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Do loggerheads sea turtles (*Caretta caretta*) gut contents reflect types, colours and sources of plastic pollution in the South West Indian Ocean?

Margot Thibault [1,2,3,4,6*], Ludovic Hoarau [1,2], Laurent Lebreton [3], Matthieu Le Corre [1], Mathieu Barret [4], Emmanuel Cordier [5], Stéphane Ciccione [4], Sarah-Jeanne Royer [3], Alexandra Ter Halle [6], Aina Ramanampamonjy [7], Claire Jean [4] & Mayeul Dalleau [2]

1 UMR ENTROPIE, University of Reunion Island, 15 Avenue René Cassin, BP 7151, 97715, Saint Denis, Reunion Island

2 Centre d'Étude et Découverte de Tortues Marine (CEDTM), Saint-Leu, Reunion Island

3 The Ocean Cleanup, Rotterdam, The Netherlands

4 Kelonia, the marine turtle observatory of Reunion Island, 46 rue du Gal de Gaulle, Saint-Leu, Reunion Island

5 Osu-Réunion, University of Reunion Island, 15 Avenue René Cassin, BP 7151, 97715, Saint Denis, Reunion Island

6 CNRS, Université Toulouse III, Laboratoire des Interactions Moléculaires et Réactivité Chimique et Photochimique (IMRCP), UMR 5623, Toulouse, France

7 Association CETAMADA, Barachois Sainte Marie, Madagascar

* Corresponding author : margotthibault@orange.fr

Abstract (150 words)

Plastic debris ingested by loggerheads from by-catches between 2007 and 2021 in the South West Indian Ocean (SWIO) were analysed. Collected plastic debris accumulated on beaches of the east coasts of Madagascar as a proxy for the ocean plastics, to compare the characteristics of plastics beached with plastic ingested by turtles. A "brand audit" of each plastics (ingested and beached) to determine its country of origin was conducted. An oceanic circulation model was used, to identify the most probable sources of plastics found in the SWIO. The results revealed that 202 of the 266 loggerheads analysed had ingested plastics. Plastics categorized as "hard" and "white" were equally dominant in loggerheads and beaches, suggesting no diet selectivity. Both brand audit and circulation modelling demonstrated that Southeast Asia is the main source of plastic pollution in the region. This study demonstrates that loggerheads are powerful bio-indicators of plastic pollution in the SWIO.

Keywords (6 max): plastic debris, *Caretta caretta*, beach accumulation, dispersal model, source, bio-indicator

1. Introduction

Because of their invaluable physical properties (lightweight, resistant, waterproof, inexpensive, and flexible), plastic products are used worldwide in a large range of applications.

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Global plastic production has increased tremendously, from 1.5 million metric tons in 1950 to 460 in 2019 (OECD 2022). It is estimated that from 4.8 million to 12.7 million metric tons of plastic waste enter the oceans annually (Jambeck et al., 2015). Terrestrial sources (rivers, land) contribute to 80% of the global ocean plastic pollution inputs while the remaining 20% originate from marine activities (fisheries, shipping, Faris and Hart, 1994). Globally, plastics represent 40 to 80% of coastal debris, and 90% of the debris floating offshore at the surface of the ocean (Galgani et al., 2013; Ryan, 2014). Floating plastics are transported by sea currents and wind along considerable distances (Pruter, 1987; Van Sebille et al., 2020). These debris can have deleterious direct effects on many marine species through their ingestion (Schuyler et al., 2014; Senko et al., 2020) or via entanglement (Mann et al., 1995; Laist, 1997). Indirect negative effects may also occur through their toxicity due to endocrine disruptors (Verla et al., 2019). In addition, plastic debris were documented as providing floating substrates for "hitchhiking organisms" such as invasive species or pathogens (Therriault et al., 2018).

Plastic debris are found everywhere, including: on the sea floor (Ryukyu Trench: Shimanaga and Yanagi, 2016; Marianna Trench: Chiba et al., 2018), in the polar environment (Convey et al., 2002), and on beaches of remote islands (Lavers and Bond, 2017; Moy et al., 2018; Lavers et al., 2019). The most persistent fraction of floating plastic debris accumulates on garbage patches within subtropical oceanic gyres in all oceans (Lebreton et al., 2012; Maximenko et al., 2012; Cozar et al., 2014, Litterbase: https://litterbase.awi.de/litter). The North Pacific subtropical gyre, with an accumulation covering an area of at least 1.6 million km^2, has garnered the most attention (Moore et al., 2001; Boerger et al., 2010; Goldstein, 2012; Choy and Drazen, 2013; Chen et al., 2018; Lebreton et al., 2018; Egger et al., 2020; Egger et al., 2021). In contrast, the location of the garbage patch in the subtropical Indian Ocean gyre is less studied. One of the possible consequences of this lack of knowledge is that the area of plastic accumulation is not well characterised and located. Some oceanographers located the patch in the western part of the basin (Maximenko et al., 2012; Van Sebille et al., 2015; van der Mheen et al., 2019; Pattiaratchi et al., 2022) and others in the eastern part (Lebreton et al., 2012; Maes et al., 2018; Peng et al., 2021). Plastic pollution in the Indian Ocean is reported at the surface (Ryan, 2013; Eriksen et al., 2014; Woodall et al., 2015) and on remote islands (Maldives: Imhof et al., 2017; Saliu et al., 2018; Saint Brandon: Bouwman et al., 2016; Seychelles: Duhec et al., 2015, Dunlop et al., 2020; review: Pattiaratchi et al., 2022). The impacts of plastic pollution in the Indian Ocean have been described on seabirds (Ryan, 2008, Cartraud et al., 2019), sea turtles (Hoarau et al., 2014, Ryan et al., 2016), sharks (Cliff et al., 2002), fishes (Fujieda et al., 2008) and deep-sea organisms (Taylor et al., 2016).

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Almost 4,000 species have been recorded to have interactions with marine litter all over the world (ingestion, entanglement, impact, Litterbase, 09/03/23: https://litterbase.awi.de/interaction). Some of these species are used as marine litter bio-indicator (Van Gestel and Van Brummelen, 1996; GESAMP, 2019). Seabirds (Van Franeker and Law, 2015), sea turtles (Schuyler et al., 2014; Savoca et al., 2022) , fishes (Chavarry et al., 2022) and invertebrates (Van Cauwenberghe and Janssen, 2014) provide different information on plastic debris depending on their feeding strategies and body size. Benthic, sessile and filtering species are generally used to monitor coastal pollution while offshore foragers are used to inform about plastic pollution in the pelagic environment (GESAMP, 2019; Savoca et al., 2022).

As a migratory species, loggerheads sea turtles (*Caretta caretta*, Linnaeus 1758) travel long distances during their life and could be impacted by ingesting plastic debris mistaken for natural prey (Carr, 1986; Bjorndal, 1997; Lazar et al., 2011; Dalleau, 2013; Schuyler et al., 2014; Pham et al., 2017; Pfaller et al., 2020}. Loggerheads sea turtles regularly ingest plastic debris (Bjorndal et al., 1994; Hamann et al., 2010; Lazar et al., 2011; Hoarau et al., 2014; Santos et al., 2016; Savoca et al., 2022). While Rizzi et al. (2019) reported loggerheads sea turtles could select and then mistake red plastics for red coastal prey (crabs, molluscs), Schuyler et al. (2012) noted less diet selectivity during the pelagic life stage. Also, loggerheads sea turtles may have a better resistance to plastic debris ingestion than other sea turtle species due to their diet and their strong intestinal wall, they are generally able to defecate ingested plastics, (Frick et al., 2009; Hoarau et al., 2014). Green turtles (*Chelonia mydas*) and hawksbills (*Erethmochelys imbricata*) are more prone to develop gastrointestinal blockage due to plastic ingestion, and both species have a higher probability to die (Schumacher et al., 1996; Abreo et al., 2016). In this study, we wanted to know if loggerheads sea turtles can be used as bio-indicators to monitor plastic pollution in the SWIO, as is already the case in the Mediterranean Sea European marine Strategy Framework Directive (MSFD, Matiddi et al., 2017; GESAMP, 2019) and in the North Atlantic (Pham et al., 2017).

In this study our objectives were: i) to quantify (type/size/colour/weight) and compare plastics debris ingested by loggerheads sea turtles and stranded on coastal beaches of Madagascar in the SWIO where these sea turtle specie are known to forage. This comparison would enable us ii) to determine the plastic debris feeding strategy of loggerheads sea turtles (selectivity or opportunistic. In addition, iii) we identified origins from plastics ingested and beached, using a “brand audit” completed by dispersal oceanic modelling.

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2. Materials and methods

2.1 Plastic debris ingested by late juvenile loggerhead

To quantify plastic debris ingested by loggerheads sea turtles, we studied 266 late juvenile loggerheads caught as by-catch by longliners operating in the South West Indian Ocean between 2007 and 2021. By catches loggerheads sea turtles were brought alive to Reunion Island and rehabilitated in a rescue centre specialised in sea turtle' rehabilitation (hereafter named Kelonia). Loggerheads sea turtles were caught in oceanic waters, mostly between Reunion Island and the east coast of Madagascar (Fig. 1). The geographical position of each capture was recorded by fishermen. After surgery for hook extraction, all sea turtles entering Kelonia received appropriate rehabilitation treatments in individual tanks by caretakers. All turtles were measured (curve carapace length (cm)) and weighted mass (kg) upon their arrival to Kelonia. We calculated the body condition index (BCI): BCI = [mass / ($length^3$) × 100,000] following Bjorndal et al. (2000). Loggerheads sea turtles defecated plastic debris in the tanks, for a mean duration of 2 weeks and a maximum of 6 months during their care. All faeces and plastic debris were collected daily with a sieve of 5 mm mesh size. Plastic debris were sorted from faeces visually, cleaned with alcohol, and left to air dry for 24h. For loggerheads sea turtles that did not survive, plastic debris were collected during necropsies from gut contents following the protocol described by Wyneken, (2001). For this study, we used the term "ingested" for all plastic debris collected after excretion (faeces) or necropsies (gut contents). We determined the frequency of occurrence (%FO) of plastic debris ingested by loggerheads sea turtles annually and globally since 2007 as the ratio between the number of loggerheads sea turtles having ingested plastic debris and the total number of loggerheads sea turtles analysed.

2.2 Plastic debris accumulated on beaches

Three beaches were monitored on the East coast of Sainte Marie Island (Madagascar, Fig. 1.A): Albran Est (16°71'38"S, 50°02'11"E), Ambohidena (16°88'89''S, 49°94'69"E) and Ampanihy (16°91'38"S, 49°93'02"E). These sites were chosen as they meet the following criteria of beach selection for plastic debris monitoring (see Henry, 2010; GESAMP, 2019; Barnardo and Ribbink, 2020): they are mostly uninhabited, they are easy to access, they are directly exposed to the open ocean and in front of the South Equatorial Current (SEC) that crosses the Indian Ocean from east to west, including the known feeding area of the loggerheads sea turtles (Mencacci et al., 2010; Dalleau et al., 2014), and finally, they have a moderate slope and small grain size substrate. All sampling was done outside the beach clean-

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up period. All samples were collected in March 2018. For each beach, plastic debris was collected along three belt transects of 50 m long and 10 m wide, parallel to the coastline and located in the supralittoral zone. The island's main economic activity is located on the west coast with the nearest villages or harbour located more than 5 km from Ampanihy and 20 km from Albran Est. For this study, we used the word "accumulated" to define plastic debris stranded on beaches.

2.3 Plastic debris characterization

In this study, we analysed plastic debris over 5mm long. This includes mesoplastics (5 to 25 mm) and macroplastics (> 25 mm) following the classification proposed by the GESAMP, (2019). Plastic debris ingested by loggerheads sea turtles and accumulated on beaches were counted, measured (length max), weighed (to 0.01 g) and sorted according to categories and colours. We defined three main categories (1) hard plastic, (2) soft plastic (i.e. rubber, styrofoam, foam), and (3) fishing-related debris (i.e. line, rope, fishing stopper, plastics originating from fishing activities). We considered seven general colour categories (1) black, (2) white, (3) blue, (4) red, (5) yellow, (6) green, and (7) transparent.

2.4 Statistical analysis

We tested the normality and homoscedasticity of the abundance and weight of plastic debris ingested by loggerheads sea turtles and accumulated on beaches, with Shapiro-Wilks and Levene's tests respectively. We checked for the difference in classes of the size of plastic debris found on feces of live loggerheads sea turtles and those found in dead turtles by necropsies by running a Kruskal-Wallis tests with a post-hoc analysis using Wilcoxon correction with an adjustment with Bonferroni. We tested for differences in abundance and weight of plastic debris beached on each site (Albran Est, Ampanihy, and Ambohidena) using Kruskal-Wallis tests and Kruskal-Wallis multiple comparison non-parametric tests. We tested for differences in abundance and weight for categories and colours of plastic debris ingested and accumulated on the beach using same non parametric tests written above. Plastic debris abundance and weights are expressed as the number of items per individual (item/ind or g/ind) and per surface (item/m^2 or g/m^2) for loggerheads sea turtles and beaches respectively. Data is reported in mean ± standard error.

2.5 Feeding strategy: selectivity or opportunity?

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The correlation of abundance and weight variables for plastic ingested and accumulated was investigated using pairwise Spearman rank correlation. A selectivity test was conducted using the Manly-Chesson index (Manly, 1974; Chesson, 1978). The selectivity value reflects a preference for specific plastic debris categories or colours ingested by loggerheads sea turtles in comparison with their availability in the environment. Values range from 0 for a complete opportunistic diet to 1 for a complete selectivity diet:

$$\alpha i = \frac{ri/pi}{\sum_{j=1}^{m}(rj/pj)},\ i = 1,2, \ldots m$$

Where αi = selectivity index for plastic category or colour *i*, *i* plastic debris category or colour, ri the proportion of plastic debris eaten of the *i* category or colours ingested, pi proportion of plastic debris of category/colour *i* in the environment. *m* is the total number of categories or colours. All analyses were performed in R version 3.2.3 (R Core Team. 2022), with the use of the ‘‘selectapref’’ package for the Manly selectivity index (Richardson, 2020).

2.6 Determination of the origin of plastic debris

2.6.1 "Brand audit"

The origin of plastic debris can be inferred with a "brand audit" (Barnardo and Ribbink, 2020). A "brand audit" consists of examining each piece of debris and noticing any information such as incrusted or painted brand name or the language, wich may help to determine the country of origin (Duhec et al., 2015; Smith et al., 2018). This analysis can be done only on large debris (macroplastics). When available, for each identified brand, we recorded the manufacturer, the type of product (e.g. food packaging, household product, personal care), 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), the total number of items ingested by loggerheads sea turtles and accumulated by brand and the website link when available (see in supplementary material). The *"*brand audit*"* was reinforced by online investigations (Duhec et al., 2015; Ryan, 2020). First, if the brand name was legible, we searched the brand into different search engines (e.g. google, yahoo, ecosia) and we changed the search setting language into: Indonesian, Chinese, Japanese, Korean or Thai, depending on the language used for the brand. If we possessed only pictures or logo, we did a "search by image". We also used keywords to describe our item, for example: brand, drink, bottle, cap, food, and cosmetic also in different languages. Once the website of the company was found, we noted all information about production and exportation area. If we did not find the official

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website, we went through sales sites, press article links or Wikipedia links to collect information. The category "International" was created when the country could not easily be identified, mostly for brands established and sold internationally. This analysis provided a first map of the sub-regional origins of macroplastics ingested by loggerheads sea turtles and accumulated on beaches on Sainte Marie Island.

2.6.2 Reverse dispersal model of plastic debris floating in the SWIO

To complete and validate our analysis of debris origin obtained by the brand audit, we used results from an existing global dispersal model for floating marine litter (see Lebreton et al., 2012). In this model, plastic debris is represented by weightless Lagrangian tracers that are released in modelled sea surface currents. For these simulations, sea surface current data are sourced from the HYCOM/NCODA global oceanic current reanalysis (Cummings, 2005). Particles were released into the model from estimated source points corresponding to two scenarios:

(i) Terrestrial sources: calculated from data on population density by all countries at a global scale (Jambeck et al., 2015),

(ii) Marine sources: calculated from data on fishing efforts (Watson et al., 2013) at a global ocean scale.

The model tracks the trajectory of particles from their date of release to a maximum simulation period of 30 years. For this study, we extracted the origin trajectories of all modelled particles arriving in the SWIO area delimited in this study by the latitudes between 10°S and 30°S and the longitudes between 42°E and 60°E, corresponding to an area of nearly 4,400,000 km^2 (Fig. 1.B). We extracted the relative contribution of particle inputs by country expressed in numbers of model particles for each scenario. This resulted in 16 sub-regions and 127 countries and islands identified. Two other maps with different source scenarios (terrestrial and marine) were created and compared to the 'brand audit' map.

3. Results

3.1 Characterization of plastic debris

3.1.1 Loggerheads sea turtles

The average curve carapace length of the 266 loggerheads sea turtles was 70.23 ± 7.31 cm with a weight of 45.94 ± 9.78 kg and a BCI of 6.36 ± 1.22. In total 202 (76%) loggerheads sea turtles had ingested plastic debris among which 41 were analysed by necropsy and 161 were analysed during their rehabilitation. We found 10,513 plastic particles for a total weight

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of 3,237 g. The frequency of occurrence plastic ingestion increased from 25% in 2007 to 79% in 2021, corresponding to an average %FO of 70 ± 20% for the entire period (2007-2021, Fig.2). The mean duration of plastic debris defecation was 15.5 ± 9.8 days, with a maximum of 179 days during care. On average loggerheads sea turtles which had plastics in their faeces or guts (N=202), ingested an abundance of 56.83 ± 4.59 item/ind (mean ± se, min = 1 item, max = 428 items). This corresponds to a mean weight of 16.69 g ± 17.62 (min = 0.01 g, max = 111.58 g). Macroplastics represented 32% of the items found in abundance and 69% in weight. Mesoplastics represented 68% of the items in abundance and 31% in weight. There were significantly more macroplastics found in guts than in defecated items (Wilcoxon Rank, p = 0.044). There was no difference in abundance between categories (hard, soft, and fishing plastic, p.values > 0.05) for loggerheads sea turtles plastics found in dead loggerheads sea turtles (gut necropsies) and alive ones (faeces analysis).

Hard plastic was the most common category ingested (χ^2 = 341.89, df=2, p < 0.0001, Fig.3.A), representing 80% of total plastic debris, with an abundance of 50.1 ± 3.94 items and weight of 15.5 ± 1.05 g per loggerhead. Soft plastic and fishing plastic type were less represented with respectively an abundance of 3.14 ± 0.47 and 0.84 ± 0.12 items per loggerhead and respectively a weight of 0.56 ± 0.15 g and 0.54 ± 0.11 g per loggerhead.

Most ingested plastics were white (χ^2 =262.54, df= 6, p < 0.0001, Fig.4.A), representing 54% of total plastic debris, with an abundance of 26.5 ± 2.28 items and a weight of 8.36 ± 0.727 g per loggerhead. The second most abundant colour was blue with an abundance of 6.38 ± 0.727 items and a weight of 3.20 ± 0.332 g per loggerhead. We observed transparent and black, with respectively, an abundance of 4.24 ± 0.775 items and 4.03 ± 0.426 items with a weight of 0.844 ± 0.203 g and 2.42 ± 0.267 g per loggerhead. Red, yellow and green colours were rarely found.

3.1.2 Beaches

A total of 12,244 plastic debris were collected on the three beaches monitored. For each beach, there were no significant differences between belt transects in terms of abundance and weight (p > 0.05). Among the three beaches, Albran Est beach presented more items in abundance and weight (p < 0.05, abundance: 5.54 ± 3.37 items/m^2; weight: 26.93 ± 18.49 g/m^2) compared to the two other sites Ampanihy (abundance: 1.43 ± 0.93 items/m^2; weight: 9.79 ± 5.70 g/m^2) and Ambohidena (abundance: 1.19 ± 0.90 items/m^2; weight: 7.29 ± 4.42 g/m^2). Plastic sizes were not statistically different between these three beaches, with an average size

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of 7.74 ± 8.11 cm for Albran Est, 7.38 ± 5.88 cm for Ampanihy and 7.42 ± 6.25 for Ambohidena.

Hard plastic was the most common category of items accumulated on beaches (χ^2 = 18.45, df=2, p < 0.0001, Fig.3.B), representing 96% of total plastic debris with an abundance of 2.62 ± 0.91 items/m^2 and a weight of 11.4 ± 4.27 g/m^2 . Soft plastic showed an abundance of 3% and a weight of 17% while fishing gear exhibited an abundance of 1% and a weight of 5% resulting in the category less represented on beaches.

White plastic debris were the most abundant (χ^2 = 19.07, df = 6, p = 0.004), representing 48% of total plastic debris with an abundance of 1.30 ± 0.471 item/m^2 and a weight of 1.9 ± 0.464 g/m^2. Blue (abundance: 20%; weight: 14%), transparent (abundance: 18%; weight: 3%), and black (abundance: 11%; weight: 23%) were less often found. Red, yellow and green plastic debris were rare.

3.2 Selectivity test

A significant positive correlation between the abundance and the weight was observed for both plastic debris ingested by loggerheads sea turtles (rho = 0.91, p = 0,001) and plastic debris accumulated on beaches (rho = 0.89, p < 0.001). So as a result, we used the abundance data to investigate loggerheads sea turtles selectivity. The Manly's test indicated no strong selectivity by loggerheads sea turtles, neither by plastic category nor by colour, with all mean index values being below 0.5. The highest selectivity index closes to 0.5, was 0.42 ± 0.43 for the hard plastic, followed by 0.41 ± 42 for the soft plastic and 0.29 ± 0.41 for the white colour. In contrast, the lowest index was for fishing gear with 0.18 ± 0.36, followed by transparent plastic with 0.07 ± 0.05, yellow plastic with 0.11 ± 0.24 and green plastic with 0.16 ± 0.32 (Fig.5).

3.3 Origin of plastic debris

3.3.1 Brand audit: composition and origin

We determined the country of origin of 980 items ($N_{loggerhead}$ = 208; N_{beach}=772). We found 186 different brands including 31 that were found both from loggerheads sea turtles and on the beaches. The three most common brands were: AquaDanone® ($N_{loggerhead}$ = 39%; N_{beach} = 29%), a product of The Coca Cola Company® ($N_{loggerhead}$ = 2%; N_{beach} = 4%) and Sungreen® ($N_{loggerhead}$ = 4%; N_{beach} = 3%; Table.1). Most items were food packaging ($N_{loggerhead}$ = 68%; N_{beach}= 69%). Personal care and household products were less often found. Plastic debris subtypes were mostly plastic cap of mineral water ($N_{loggerhead}$= 56%; N_{beach} = 42%) followed by caps from other drinking products (soda, juice), food, and oil containers (see in supplementary

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material). The most abundant polymer type was HDPE ($N_{loggerhead}$= 69%; N_{beach} = 59%), which is the main component of caps of plastic bottles (Table.1). Seventy-seven percent of the debris of known origins came from Southeast Asia, 17% of the items were classified "International" sources. The top three source countries were Indonesia (64% of the items of known origin), China (11%) and Thailand (3%) (Fig.6; see in supplementary material).

3.3.2 Reverse dispersal model of plastic debris from SWIO area

Dispersal modelling described the potential sub-region of origin of the plastic debris found in the SWIO. In our model, the main sub-region contributing to plastic debris towards the SWIO area, was Southeast Asia for 65% of the terrestrial sources and 52% of the marine sources with a major contribution from Indonesia (Fig.7). In both source scenarios, Indonesia, China and South Africa, were identified as substantial contributors with respectively 48%, 13% and 9% of inputs for terrestrial sources and 33%, 10% and 4% for marine sources (Fig.7; see in supplementary material). The marine sources scenario had more different plastic debris emitting sub-region toward SWIO against the terrestrial sources scenarios, highlighting East Asia, Europe, SWIO, Oceania, Latin America, Northern America, and South Asia as contributors. Additionally, these marine sources scenario indicated a pathway between the Pacific and Indian Oceans was highlighted by the islands of the Melanesian and Polynesian sub-regions in terms of their contribution to plastic debris.

4. Discussion

4.1 Loggerheads sea turtles: Opportunistic or selective diet?

Our study indicated that 202 (76%) of the 266 loggerheads sea turtles bycaught by Reunion Island longliners in the SWIO had ingested plastic debris. From 2007 to 2021, the frequency of occurrence of plastic ingested by loggerheads sea turtles increased from 25% to 78% with a mean of 70% ± 20%. This frequency of occurrence is similar to or higher than most of the ones observed in the Southwest Pacific Ocean (57.1%, Boyle and Limpus, 2008), in the Gulf of Mexico (51.2%, Plotkin et al., 1993), and in the Mediterranean Sea (71% Campani et al., 2013; 85% Matiddi et al., 2017; 72% Digka et al., 2020). For all loggerheads sea turtles with plastic, they ingested an average abundance of 56.83 ± 4.59 plastic debris per turtle. This level of plastic ingestion is higher than the one reported in turtles foraging in the North Atlantic gyre, in the Mediterranean, and in the Southern Atlantic Ocean, where the number of items is around 30 plastic debris per turtle on average (Savoca et al., 2022). Our results were similar to the rate of ingestion found in loggerheads sea turtles of the North Pacific, where loggerheads

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sea turtles ingested an average of 65 ± 30 plastic debris per turtle (Savoca et al., 2022). This suggests that plastic accumulation in the western Indian Ocean is nearly as severe as in the Northern Pacific Ocean.

Despite the ingestion of plastics, most of the loggerheads sea turtles rehabilitated at Kelonia survived (80%). Loggerheads sea turtles can eliminate plastic items through defecation and demonstrate a high tolerance for plastic ingestion (Tomas et al., 2002; Hoarau et al., 2014; Fukuoka et al., 2016;Nelms et al., 2016; Matiddi et al., 2017). In our study, loggerheads sea turtles defecated plastic debris during a mean period of 15.5 ± 9.8 days (minimum of 1day and maximum of 179 days). Solomando et al. (2022), evaluated a mean of 12.4 ± 2 days, with a minimum of 11 days and a maximum of 151 days, in Balearic Island. As macroplastics were mostly found in dead loggerheads sea turtles, we could hypothesize these debris were retained longer than other categories (soft plastic, fishing plastic) for excretion. Necropsies of loggerheads sea turtles at Kelonia revealed that, their death was caused by internal haemorrhage (hook) or impacted by ships. Our results are in agreement with the paper of Hoarau et al. (2014) where larger size debris are mostly found into gut content of loggerheads sea turtles died.

Loggerheads sea turtles did not appear to select a particular category and colour of plastic debris, they adopt an opportunistic diet. Primarily, mainly hard plastic types were ingested then a small amount of soft plastic, of fishing debris, and no industrial pellets. In other subtropical gyres, the same result was observed for loggerheads sea turtles with a lesser trend for industrial pellets (North Atlantic, Barreiros and Raykov, 2014, Pham et al., 2017; South Atlantic, Rizzi et al., 2019; North Pacific, Jung et al., 2018), while, close to the coastline, loggerheads sea turtles ingested principally soft plastic as sheet or film (Mediterreannen, Camedda et al., 2014; Campani et al., 2013; Casale et al., 2016; Digka et al., 2020; Solomando et al., 2022). For the environment, in our study, we found same proportions of plastic debris type for accumulated beaches with hard plastic debris items represented 96.3%, followed by soft and fishing plastic debris. These results are also similar for other islands in the Indian Ocean (the Amirantes, Duhec et al., 2015; Saint Brandon, Bouwman et al., 2016; Cocos Islands, Lavers et al., 2019). In fact, hard plastics, including caps, bottles, and toothbrushes are composed of PET or HDPE polymers (Andrady, 2011; Jung et al., 2018). These items can cross long distances by floating at the surface, whereas soft plastics such as plastic bags, are composed of PE polymer, which are more sensitive to degradation and may sink rapidly when fixed biofilm accumulates closer to the coastline (Morét-Ferguson et al., 2010; Ryan et al., 2019; Ryan, 2020; van der Mheen et al., 2020). Digka et al. (2020), noted that adult loggerheads sea turtles ingested more sinking polymers as soft plastic closer to the coastline, than late

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juvenile loggerheads sea turtles, their feeding area is more pelagic with hard plastic type. Concerning colours, loggerheads sea turtles ingested mostly white plastic (54%) followed by blue, transparent and black and we found exactly the same top colours for plastic debris beached in our study highlighted white for 48%. These results are in line with previous studies where the white colour was also predominantly ingested by loggerheads sea turtles (44%, Hoarau et al., 2014; 59%, Clukey et al., 2017; 45%, Pham et al., 2017), collected on beaches (Duhec et al., 2015;Bouwman et al., 2016) and at sea surface (Shaw and Day, 1994; Gregory & Andrady, 2003; Shah et al., 2008; Titmus and Hyrenbach, 2011; Ryan et al., 2016; Martí et al., 2020, Connan et al., 2021).

4.2 Identification of plastic pollution origin: brand audit and reverse dispersal modelling

Both brand audit and reverse dispersal modelling showed that the main origin of marine plastic pollution in the western Indian Ocean is Southeast Asia, with a special focus on Indonesia. We identified the brand and origin of 980 items, thanks principally to caps of bottles of mineral water and other drinks. This is in contrast with Duhec et al. (2015) and Ryan, (2020), who principally identified brands directly on plastic bottles. In our study, we found fewer bottles than caps. Caps are made of HDPE, which has a lower density than seawater, thus increasing their buoyancy. For this reason, caps are transported over long distances. Plastic bottles are made of PET, which has a higher density than seawater and thus bottles can sink (if not clogged) and are therefore accumulated closer to their origin (Brignac et al., 2019; Ryan, 2020).

AquaDanone® was by far the most abundant brand found both in loggerheads sea turtles and the beaches. This brand was also very abundant in Seychelles (Duhec et al., 2015, 10 bottles and 94 caps), in Kenya (Ryan, 2020) and in Reunion Island (Cartraud et al., 2016). Products of this brand are manufactured in Indonesia and this company is the largest water plastic bottle producer in this country. This is due to its low production cost, high quality and high level of advertising in comparison to other plastic water bottle brands (Andika and Mandang, 2004). Free drinking water in Indonesia is not accessible everywhere, so most people rely on drinking water sold in plastic bottles, resulting in millions of plastic bottles being used every day (Achmad et al., 2016). In the Seychelles, (Duhec et al., 2015, Dunlop et al., 2020, Vogt-Vincent et al., 2022), Saint Brandon (Bouwman et al., 2016), Sri Lanka (Jang et al., 2018) and South Africa (Ryan et al., 2019), plastic debris found on beaches was also identified as originating predominantly from Southeast Asia. The marine sources scenario added also a potential connection between the Pacific Ocean and the Indian Ocean, with a possibility of

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plastic coming from the Pacific islands and East of Asia due to ocean currents thus bringing plastic pollution from shipping and maritime traffic. Previous studies already observed this connection, through the Indonesian ocean currents and intense winds (Maes et al., 2018; Miron et al., 2021; Van Sebille et al., 2014; Pattiaratchi et al., 2022). Indian Ocean is complex and Monsoons have a strong influence on sea currents and therefore directly influence plastic debris accumulation, for example Vogt-Vincent et al.(2022) observed that debris from terrestrial sources and fisheries are mostly deposited in the coastlines of Seychelles during the northeast monsoon and positive Indian Ocean dipole. In the recent study of Vogt-Vincent et al.(2022) it was confirmed that Seychelles had a very high risk of plastic stranding of marine debris from Chinese, Malaysian or Thai vessels transiting the Indian Ocean. Floating debris are transported by sea currents for years and may finally accumulate on islands (Morishige et al., 2007;van der Mheen et al., 2020; Vogt-Vincent et al., 2022). Islands act as traps of marine debris, the so-called "island scavenging effect" (Bouwman et al., 2016).

4.3 Loggerheads sea turtles as bio-indicator of plastic marine pollution in the South West Indian Ocean

We recommend using loggerheads sea turtles as a plastic pollution bio-indicator in the South West Indian Ocean, as it fills the requirements established by the GESAMP, (2019) and the review of Savoca et al. (2022):

- *Regional representation*

Loggerheads sea turtles are widely distributed in the western Indian Ocean and late juveniles forage mostly in offshore habitats of the subtropical gyre, where they are in contact with marine plastic pollution (Dalleau, 2013; Dalleau et al., 2014).

- *Ethically sound*

Loggerheads sea turtles are by-catch by longline fishing vessels based in Reunion Island and bring at Kelonia center for cares. During this period, plastic debris are collected from dejections of alive sea turtles until no one dejected. 80% of loggerheads sea turtle are rehabilitated and released successfully in their environment.

- *Abundant in the chosen environment and easy, practical analysis*

A memorandum of agreement has been established in 2007 between fishermen and Kelonia to rehabilitate all turtles caught by longlines. On average 20 loggerheads sea turtles are included in the analysis per year. The protocol of rehabilitation includes care in individual tanks, where faeces are collected daily by trained keepers, which is easy

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and practical. All dead loggerheads sea turtles are necropsied by the veterinary of Kelonia for gut content analysis and other veterinarian investigations. This organisation is appropriate for generating a long-term dataset.

- *Already used as bioindicator species*

Loggerheads sea turtles are already used as plastic pollution bio indicator species in the Mediterranean Sea (Matiddi et al., 2017), in the North Atlantic (Barreiros and Raykov, 2014; Pham et al., 2017), and in the North Pacific (Parker et al., 2005).

- *Species directly linkable to impact and effect and high plastic occurrence in the diet*

Loggerheads sea turtles forage in bottom dwelling animals but also on oceanic waters. They normally feed on invertebrate such as molluscs, crustaceans, and jellyfish. Plastic particles can easily be mistaken for potential prey, which probably explains the high frequency of occurrence of plastic ingestion in this species (70% in our study).

- *Comparable globally similar species identified worldwild*

The results obtained on loggerheads sea turtles in the western Indian Ocean are comparable to the ones obtained on the same species in other oceans (Schuyler et al., 2012; Campani et al., 2013; Camedda et al., 2014; Hoarau et al., 2014; Ryan et al., 2016; Matiddi et al., 2017; Pham et al., 2017; Savoca et al., 2022)

Conclusion

Our study demonstrates that loggerheads sea turtles of the western Indian Ocean ingest a large amount of plastic debris. The characteristics of this debris are similar to the ones found on beaches, suggesting that turtles do not select specific types of plastics. Both brand audits and reverse dispersal model have shown that the main origin of plastic pollution is Southeast Asia. We recommend using this species as a bioindicator of marine plastic pollution in this region.

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debris each day from sea turtles' dejections and for the care provided. We are also grateful to Eejfe Blöm, Jennifer Appoo and Lee Hankinson for improving the manuscript. Thanks to Afifah Hanum from Indonesia for helping with the identification of many brands.

Contributors

Margot Thibault: Conceptualization, Methodology, Software Qgis and R, Formal analysis, Investigation, Writing Original Draft, Visualization

Ludovic Hoarau: Methodology, Validation, Investigation, Review

Laurent Lebreton: Modelling, Investigation, Review, Funding acquisition

Matthieu Le Corre: Validation, Review

Mathieu Barret: Resources: coordinate sampling and gave access to the rehabilitation center of sea turtle, Review

Emmanuel Cordier: Software Arcgis, Review

Stéphane Ciccione: Review, Funding acquisition

Sarah-Jeanne Royer: Review

Alexandra ter Hale : Review

Aina Ramanampamonjy: Resources: coordinate sampling in Madagascar, Review

Mayeul Dalleau: Conceptualization, Validation, Funding acquisition, Review, Supervision, Project administration

Claire Jean: Conceptualization, Validation, Review, Supervision, Project administration

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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