Plastic debris (> 500µm) concentration gradient detected across the Southwest Indian Ocean

Margot Thibault
margotthibault@orange.fr

University of Reunion Island

Adrian Fajeau
GLOBICE association

Aina Ramanampananjy
CETAMADA association

Sarah-Jeanne Royer
The Ocean Cleanup

Gwennaïs Fustemberg
BESTRUN association

Vyctoria Marillac
BESTRUN association

Julie Gindrey
University of Reunion Island

Anjara Saloma
CETAMADA association

Manon Condet
CITEB

Perrine Mangion
CITEB

Matthias Egger
The Ocean Cleanup

Maxime Amy
Terres australes et antarctiques françaises

Sébastien Jaquemet
University of Reunion Island

Philippe Jourand
University of Reunion Island

Alexandra ter Halle
Université Toulouse III - Paul Sabatier

Matthieu Le Corre

University of Reunion Island
Thierry Mulochau
BioRécif
Laurent Lebreton
The Ocean Cleanup

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Abstract

Marine plastic pollution is increasing. The Indian Ocean is understudied compared to the Pacific and Atlantic Oceans. This study investigates plastic pollution in the Southwest Indian Ocean using a multi-faceted approach that includes both floating (visual survey and manta trawls) and beach-collected plastics, assessing their concentration, composition, and origin. Through 19 oceanographic campaigns and 153 uninhabited beach surveys, a total of 101,055 pieces of marine litter were identified, with 95% being plastics. Floating macroplastics were predominantly found near remote island waters, particularly at Glorieuses (10^3 items.km^{-2}). Meanwhile, an increasing gradient of floating microplastic concentrations was observed from 40°E (10^3 items.km^{-2}) to 65°E (10^5 items.km^{-2}) along 30°/33°S. High concentration of beached macroplastics where observed on the east coast of Madagascar and Tromelin. Mesoplastics were more abundant than macroplastics, on remote islands. Floating and beached plastic debris were mainly hard fragments, mostly made of polyethylene (floating, beached: 72%, 57%) or polypropylene (26%, 34%). The majority of macroplastics identified in the brand audit, was mainly mineral water food packaging (81%) from Southeast Asian manufacturers. Our results will inform national management and provide evidence to support international plastic treaty negotiations on legacy plastics.

Introduction

There is growing evidence of the accumulation of plastics in marine and coastal ecosystems[1,2,3,4,5]. This accumulation is impacting wildlife and humans but is costly to remediate. While a global plastics treaty is currently being negotiated with the aim of ending plastic pollution, the ongoing production of plastics and the resulting amount entering the ocean means that there is an urgent need to locate accumulation zones. These zones can be targeted for ocean and coastal clean-up, maximizing the use of limited resources. Plastic debris in the Indian Ocean, especially the Southwest Indian Ocean has been under-sampled and under-studied compared to other oceans, despite half of the top 10 countries contributing most to ocean plastic pollution being located along the Indian Ocean rim[6]. Locating accumulation zones in this region, will inform national management and provide evidence to support international plastic treaty negotiations on legacy plastics[7].

Floating plastics can be transported over long distances by wind, ocean currents[8] and accumulate along coastlines or in subtropical gyres where they form the so-called 'garbage patches'. Five 'garbage patches' have been identified in the global ocean: two in the Pacific (North[9–11]; South[12]), two in the Atlantic (North[13,14]; South[15–17]), and one in the Southern Indian Ocean [8,18–20]. The exact location of the latter is still debated. Some studies place it in the southwestern part of the Indian Ocean [21–23], while others place it on the southeastern side of the basin [4,19,24,25] and one model in the central part of the basin[26]. The Indian Ocean 'garbage patch' is predicted by numerical models to be the second largest accumulation of floating plastics in the ocean[22] but direct observations are limited in this region. Only four oceanographic campaigns have been conducted in the Southern Indian Ocean to sample floating plastic debris [18,19,27,28]. The greater sampling effort has focused on beached plastic debris, with data indicating Southeast Asia as potential main origin [5,29–36]. With only a handful of pelagic field observation campaigns, very little is known about the concentration, location, composition, and distribution of floating plastic pollution accumulation in this part of the ocean.

In this study, we conducted an extensive *in situ* sampling all around the Southwest Indian Ocean. Our aim was to cover a large geographical area in order to complete previous studies and gain a deeper understanding of the concentration, composition, origin of the plastic accumulation zones in the Southwest Indian Ocean. Our specific objectives were (i) to estimate the concentration of plastic debris (macro-meso-micro) using different *in situ* samplings: visual survey, manta trawling deployment, and beach surveys, (ii) to characterize the composition of plastic debris in terms of shape, size class, polymer, and (iii) to determine the origin of macroplastics beached on uninhabited remote islands through a "brand audit" method. By strengthening our understanding of accumulation zones we can, with more confidence, allocate resources for ocean and coastal clean-up activities.

Methods

Study site. This research utilizes data collected during 19 oceanographic campaigns that have been conducted in the Southwest Indian Ocean (SWIO, 4°/40°S – 38°/82°E, Fig. 1) between 2019 and 2023. During these campaigns, data on the concentration of plastic debris at the ocean surface was collected using visual surveys and manta trawls. In addition, nine beaches were surveyed to record the number of items of beached marine litter collected. Campaign details, such as date, location, type of vessel, are listed in Supplementary Tables S1, S2, and Figures S1, S2.

Sea surface surveys. Before each offshore campaign, we conducted training sessions for each observer on board the vessel, focusing on the identification of floating plastic debris at the sea surface. Observations were made during daylight hours while the vessel was moving at constant speed [27,37–40]. At least two observers were situated on the bridge to allow a visual survey area of 180 degrees. Observers used both naked eye and binoculars to make observations. There was no standard survey duration or distance but observers recorded start/end GPS coordinates for the starting and ending points of the survey, duration of the survey, vessel speed, platform height, number of observers, and environmental parameters (sea state, wave height, and weather). During these surveys, observers counted plastic debris larger than 2.5 cm up to 1 meter (referred to as macroplastics[41]) and those exceeding 1 meter (referred to as megaplastics[41]).

Beach surveys. Each of the nine beaches we surveyed met the following criteria: (i) open to the ocean (without coral barrier); (ii) moderate slope; (iii) low granulometry; (iv) with no beach cleanup activities; (v) long distance (> 10 km) from city or harbor, (vi) with a maximum of 100 habitants living around the beach. Macrolitter items were collected along a transect parallel to the coastline on all beaches from the vegetation supralittoral to the sea (length size transect by beach is written in Supplementary Table S2). Each macrolitter was counted, measured, and weighted by category used by each program according to Barnardo & Ribbink (2020)[42] (e.i. ceramic, clothing, paper/cartoon, glass, metal, rubber, wood, plastic, fishing items, personal care, other, wood). Mesolitter items (5 mm – 2.5 cm) were sampled on only four beaches i.e. Ampanihy, Ampahiry, Juan de Nova, and Lys. Items were collected on the surface of the sand using a sieve (size mesh: 3 mm) in 50cm wide transects stretching from the sea to the vegetation

To ensure optimal information and comparability in this study, we meticulously collected all raw data from each program[10,41,42] using different list characterization to then create a unified list for comparison for this paper (Supplementary Table S3).

Brand audit. The identification of the origin of macrolitter was undertaken by the “brand audit” method[42] for all beaches. When a brand was visible or incrusted, we recorded for each identifiable item: the manufacturer, the type of product (e.g., food packaging, household product, personal care product), the subtype of the product (e.g., drink, mineral water, oil container), the written polymer code (e.g., high-density polyethylene, HDPE; polyethylene terephthalate, PET; polystyrene, PS). We used online investigations[29,43] to supplement and fact-check our data. First, we searched by using different search engines (e.g., Google, Yahoo, Ecosia) with different search setting language (e.g: Indonesian, Chinese, Japanese, Korean, Thai …) when it was identifiable[35]. Once the website of the company was found, we noted all information about production and exportation areas. The category “International” was created when the country could not easily be identified, mostly for brands established and sold internationally (e.g: The Coca-Cola Company®). This analysis provided a first-order map for the origin of the macroplastics we collected on these remote beaches.

Manta trawl sampling. On board, the manta net was deployed at > 30 meters behind the vessel to avoid the vessel's wake; it collected plastic debris at the sea surface[11] (all information about dimensions of nets and flowmeters are given in Supplementary Table S1). At each site, three consecutive 30-minute transects were conducted at a speed of 2 knots using an individual single-use cod-end for each transect. Between transects, the net was rinsed with seawater on the outside of the net to move any missed plastic debris towards the cod-end. The cod-end was then removed, placed into an annotated Ziplock bag (date, mission, cod-end identification number), and stored in a freezer until transferred for analysis in the laboratory ashore. For the next deployment, a new code-end was placed. For each manta trawling, the following environmental parameters were recorded: wave height (m), wind speed ($m.s^{-1}$), atmospheric pressure (hPa), year, month, season (Dec-Feb: Wet season; Mar-May: Interseason1; Jun-Aug: Dry season; Sept-Nov: Interseason2), surface area of sampling (km^{-2}, flowmeters, gps points) and vessels characteristics. The manta net was not deployed if wave height exceeded 2 meters. Once at the laboratory, each manta trawl cod-end was externally rinsed to deposit all the content on a sieve (500 µm). Under light and a magnifying glass, all plastic debris were collected with ultra-fine tweezers (300 µm point diameter) and placed in a Petri dish until analysis and characterization. When all plastic debris were placed on the Petri dish, an image was taken with a camera and used to count the number of items (Nikon D7500 - lens: AF-S MICRO NIKKOR 105 mm). Then we attributed were determined for each item: (i) shape (hard plastic, foam, pellet, fiber); (ii) dry weight (10^{-5} g precision balance); (iii) size (ImageJ software 1.5K[44]). The concentration of plastic debris was calculated by incorporating the effect of wind mixing into the calculation of the concentration of plastic debris at the sea surface[45]:

$$C_i = \frac{c_s}{1 - e^{-dW_b\left(1.5\sqrt{\frac{\rho\ a}{\rho\ w}C_d U^2},\ k,\ \frac{0.96}{g},\ \sigma^{\frac{3}{2}},\ C_d,\ U^2\right)^{-1}}}$$

1

Where C*i* is the depth-integrated concentration for the upper 5 m of the water column (item/km^{-2}), C*s* corresponds to the raw concentration of plastic debris type and size class as measured in the laboratory linked with the sampling surface area (km^{-2}), d is the depth of the manta net, W_b is the rising velocity by plastic type and size (m/s determined by Lebreton et al.[11]), ρ_a is the air density ($kg.m^{-3}$), ρ_w is the seawater density ($kg.m^{-3}$), C_d is the drag coefficient (0.0012), U is the sea surface wind speed during sampling ($m.s^{-1}$), k is the Karman constant (0.4), g is the gravitational constant (9.81 $m.s^{-2}$) and σ is the wave age equal to the constant 35.

Infrared spectroscopy ATR-FTIR. For each plastic debris collected from manta sampling and mesolitter from beach surveys, we determined the polymer type of each item using Fourier Transform InfraRed (FTIR) spectroscopy at the UMR Softmat laboratory, in University Paul Sabatier II, France. This was done with a Thermo Nicolet Nexus 6700 instrument equipped with a diamond crystal Attenuated Total Reflection (ATR) mode and a deuterated triglycine sulphate detector. During the analysis, white background and sample spectra were obtained using 16 scans covering the wavelength range of 400 cm^{-1} to 4,000 cm^{-1} with a resolution of 4 cm^{-1}. A white background spectrum was taken every 2 hours to ensure accuracy. Each piece of plastic debris was pressed between the diamond crystal and the base. The diamond crystal was cleaned between each measurement to avoid any bias between spectra. The obtained spectra were corrected using the ATR thermo-correction method to obtain transmission-like spectra[46]. The final infrared spectra were observed using the Omnic software (version 9.9.0.473). Only spectra with more than 80% similarity to one of the spectra in the spectra database created by the laboratory SOFTMAT at the University of Toulouse Paul Sabatier, were validated. In the cases where the similarity was less than 80%, the assignment to a specific polymer type was not made to avoid identification errors.

To provide additional information on the level of degradation of plastic debris, a carbonyl index was determined for polyethylene (PE) and polypropylene (PP) polymer particles. These particles were matched with a similarity of over 80%. For the PE carbonyl index, the ratio between the integrated absorbance of the carbonyl peak in the range of 1,850 cm^{-1} to 1,650 cm^{-1} and the methylene scissoring peak in the range of 1,500 cm^{-1} to 1,420 cm^{-1} was calculated. The Specified Area Under these two bands (SAUB) provided by Almond et al.[47] was calculated using Omnic software with the options band analysis tool. For the PP carbonyl index, the ratio between the peak height at 1,715 cm^{-1} and the area under the band in the range of 1,500 cm^{-1} to 1,450 cm^{-1} was also calculated. The area under the band and peak height were calculated by the same software using the options peak analysis tool. For each measurement, a flat baseline was applied using the data between 4,000 cm^{-1} and 2,000 cm^{-1}.

Statistical analysis. The normality and homoscedasticity of our data were tested by Shapiro and Levene tests, respectively. Linear models (LM) were performed to explain the fluctuation in abundance of plastic debris collected by manta nets (Y variable) by these explicative variables (X_n): latitudes, longitudes, sea states and seasons (Dec-Feb: wet; Mar-May: Interseason1; Jun-Aug: Dry; Sep-Nov: Interseason2). LM were also used to explain the concentration observed by visual surveys by these explicative variables: latitude, longitude, year, season, platform height (m, 0–3; 3–6; 6–9; 9–12), cloud coverage (%, 0, 25, 50, 75, 100), sea state, and effort. When, we had replicated data from beaches by season and year, LM were conducted on plastic debris abundance beached on remote islands and investigated the influence of the following variables: site, year, and season. For each LM, we tested the normality and selected models with Akaïke's Information Criteria adjusted for small sample sizes (AICc). All statistical tests were conducted in the R computing environment (R Core Team, 2023).

Results

Overall. A total of 101,055 marine debris items were recorded, from manta trawling (n = 2,780 items; > 500µm), sea surface survey (n = 8,655 items; > 2.5 cm), and beach monitoring (n = 89,620 items; > 5 mm).

Sea surface plastic concentration. Among the 220 manta trawl samples, 97% contained plastic debris. The highest concentration of sea surface microplastics was 1,194,230 $items.km^{-2}$, recorded northwest of Reunion Island from the IOTA program. The lowest was recorded on Aldabra 9 $items.km^{-2}$. (Fig. 2A). Overall, the microplastic concentration exhibits a noticeable increasing longitudinal gradient along latitude 30°/33°S, ranging from 10^3 $items.km^{-2}$ at 40°E to 10^5 $items.km^{-2}$ at 65°E. The season of Interseason2 and sea state calm also had an impact on the high concentration of microplastic (N = 220, LM, p-values < 0.001, Supplementary Table S4, Figure S3.).

During the 1,884 hours of sea surface survey from different oceanographic campaigns, 8,655 pieces of marine litter were observed, of which 97% were plastic debris. Macroplastics concentration (mean ± sd) was 90.8 ± 411 $items.km^{-2}$ (Fig. 2B). The maximum concentration, reaching 4,585 $items.km^{-2}$, was observed around Mayotte and Glorieuses Islands. A gradient was also observed from the west (10^0 $items.km^{-2}$) to the east (10^2 $items.km^{-2}$) on the latitude 30/33°S for macroplastics. The average abundance at 32°S latitudes was 40 ± 869 $items.km^{-2}$ (max: 237 $items.km^{-2}$, 32°S and 60°E). However, LM did not reveal a significant explanatory factor to explain the visual survey concentration (N = 236, LM, p-value > 0.05, Supplementary Table S4, Figure S1).

Beached plastic concentration. Since 2019, a total of 89,620 pieces of marine litter have been collected, of which 95% were identified as made of plastic. The concentrations of macroplastics were particularly higher for: Tromelin with 11.7 ± 16.8 $items.m^{-1}$, Juan de Nova with 7.8 ± 0.2 $items.m^{-1}$, and Ampanihy with 5.84 ± 5.74 items.m^{-1}(Fig. 3A, Supplementary Table S5). Furthermore, the highest concentrations of mesoplastics were mainly observed on Ampanihy with 140 ± 89 items.m^{-1}, Ampahiry 62 ± 59 items.m^{-1}, and Juan de Nova with 92.3 ± 13.6 items.m^{-1} (Figure.3B). LM indicate no influence of the season on the concentrations of beached plastic debris, however a trend to a high concentration was observed during dry season (N = 153, LM > 0.05 Supplementary Figure S4, Table S4).

Composition of marine litter and polymer identification. Hard plastic was the most frequently recorded marine debris category in all surveys with averages of 70%, 77% and 85% for sea surface surveys, beach surveys and manta trawling, respectively (LM, p-value < 0.001; Supplementary Table S4). Fishing gear (line, rope, bucket, drum), foam, and soft materials (film, sheet) constituted the second most common category in terms of floating and beached marine litter, while glass, ceramic, and healthcare-related items were generally less frequently collected (Fig. 4A, Supplementary Table S3 for list of categories). The category, "Hard Plastics" was predominantly composed of "small fragments under 50 cm", specifically 82 ± 17% for floating plastic debris and 28 ± 30% for beached plastic debris (Fig. 4B). The second significant subcategory observed with surveys at sea consisted of "PET bottles", followed by "large fragments exceeding 50 cm". However, on beaches, the second most represented subcategory was "bottle caps". Microplastics collected by manta sampling were composed of hard plastic (77%), then fiber (21%) and a few items were foam (2%) or pellet (1%, (LM, p.value < 0.01, Supplementary Table S4).

Out of the total of 101,055 collected and observed items, we specifically selected all the mesoplastics, beached on remote islands (N = 106 beached items), and all microplastics collected with manta trawl nets (N = 1,175 floating items) to analyse using ATR FTIR. In the end, a total of 1,281 items were analyzed using ATR FTIR, and 82% (N = 960 floating; N = 87 beached) were successfully matched in the database. Floating microplastics and beached mesoplastics debris were predominantly composed of PE (72% of floating; 57% of beached) followed by PP (26% of floating; 34% of beached) of various shapes and size classes. Foam-shaped plastics, for both floating and beached debris, exhibited a diverse range of polymers. Plastic debris found floating inshore (< 12 miles) consisted of 25% PE, 44% PP, and 31% (PVA, PES, PS), whereas offshore (> 12 miles) debris was composed of 75% PE, and 23% PP and 2% (PVA, PES, PS). There was no significant difference in polymer composition among different islands and distance from the coastline. PE and PP carbonyl index showed no significant difference between onshore and offshore samples. Nevertheless, there was a noticeable trend indicating increased degradation of PP with distance from the coast towards offshore (Supplementary Figure S5, Table S6).

Origins of beached macroplastics. Among 89,620 items, we counted 2,787 macroplastics with identified brands, beached on remote islands in the SWIO. In total, we listed 282 different brands. The most recognized brand was Aqua® from Danone®, accounting for 39% of identified markings, followed by a product of The Coca-Cola Company® in the 2nd place (6%), and Sungreen® from Thailand ranking 3rd (4%, Table 1). The identified brands originated primarily from Southeast Asia, accounting for more than 50% of identified origins on items. Additionally, 21% of brands were involved in international trade for exportation and importation. The East Africa sub-region appeared as the second main origin of beached macroplastics on uninhabited remote islands, accounting for 1–9% of the total (Figure. 5A). Among all brands, 76 (27%) represented “food packaging products” and concerned mainly “mineral water bottle brands”, predominantly identified by caps (N = 1,464 made of HDPE) and bottles (N = 20 made of PET, Figure. 5B, Supplementary Table S7_ List of the 282 brands).

Discussion

Our results confirm the problem of sea surface and beached plastic pollution in the Southwest Indian Ocean. Our key finding was an increasing concentration gradient of plastic debris, mainly composed of hard fragments, on the sea surface at latitude 30°/33°S from 40°E to 65°E, reaching up to 10^5 items.km^{-2} (500 µm – 5 mm). In this gradient, the concentrations are higher than those found in the South Atlantic (10^4 items.km^{-2}), but lower than those in the North Pacific garbage patches (> 10^6 items.km^{-2}) [10,17]. This result indicates a large amount of plastic debris is entering the Indian Ocean and circulates towards the subtropical latitudes. Locally, the important amount of microplastics located on the Northwest of Reunion Island reaching 10^6 items.km^{-2}, which could be the result of mesoscale anticyclonic eddies created by the island mass effect [48,49]. Consequently, high concentrations of microplastics in pelagic or coastal regions of the Southwest Indian Ocean have impact on marine ecosystems. It can increase the likelihood of ingestion by marine fauna, ranging from zooplankton to megafauna species, through bioaccumulation, leading to the development of diseases[35,50,51]. Further sampling is required, in the middle and eastern parts of the Indian Ocean, to observe the gradient of floating plastic concentration identified in this study, across different seasons and understand the long-term impact on marine fauna.

Macroplastics beached on the eastern side of Madagascar (Ampanihy, Ampahiry, Tromelin), mostly came from Southeast Asia. The South equatorial current, monsoons, and inadequate waste management in this region contribute to the influx of plastic debris towards islands of the Southwest Indian Ocean like the Seychelles [29], Saint Brandon[30], and the Maldives[52,53]. In the Mozambique Channel, our study recorded more plastic debris beached on Juan de Nova than on Europa. However, among the 1,000 top most plastic-emitting rivers, two are located in Mozambique and one in Kenya[54]. In the Mozambique Channel, mesoscale eddies[55] can carry floating plastic debris to remote islands such as Juan de Nova and Europa[56]. In our study, mesoplastics were more abundant than macroplastics on the beaches, however our concentrations may be underestimated, because plastic debris can be buried in the sand[43,57] or remain trapped in the coral reefs[58]. As these uninhabited islands are protected areas with biodiversity hotspots, species can directly interact with beached plastic, impacting their life[34].

Identifying the use of plastic pollution on these remote uninhabited islands can be crucial to reducing future marine debris deposition. The “brand audit” in our study, indicated that macroplastics collected on the remote beaches located both in the east and west of Madagascar, mainly originated from Southeast Asia (more than 50%) and were primarily associated with “food packaging”, specifically branded mineral water bottles identifiable by caps or bottles, with Aqua® from Danone® being the most prevalent. This brand represents the first mineral water sold by Danone® in Indonesia[59,60]. Similar observations were done in various studies on remote islands such as the Seychelles[29,61], Saint Brandon[30], and countries including South Africa[62] and Madagascar[35].

While this study sheds further lights on the origin and extent of floating plastic pollution in the Southwest Indian Ocean, its long tem fate remains unclear. Models of plastic debris dispersion predict a residence time of around 50 years, with plastic debris gradually moving towards the South Atlantic and a total disappearance of the predicted accumulation after 100 years[23,63]. Systematic collection of plastic debris in both the South Indian and South Atlantic Oceans, along with the identification of their origins and age, could help verify these model predictions and provide a better understanding of the long-term fate and persistence of the South Indian garbage patch.

Declarations

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Authors contributions

M.T. and L.L. designed the study; M.T., A.F., A.R., A.S., G.F., M.C., P.M., M.A., S.J., P.J., S.J.R., M.E., A.T.H., M.L.C., L.L managed expeditions cruises or beach monitoring or directly facilitated the expeditions; M.T., A.F., A.R., G.F., V.M., M.C., T.M., S.J collected the samples; M.T., A.R., M.C., V.M., J.G., analysed the samples at laboratory; M.T. conducted the data analyses and the calculations, and prepared figures and tables; M.T. wrote the manuscript. All authors reviewed and edited the manuscript.

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Competing interests

M.T., L.L., M.E., S.J.R. are employed by The Ocean Cleanup, a non-for-profit developing and scaling technologies to rid the oceans of plastics, headquartered in the Netherlands. A.F., A.R., A.S., G.F., M.C., P.M., M.A., S.J., T.M., P.J., A.T.H., M.L.C declare no competing interests. All the remaining authors declare no competing interest.

Additional information

Supplementary information: Tables S1, S2, S3, S4, S5, S6, S7 and Figures S1, S2, S3, S4, S5

Data availability

The datasets generated during manta trawling are available in the [Raw data of plastic debris collected in the Southwest Indian Ocean by manta trawling] repository, [10.6084/m9.figshare.26828164].

The data generated for brand audit is included in this published article (and its Supplementary S7).

The datasets concerning sea surface survey and beach monitoring are available from the corresponding author on reasonable request.

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Figures

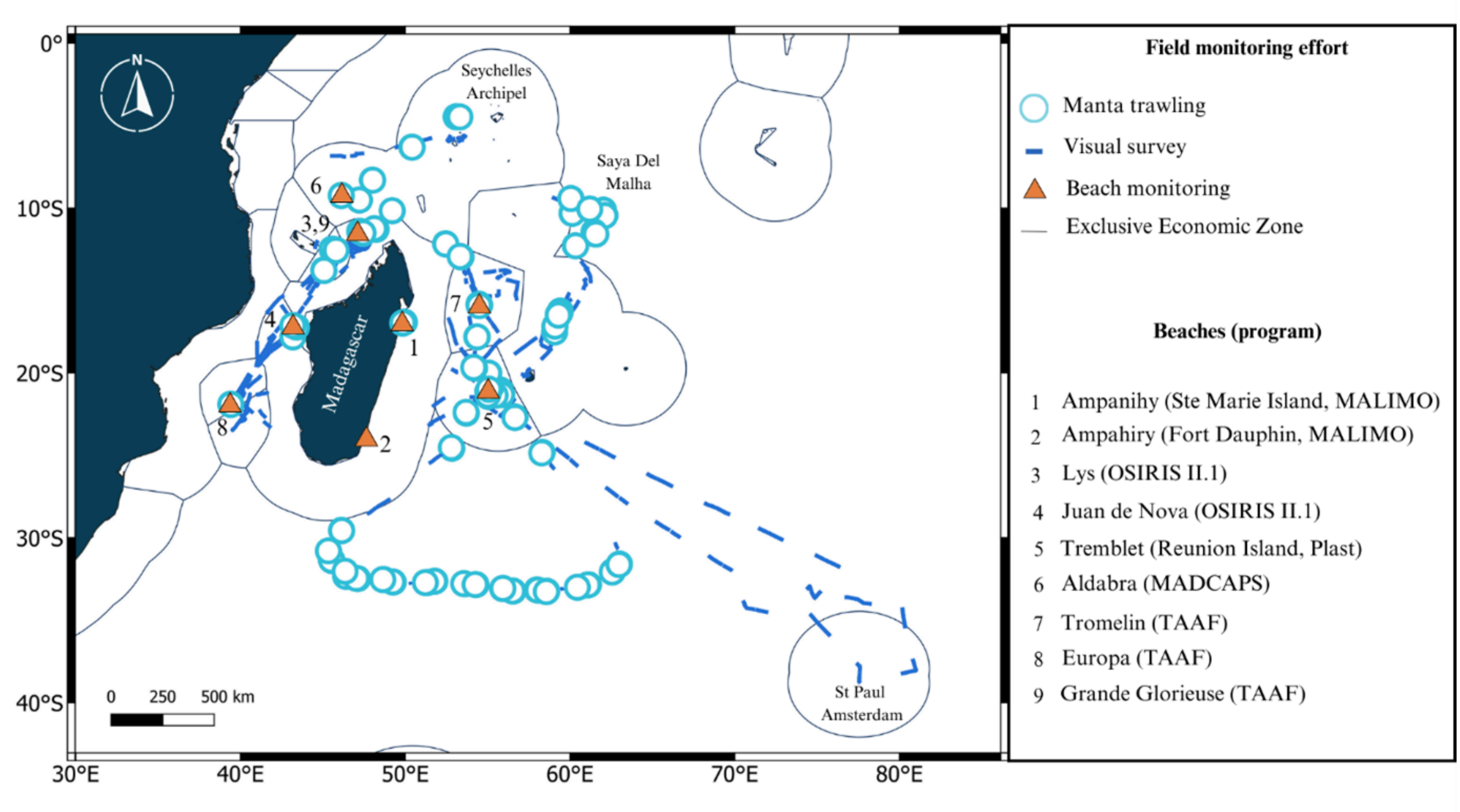

Figure 1

Map of the Southwest Indian Ocean showing the different field trips for plastic collection at sea and on beaches. Circles correspond to manta trawl samples (N=220). The blue line corresponds to visual surveys (N=1,884 hours effort). Orange triangles correspond to beach monitoring (N=153 beach surveys). All information about oceanographic campaigns and programs are included in the Supplementary information Tables S1, S2 and Figure S1 and S2.

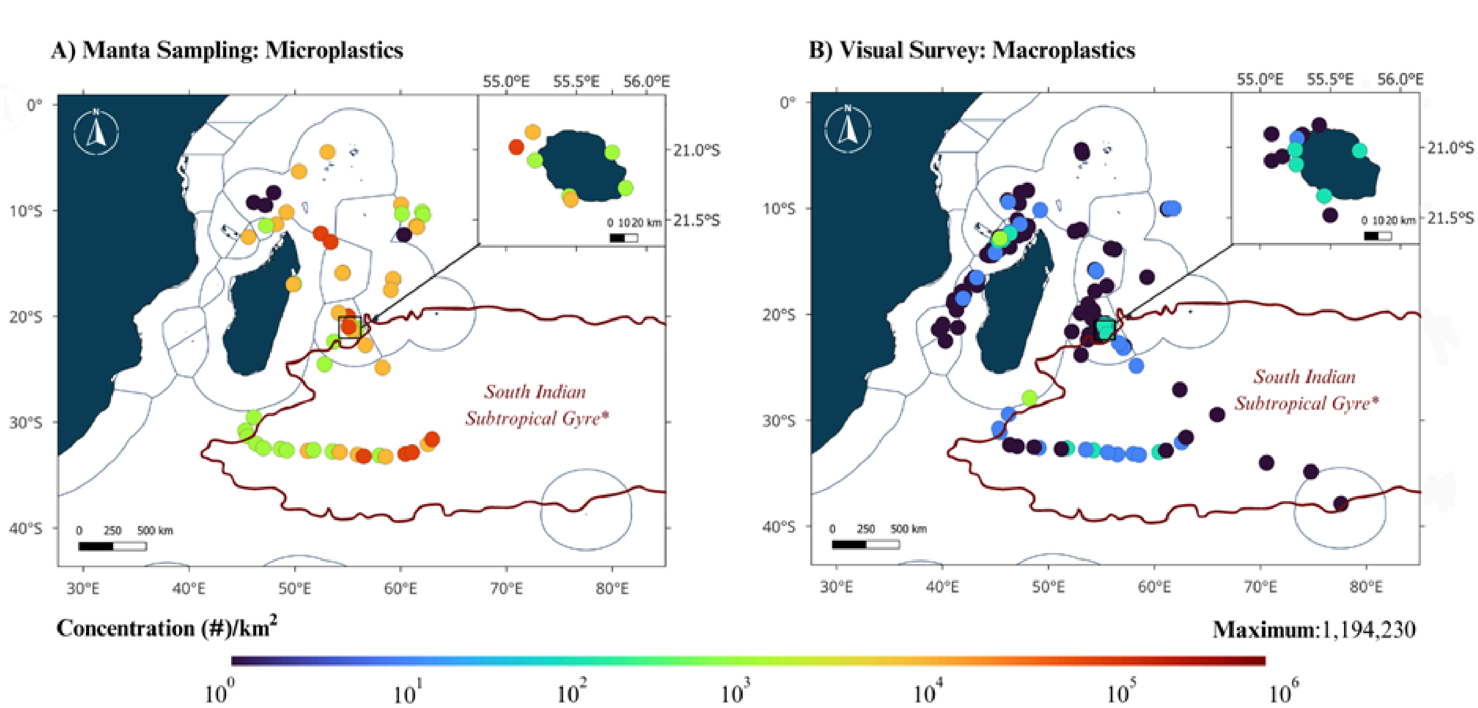

Figure 2

The concentration of plastic debris by abundance recorded from A) manta trawl sampling (size class: 500 µm - 5 mm) and B) visual surveys (size class: 2.5 cm - 100 cm). *The South Indian Subtropical Gyre boundary is adapted from Lebreton[23]

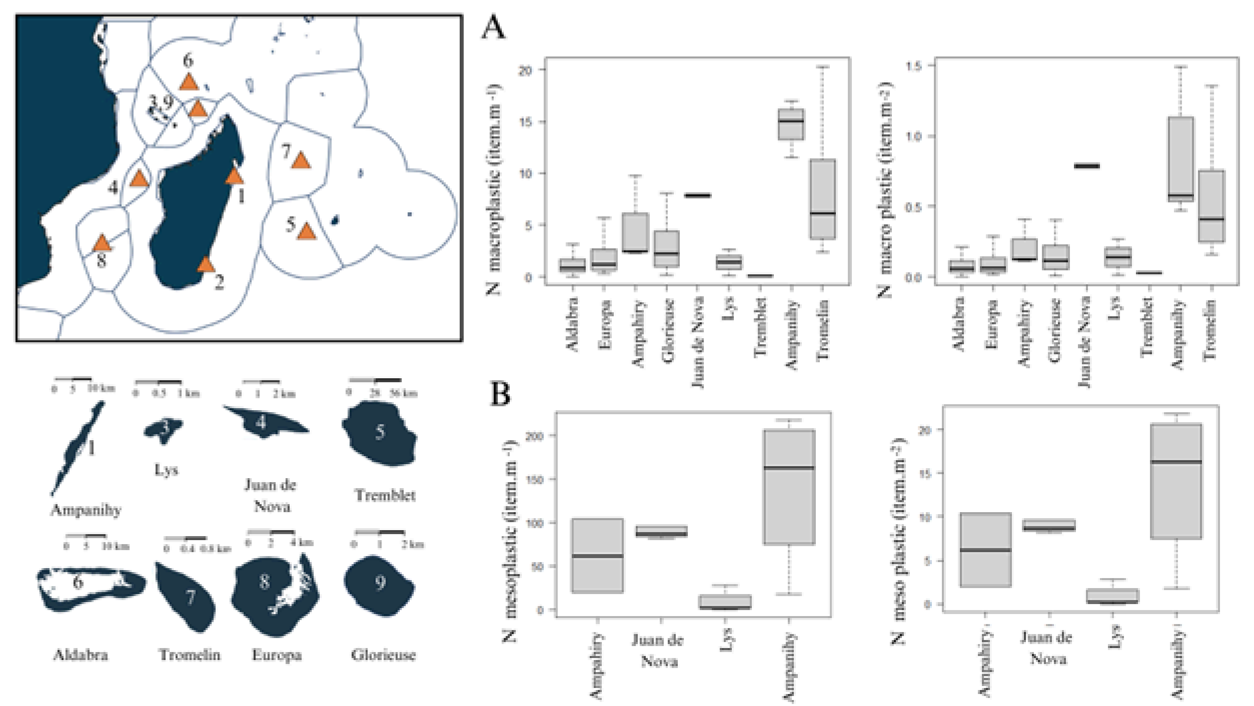

Figure 3

Mean concentration by beaches for A) macroplastics (> 2.5 cm) in items.m^{-1} and items.m^{-2} and B) mesoplastics (5 mm – 2.5 cm) in items.m^{-1} and items.m^{-2}. 1: Ampanihy (Ste Marie Island), 2: Ampahiry (Fort Dauphin),), 3: Lys, 4: Juan des Nova, 5 : Tremblet, 6 : Aldabra, 7 : Tromelin, 8 : Europa, 9 : Glorieuses (Supplementary information Figure S2).

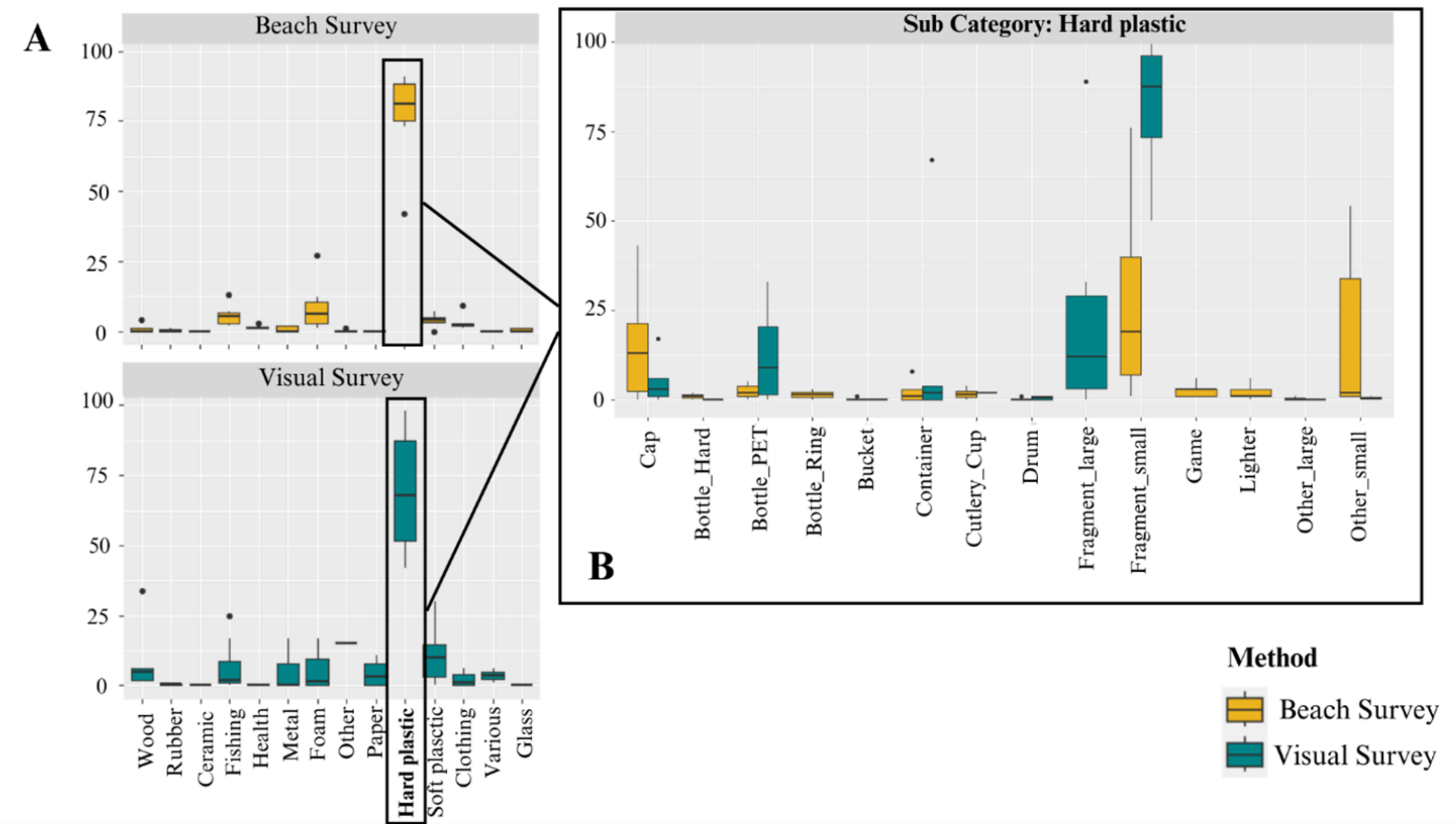

Figure 4

A) Percentage abundance of marine litter by category, B) percentage abundance of hard plastic subcategory. The yellow boxplot corresponds to beach surveys and the green boxplot corresponds to visual surveys.

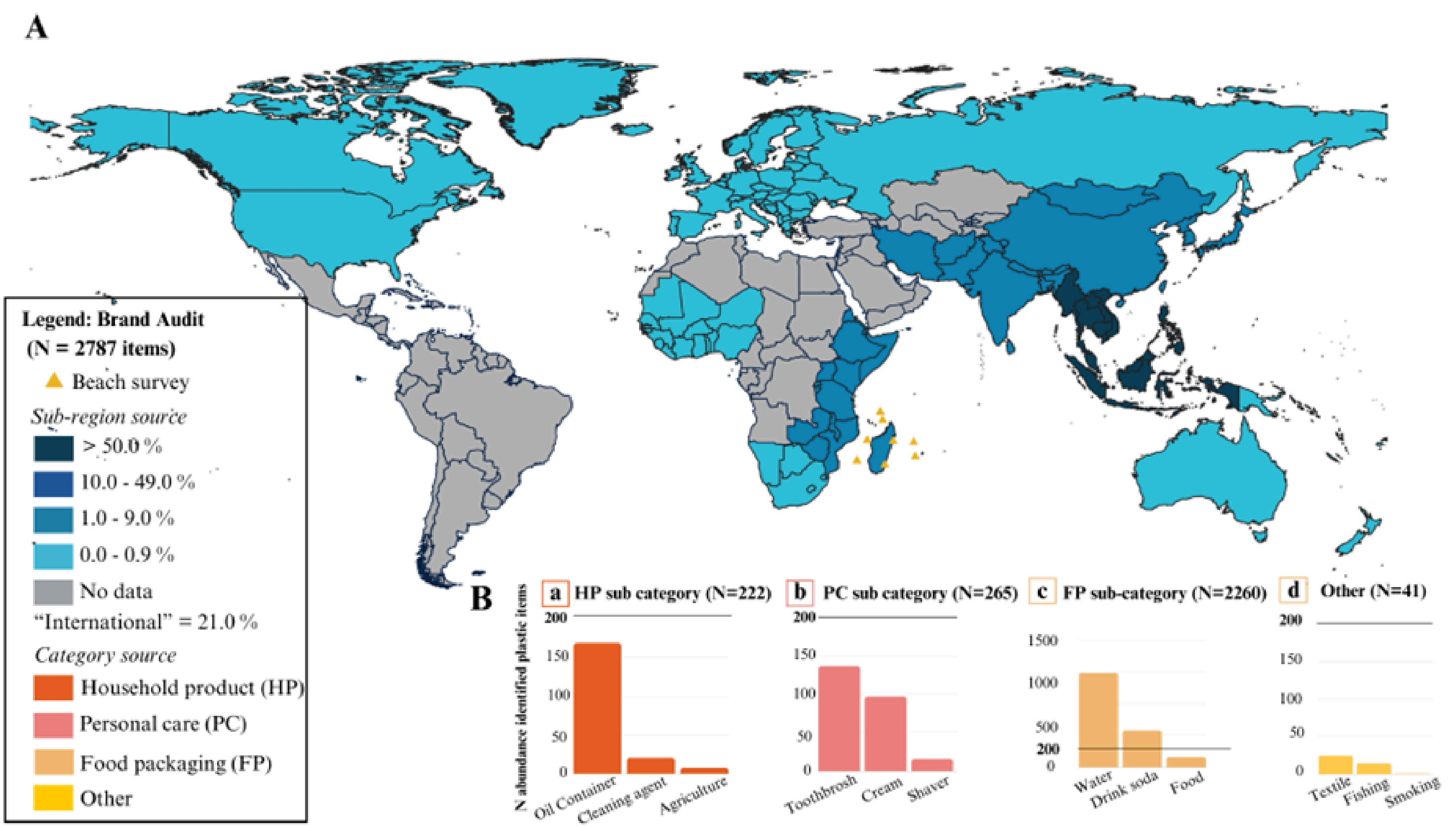

Figure 5

A) Origin of plastic debris used for the brand audit collected from beach surveys, quantified by proportion; B) Categorization of plastic debris from the brand audit (N=2787 items), a) abundance of three major subcategories in 'household product', b) abundance of three major subcategories in 'personal care', c) abundance of three major subcategories in 'food packaging' and d) abundance of other categories

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryDataFigureS1S5.docx
- SupplementaryinformationTableS1S7.xlsx
- Table1.xlsx