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Quantification of anthropogenic debris from small-scale fisheries and community-based aquaculture in marine and coastal ecosystems of Southwestern Madagascar

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ABSTRACT

Most coastal populations in Southwestern Madagascar live on the resources provided by small-scale fishery (SSF), and over the past twenty years, sea cucumber and seaweed farming has grown significantly. This study analyzes the importance of these fisheries and community-based aquaculture (CBA) activities in the contribution of anthropogenic marine debris (AMD) to coastal ecosystems in Southwestern Madagascar. Sampling was conducted in the rainy and dry seasons in three sites with contrasted fishing and farming activities. We have investigated two important coastal ecosystems in these sites, the mangroves and the beaches. At all, about 16,000 AMD items, were collected predominantly plastics. A lower amount of AMD was observed in the rainy season compared to the dry season. The contribution of SSF and CBA activities to the AMD pollution is very important representing 40 % of all AMD in the initial survey. On beaches, 4003 items were found with an average density of 0.17 items m^{-2}. In mangroves, 1039 items were found with an average density of 0.04 items m^{-2}. The most polluted site by SSF and CBA items is Toliara with 3218 debris, Toliara being the one with the highest number of fishermen. The pollution brought by fishing is much more important than that brought by farming. The pollution concerns much more the beaches, where the fishermen start their activities.

1. Introduction

Marine and coastal ecosystems are vital for the environment, human well-being (Palmer, 2017), and economic development (Costanza et al., 1997; Barbier et al., 2011). However, they are threatened by the accumulation of anthropogenic marine debris (AMD), composed of over 80 % plastics (UNEP, 2021). Thus, plastic pollution exacerbates existing environmental challenges, including climate change, overfishing, habitat destruction, invasive species, and biodiversity loss (Browne et al., 2008; Worm et al., 2017). Of the 275 million metric tons (MT) of waste generated by 192 coastal countries in 2010, an estimated 4.8 to 12.7 million MT of plastic debris were dumped into marine environments (Jambeck et al., 2015). Such dumped plastic waste in marine aquatic ecosystems contributes to disrupting natural habitats, including beaches and mangroves, compromising their ability to provide essential ecosystem services (Beaumont et al., 2019), and thus affecting the overall health of the oceans.

Beaches provide essential ecosystem services, including provisioning (biotic and abiotic), regulation, and cultural services (Harris and Defeo, 2022). They, for example, contribute to water purification (McLachlan

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et al., 1985) and the nutrient cycle, while hosting essential marine and coastal biodiversity by providing crucial habitats for the reproduction and feeding of numerous species (Defeo and McLachlan, 2013). Known as places of relaxation and well-being, beaches support local economies through recreational and tourism activities (e.g., Houston, 2018). They also serve as key sites for scientific research on coastal ecosystems and climate change (Schlacher et al., 2008). However, the presence of plastic debris can damage the aesthetic appeal of beaches, reducing the number of tourists and impacting local revenues (UNEP, 2009).

Mangroves act as natural barriers, protecting shorelines from erosion and storms, (Alongi, 2008). They contribute to the nutrient cycle and climate regulation by absorbing a significant amount of atmospheric carbon dioxide and producing oxygen, functioning as natural carbon sinks (Nellemann and Corcoran, 2009). They support local fisheries and improve the living conditions of local residents by providing additional income through the sale of carbon credits (Rakotomahazo, 2022). However, plastic debris in mangroves can block freshwater channels, disrupting natural hydrological cycles and affecting species that depend on these ecosystems for survival (Tekman et al., 2022, 2023). Further, plastics can hinder the growth of young plants and clog their roots, disrupting their ability to stabilize soils and filter water, potentially leading to increased coastal degradation and biodiversity loss (Walther and Bergmann, 2022).

Marine pollution is not solely caused by land-based activities but also by activities occurring at sea (Galgani et al., 2020). Fishing and aquaculture can generate debris that contributes to marine pollution. According to a review of 68 publications conducted by Richardson et al. (2019a), 5.7 % of all fishing nets, 8.6 % of all traps and 29 % of all lines were lost in the oceans in 2017. Debris from nets, lines, and ropes constitute 46 % of the 45,000 to 129,000 tons of debris in the North Pacific Gyre (WWF, 2019). Abandoned, lost, or otherwise discarded fishing gear (ALDFG) represents over 10 % of marine debris, with an estimated 640,000 tons of gear lost globally each year (Macfadyen et al., 2009). Nets, ropes, buoys, and plastics used in aquaculture installations can detach and become marine debris. Additionally, studies have also confirmed the abundance of microplastics (MPs) in waters near aquaculture sites, where mariculture has contributed to the contamination of the aquatic environment and local marine organisms (e.g., Zhu et al., 2019).

Small-scale fisheries (SSF) are those carried out by fishermen individually or in associations, using different types of boats or practicing fishing on foot within a limited radius of action. Toliara Bay is one of the main fishing areas for the exploitation of reef resources in the southwest of Madagascar. Fishermen use a wide variety of fishing gear, the most common of which are: gillnets, handlines, beach seines, harpoon guns and mosquito net trawls (Behivoke, 2022). Community-based aquaculture (CBA) are aquacultures carried out in a marine environment where the organisms of interest are produced by families or coastal village communities. They generally involve extensive or semi-intensive production technologies, at low cost and adapted to local economic resources. In Southwestern Madagascar, SSF and CBA, particularly of sea cucumber and seaweed, play a crucial role in both local livelihoods and the health of marine ecosystems (Robinson and Pascal, 2009; Lavitra et al., 2024). These activities provide economic benefits to local communities, offering sustainable alternatives to overfishing and habitat destruction (H. Eriksson et al., 2012; Lavitra et al., 2024). However, sea cucumber and seaweed farming can increase coastal pollution: seaweed farming uses ropes and floats made from plastic materials, and sea cucumbers are kept in sea pens delimited by rigid-mesh plastic nets. The use of plastic materials in these aquaculture systems, if lost, eroded, or discarded, adds to the AMD problem, affecting surrounding ecosystems. Data on marine pollution in Southwestern Madagascar are limited. Only the master thesis of Rabemanantsoa (2021), cited in Kunzmann et al. (2023), has investigated the impacts of seaweed farming in villages close to Toliara. No information on the pollution of mangroves has been reported, despite ongoing efforts for the sustainable management of this ecosystem.

The objective of this work is to assess the importance of AMD brought by SSF and CBA, concerning sea cucumber and seaweed aquaculture. To do this, we quantified this pollution and compared its importance to other potential sources such as households. The pollution brought by SSF and CBA was analyzed in two major coastal ecosystems of the region, beaches and mangroves. The analyses were carried out in dry and rainy seasons in three municipalities with contrasted fishing and farming activities.

2. Materials and methods

2.1. Studied zones and sampling methods

Samplings of AMD were investigated in three sites: Toliara, Andrevo, and Sarodrano (Fig. 1), Southwestern Madagascar. We chose these sites because, according to available census data, they present interesting differences from the demographic point of view and from fishing and farming activities. Toliara (Fig. 1) is the main city in the Southwestern region of Madagascar, located at 23°21′25.45″S 43°40′21.86″E. It showed a high population density with 115,319 inhabitants in 2024. The part of the city close to the sea included people that work on various types of activities, some being fishermen (490 fishermen in Mahavatse I and II). There is no farming activity (seaweed and sea cucumber) in Toliara. The city has >40 hotels and attracts many tourists annually. It features a port area and is a key area to consider for assessing marine pollution in the southwest of Madagascar.

Andrevo (Fig. 1) is a village in the commune of Manombo, in the Southwestern region, located approximately 40 km north (23° 2′1.76″S 43°32′53.26″E) of the city of Toliara. The population is 1637 (Golden et al., 2024), with 470 fishermen and 269 farmers working on sea cucumbers and/or seaweeds. Sarodrano (Fig. 1) is a village in the commune of Saint-Augustin, also in the Atsimo Andrefana region, located 27 km south (23°30′36.25″S4 43°44′4.66″E) of Toliara. The population is 2211, including 150 fishermen with 120 pirogues[1]. The number of farmers working on sea cucumbers is 100 and on seaweeds 239 (Rabemanantsoa, 2021). CBA in this location were established earlier than those in Andrevo.

Samplings were done in the dry season (from August to September 2021) and in the rainy season (from February to March 2022). The survey methodology was adapted from the Group of Experts on the Scientific Aspects on Marine environmental Protection (GESAMP, 2019) and Barnardo and Baleta (2020) guidelines, tailored to the available resources (in this case, groups of students) and the conditions of the studied sites. All macroscopic debris (>25 mm) found on the ecosystems of the three sites were collected during low tide over 11 consecutive days. The first day of collection was designated as the initial collection (day 0: standing-stock survey), while the subsequent 10 days (days 1–10) were designated for the accumulation survey.

In Toliara, Andrevo, and Sarodrano, SSF and CBA-related AMD has been compared in beaches and mangroves. Two transects were done in each beach and three in each mangrove (see below for details). Local communities were informed about our study through these associations with the local chiefs and the local guides who assisted us in the field. Local communities were educated not to litter at the study sites and not to remove the ribbons tied in the mangroves during the study time.

For the beaches, a transect was done in the wet zone (intertidal zone, wet sand) and the other in the dry zone (supratidal zone, dry sand). The first day, a first sampling (named "the standing-stock survey" here after) was conducted along two 100-meter-long transects running parallel to the coast, with 20-meter buffer zones at each end. AMD collected in these buffer zones was excluded from the data processing. During the next 10 days, another sampling was done (named "the accumulation

[1] small dugouts or canoes, often handcrafted

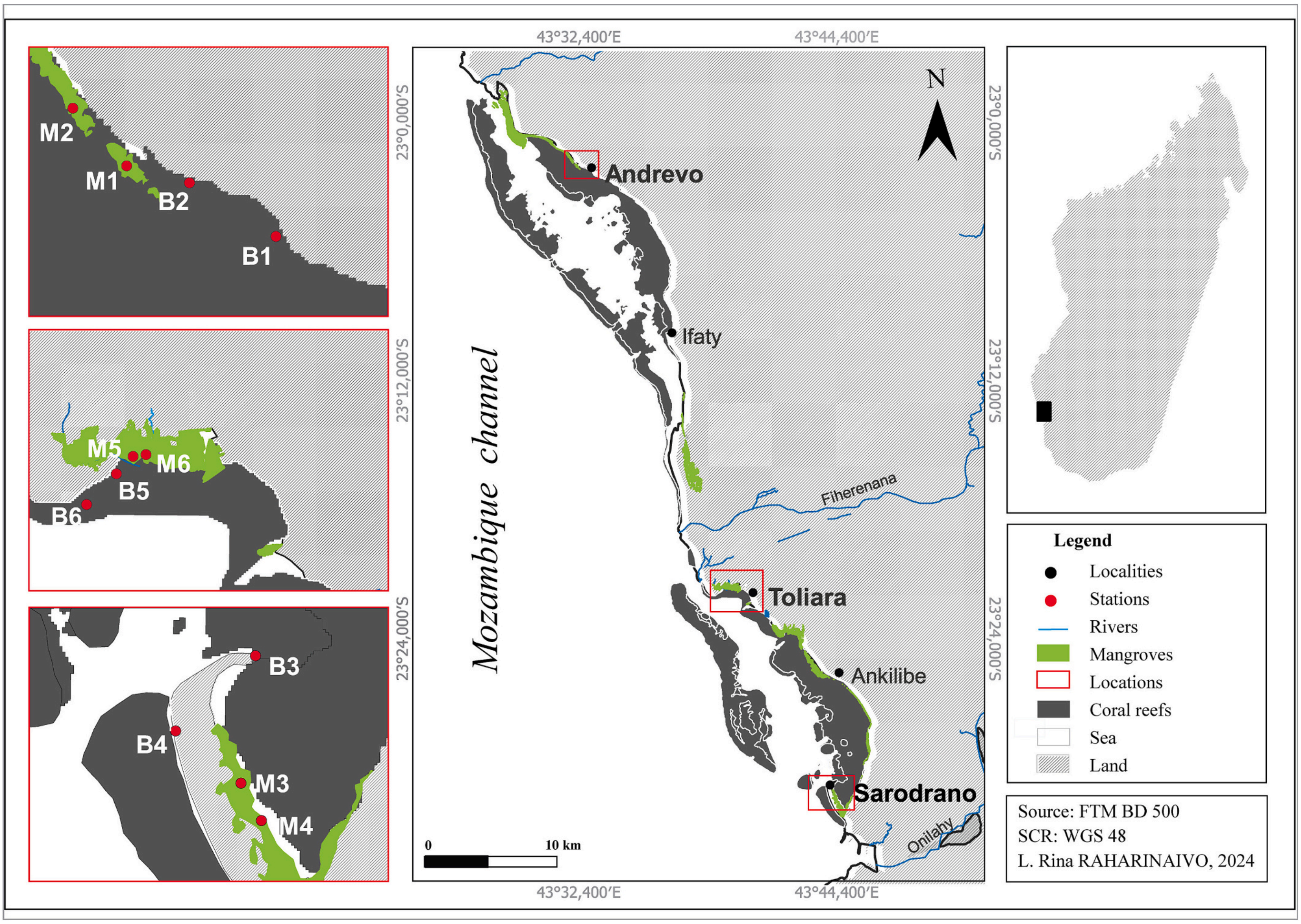

Fig. 1. Location of the study area within marine and coastal ecosystems in Southwestern Madagascar. Anthropogenic marine debris samples were collected from six mangrove stations (M1–M6) and six beach stations (B1–B6) across three study sites: Andrevo, Toliara, and Sarodrano.

survey" here after) was carried out within 20 square quadrats (5 quadrats per zone) of 100 m^2 each spaced 10 m apart and distributed across the zones. AMD found outside the quadrats were removed from the studied stations and collected in garbage bags to avoid contaminating the study area and introducing bias into the data. The start and end points of the surveyed beach were established and geo-referenced using a Garmin GPS Map 2S. The locations of the quadrats were recorded, and markers were placed to ensure that daily work was conducted in the same quadrats. For the mangrove areas, transects were done in considering the tidal regimes: in seaward (SWZ), middle (MZ), and landward (LWZ) zones. The first day, the standing-stock survey was conducted along three transects, each 10 m wide and 70 m long, as recommended by the "standard bronze" method by Barnardo and Baleta (2020). The next 10 days, the accumulation survey was carried out within 30 square quadrats of 100 m^2 each, spaced 5 m apart and distributed along transects. The geographical coordinates of the ends of the transects were recorded and marked with two different colored ribbons, while the transects themselves were marked with ribbons of a single color attached to the branches of the mangroves. The quadrats, including their corners and sides, were marked with ribbons attached to the mangrove trunks. Ribbons were used to delineate the boundaries of the transects and quadrats. Using ribbons instead of continuous ropes simplifies monitoring by eliminating the need for daily quadrats and transects, maintaining consistent markings and minimizing disturbances in the mangrove.

2.2. Anthropogenic marine debris characterization

Collected AMD from both the beach and mangrove areas were sorted and counted. First, item types were classified according to their materials and included nine categories: (1) cloth, (2) foam, (3) glass & ceramics, (4) metal, (5) paper & cardboard, (6) plastics, (7) processed wood, (8) rubber and (9) others (if applicable). This classification system was adapted from Barnardo and Baleta (2020) and Cheshire et al. (2009). The uses of sorted AMD were determined by referring to the GESAMP (2019) categories and new categories related to local marine activities, such as SSF and CBA, to identify their sources. For each type of litter, we assigned its usage into one of the following seven classes: (1) cosmetic/personal care, (2) dumping activities (including construction materials), (3) household production, (4) medical/personal hygiene, (5) smoking-related activities, (6) SSF and CBA and (7) not categorized.

For SSF and CBA, specific AMD related to these activities were considered. For plastic items, an additional classification based on their shapes was considered. AMD subcategories such as hard, soft and twine/rope plastics were adopted from shapes determination. However, the precise determination of debris related to SSF and CBA is somewhat limited. Based on prior knowledge of local resident activities and the likely debris generated by these activities, we were able to differentiate between household production debris and those originating from SSF and CBA. Nonetheless, there was a risk of confusion, especially regarding grids, plastic bottles, and synthetic ropes/strings when trying to identify their exact sources (fishing, seaweed farming, or sea cucumber farming). To address this, we categorized the grids as originating from sea cucumber farming, assuming the grid debris found in the ecosystems came from sea-based activities and not from land-based ones (such as drying seaweed). Since plastic bottle floats are predominantly used in seaweed farming, we attributed them to this activity. For ropes, those that could be clearly identified were assigned either to SSF or seaweed farming. However, ropes with unclear origins were categorized as "fishing/seaweed farming".

2.3. Data analysis

The data from the initial marine collections were processed to determine the overall composition and density of AMD for both ecosystems at each site and across the two considered seasons. The composition was expressed on percentage. The class referred to the category and use of debris, including subcategories under plastics.

Data from the accumulation surveys were processed to determine the accumulation rate of debris for both ecosystems at each site and across the two seasons. Accumulation rates were expressed as the daily rate of items per square meter of surface area. Debris types not recorded in the initial collection were classified as "new debris" and set aside to ensure accurate data and interpretation of the daily debris accumulation rate (Cheshire et al., 2009). The data from debris accumulation were normalized based on the collection area (100 m^2) and then subjected to a logarithmic transformation.

Principal Component Analysis (PCA) was conducted using the PAST 4.02 software (Hammer et al., 2001), based on a variance-covariance matrix. The PCA aimed to explore patterns in waste types associated with SSF and CBA. A logarithmic transformation was applied to normalize the data. Then, statistical analysis was conducted using R version 4.4.0 (R Core Team, 2024) with an alpha value of 0.05. Data normality and homogeneity were respectively assessed using Shapiro-Wilk and Levene's tests. Then parametric or non-parametric tests were adopted according to the normality and homogeneity results.

3. Results

3.1. General view of the AMD pollution in Southwestern Madagascar

Over the two seasons, 5042 items were sampled during the initial standing-stock survey. These items fall into nine categories (Fig. 2A), and 69 types (Fig. 2C). Plastics (3072 items) are the most abundant AMD (Fig. 2A), followed by processed wood (890 items), clothes (636 items), and rubber (362 items), while foams, glass/ceramics, and metals each accounted for <1 % of the AMD (Fig. 2A). Based on their usage, 4699 items (93.20 % of the initial AMD) collected in the present study were identified as originating from either land-based and marine activities related to SSF and CBA, the 343 items remaining items were ambiguous (e.g., metal or plastic fragments with no identifiable origin) (Fig. 2B). Debris related to household production constituted the main contributors to pollution (47 %), however SSF and CBA items represent a considerable proportion of the AMD (40 %) (Table 1).

A lower amount of AMD collected was observed in the rainy season (1562 items; 31 %; Table 1) compared to the dry season (3480 items; 69 %; Table 1). Contrary to what one might expect, most of the AMD came from beaches (79 %; from 0.14 to 0.21 21 items m^{-2}) compared to mangroves (21 %; from 0.01 to 0.07 items m^{-2}). From the three sites, Andrevo (north of Toliara) had the highest percentage of AMD items (42 %), then Toliara (34 %), and Sarodrano with the lowest proportion (24 %) (Table 1).

Soft plastics were the most common subcategory of plastic debris, comprising 55.47 % of the 3072 plastic debris, including wrappers/packaging, film fragments, shopping bags, woven bags, and nets (Fig. A.1e–h). The twine/ropes subcategory, including fishing lines, wires, and synthetic ropes/strings, accounted for 23.73 % (Fig. A.1i–l), while hard plastics made up 20.80 % and consisting of both thermosetting and thermoplastic materials (e.g., fragments of basins, bottles, jerry cans, lollipop sticks, pipes, toys and caps/lids/rings, with some illustrated in Fig. A.1a–d).

3.2. Global AMD composition and density in beaches and mangroves

A total of 69 types of AMD were observed during the initial standing-stock survey: 26 types (37.68 %) were found in both ecosystems, five exclusively in mangroves, and 38 exclusively on beaches (Fig. 2C).

On beaches, 4003 items were found with an average density of 0.17 items m^{-2}. They consisted of 54.08 % plastics, 21.68 % processed woods, 13.84 % clothes, and 8.69 % rubbers (Table 1). The 10 most common AMD types found were plastic films, woven polypropylene bags, mosquito netting, food packaging material, shopping bags, beverage bottles, footwear, fabric, synthetic ropes/string and fragments from wooden canoes (Fig. 2C).

In mangroves, 1039 items were found with an average density of 0.04 items m^{-2}. Plastic debris represented 87.30 % of the 1039 items, clothes 7.89 %, with processed wood and rubber each under 3 % (Table 1). The top 10 most common AMD types were hygiene packaging material, food packaging material, mosquito netting, fishing net, fabric, beverage bottle, shopping bags, plastic films, woven polypropylene bags, and synthetic rope/string (Fig. 2C).

Debris density (all confounded) were significantly higher in beaches than mangroves ($p = 0.015$) in particular, the densities of fabric, footwear, fragments from wooden canoes and food packaging material differ significantly between beaches and mangroves ($p < 0.05$), while the difference were not significant for the other types.

3.3. Accumulation of AMD

A total of 11,452 items were accumulated from which 5401 came from SSF and CBA activities. The 11,452 items were categorized into 120 types, including 58 new types compared to the initial standing-stock survey. As we have observed on the initial standing-stock survey, the type of AMD was more diversified on beaches with 114 types of debris identified compared to mangroves, with 62 types identified.

All AMD confounded; the accumulation rate does not fluctuate much from day to day in beaches as well as in mangroves (Fig. 3A–B). Toliara beaches accumulated the most debris (0.09 items m^{-2} day^{-1}), and Sarodrano mangroves the least (0.28×10^{-2} items m^{-2} day^{-1}). The AMD accumulation rate was less in mangroves than in beaches. The highest accumulation rate was observed for plastic and processed wood debris, reaching up to 0.04 and 0.03 items m^{-2} day^{-1}, respectively (Fig. 3C–D, Table 2). The items from fishing and from household production have the highest accumulation rate in both beaches and mangroves (Fig. 3E–F): the rate ranges from 0.01 to 0.04 for fishing items in beaches and from 0.02 to 0.03 for household production at the same place.

3.4. The importance of SSF and CBA in AMD pollution

The PCA results revealed two principal components, PC1 and PC2, which together accounted for 61 % of the total variance in waste types across the studied areas (36.1 % for PC1 and 24.9 % for PC2). Waste types associated with SSF and CBA such as fishing nets, lines, and canoe fragments were found to be globally similar across the studied beaches and mangroves (Fig. 4A–B). This pattern is also observed across both seasons (S1 and S2) (Fig. 4A–C), across all habitat zones (Fig. 4A–D), and among the three villages (Andrevo, Toliara, and Sarodrano) (Fig. 4A–E). Seasonal variations (S1 and S2) had a minimal impact on waste distribution, and no significant differences were observed between villages or between habitat types (beaches and mangroves). Data from the two transects (t1 and t2) used as replicates confirmed these results, with no clear differences found between the transects (Fig. 4A).

In both surveys (initial standing stock and accumulation), the contribution of SSF and CBA activities to the AMD pollution is very

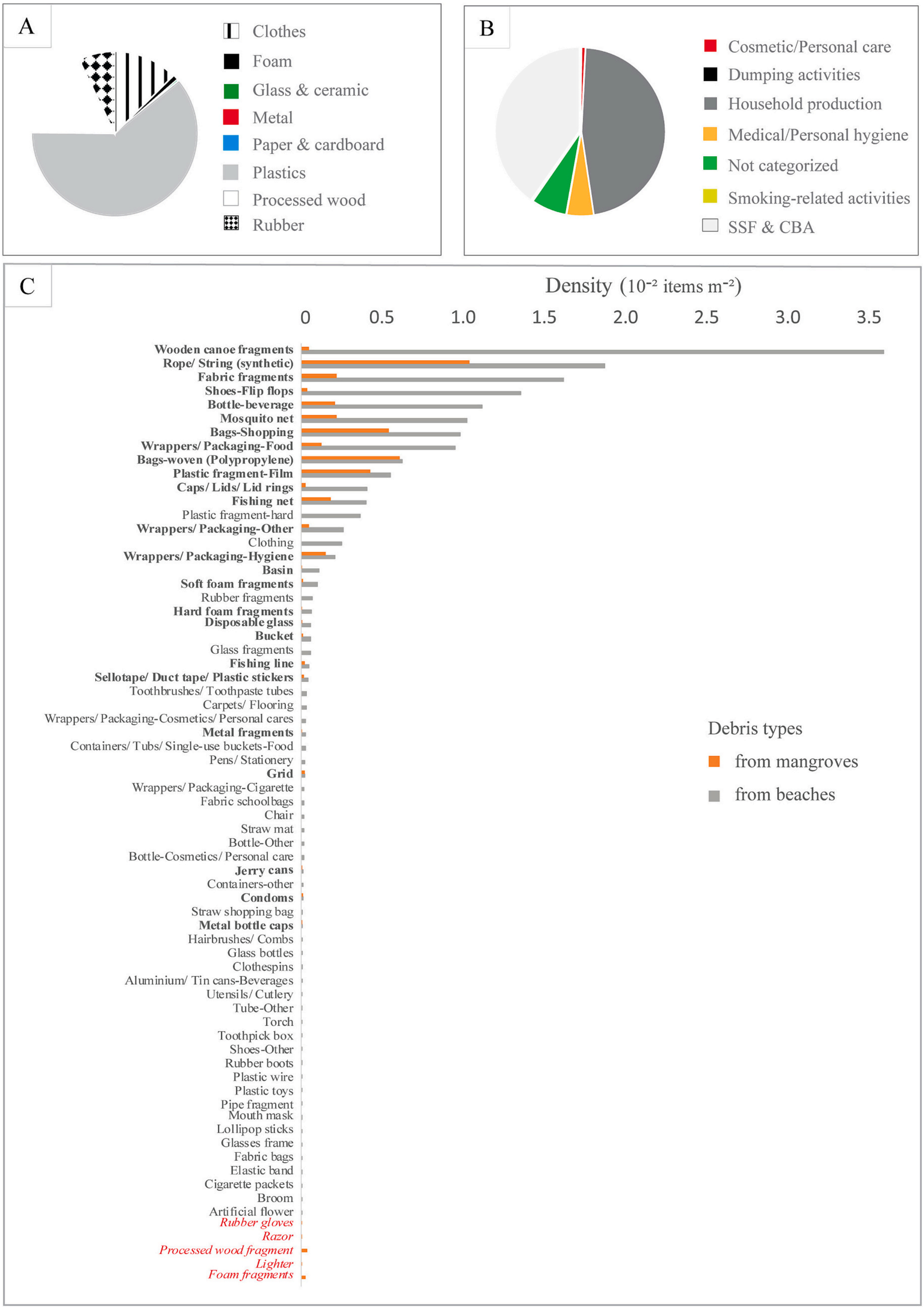

Fig. 2. Composition of anthropogenic marine debris (AMD) collected during the initial survey. The AMD was grouped into eight categories (A), and seven usage types were identified, including an uncategorized class (B). Of the 69 debris types identified, 26 were found in both ecosystems (bold labels), five were found only in mangroves (red labels), and 38 were found only on beaches (grey labels) (C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Categories and usages of anthropogenic marine debris (AMD) collected from initial standing-stock survey, across the two seasons (dry and rainy), the two ecosystems (beach and mangrove), and the three collection sites (Andrevo, Sarodrano, and Toliara).

AMD categories	Total	Seasons		Ecosystems		Sites		
		Dry	Rainy	Beach	Mangrove	Andrevo	Sarodrano	Toliara
Clothes	636	487	149	554	82	262	327	47
Foam	51	40	11	40	11	7	3	41
Glass and ceramics	16	13	3	16		1	10	5
Metal	14	13	1	11	3	2	9	3
Paper & Cardboard	1	1		1				1
Plastics	3072	1935	1137	2165	907	1145	683	1244
Processed wood	890	781	109	868	22	550	88	252
Rubber	362	210	152	348	14	134	100	128
AMD usages								
Cosmetic/Personal care	11	2	9	11		5		6
Dumping activities	29	25	4	18	11		1	28
Household production	2362	1527	835	1807	555	850	697	815
Medical/Personal hygiene	261	191	70	189	72	155	56	50
Not categorized	343	304	39	314	29	59	88	196
Smoking-related activities	7	1	6	6	1			7
SSF and CBA	2029	1430	599	1658	371	1032	378	619
Total	5042	3480	1562	4003	1039	2101	1220	1721

important representing 40 % of all AMD in the initial survey, being with the household production the first source of AMD pollution (Table 1). The SSF and CBA items were bottle beverage (used as floats), fishing lines, fishing nets, grid, mosquito nettings (used like fishing nets in bottom trawl fishing), flip-flop shoes (used as floats), and wooden canoe fragments (Figs. 5 and 6). The most polluted village if we sum the debris of the two survey is Toliara with 3218 SSF and CBA debris, then Andrevo with 2877 items and finally Sarodrano with 1335 items. Toliara is the municipality where the fishermen are the most important.

Beaches are seven times more polluted by the farming and fishing activities than mangroves, with an average density of 0.07 items m^{-2}; compared to 0.01 items m^{-2} in mangrove ($p = 0.015$). Debris related to SSF and CBA found in mangroves were also observed on the beaches, such as fishing lines, fishing nets, mosquito nettings, flip-flop shoes, and wooden canoe fragments (Table 3).

The debris related to SSF accounted for 1305 items, out of a total of 2029 debris items identified as related to marine activities and were thus more important than those resulting from CBA. SSF-related debris were the most dominant AMD on beaches, representing 30.23 % of all the debris with an average density was of 0.05 items m^{-2}. Those related to seaweed farming were 59 items including beverage bottle and synthetic rope/string with an average density of 0.19×10^{-2} items m^{-2} for beaches and 0.06×10^{-2} items m^{-2} for mangroves. Concerning sea cucumber farming, specifically, there were 12 debris items including grids which are used in hatchery enclosures (Fig. 5l) and crab traps. These items represented 0.18 % of debris collected on beaches, with an average density of 0.03×10^{-2} items m^{-2} and 2.05 % of those in the mangroves, with an average density of 0.02×10^{-2} items m^{-2} (Table A.1).

Details about SSF and CBA AMD collected during the accumulation survey are illustrated in Table 4. A total of 3545 items were due to SSF activities, a number much higher than the items coming from aquaculture (270). The debris coming from SSF and CBA represent 70.72 % of all the debris accumulated during 10 days. The accumulation rate of items coming from SSF activities is much higher (in average 13.73×10^{-2} items m^{-2} day^{-1}) than those coming from CBA. Logically, the number of items coming from SSF activities is higher in the city of Toliara where more fishermen live. These fishermen mainly start their fishing activities from the beaches and the amount of debris is consequently 3 times more important on beaches than in mangroves.

4. Discussion

4.1. General view of the anthropogenic marine debris pollution in Southwestern Madagascar

Our results revealed patterns and sources of marine litter pollution accumulating on beaches and in mangroves of Southwestern Madagascar (Fig. A.2). A total of 16,494 items were collected in this study, including 5042 items from the initial standing-stock survey and 11,452 items from the accumulation survey. The items collected during the initial survey reflected debris accumulation over several months or even years, as indicated by local villagers. In contrast, the accumulation survey, conducted over just ten days per season, captured a higher quantity and diversity of debris. This suggests that marine currents and winds play a significant role in spreading debris across space and time, influencing the distribution of AMD on beaches and in mangroves (Donohue et al., 2001; Ivar Do Sul and Costa, 2007). (Donohue et al., 2001; Ivar Do Sul and Costa, 2007).

Beaches were found to be more polluted than mangroves, representing 79 % of the total AMD collected. The average density of 0.17 items m^{-2} debris on beaches is significantly higher than the 0.04 items m^{-2} found in mangroves. In Gjerdseth (2017) study, a similar average density of AMD (0.16 items m^{-2}) was found in northwestern (Ampasindava) and northeastern Madagascar (Ramena and Baie de Sakalava) beaches, suggesting that beaches in those zones of Madagascar have still a relatively low litter pollution (<0.37 items m^{-2}), according to the Ansari and Farzadkia (2022)'s classification.

Additionally, beaches serve as primary accumulation zones for debris due to their direct exposure to marine currents and human activity (Donohue et al., 2001), including tourism and sports events, which contribute to debris accumulation (Andrady, 2011).

Our expectation that Toliara, being more urbanized area, would be more impacted by AMD pollution was not entirely confirmed. Andrevo (north of Toliara) had the highest percentage of AMD items (42 %) in the initial survey. While city accumulates a large amount of debris, winds and tides likely spread the debris beyond the immediate urban areas. Accumulation rates are influenced by various factors including the distance to urban areas, coastal activities, wind and ocean currents, and geographic location (Barnes et al., 2009). Our results also show that, although mangroves were less polluted in terms of total debris density, they still face anthropogenic pressure due to a gradual accumulation of debris.

Plastic was the predominant category accounting over 60 % of the total collected AMD. This result aligns with findings in other studies: in a

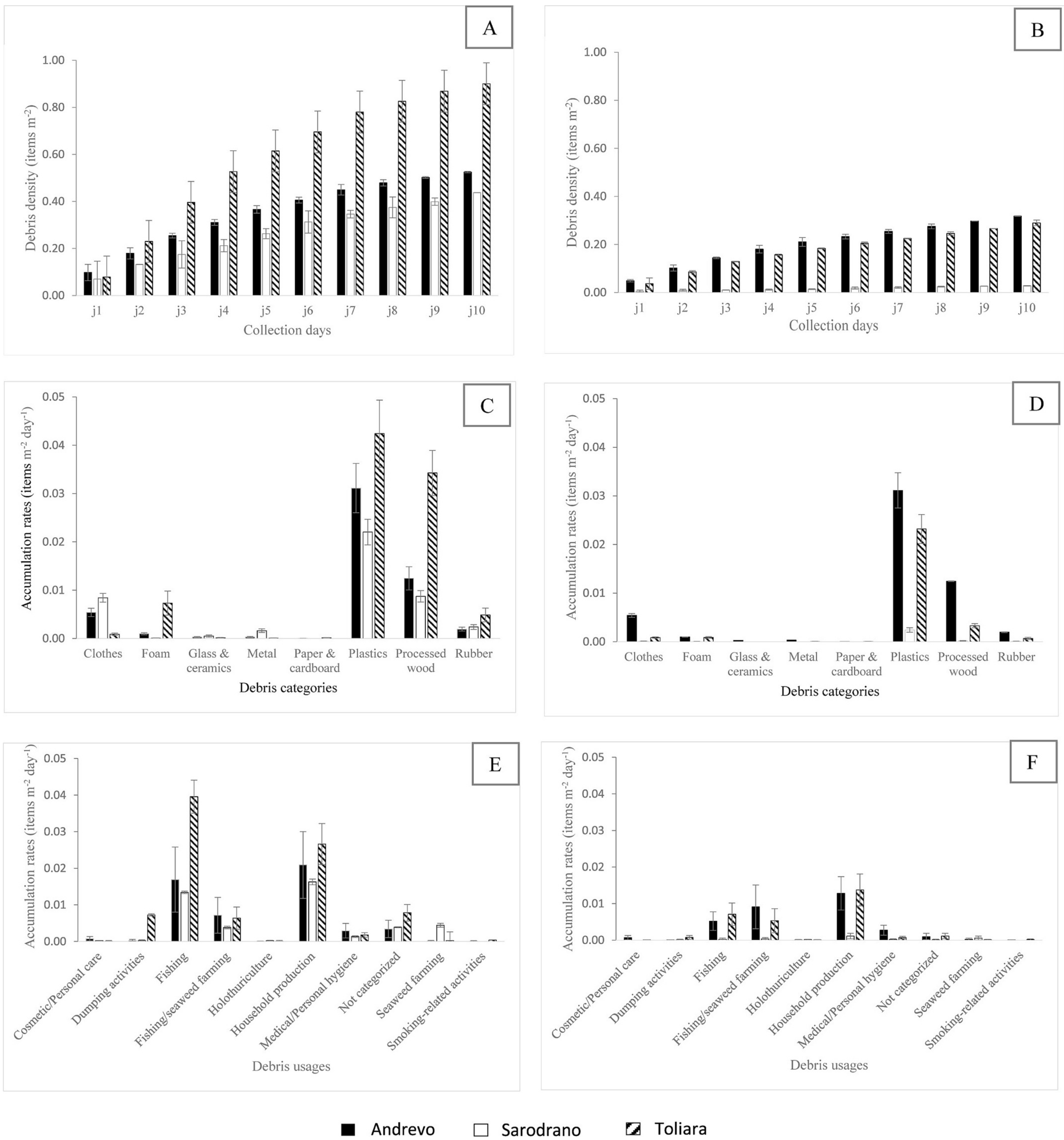

Fig. 3. Accumulation of anthropogenic marine debris (AMD) in beaches (in the left) and mangroves (in the right) ecosystems of the three studied sites Andrevo, Sarodrano and Toliara. The debris accumulation density from first to 10th days of collection through the beach (A) and mangrove (B) ecosystems. Accumulation rate of the AMD according to their categories (C and D) and usages (E and F).

review of 631 publications, Ansari and Farzadkia (2022) confirmed that plastic items represented 61.25 % of AMD collected on beaches from 66 countries worldwide. Similarly, on three beaches in northern Madagascar, Gjerdseth (2017) observed a comparable percentage (62.34 %) of plastic debris, with an average density of 0.11 items m^{-2}, whereas in our study, the density was 0.09 items m^{-2} on beaches. Among plastics, soft plastics were the most dominant subcategory of plastics (55.47 % of all plastics). They included single-use items such as wrappers/packaging, film fragments, shopping bags, woven bags and nets, which contribute to 60–95 % of global marine plastic pollution (see Geyer et al., 2017; Morales-Caselles et al., 2021).

The dominance of soft plastics among the debris reflects the habits of residents. Malagasy people often repurpose most of hard plastic items for various uses, such as using plastic bottles in fishing activity or turning old jerrycans into liquid containers (e.g., Fig. A.3) or into other fates (as explored by Fache et al., 2024). This reuse culture likely contributes to the higher presence of soft plastics in marine environments, as opposed to hard plastics, which are more commonly recycled. In

Table 2
Accumulation rates (10^{-3} items m^{-2} day^{-1}) of anthropogenic marine debris (AMD) categories and usages as well as plastic subcategories identified in beach and mangrove ecosystems at Andrevo, Sarodrano and Toliara, Southwestern Madagascar.

AMD categories	Beach			Mangrove		
	Andrevo	Sarodrano	Toliara	Andrevo	Sarodrano	Toliara
Clothes	5.40	8.43	0.88	2.07	0.10	0.85
Foam	0.98	0.08	7.33	0.07	0.03	0.88
Glass and ceramics	0.28	0.50	0.13	–	–	–
Metal	0.30	1.63	0.08	–	–	0.05
Paper & Cardboard	0.03	–	0.13	–	–	0.05
Plastics	31.13	22.03	42.40	29.10	2.42	23.18
Processed wood	12.45	8.73	34.25	0.33	0.18	3.30
Rubber	1.95	2.38	4.88	0.27	0.07	0.67
Plastic subcategories						
Hard	4.08	2.33	11.30	1.62	0.48	1.90
String/twine or rope	7.23	9.23	8.65	9.12	0.80	7.75
Soft	19.83	10.48	22.45	18.37	1.13	13.53
AMD usages						
Cosmetic/Personal care	0.75	0.23	0.03	0.67	–	0.02
Dumping activities	0.23	0.23	7.25	0.02	0.07	0.75
Household production	20.90	16.28	26.63	12.80	1.12	13.72
Medical/Personal hygiene	2.93	1.33	1.78	2.73	0.18	0.67
Not categorized	3.43	3.88	7.83	1.00	0.12	1.13
Smoking-related activities	0.10	–	0.38	0.02	–	0.17
SSF and CBA	24.18	21.83	46.18	14.60	1.32	12.53

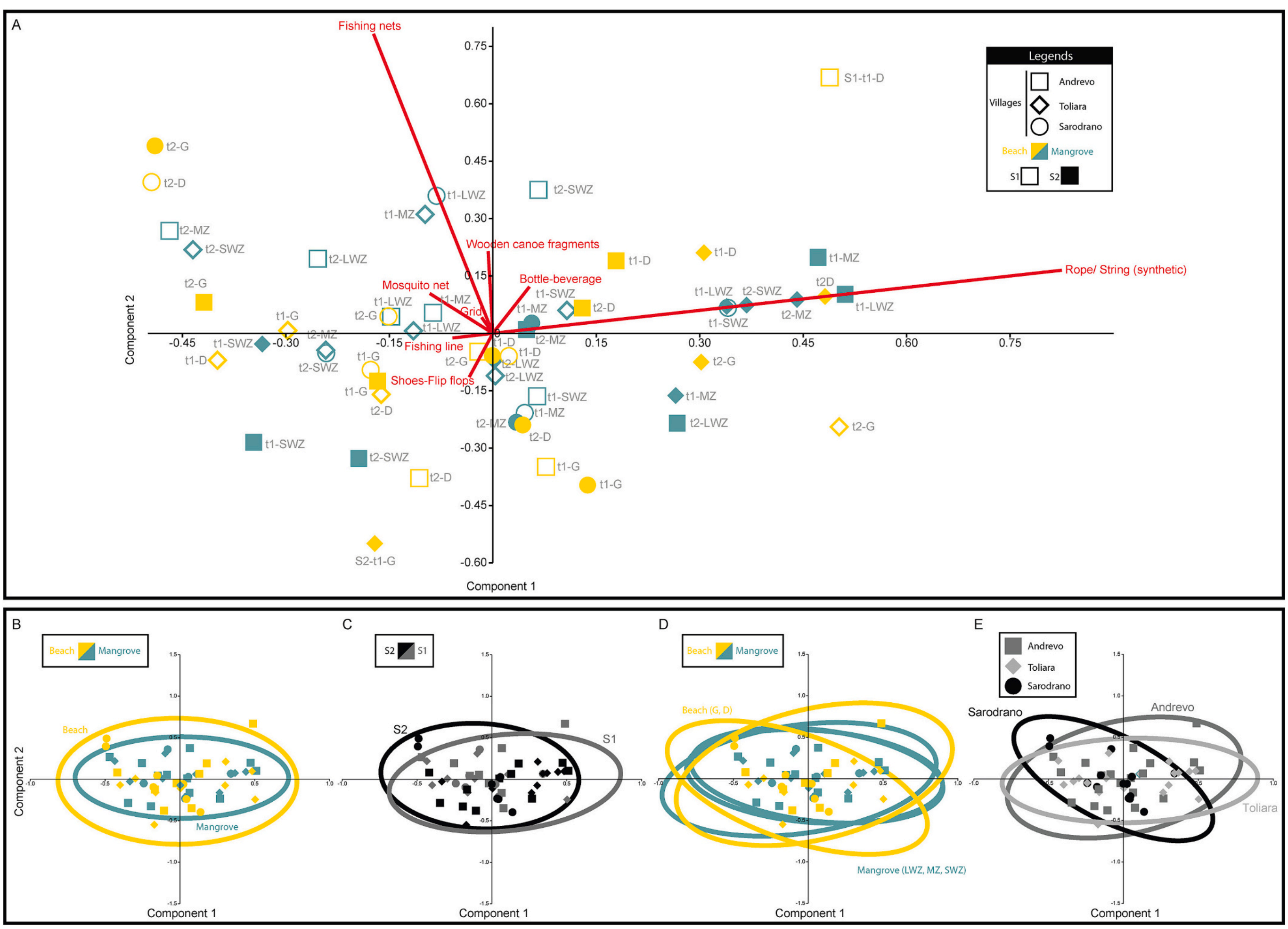

Fig. 4. Global ACP exploring the waste types (A) associated with small-scale fisheries (SSF) and community-based aquaculture (CBA). This analysis considers factors such as habitats (B), seasons (C), zones (D) and sites (E). Data were collected from various beaches and mangrove habitats across three villages (Andrevo, Toliara, and Sarodrano) during two seasonal periods (S1 and S2). Waste types related to SSF and CBA, including fishing nets, fishing lines, and canoe fragments, were recorded across multiple habitat zones: wet (G) and dry (D) sand zones on the beaches, and seaward (SWZ), middle (MZ), and landward (LWZ) zones in the mangroves. Additionally, two transects (t1 and t2) were surveyed as replicates to ensure the consistency of the findings.

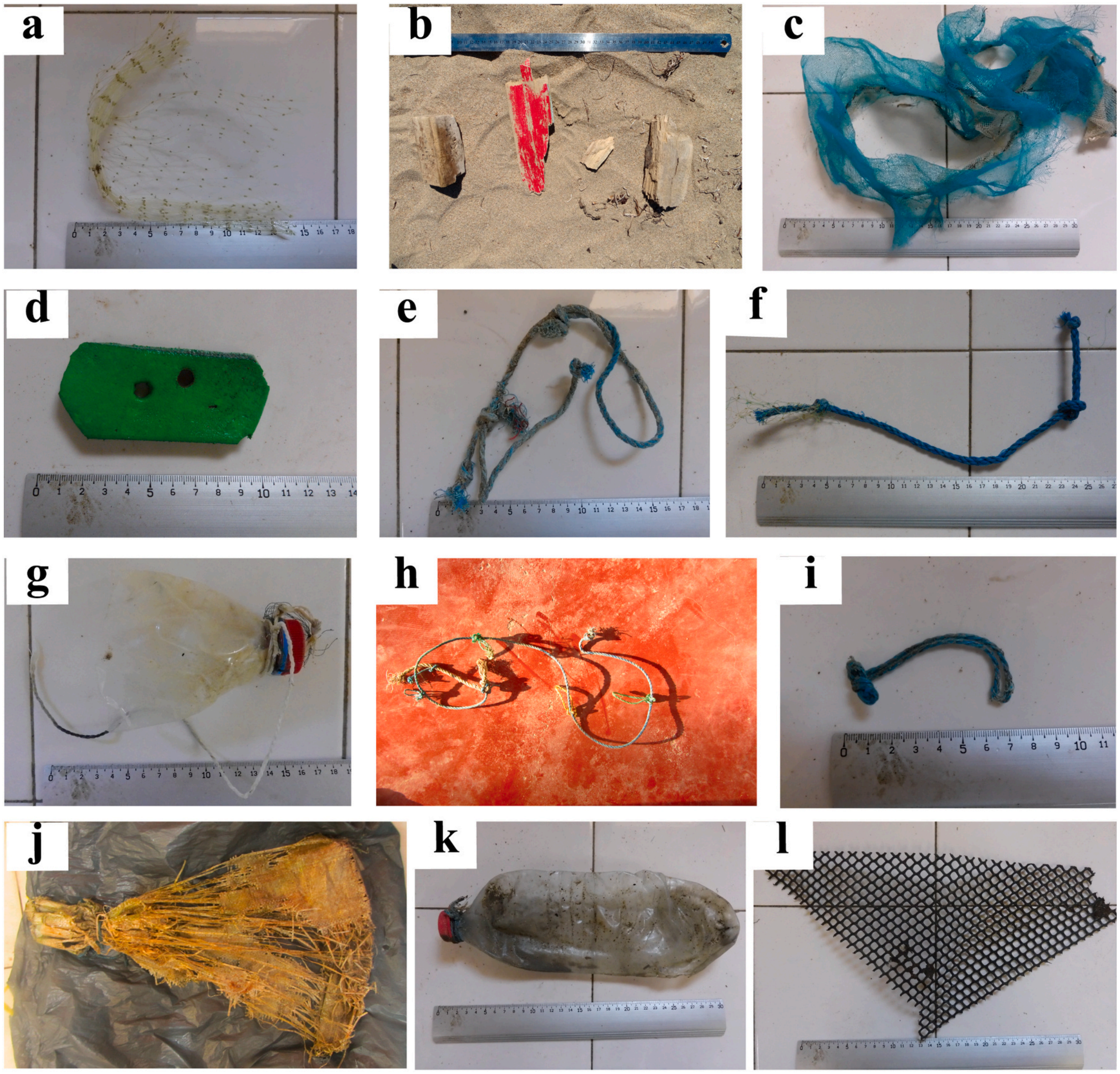

Fig. 5. Anthropogenic marine synthetic debris related to fishing and aquaculture activities, and found on the beaches and mangroves of Andrevo, Sarodrano, and Toliara, Southwestern Madagascar. Fragments of nets (a), wooden canoe (b), mosquito net (c), and shoes flip flop (d) presumed to be small-scale fishing (SSF) wastes. Cordage consisting of knots (e and f) presumed to be SSF or seaweed farming wastes. Drink bottle fragments (g) or whole drink bottles (k) with ropes tied to the neck, ropes with bracelet ropes (h) and bracelet ropes called "madeloop" (i), rice bag fragments filled with sand and tightly tied openings (j) presumed to be village seaweed farming waste. Black grid fragments (l) presumed to be from sea cucumber farming.

contrast, studies in other regions of Madagascar, such as those by Gjerdseth (2017) and Thibault et al. (2023) reported the dominance of hard plastics in north of Madagascar and on beaches of Eastern Sainte Marie Island (Albran East, Ambohidena, and Ampanihy). This discrepancy may reflect differences in regional waste management practices or the influence of debris from elsewhere (e.g., Asia) in these areas. Our study confirms the persistent plastic pollution in Southwestern Madagascar, with soft plastics posing significant risks to marine wildlife, particularly marine animals including sea turtles (Lazar and Gračan, 2011; Da Silva Mendes et al., 2015).

4.2. Contribution of SSF and CBA to AMD pollution

The results confirmed the significant contribution of SSF and CBA activities to AMD pollution in Southwestern Madagascar, reflecting the intensity of these activities in the region. SSF activities, in particular, were identified as the primary source of marine debris, contributing 30.23 % of the total AMD from beaches. The abundance of SSF-related items, such as fishing gear and materials repurposed for fishing, underscores the close relationship between local livelihoods and the generation of AMD. As highlighted by Boucher and Billard (2019), fishing is associated with rates of plastic waste generation. The high accumulation of SSF-related debris on beaches and mangroves compared to CBA-related debris highlights the challenges of effectively managing the end-of-life of these materials used and their dominant role in pollution dynamics. Abandoned fishing nets and lines can turn into ghost nets, posing a major threat to marine wildlife, as shown in previous studies (Richardson et al., 2019b). The significantly higher density of SSF-related debris on beaches compared to mangroves suggest differential use patterns of these environments. Beaches likely act as both activity hotspots and depositional zones for SSF-generated waste. In the studied zone, beaches, often used for unloading catches, repairing nets and building canoes, act both as activity hotspots and depositional zones for SSF-generated waste. However, Zemke-White (2006) stated that aquaculture infrastructure, often abandoned on beaches or at the bottom of the sea, also contributes to debris accumulation, threatening the environment.

Although CBA activities contribute less than SSF to AMD pollution (Table A.1), they remain a significant source, particularly in the context of sea cucumber and seaweed farming. Items such as plastic grids and

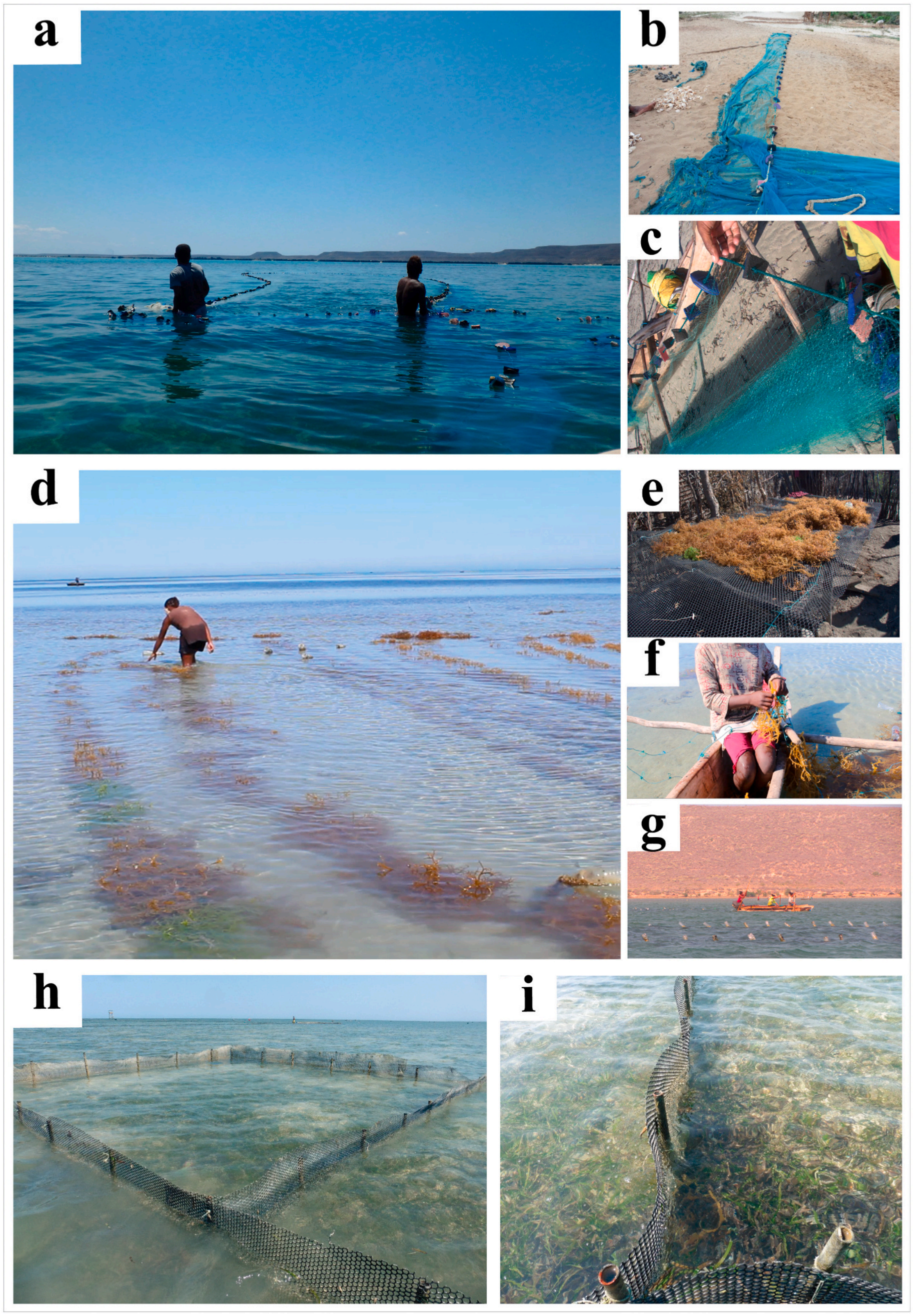

Fig. 6. Marine activities and used materials assumed to be among of the marine pollution sources. Small-scale fishing (a) using synthetic mosquito nets (b) or gill nets (c) bordered by knotted ropes which support shoes flip flop fragments used as floats (b and c). Seaweed farming (d) using ropes as support, featuring both the bracelet ropes called "madeloop" (f) fixing seaweed cuttings and the plastic drink bottles (floats) (g). Grids (e) used to dry seaweed after harvesting but primarily used as sea cucumber farming enclosures (h and i) at sea.

Table 3
Abundance of AMD types related to SSF and CBA collected in both ecosystems (beach and mangrove) across the three study sites: Andrevo, Sarodrano, and Toliara, in Southwestern Madagascar.

AMD types	Mangrove			Beach		
	Andrevo	Sarodrano	Toliara	Andrevo	Sarodrano	Toliara
Bottle-beverage	3	3	4	6	1	2
Fishing line			6		12	
Fishing net	30	6	10	21	50	25
Grid	1	5			6	
Mosquito net	3		27	113	26	4
Rope/String (synthetic)	96	7	157	212	168	69
Shoes-Flip flops			1		9	72
Wooden canoe fragments	4		8	543	85	234

Table 4
Number of accumulated items (Ni), proportion of the items relative to total accumulated items (Ni/Ti), and accumulation rates (AR) per day of the anthropogenic marine debris from SSF and CBA activities, such as seaweed farming and sea cucumber farming.

	SSF	Seaweed farming	Sea cucumber farming
Village (global)			
Ni	3545.00	245.00	25.00
Ni/Ti (%)	65.72	4.54	0.46
AR (10^{-3} items m^{-2} day^{-1})	13.73	0.94	0.08
Andrevo			
Ni	988.00	18.00	5.00
Ni/Ti (%)	53.61	0.98	0.27
AR (10^{-3} items m^{-2} day^{-1})	11.05	0.17	0.05
Sarodrano			
Ni	551.00	212.00	16.00
Ni/Ti (%)	57.88	22.27	1.68
AR (10^{-3} items m^{-2} day^{-1})	6.83	2.50	0.17
Toliara			
Ni	2006.00	15.00	4.00
Ni/Ti (%)	77.18	0.58	0.15
AR (10^{-3} items m^{-2} day^{-1})	23.31	0.16	0.04
Beaches (global)			
Ni	2794.00	190.00	10.00
Ni/Ti (%)	75.78	5.15	0.27
AR (10^{-3} items m^{-2} day^{-1})	23.28	1.58	0.08
Mangroves (global)			
Ni	751.00	55.00	15.00
Ni/Ti (%)	44.00	3.22	0.88
AR (10^{-3} items m^{-2} day^{-1})	4.17	0.31	0.08

ropes used in aquaculture were found even in Toliara, which is not an aquaculture site. The accumulation of CBA-related debris is thus not limited to aquaculture sites like Sarodrano and Andrevo, thus contributing to local pollution (Table A.2). This reflects poor waste containment (during use) and management (after use) practices by CBA companies, underscoring the need for improvement in the sector.

Despite variations in the intensity of SSF and CBA activities across sites, the types of waste observed were consistent, suggesting regional uniformity in pollution sources. The spatial variability observed in SSF and CBA debris distribution highlights localized pressures, with Toliara emerging as the most polluted site, followed by Andrevo and Sarodrano. This distribution may reflect the intensity of fishing and farming activities, population density, and site accessibility. A minor contribution of non-SSF and non-CBA sources such as cosmetics, personal care, and medical items, to AMD pollution were also observed, further confirming that local activities, particularly SSF and CBA, are the primary drivers of debris accumulation in this region.

4.3. Ecological and socioeconomic impacts

The ecological and socioeconomic impacts of this AMD pollution, particularly plastic debris, are alarming. Macroplastics debris cause entanglement and suffocation in marine species. They can damage the aesthetic appeal of beaches, reducing the number of tourists and impacting local revenues (UNEP, 2009). In mangroves, they can affect the growth of young plants, block freshwater channels, disrupting natural hydrological cycles and affecting species that depend on these ecosystems for survival (Walther and Bergmann, 2022; Tekman et al., 2022, 2023). While MPs affect marine substrates, biogeochemical cycles, and the food chain, as described by Tekman et al. (2022) and Galloway et al. (2017). Once released into the oceans, MPs are transported by currents, becoming embedded throughout the water column, sediments, and marine biota (Acarer Arat, 2024; Dai et al., 2018; Van Bijsterveldt et al., 2021). They interact rapidly with organisms across trophic levels, leading to ingestion, bioaccumulation, and physiological impairments (Wright and Kelly, 2017). Additionally, MPs serve as vectors for persistent organic pollutants and heavy metals, exacerbating their toxicity within marine food webs. Regarding the socioeconomic effects, macroplastics are reducing fish catches and leading to lower incomes for local fishing communities. This dynamic has been well documented in Philippines (Jambeck et al., 2015), where degraded marine environments result in decreased productivity and economic opportunities for coastal communities. Hence, the increasing marine debris levels are a growing threat to food security and economic stability in areas highly dependent on marine resources.

4.4. Conclusion and recommendations

In conclusion, beaches and mangroves of Southwestern Madagascar are heavily impacted by anthropogenic pollution, primarily caused by plastics, with significant contributions from SSF and CBA activities. Measures such as i) promoting the use of sustainable equipment (biodegradable nets, ropes, and floats); ii) improving waste management by setting up collection points, strengthening waste treatment infrastructure, and recovering used gear; iii) educating and raising awareness within local communities about sustainable waste management practices; and iv) reducing single-use plastics by limiting plastic imports into the country and introducing biodegradable alternatives, such as seaweed-based plastic films, in initiatives like the "Bioplastics and Village Aquaculture" project,[2] are needed in addition to existing efforts (awareness campaigns, clean-up efforts, waste sorting, and recycling). These efforts will support integrated governance of SSF and CBA activities, balancing the subsistence needs of local communities with the protection of marine ecosystems.

While this study provides an initial analysis of the contributions of SSF and CBA to beach and mangrove pollution, further research is still needed. Determining the sources of secondary MPs accumulated in the region marine ecosystems from data on identified macroplastics would help ensure consistent management and stricter actions against marine pollution.

CRediT authorship contribution statement

Lovasoa Rina Raharinaivo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gildas Boleslas Georges Todinanahary:** Visualization, Supervision, Project administration, Methodology, Funding acquisition. **Jérôme Delroisse:** Writing – review & editing, Validation, Formal analysis. **Jean-Marie Raquez:** Supervision. **Carla Bittencourt:** Writing – review & editing. **Tiandrainy Gédice Fernand Maherizo:** Supervision. **Thierry Lavitra:** Writing – review & editing, Supervision. **Igor Eeckhaut:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lovasoa Rina RAHARINAIVO reports financial support was provided by ARES-CCD (Belgium). If there are other authors, they 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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[2] Project in Southwestern Madagascar funded by the Belgian ARES-CCD organization.

Appendix A. Supplementary data

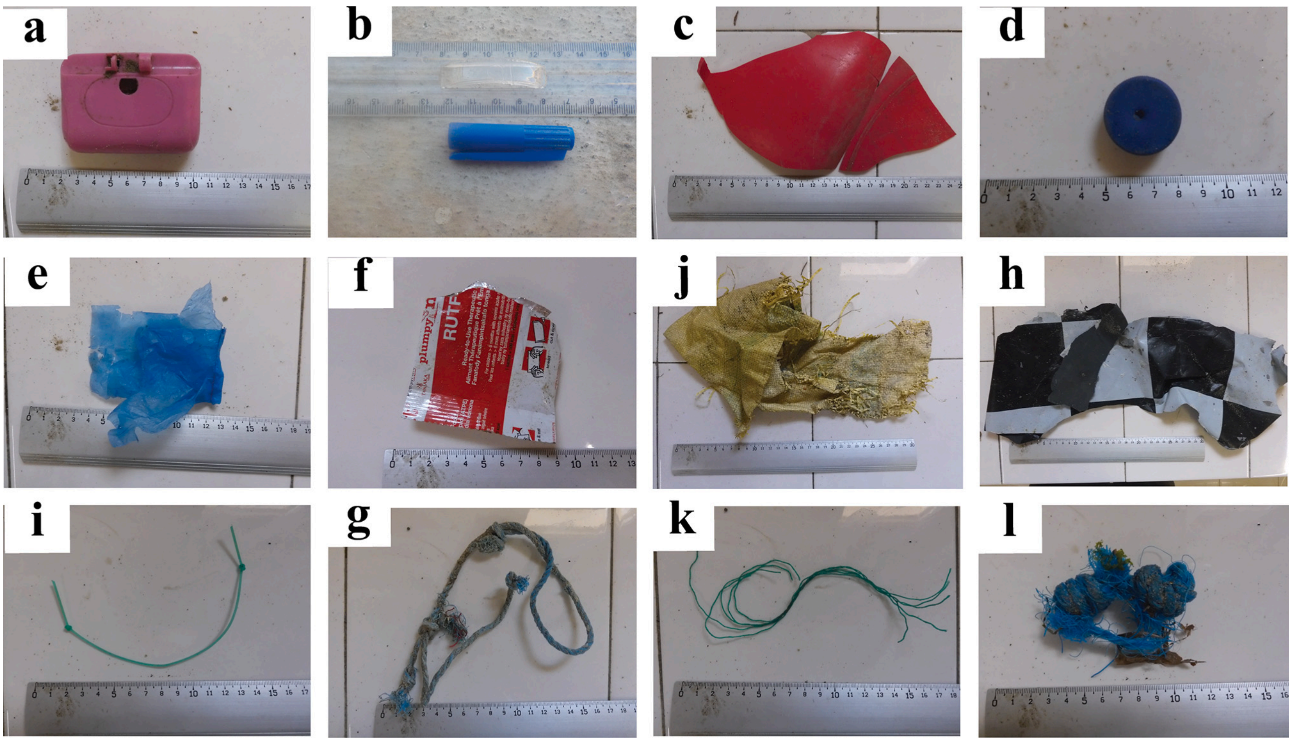

Fig. A.1. Plastic debris subcategories removed from beaches and mangroves in Southwestern Madagascar: hard plastics (a–d), soft plastics (e–h), and twine/ropes (i–l).

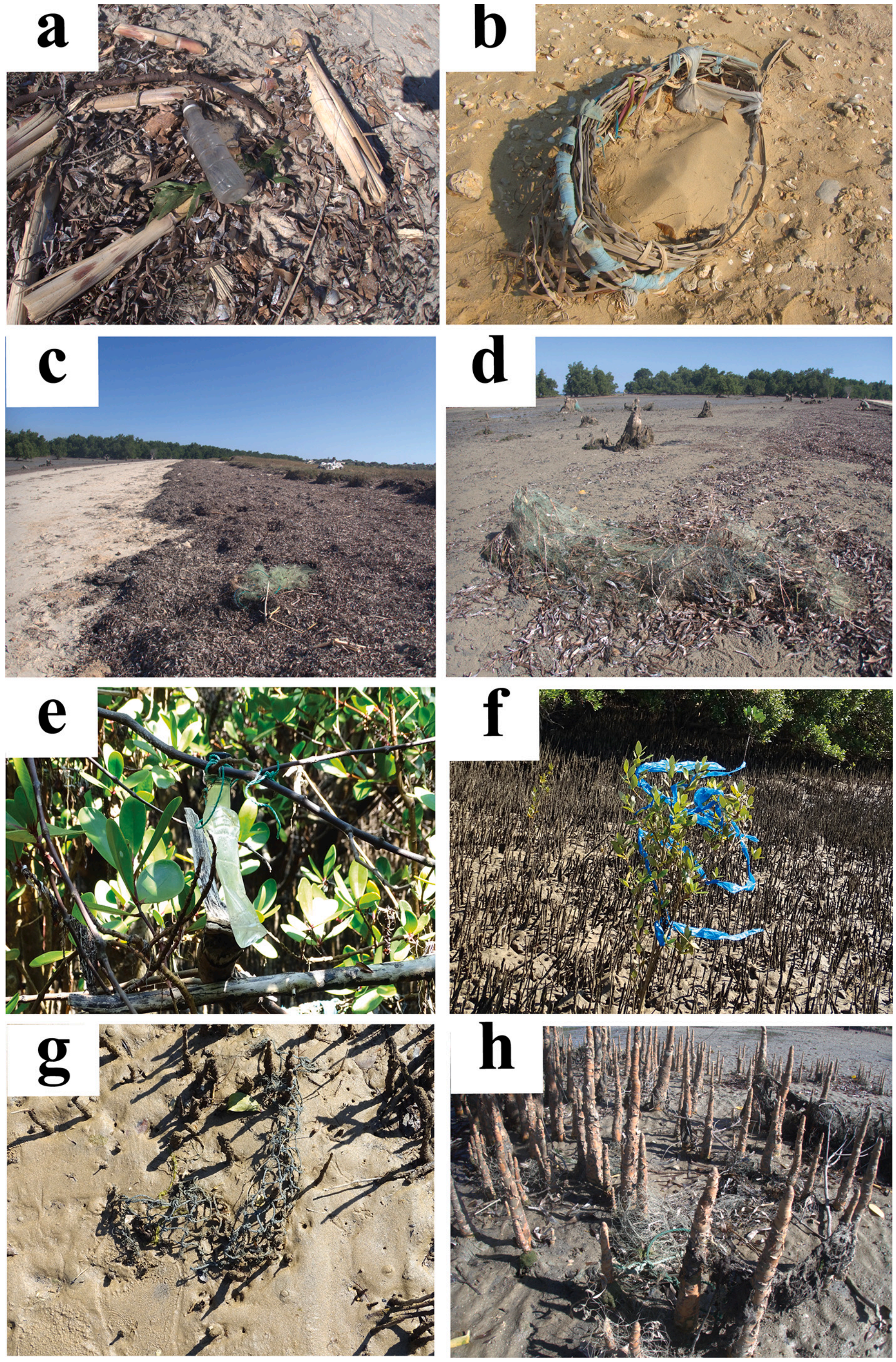

Fig. A.2. Accumulation of anthropogenic debris, related and unrelated to marine activities (fishing and aquaculture), in the marine and coastal ecosystems of Southwestern Madagascar. Examples of debris unrelated to marine activities (a and b) and those from fishing (c and d) polluting the beaches. Examples of debris unrelated to marine activities (f), and those from seaweed farming (e) and fishing (g and h) polluting the mangroves.

Fig. A.3. Examples of anthropogenic marine debris recycled by Malagasy communities. Shopping bags made from belts used to wrap secondhand clothing bundles (A). A 20 L yellow oil container repurposed as a drinking-water jug (B), bucket for storing charcoal (C), flower pot (D), water reservoir for detecting punctures in bicycle tires used by a repairman (E), and feeding bowls for poultry (F). A 1.5 L soda bottle repurposed for tamarind juice (G) and as a "lima" used in fishing (H). A 0.5 L vinegar bottle repurposed for oil storage (I). A 20 L paint bucket reused for storing rice (J). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table A.1
Density (10^{-2} items m^{-2}) of the synthetic debris types related to the small-scale fisheries (SSF) and community-based aquaculture (CBA) identified in beach and mangrove ecosystems at Andrevo, Sarodrano and Toliara, Southwestern Madagascar.

Activities	Debris categories	Debris types	Beaches			Mangroves		
			Andrevo	Sarodrano	Toliara	Andrevo	Sarodrano	Toliara
Fishing			8.46	2.28	4.39	0.44	0.07	0.62
	Plastic		1.68	1.1	0.56	0.39	0.07	0.51
		Bottle-beverage			0.03			
		Fishing line		0.15				0.07
		Fishing net	0.26	0.63	0.31	0.36	0.07	0.12
		Mosquito net	1.41	0.33	0.05	0.04	0.07	0.32
		Rope/String			0.18			
	Rubber			0.11	0.9			0.01
		Shoes-Flip flops		0.11	0.9			0.01
Fishing/seaweed farming			2.48	1.8	0.69	1.12	0.06	1.87
	Plastic		2.48	1.8	0.69	1.12	0.06	1.87
		Rope/String	2.48	1.8	0.69	1.12	0.06	1.87
Sea cucumber farming				0.08		0.01	0.06	
	Plastic			0.08		0.01	0.06	
		Grid		0.08		0.01	0.06	
Seaweed farming			0.25	0.31		0.06	0.06	0.05
	Plastic		0.25	0.31		0.06	0.06	0.05

(continued on next page)

Table A.1 (*continued*)

Activities	Debris categories	Debris types	Beaches			Mangroves		
			Andrevo	Sarodrano	Toliara	Andrevo	Sarodrano	Toliara
		Bottle-beverage	0.08	0.01		0.04	0.04	0.05
		Rope/String	0.18	0.3		0.02	0.02	

Table A.2
Accumulation (10^{-2} items m^{-2} day^{-1}) of the synthetic debris types related to the small-scale fisheries (SSF) and community-based aquaculture (CBA) identified in beach and mangrove ecosystems at Andrevo, Sarodrano and Toliara, Southwestern Madagascar.

Activities	Debris categories	Debris types	Beach			Mangrove		
			Andrevo	Sarodrano	Toliara	Andrevo	Sarodrano	Toliara
Fishing			0.90	0.96	1.18	0.97	0.03	0.76
	Plastics		0.90	0.92	0.49	0.97	0.03	0.72
		Bottle-beverage	–	–	–	–	–	0.02
		Fishing line	–	0.12	0.12	0.00	0.01	0.30
		Fishing net	0.56	0.44	0.06	0.48	0.02	0.13
		Mosquito net	0.34	0.28	0.03	0.49	–	0.11
		Rope/String (synthetic)	–	0.09	0.29	–	0.00	0.16
	Rubber		–	0.04	0.69	–	–	0.04
		Shoes-Flip flops	–	0.04	0.69	–	–	0.04
Fishing/seaweed farming			1.43	0.76	1.28	1.82	0.07	1.06
	Plastics		1.43	0.76	1.28	1.82	0.07	1.06
		Rope/String (synthetic)	1.43	0.76	1.28	1.82	0.07	1.06
Sea cucumber farming			0.01	0.04	0.01	0.01	0.03	0.01
	Plastics		0.01	0.04	0.01	0.01	0.03	0.01
		Grid	0.01	0.04	0.01	0.01	0.03	0.01
Seaweed farming			0.02	0.89	0.05	0.05	0.12	0.02
	Plastics		0.02	0.89	0.05	0.05	0.12	0.02
		Bags-woven (Polypropylene)	–	–	–	0.01	–	–
		Bottle-beverage	0.01	0.02	0.02	0.04	0.04	0.02
		Rope/String (synthetic)	0.01	0.87	0.03	–	0.08	0.00

Data availability

Data will be made available on request.

References

Acarer Arat, S., 2024. An overview of microplastic in marine waters: sources, abundance, characteristics and negative effects on various marine organisms. Desalin. Water Treat. 317, 100138. https://doi.org/10.1016/j.dwt.2024.100138.

Alongi, D.M., 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast. Shelf Sci. 76 (1), 1–13. https://doi.org/10.1016/j.ecss.2007.08.024.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62 (8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Ansari, M., Farzadkia, M., 2022. Beach debris quantity and composition around the world: a bibliometric and systematic review. Mar. Pollut. Bull. 178, 113–637. https://doi.org/10.1016/j.marpolbul.2022.113637.

Barbier, E.B., Hacker, S.D., Kennedy, Ch., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169–193. https://doi.org/10.1890/10-1510.1.

Barnardo, T., Baleta, T., 2020. A guide to litter monitoring in Africa. In: Barnardo, T., Ribbink, A.J. (Eds.), African Marine Litter Monitoring Manual. African Marine Waste Network, 2020. Sustainable Seas Trust, Port Elizabeth, South Africa, 152pp.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B, Biol. Sci. 364 (1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., Hooper, T., Lindeque, P.K., Pascoe, Ch., Wyles, K.J., 2019. Global ecological, social and economic impacts of marine plastic. Mar. Pollut. Bull. 142, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022.

Behivoke, F., 2022. Caractérisation spatio-temporelle de la pêche aux poissons récifo-lagonaires par trajectométrie dans la baie de Toliara (sud-ouest de Madagascar), 122pp.

Boucher, J., Billard, G., 2019. The challenges of measuring plastic pollution. Field actions science reports. J. Field Actions 68–75. http://journals.openedition.org/factsreports/5319.

Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus Edulis* (L.). Environ. Sci. Technol. 42 (13), 5026–5031. https://doi.org/10.1021/es800249a.

Cheshire, A.C., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R.T., Kinsey, S., Kusui, E.T., Lavine, I., Manyara, P., Oosterbaan, L., Pereira, M. A., Sheavly, S., Tkalin, A., Varadarajan, S., Wenneker, B., Westphalen, G., 2009. UNEP/IOC guidelines on survey and monitoring of marine litter. In: UNEP Regional Seas Reports and Studies. No186. IOC Technical Series, 83 (12), 120 pp.

Costanza, R., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., 1997. The Value of the World's Ecosystem Services and Natural Capital, 387, pp. 253–259.

Da Silva Mendes, S., De Carvalho, R.H., De Faria, A.F., De Sousa, B.M., 2015. Marine debris ingestion by *Chelonia Mydas* (Testudines: Cheloniidae) on the Brazilian coast. Mar. Pollut. Bull. 92 (1–2), 8–10. https://doi.org/10.1016/j.marpolbul.2015.01.010.

Dai, Z., Zhang, H., Zhou, Q., Tian, Y., Chen, T., Tu, C., Fu, C., Luo, Y., 2018. Occurrence of microplastics in the water column and sediment in an inland sea affected by intensive anthropogenic activities. Environ. Pollut. 242, 1557–1565. https://doi.org/10.1016/j.envpol.2018.07.131.

Defeo, O., McLachlan, A., 2013. Global patterns in sandy beach macrofauna: species richness, abundance, biomass and body size. Geomorphology 199 (October), 106–114. https://doi.org/10.1016/j.geomorph.2013.04.013.

Donohue, M.J., Boland, R.C., Antonelis, G.A., 2001. Derelict fishing gear in the northwestern Hawaiian Islands: diving surveys and debris removal in 1999 con®rm threat to coral reef ecosystems. Mar. Pollut. Bull. 42 (12), 1301–1312.

Eriksson, H., Robinson, G., Slater, M.J., Troell, M., 2012. Sea cucumber aquaculture in the Western Indian Ocean: challenges for sustainable livelihood and stock improvement. AMBIO 41 (2), 109–121. https://doi.org/10.1007/s13280-011-0195-8.

Fache, E., Toussaint, M., Djahere, A.S., Manjaka, F.R., Randrianomenjanahary, A.F., Veriza, E.F., 2024. Suivre les bidons jaunes à Toliara, ville du Sud-Ouest de Madagascar : Contribution exploratoire au développement d'une écologie globale des plastiques. Nat. Sci. Soc. 32 (3) hal-04341847.

Galgani, F., Bruzaud, S., Duflos, G., Fabre, P., Gastaldi, E., Ghiglione, J., Grimaud, R., et al., 2020. Pollution des océans par les plastiques et les microplastiques. In: Bioprocédés et bioproductions. https://doi.org/10.51257/a-v1-bio9300. January. 13pp.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1 (5). https://doi.org/10.1038/s41559-017-0116, 116p. PMID: 28,812,686.

GESAMP, 2019. Guidelines for the monitoring and assessment of plastic litter in the ocean, 99pp. gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782. https://doi.org/10.1126/sciadv.1700782.
Gjerdseth, E., 2017. Quantitative analysis of debris and plastic pollution on beaches in northern Madagascar. Or. Undergrad. Res. J. 10 (1), 32–46. https://doi.org/10.5399/uo/ourj.10.1.5.
Golden, C.D., Hartmann, A.C., Gibbons, E., Todinanahary, G., Troell, M.F., Ampalaza, G., Behivoke, F., et al., 2024. HIARA study protocol: impacts of artificial coral reef development on fisheries, human livelihoods and health in Southwestern Madagascar. Front. Public Health 12 (July). https://doi.org/10.3389/fpubh.2024.1366110, 1,366,110.
Hammer, O., Harper, D.A.T., Ryan, P.D., 2001. Past: Paleontological Statistics Software Package for education and data analysis. Palaeontol. Electron. 4 (1) art 4. 9pp., 178kb. http://palaeo-electronica.org/2001_1/past/issue1_01.htm.
Harris, L.R., Defeo, O., 2022. Sandy shore ecosystem services, ecological infrastructure, and bundles: new insights and perspectives. Ecosyst. Serv. 57 (101), 477. https://doi.org/10.1016/j.ecoser.2022.101477.
Houston, J.R., 2018. The economic value of america's beaches — a 2018 update, 86 (2), 13pp.
Ivar Do Sul, J.A., Costa, M.F., 2007. Marine debris review for latin america and the wider Caribbean region: from the 1970s until now, and where do we go from here? Mar. Pollut. Bull. 54 (8), 1087–1104. https://doi.org/10.1016/j.marpolbul.2007.05.004.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.
Kunzmann, A., Todinanahary, G., Msuya, F.E., Alfiansah, F., 2023. Comparative environmental impacts and development benefits of coastal aquaculture in three tropical countries: Madagascar, Tanzania and Indonesia. Trop. Life Sci. Res. 34 (3). https://doi.org/10.21315/tlsr2023.34.3.15.
Lavitra, T., Moridy, F., Rabearison, M., Rodine, C., Rakotomahazo, C., Nomenisoa, A.L., Ranivoarivelo, L.N., et al., 2024. Local perceptions of the socioeconomic and environmental impacts of sea cucumber farming in Southwestern Madagascar. In: Secretariat of the Pacific community bêche-de-mer information bulletin, 44, pp. 48–58.
Lazar, B., Gračan, R., 2011. Ingestion of marine debris by loggerhead sea turtles, *Caretta Caretta*, in the Adriatic Sea. Mar. Pollut. Bull. 62 (1), 43–47. https://doi.org/10.1016/j.marpolbul.2010.09.013.
Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. In: UNEP Regional Seas Reports and Studies, No. 185. FAO Fisheries and Aquaculture Technical Paper, No. 523. UNEP/FAO, Rome, 115pp.
McLachlan, A., Eliot, I.G., Clarke, D.J., 1985. Water filtration through reflective microtidal beaches and shallow sublittoral sands and its implications for an inshore ecosystem in Western Australia. Estuar. Coast. Shelf Sci. 21 (1), 91–104. https://doi.org/10.1016/0272-7714(85)90008-3.
Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, J.I., Montero, E., et al., 2021. An inshore–offshore sorting system revealed from global classification of ocean litter. Nat. Sustain. 4 (6), 484–493. https://doi.org/10.1038/s41893-021-00720-8.
Nellemann, C., Corcoran, E., 2009. Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment. In: UNEP/Earthprint, 80pp.
Palmer, C.P., 2017. La biodiversité marine et les écosystèmes marins assurent la santé de la planète et le bien-être social. Chronique ONU 54 (2), 59–61. https://doi.org/10.18356/86521f36-fr.
R Core Team, 2024. R: The R project for statistical computing. 2024. https://www.r-project.org/.
Rabemanantsoa, A., 2021. Évaluation des impacts environnementaux relatifs aux déchets plastiques issus des activités halieutiques et aquacoles dans le village de Sarodrano. Study report. Fisheries and Marine Sciences Institute, University of Toliara, p. 63pp.
Rakotomahazo, C., 2022. Etude de la mise en place d'une initiative de Paiements pour les Services Ecosystémiques (PSE) communautaires des mangroves de la Baie des Assassins. Sud-Ouest de Madagascar, 243pp.
Richardson, K., Asmutis-Silvia, R., Drinkwin, J., Gilardi, K.V.K., Giskes, I., Jones, G., O'Brien, K., et al., 2019a. Building evidence around ghost gear : global trends and analysis for sustainable solutions at scale. Mar. Pollut. Bull. 138, 222–229. https://doi.org/10.1016/j.marpolbul.2018.11.031.
Richardson, K., Hardesty, B.D., Wilcox, Ch., 2019b. Estimates of fishing gear loss rates at a global scale: a literature review and meta-analysis. Fish Fish. 20 (6), 1218–1231. https://doi.org/10.1111/faf.12407.
Robinson, G., Pascal, B., 2009. From hatchery to community – Madagascar's first village-based holothurian mariculture program. In: Secretariat of the Pacific Community Bêche-de-mer Information Bulletin, 29pp.
Schlacher, T.A., Schoeman, D.S., Dugan, J., Lastra, M., Jones, A., Scapini, F., McLachlan, A., 2008. Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. Mar. Ecol. 29 (s1), 70–90. https://doi.org/10.1111/j.1439-0485.2007.00204.x.
Tekman, M.B., Walther, B.A., Peter, C., Gutow, L., Bergmann, M., 2022. Impacts of Plastic Pollution in the Oceans on Marine Species, Biodiversity and Ecosystems. WWF Germany, Berlin, pp. 1–122. https://doi.org/10.5281/ZENODO.5898684.
Tekman, M.B., Walther, B.A., Peter, C., Gutow, L., Bergmann, M., Bauske, B., 2023. The effects of plastic pollution on marine ecosystems, 8 (2), 173–186.
Thibault, M., Hoarau, L., Lebreton, L., Le Corre, M., Barret, M., Cordier, E., Ciccione, S., et al., 2023. Do loggerhead sea turtle (*Caretta Caretta*) gut contents reflect the types, colors and sources of plastic pollution in the Southwest Indian Ocean? Mar. Pollut. Bull. 194 (2023), 115,343. https://doi.org/10.1016/j.marpolbul.2023.115343.
UNEP, 2009. Marine Litter: A Global Challenge. UNEP, Nairobi, 232pp.
UNEP, 2021. UNEP in 2021: planetary action: climate, nature, chemicals & pollution. In: Annual Report. United Nations Environment Programme, 20pp. https://wedocs.unep.org/handle/20.500.11822/37081.
Van Bijsterveldt, C.E.J., Van Wesenbeeck, B.K., Ramadhani, S., Raven, O.V., Van Gool, F. E., Pribadi, R., Bouma, T.J., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci. Total Environ. 756 (February), 143,826. https://doi.org/10.1016/j.scitotenv.2020.143826.
Walther, B.A., Bergmann, M., 2022. Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the arctic ocean and the deep seafloor. Emerg. Top. Life Sci. 6 (4), 371–387. https://doi.org/10.1042/ETLS20220017.
Worm, B., Lotze, H.K., Jubinville, I., Wilcox, Ch., Jambeck, J., 2017. Plastic as a persistent marine pollutant. Annu. Rev. Environ. Resour. 42 (1), 1–26. https://doi.org/10.1146/annurev-environ-102016-060700.
Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423.
WWF, 2019. Pollution plastique : à qui la faute ? https://www.wwf.fr/sites/default/files/doc-2019-03/20190305_Rapport_Pollution-plastique_a_qui_la_faute_WWF.pdf, 46pp.
Zemke-White, W.L., 2006. Environmental Impacts of Seaweed Farming in the Tropics, 89pp.
Zhu, J., Zhang, Q., Li, Y., Tan, S., Kang, Z., Yu, X., Lan, W., Cai, L., Wang, J., Shi, H., 2019. Microplastic pollution in the Maowei sea, a typical mariculture bay of China. Sci. Total Environ. 658, 62–68. https://doi.org/10.1016/j.scitotenv.2018.12.192.