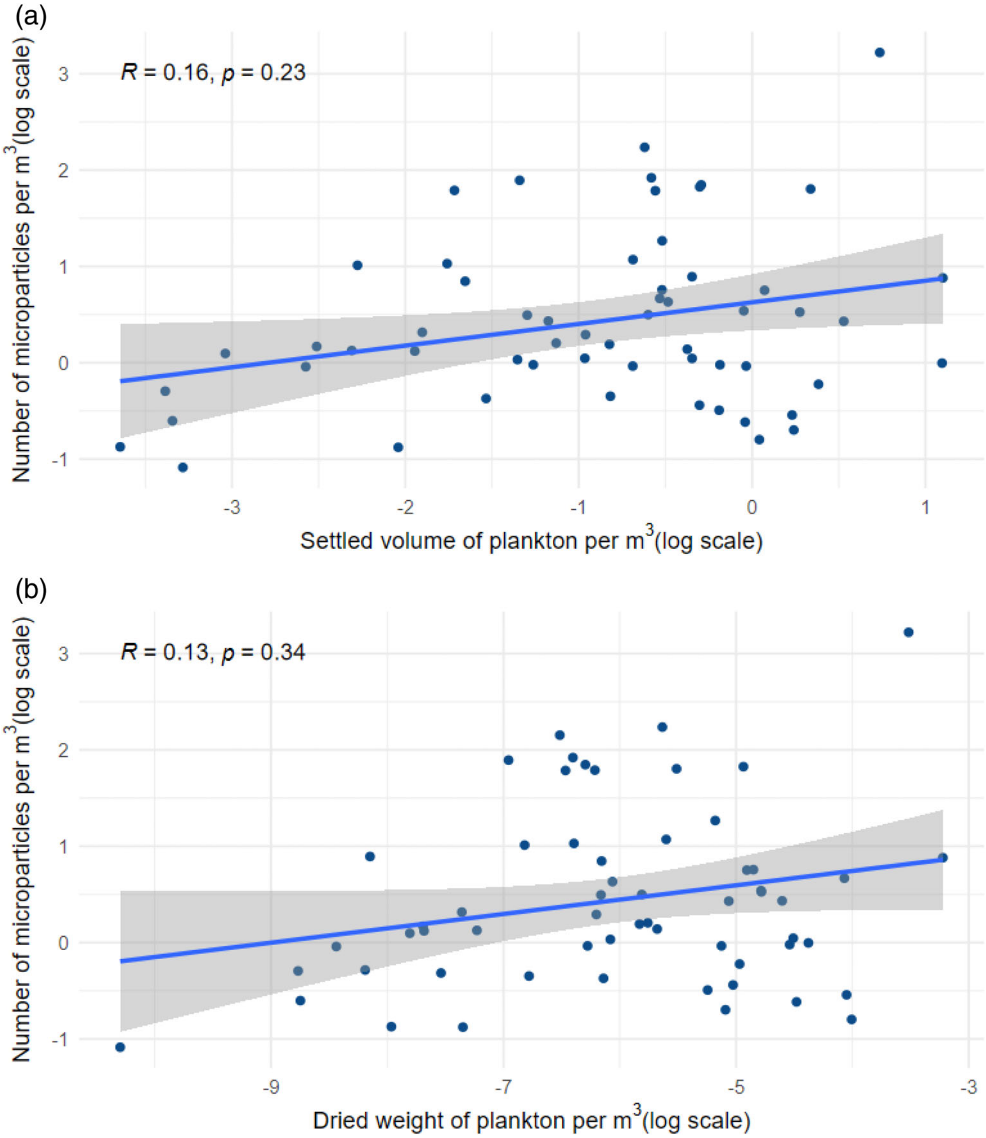

FIGURE 3 Spearman correlation (and standard error) identified no relationship between the concentration of microparticles and (a) the settled volume of plankton per cubic meter ($p > .2$) and (b) the dried weight of plankton per cubic meter ($p > .3$; all variables on the log scale).

3.4 | Geographical variation in particle concentrations and characteristics

The GLM (diagnostic plots in Figure S5) identified no significant difference between feeding and non-feeding areas ($p > .3$), so the variable was removed from the final model. There was a significantly lower microparticle concentration around Diego Garcia (South—inhabited, mean of 0.8 particles/m^3) than around the northern atolls ($p < .05$, mean of 1.2 particles/m^3) and Egmont Atoll (South—uninhabited) ($p < .05$, mean of 1.6 particles/m^3; Figure 4). No significant difference was identified between Egmont Atoll (South—uninhabited) and the northern atolls ($p > .9$).

Finally, the profile of particle types (natural, semi-synthetic, and synthetic) did not differ between inhabited (Diego Garcia) and uninhabited (the rest) atolls ($\chi^2 = 2.2$, df $= 2$, $p > .3$). However, across the top 11 polymers, there were significant differences between inhabited and uninhabited atolls (Figure 5; $\chi^2 = 29.1$, df $= 10$, $p < .002$). The pairwise comparisons revealed the inhabited atoll (Diego Garcia) had more cellulose, nylon, polyester, and viscose, whereas uninhabited atolls had more cotton, polyethylene, polymethyl acrylate, polypropylene, polyvinyl chloride, rayon, and wool ($p < .001$ in all pairwise combinations).

4 | DISCUSSION

4.1 | Chagos microplastic exposure

Large filter-feeders, such as reef manta rays, are susceptible to microplastic ingestion, which could have a detrimental impact on fitness at an individual and population level (Germanov et al., 2018, 2019). The Chagos

Archipelago is one of the least chemically polluted atolls in the world (Sheppard et al., 2012). However, contrary to expectations, the reef manta ray population of the Chagos Archipelago is exposed to similar levels of microparticle contamination in the sea surface of their feeding areas as some of the Indonesian population and higher than the Maldivian population and the Red Sea population (Table 1; when comparing to studies using the same microplastic sampling method). More than half the examined particles were confirmed as synthetic via FTIR spectroscopy, and there were significantly more synthetic particles than natural and semi-synthetic. The quantities of non-fiber microparticles observed in this study were similar to the quantities of non-fiber microparticles found in the top 0.5 m of the water column in reef manta ray feeding areas in Indonesia (Nusa Penina and Komodo; Germanov et al., 2019), all of which were confirmed to be plastic by FTIR spectroscopy (Argeswara et al., 2021). In the Maldives, the closest landmass to the Chagos Archipelago, similar quantities of non-fibers to the present study were observed in the top 0.5 m of the water column, but far fewer fibers, although the study did not focus specifically on manta ray feeding areas (Saliu et al., 2018). Finally, the present study found more microparticles than in the top 0.5 m of the water column of the Saudi Arabian coast of the Red Sea (Martin et al., 2019), although the study was performed on the opposite coast to the Red Sea reef manta ray aggregation (Kessel et al., 2017). When looking at wider studies conducted in the top 0.5 m of other filter-feeding elasmobranch feeding areas, the Chagos Archipelago has a higher microparticle quantity than the Gulf of California, in Mexico, home to

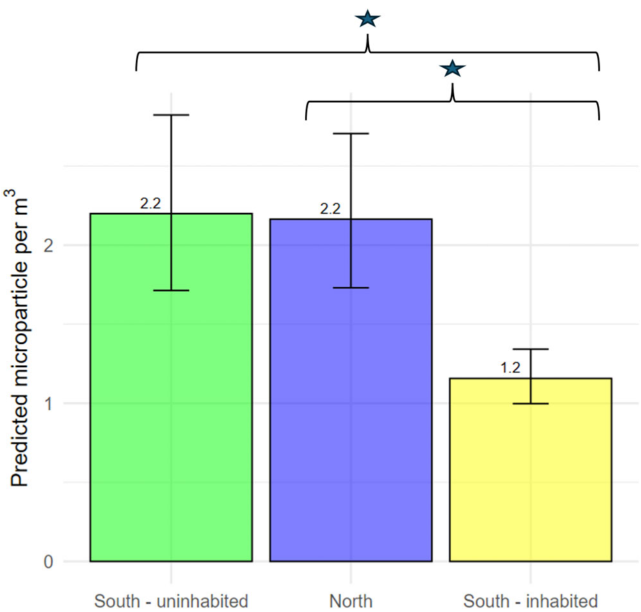

FIGURE 4 Generalized linear model predictions (and standard error) for differences in concentrations of microparticles in southern-inhabited, uninhabited, and northern atolls (significant results represented by a star).

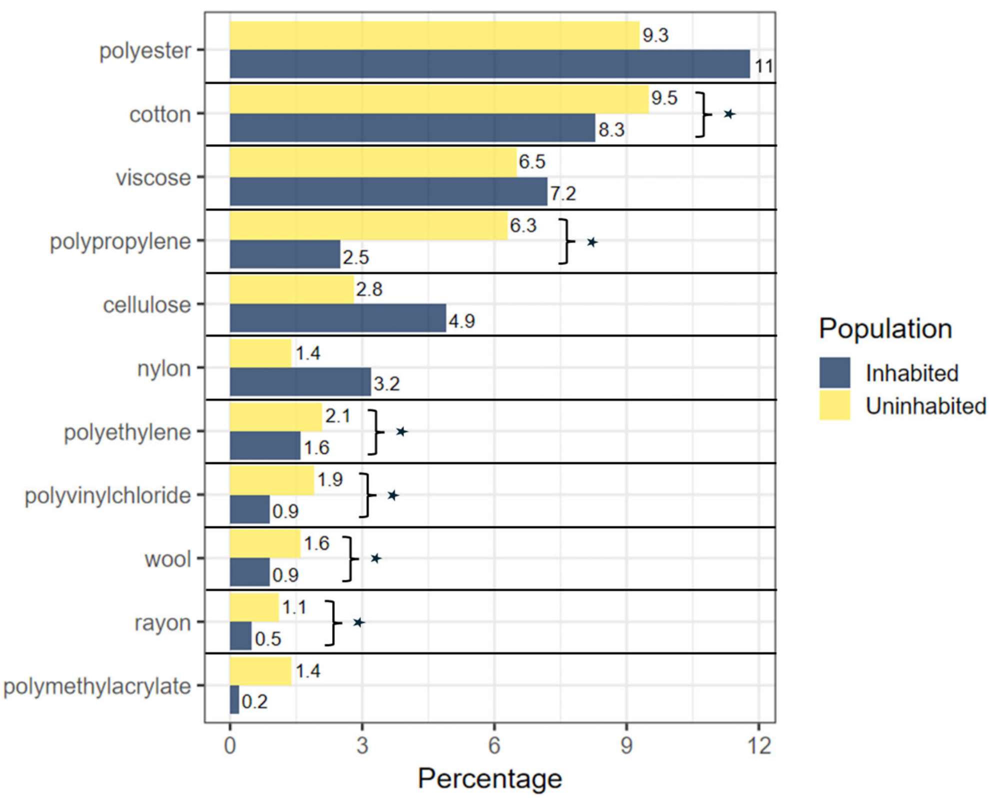

FIGURE 5 Top 11 polymer percentages of total items inspected under Fourier transform infrared spectroscopy (FTIR, $n = 569$), split between Diego Garcia and the uninhabited atolls (Egmont, Salomon, Peros Banhos, and Great Chagos Bank Atolls; significant pairwise comparisons are represented by a star).

TABLE 1 Comparative table of the results of all other studies of microplastic contamination of filter-feeding elasmobranchs feeding grounds, using the same methods as our study (200 μm net mesh and sub-surface trawls of the top 0.5 m of the water column).

Location	Species	Non-fiber particle quantity	Total particle quantity	Predominant types of particles	Predominant polymers	Estimated ingestion rate of plastic particles	References
Chagos Archipelago	Reef manta ray	0.2/m^3	1.1/m^3 with over half confirmed as microplastics	Fibers (78.2%) and fragments (10.5%); blue (32.1%) and black (18.7%) fibers	Polyester (21.1% of items examined under FTIR spectroscopy), polypropylene (8.8%) and nylon (4.6%).	95 pieces/h (half of which are confirmed microplastics)	This study
Komodo National Park, Nusa Penida MPA, and Pantai Bentar, Indonesia	Reef manta ray and whale shark	Between 0.04 and 0.90/m^3	NA (Not Applicable)	Fragments (48%) and films (47%); transparent (45.9%), white (23.8%), blue/green (21.6%)	Polyethylene and polypropylene (99% together)	4–63 non-fiber pieces/h (manta ray) 137 non-fiber pieces/h (whale shark)	Germanov et al. (2019) Argeswara et al. (2021)
The Maldives	Reef manta ray	0.23/m^3	0.26/m^3	Fragments (52%)	Polyethylene and polypropylene	22 pieces/h	Saliu et al. (2018) (note: location of study not manta ray specific)
Red Sea (Saudi Arabia)	Reef manta ray	0.37/m^3	NA	Fragments (73%) and films (14.9%)	Polyethylene (65.6%) and polypropylene (26.3%)	32 pieces/h	Martin et al. (2019) (note: location of study on opposite side of Red Sea to manta ray aggregation)
Gulf of California, Mexico	Whale shark	NA	0–0.14/m^3	NA	Polyethylene (35% of items)	0–46 pieces/h	Fossi et al. (2016, 2017)
Mediterranean (Pelagos Sanctuary)	Basking shark	NA	0.62 particles/m^3	NA	NA	546 pieces/h	Fossi et al. (2012)
		NA	0.31 particles/m^3	NA	NA	273 pieces//h	Fossi et al. (2016)

Abbreviations: FTIR, Fourier transform infrared spectroscopy; MPA, marine protected areas.

whale sharks (Fossi et al., 2016, 2017), and the Pelagos Sanctuary in the Mediterranean, home to basking sharks (Fossi et al., 2012, 2016) (Table 1).

4.2 | Implication for local reef manta ray conservation

The particles identified in this study were mainly blue and black fibers (32.1% and 18.7%, respectively), which are the predominant type of particles ingested by other marine chondrichthyans (Gong et al., 2024). Different polymers have different leaching properties (Lithner et al., 2011) and different capacities to accumulate toxic chemicals (Bond et al., 2018), and microfibers are the particles of most toxicological concern (Brander et al., 2024). While the impacts of microplastic ingestion are difficult to assess and generally not lethal (Bucci et al., 2020; Galloway et al., 2017), especially in large-bodied megafauna (Roman et al., 2020), chronic exposure raises concerns for feeding, behavior, and reproductive issues (Galloway et al., 2017). Additionally, the presence of microplastics in seawater has been linked with phthalates (a very common type of plasticizer) in coastal environments (Dhavamani et al., 2022; Saliu et al., 2019), in plankton, and in the tissue samples of co-occurring filter-feeders (Fossi et al., 2012, 2014, 2016, 2017; Galli et al., 2023). The mechanisms by which phthalates and other plasticisers affect species are very complex (Marchant et al., 2022), and their impacts are often unclear. However, long-term chronic exposure to phthalates, even in low doses, could disrupt the reproductive system, especially for pregnant and developing individuals (Warner and Flaws 2018), and cause oxidative stress (Wang et al., 2020). In addition to the potential risk of toxic chemicals in their prey and their own tissues, microplastic presence in manta ray feeding grounds may also influence prey availability, as microplastic ingestion has been shown to affect zooplankton feeding, behavior, growth, metabolism, energy, reproduction, and lifespan (Bai et al., 2021; Botterell et al., 2019; Coppock et al., 2019). Furthermore, microplastic presence may influence reef manta ray feeding behavior. For example, if it contributes to the prey density threshold (the biomass of zooplankton required to trigger feeding) (Armstrong et al., 2016), it could potentially lead to less energetically efficient foraging, impacting their fitness.

As the quantities of microparticles observed here did not differ between reef manta ray feeding and non-feeding areas, the exposure to microplastics of this geographically isolated population is likely unavoidable around the archipelago. The lack of a relationship between microplastic and zooplankton accumulation, also observed by Germanov et al. (2019) in Indonesia, may be because plankton are "active free-swimming drifters" which migrate vertically at nighttime (Alldredge & King, 1980), while plastic is inert (Wiafe & Frid, 1996). However, since all samples in this study were taken during the day, the influence of the diel movement of plankton on these results is likely minimal. Factors other than oceanography and currents may influence plankton distribution in the marine environment; for example, changes in temperature and salinity (driven by events of high rainfall) can change the zooplankton community and abundance (Wells et al., 2022). Additionally, small-scale oceanographic processes, such as internal waves, which would not impact buoyant plastic, drive the plankton accumulation, and therefore reef manta ray aggregation, as observed at Egmont Atoll (Harris et al., 2021). Based on the observed number of particles, exposure is likely to be highest at Egmont Atoll, where reef manta rays have an exceptional degree of residency and forage year-round (Harris et al., 2024). Additionally, the increasing trends between concentrations of plankton and plastic observed around Salomon Atoll indicate that in this location, their preferred feeding areas also contain microparticles in high quantities. Egmont and Salomon Atolls have been designated as IUCN Important Shark and Ray Areas (IUCN SSC Shark Specialist Group, 2023a, 2023b). Nonetheless, this protection does not prevent the risks from global threats such as microplastic contamination. Microplastic removal is difficult, with limited efficiency of current technologies (Schmaltz et al., 2020), so it is key to understand their local and regional sources, to prevent their input.

4.3 | Implications for island conservation

Most islands globally, and in particular remote islands with little capacity for large-scale waste management, are receiving large quantities of plastic debris, mostly originating from elsewhere (Bouwman et al., 2016; Burt et al., 2020; Duhec et al., 2015; Hoare et al., 2022; Lavers & Bond, 2017; Patti et al., 2020). This debris poses risks to the ecosystem of these islands (Filho et al., 2019; Garrard et al., 2024; Hoare et al., 2022; Jones et al., 2021), but the costs associated with cleanup are considerable (Burt et al., 2020; Rodríguez et al., 2020). Microplastic cleanup in particular is difficult due to its small size and high diffusivity (Nafea et al., 2024; ten Brink et al., 2018) and cleanup initiatives tend to focus on larger debris items (Schmaltz et al., 2020). In the first instance, locally generated plastic that is ending up in the environment can be reduced, even though these solutions are only feasible on Diego Garcia (Filho et al., 2019; Lawen et al., 2024; Verlis & Wilson, 2020). In the Chagos Archipelago, the large quantities of plastic observed on the beaches (Hoare et al., 2022) could be breaking down into smaller microplastics due to the high temperatures and Ultraviolet light (Andrady, 2015). Therefore, regular beach cleans are recommended to reduce this potential local source of microplastics, particularly targeting locations of ecological importance with known high debris quantities (Hoare et al., 2022). Further research into beach sediment microplastics could help understand the link between beached macroplastic and sea surface microplastics. Such a link would allow for targeted beach cleans on beaches close to known reef manta ray feeding areas. Additionally, the only potential local source of microparticles within the archipelago is the military base and associated population on Diego Garcia. In this location, the higher proportions of fibers and clothing-related polymers (cellulose, nylon, polyester, and viscose) could be linked to wastewater outflow (Kay et al., 2018) and washing machines (Napper et al., 2020). One easily implementable solution to prevent the input of microparticles into Diego Garcia's lagoon is to attach filters on washing machines (Napper et al., 2020) and in wastewater treatment plants, which have been found to be highly efficient (Nasir et al., 2024). Research into the concentrations of microplastics in the wastewater discharge from Diego Garcia could help understand whether this is indeed a source of microparticles in the marine environment (Rapp et al., 2020). However, the higher concentration of particles on the uninhabited atolls suggests the majority of particles arrive from elsewhere, either from the breakdown of beached debris or from further away as microparticles.

Microplastic particles can travel long distances through the ocean (Andrade et al., 2021; Liu et al., 2019), with smaller microplastics (<1 mm, such as fibers) input into the Indian Ocean from land (Li et al., 2022) and transported with water masses (Poulain et al., 2018; Vega-Moreno et al., 2021, 2024). The Chagos Archipelago was modeled to receive most of its small buoyant plastic debris from Indonesia, while the Maldives was estimated to receive them from India and Sri Lanka (Vogt-Vincent et al., 2023). This could explain why the concentrations of microplastics in the Chagos Archipelago are more comparable to Indonesia than to the Maldives. Indonesia is also the main origin of plastic drink bottles observed on the beaches of the Chagos Archipelago (Savage et al., 2024) and a large source of debris observed on other islands in the Indian Ocean (Vogt-Vincent et al., 2023), with only four of its rivers estimated to contribute the majority of debris on other Indian Ocean remote islands (van der Mheen & Pattiaratchi, 2024). Therefore, the higher concentrations of microparticles in the northern atolls of the Chagos Archipelago could be a result of the geographical closeness to these sources, particularly Indonesia and India, which are in the top three riverine emitters of plastic globally (Mai et al., 2023). While it is difficult to apportion sources to fibers (Helm, 2017), the predominant types of microparticles identified in this study, blue and black fibers, are also the main types of particles emitted into the Indian Ocean by the River Ganges, which releases up to 3 billion microparticles every day (Napper et al., 2021), and by storm water drains from Western Australia (Lutz et al., 2021) and the southeastern coast of South Africa (Nel & Froneman, 2015). These microparticles could be traveling long distances through the ocean to arrive on the coastlines of the Chagos Archipelago. Finally, microplastic can originate from fishing activity (Andrady, 2011; Moore, 2008). Fishing gear and nets can shed nylon, polypropylene, and polyester fibers (Sharma et al., 2024), and rope abrasion can create polypropylene fragments (Napper et al., 2022), all polymers widely observed in this study, particularly around the uninhabited atolls. The high fishing activities in the Indian Ocean (Roberson et al., 2022) could be adding to the microplastic load in the Chagos Archipelago and could be reduced by using adequate fishing equipment (Napper et al., 2022).

4.4 | Opportunities for improvement and next steps

The current study provides, for the first time, a snapshot of the quantity and characteristics of microplastic particles found in the nearshore marine environment of the Chagos Archipelago. Results could be more readily compared to other remote island microplastic studies by standardizing methods (Cowger et al., 2020; Lusher, Munno, et al., 2020; Rochman et al., 2017). Our study used a smaller mesh size to accurately reflect the feeding mechanisms of reef manta rays (Germanov et al., 2019), potentially leading to the detection of more plastic particles compared to studies using the standard 330 μm mesh (Lindeque et al., 2020). Therefore, we only compared our findings with those of studies using the same mesh size. While this study advances our understanding of reef manta ray exposure to microplastics in the region, the findings are spatially and temporally limited. Plastic concentration has been shown to exponentially decrease with depth (Kooi et al., 2016), but other studies show a 2.5-fold increase in microplastics in the mixed layer (Kukulka et al., 2012), where reef manta rays are known to feed (Peel et al., 2019, 2020; Lassauce et al., 2020). Future research would benefit from further vertical measurements of plastic around the archipelago, including the mesopelagic environment where reef manta rays also feed (Braun et al., 2014), and plastic could be present (Wieczorek et al., 2018). Additionally, more regular sampling is required to allow the assessment of seasonal variations in plastics (Evans & Ruf, 2021; Vogt-Vincent et al., 2023) and how these may influence the risk of exposure to the local reef manta ray population (Germanov et al., 2019; Guerrini et al., 2019).

Given that reef manta ray may ingest microplastics indirectly through the plankton they consume (Kahane-Rapport et al., 2022; Zantis et al., 2022), the current ingestion estimates could be conservative. Future research should address this by sampling microplastics in seawater, prey, and filter-feeder scat simultaneously, as done in Indonesia (Germanov et al., 2019), or by analyzing gut contents if feasible (Besseling et al., 2015). Moreover, the processes and impacts of microplastic ingestion remain largely unknown (Bucci et al., 2020), as well as the mechanisms by which the plastic-derived chemicals affect species (Marchant et al., 2022), so it is crucial to distinguish between studying exposure and the actual effects of microplastic pollution on species (Underwood et al., 2016). While this study examines exposure and risk, future long-term studies should seek to understand associations between exposure and animal fitness and population health (Senko et al., 2020). Further research on stress biomarkers of phthalates and wider plasticizers in elasmobranchs (Alves et al., 2022), gut retention time, and the presence of phthalates in water, plankton, and reef manta ray tissue biopsies (Germanov et al., 2019) is required to help provide a more comprehensive understanding of the risks and impacts of plastic ingestion on reef manta rays.

5 | CONCLUSION

This study provides empirical evidence of the microplastic pollution in a remote island in the central Indian Ocean, as well as the contamination of the feeding grounds of the reef manta ray population it supports. Microplastic ingestion risk can affect species from the cellular to individual and population levels, potentially impacting whole ecosystems (Galloway et al., 2017; Senko et al., 2020). Reef manta rays, already at risk of extinction due to overexploitation and other anthropogenic threats (Dulvy et al., 2021; Marshall et al., 2022; Pacoureau et al., 2021), face additional threats from microplastics in their feeding areas. With projected growth in plastic production predicted to exceed mitigation efforts (Borrelle et al., 2020), it is important to continue investigating the impacts of plastic pollution on vulnerable species, particularly at the level of populations or species rather than individuals. Additionally, while it is important to make use of local short-term mitigation solutions, such as washing machine filters and regular beach cleans, the transboundary nature of plastic and microplastic pollution emphasizes the need for international cooperation in the United Nations Global Plastic Treaty negotiations, on one hand to fund expensive cleanup action of the plastic already in the environment, and on the other hand to create international, legally binding legislation to prevent further input of microplastics into the ocean (Fiore et al., 2022; Richon et al., 2023).

AUTHOR CONTRIBUTIONS

J. Savage: Study design, data collection, data processing, data analysis, manuscript writing, manuscript editing. **J. L. Harris**: Study design, data collection, manuscript editing. **H. J. Koldewey**: Study design, manuscript editing. **T. B. Letessier**: Study design, manuscript editing. **M. Rowcliffe**: Study design, data analysis, manuscript editing. **D. Morritt**: Study design, manuscript editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. The authors used no Artificial Intelligence (AI) as part of the process of writing this manuscript.

DATA AVAILABILITY STATEMENT

The data and code for this study are fully available on a Figshare repository. (https://doi.org/10.17637/rh.27046120.v1).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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