Estuaries and Coasts (2025) 48:135
https://doi.org/10.1007/s12237-025-01573-6

Assessing Plastic Pollution in Kenyan Mangroves: Distribution, Sources, and Social Impact in Gazi Bay

Elissa P. B. Pelsmaekers[1,2] · Colin R. Janssen[3] · Stefano Cannicci[4,5] · Cosmas Nzaka Munga[6] · Farid Dahdouh-Guebas[1,2,5,7]

Received: 22 March 2025 / Revised: 4 June 2025 / Accepted: 8 June 2025

Abstract
The increase in global production of plastics has led to widespread environmental pollution, with mangrove ecosystems becoming significant traps for both macro- and microplastics. This study investigated plastic pollution in the mangrove forest of Gazi Bay, Kenya, focusing on the spatial distribution, types and sources of plastic debris. Macroplastic and large microplastic (LMPs; 1–5 mm) samples were collected from different zones in the mangroves and adjacent beach areas. The average concentration of plastic debris on the forest floor was 0.79 ± 0.35 items m^{-2}, with an additional 0.17 ± 0.04 items $tree^{-1}$ entangled in the trees. Fishing-related plastics, such as ropes and fishnets, were prevalent in the seaward zones, while domestic waste was more common in the landward zones. LMPs were primarily concentrated in the landward zone and beach areas. Landward transects showed the highest average concentrations (1.25 ± 0.66 LMPs kg^{-1} dry sand), while the beach zone had the largest proportion of polluted samples, with 25.93% of replicates containing LMPs. A social survey in Gazi village revealed ongoing waste management challenges, with 55% of residents admitting to littering despite Kenya's 2017 ban to reduce the use of single-use plastics. While the ban has had some positive effects, compliance remains difficult due to economic constraints and limited waste management. Respondents expressed willingness to reduce plastic use, indicating that policy enforcement must be combined with community-driven solutions. The findings emphasise the need for integrated waste management strategies, public engagement and improved infrastructure to mitigate plastic pollution in Kenyan mangrove ecosystems.

Keywords Plastic pollution · Microplastics · Macroplastics · Waste management · Mangrove ecosystems

Communicated by Isabel Jalon-Rojas

✉ Elissa P. B. Pelsmaekers
elissa.pelsmaekers@gmail.com

Colin R. Janssen
Colin.Janssen@UGent.be

Stefano Cannicci
stefano.cannicci@unifi.it

Cosmas Nzaka Munga
ckamunga2014@tum.ac.ke

Farid Dahdouh-Guebas
Farid.Dahdouh-Guebas@ulb.be

1 Systems Ecology and Resource Management (SERM), Département de Biologie des Organismes, Université Libre de Bruxelles, ULB, Av. F.D. Roosevelt 50, CPi 264/1, B-1050 Brussels, Belgium

2 Ecology, Evolution & Genetics Research Group (bDIV), Department of Biology, Vrije Universiteit Brussel, VUB, Pleinlaan 2, B-1050 Brussels, Belgium

3 Blue Growth Research Lab, Department of Animal Sciences and Aquatic Ecology, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

4 Department of Biology, University of Florence, 50019 Sesto Fiorentino, Italy

5 Mangrove Specialist Group (MSG), Species Survival Commission (SSC), International Union for the Conservation of Nature (IUCN), c/o Zoological Society of London, London, U.K.

6 Department of Environment and Health Sciences, Marine and Fisheries Program, Technical University of Mombasa, P.O. Box 90420 - 80100, Mombasa, Kenya

7 Interfaculty Institute of Social-Ecological Transitions - iiTSE, Université Libre de Bruxelles (ULB), Av. Roosevelt 50, CPi 264/1, B-1050 Brussels, Belgium

Introduction

The development of viable, inexpensive plastic synthesis methods in the early to mid-twentieth century led to an increase in global plastic production (Geyer et al., 2017). While plastic has become indispensable due to its versatility, its production and use have created significant environmental concerns (Law, 2017). Over 400 million tonnes of plastic are produced annually, a large portion of which constitute single-use items (PlasticsEurope, 2023). Despite advances in recycling methods, only about 10% of plastic waste is recycled globally (Bornscheuer, 2016; UNEP, 2018a; UNEP, 2018b). Poor waste management practices, including littering, contribute to the accumulation of plastic in the environment. This leads to long-term persistence due to its durability (Jambeck et al., 2015). Additionally, defined as plastic particles less than 5 mm in size (Thompson et al., 2004), microplastics (MPs) also form a threat to the environment. These small particles can easily disperse across various ecosystems, contaminating even remote environments (Law et al., 2010; Morét-Ferguson et al., 2010).

The expansion of coastal cities is one of the main contributors to plastic contamination of marine ecosystems (Jambeck et al., 2015), discharging between 3.1 and 12.7 million tonnes of plastic into oceans annually (Jambeck et al., 2015; Lebreton & Andrady, 2019). Most plastic pollution does not remain at the ocean's surface (Van Sebille et al., 2015); it accumulates in sediments (Van Cauwenberghe et al., 2013a), is ingested by marine organisms (Kershaw, 2015; Ribeiro et al., 2019, So et al., 2022), or becomes trapped in estuarine habitats such as mangroves (Willis et al., 2017; Ouyang et al., 2022).

Modified from Mukherjee et al. (2014) 'mangrove' ecosystems are tidally influenced coastal wetlands that are present primarily in tropical and subtropical latitudes (30°N to 37°S). These habitats cover approximately 147,359 km^2 of the world's coastlines, with 20% located in Africa (Bunting et al., 2018; Bunting et al., 2022). Here, they support the livelihoods of around 4.1 million fishermen (Zu Ermgassen et al., 2021). Mangroves play an important role in coastal protection (Dahdouh-Guebas et al., 2005), they provide a range of ecosystem services, including carbon storage (Donato et al., 2011), and are home to and act as nurseries for ecologically and commercially significant species (Cannicci et al., 2008). However, they are seriously threatened by both natural and anthropogenic stressors, such as erosion, land reclamation, the expansion of aquaculture (Friess et al., 2019; Friess et al., 2020; Dahdouh-Guebas et al., 2022; United Nations Environment Programme, 2023) and the accumulation of anthropogenic debris. Due to their complex root systems, mangroves are highly efficient at trapping debris (Martin et al., 2019; Martin et al., 2020; Luo et al., 2021), with plastics comprising at least 70% of the waste found in these habitats (Deng et al., 2021; Luo et al., 2022). The high sedimentation rates of mangroves allow plastics to accumulate over time, creating potentially anoxic conditions that disrupt many ecosystem processes (Smith, 2012). Meanwhile, mangrove trees exhibit signs of stress when plastic litter covers more than 50% of their root system (Van Bijsterveldt et al., 2021). Ultimately, accumulated waste could physically damage the trees (Pranchai et al., 2019). These factors could impair the mangroves' ability to regenerate and recover (Gorman & Turra, 2016; Pranchai et al., 2019). Furthermore, mangroves may serve as hotspots for MP formation and accumulation due to microbial degradation, faunal activity, mechanical fragmentation and tropical climatic conditions (Ouyang et al., 2022; So et al., 2022, So et al., 2023; Abd Rahim et al., 2023).

Despite the importance of mangrove ecosystems and increased global attention, research on plastic pollution in mangroves is limited compared to other coastal habitats (Smith & Edgar, 2014; Browne et al., 2015; Deng et al., 2021; Luo et al., 2021; Mendes et al., 2023). Several studies to date have documented plastic accumulation in mangrove systems, revealing highly variable contamination levels depending on proximity to urban areas, mangrove structure, and dominant plastic sources (*e.g.* fishing vs. household waste). These studies highlight that mangroves act as sinks for both land- and marine-based debris, with reported plastic densities ranging from < 1 item m^{-2} in rural areas (Maharani et al., 2018; Martin et al., 2019; Riascos et al., 2019; Abreo et al., 2020) to over 200 items m^{-2} in highly urbanised bays (Hastuti et al., 2014; Rahim et al., 2020; Suyadi & Manullang, 2020). However, most studies on plastic pollution in mangrove ecosystems have been carried out in Southeast Asia and South-America, while only 5.7% of all studies have taken place in Africa, focussing almost exclusively on MPs (Mendes et al., 2023). The lack of research in African mangroves limits our understanding of local pollution patterns and highlights the need for more comprehensive, region-specific studies targeting both macro- and microplastics. Additionally, there is a notable lack of research that integrates environmental data with socio-economic insights. The combined influence of ecological factors and human behaviours (*e.g.* waste management practices) is rarely addressed, despite its importance in understanding the drivers of plastic accumulation. This interdisciplinary gap is increasingly recognised as essential for developing effective, long-term solutions (Martínez-Espinosa et al., 2020).

Mangroves are estimated to be more vulnerable to plastic pollution from riverine inputs than other coastal ecosystems, with 54% of mangroves worldwide located within 20 km of rivers discharging over 1 tonne of plastic debris into the ocean annually (Harris et al., 2021). In Africa, a projected population growth of 1.3 billion by 2050 is expected to increase the strain on these already vulnerable coastal ecosystems (UNEP, 2015; Neumann et al., 2015). Insufficient waste collection systems and limited public awareness have already resulted in widespread plastic pollution in natural and urban areas (Okuku et al., 2011; Oyake-Ombis et al., 2015). Kenya, in particular, faces significant challenges in managing plastic waste, with over 80% of the total waste being mismanaged (Jambeck et al., 2015; Griffin & Karasik, 2022). Although the Kenyan government has introduced bans on certain single-use plastics in 2017, making it one of the first and few African countries to adopt these measures, enforcement is inconsistent. Additionally, whilst these policies are admirable, they have not yet been successful in mitigating the increasing levels of other plastic items, which continue to negatively affect marine environments. Plastic products such as polyethylene terephthalate (PET) bottles and woven polypropylene (PP) bags remain in widespread use (Oyake-Ombis et al., 2015; Moss et al., 2017). Additionally, coastal artisanal fisheries in Kenya play a crucial role in the livelihood of many coastal communities (Barnes-Mauthe et al., 2013). These fisheries also significantly contribute to marine plastic pollution, as fishing gear often ends up in the ocean (Richardson et al., 2019; Ryan et al., 2019). Marine litter was already documented along Kenyan coastal beaches (Okuku et al., 2011; Ryan, 2020), but few studies have quantified plastic pollution in mangrove habitats. Given the ecological and social significance of mangroves and the increasing pressures from plastic pollution in Kenya, there is a need to assess the extent of macro- and microplastic contamination in these forests (Dahdouh-Guebas et al., 2022).

This study aimed to investigate the spatial distribution and potential sources of macro- and microplastic pollution within the mangrove area of Gazi Bay, located on the south coast of Kenya. To assess the extent of plastic contamination and identify accumulation patterns in different mangrove zones, plastic distribution across the mangrove forest and adjacent beach areas was mapped out. Additionally, we investigated the potential sources of plastic pollution, including riverine, oceanic, and terrestrial inputs, with particular focus on the role of local fishing activities and community waste management practices in Gazi village. Lastly, a survey was conducted to assess the perceptions and habits of Gazi village residents regarding plastic use and disposal. This combination of field data with socio-economic insights is essential for the development of targeted policies and localised mitigation strategies aimed at reducing plastic pollution in Kenyan mangrove ecosystems. Furthermore, the findings may contribute to future evaluations of the environmental, social and regulatory impacts of the plastic bans in Kenya. We anticipated that plastic accumulation would vary by mangrove zone, with seaward areas containing more fishing-related debris due to local fishing activities, and landward areas showing higher concentrations of domestic waste. Higher plastic abundance was also expected in zones closer to Gazi village, reflecting local waste management practices. By integrating spatial distribution data with a social survey, we tried to better understand how ecological and community-level drivers interact to influence plastic pollution in mangrove ecosystems.

Materials & Methods

Study Area

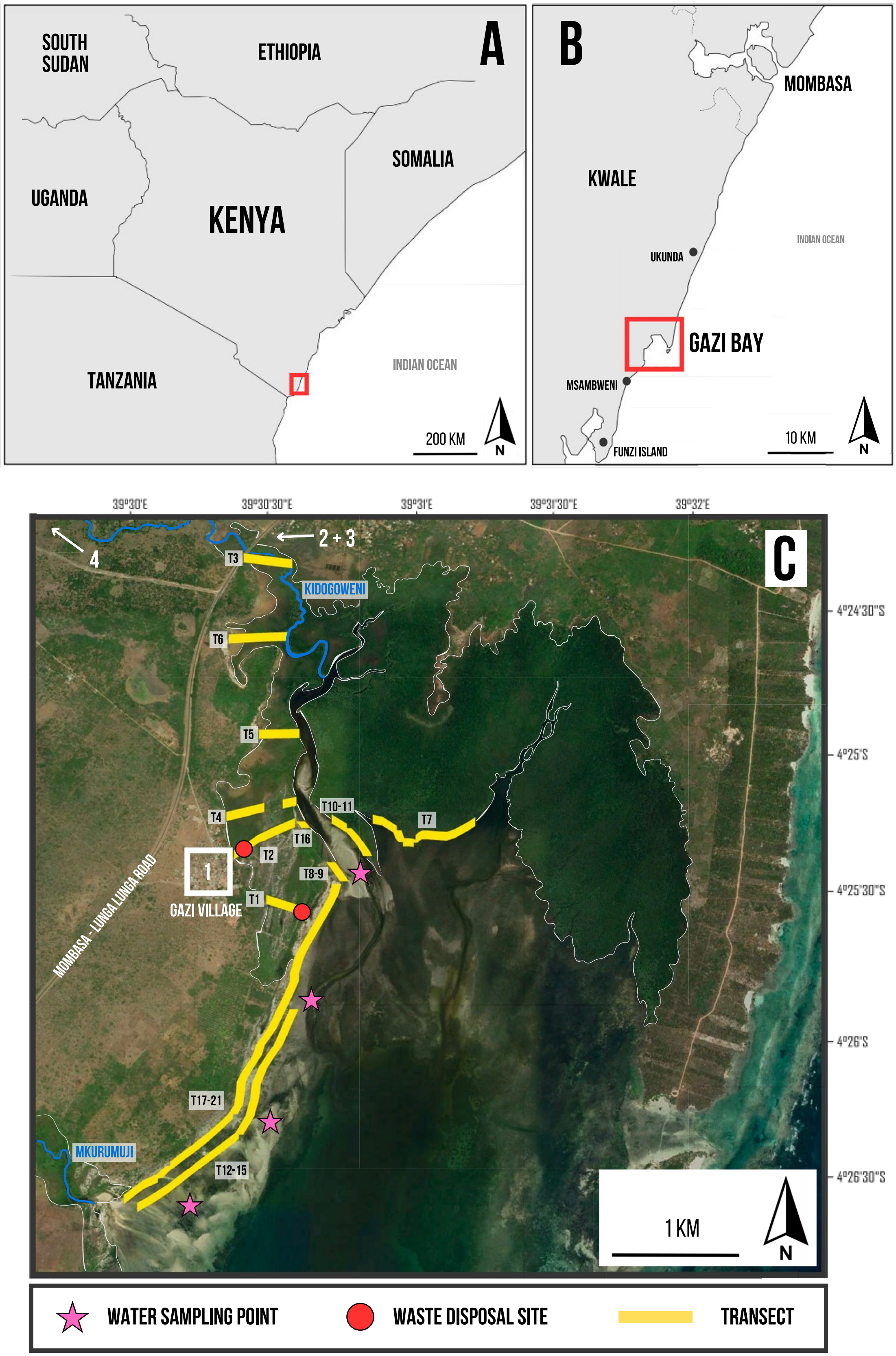
Gazi Bay (04°25’S, 039°30’E) is located on the south coast of Kenya, approximately 50 km from Mombasa (Fig. 1) (Dahdouh-Guebas et al., 1998). The bay comprises an area of about 1000 ha and opens towards the Indian Ocean, with an average depth of 5 m (Kimani et al., 2006; Neukermans et al., 2008). The nearby village of Gazi is home to around 4000 residents, and primarily relies on small-scale coastal fisheries (Ndarathi et al., 2020).

A mangrove forest (~ 6 km^2) stretches along the bay and is connected to a coral reef on the seaward side (Crona & Rönnbäck, 2007; Neukermans et al., 2008). The coral reefs contribute significantly to the fish populations inhabiting adjacent seagrass beds and mangroves (Ndarathi et al., 2020). Gazi Bay hosts nine East African mangrove species: *Avicennia marina* (Forssk.) Vierh., *Sonneratia alba* Sm., *Rhizophora mucronata* Lam., *Xylocarpus granatum* J.Koenig, *Ceriops tagal* (Perr.) C.B. Rob., *Bruguiera gymnorrhiza* (L.) Lam., *Heritiera littoralis* Aiton, *Lumnitzera racemosa* Willd., *Xylocarpus moluccensis* (Lam.) M.Roem., as well as the associate species *Pemphis acidula* J.R.Forst & G.Forst (Coppejans & Beeckman, 1989; Neukermans et al., 2008).

The climate is influenced by seasonal monsoons. From April to August, the southeastern monsoon prevails, while the northeastern monsoon dominates from October to November, leading to lighter rainfall during this period (Bosire et al., 2003; Crona & Rönnbäck, 2007). Freshwater inflow into the mangroves during the rainy season is provided by the Mkurumuji River (referred to as Mkurumudzi in the local Digo language), located in the southwest of the bay. In addition, two tidal creeks, Kinondo and Kidogoweni, drain into the northern part of the bay (Bosire et al., 2003).

Macroplastic Sampling

Litter surveys were carried out during the dry season in March and April 2022. Plastic was assessed by counting (i) the number of plastic items identified on the ground and in


SOUTH SUDAN
ETHIOPIA
A
UGANDA
KENYA
SOMALIA
TANZANIA
INDIAN OCEAN
200 KM
N
B
MOMBASA
KWALE
INDIAN OCEAN
UKUNDA
GAZI BAY
MSAMBWENI
FUNZI ISLAND
10 KM
N
39°30'E
39°30'30"E
39°31'E
39°31'30"E
39°32'E
4°24'30"S
4°25'S
4°25'30"S
4°26'S
4°26'30"S
C
4
2 + 3
T3
KIDOGOWENI
T6
T5
T4
T10-11
T7
T16
T2
1
GAZI VILLAGE
T8-9
T1
MOMBASA - LUNGA LUNGA ROAD
T17-21
MKURUMUJI
T12-15
1 KM
N
WATER SAMPLING POINT
WASTE DISPOSAL SITE
TRANSECT

◂**Fig. 1** (**A**) Map of Kenya showing the location of the Gazi Bay study site (approximately 04°25′25″S, 039°30′23″E). (**B**) Map detailing Gazi Bay on the southern coast of Kenya. (**C**) CNES Airbus satellite image Gazi Bay sampling area, showing transects for plastic monitoring within the mangrove forest (T1-6), parallel to the bay (T7-15), and along the beach (T16-21). The Kidogoweni and Mukurumudji Rivers are marked in blue, and follow the flow direction from upstream to the coast. The extent of the mangrove forest is outlined in white, and includes some small areas of terrestrial vegetation. Four potential plastic pollution sources are marked in white: (1) Gazi village, (2) the intersection of the Mombasa-Lunga Lunga Road with the Kidogoweni River, (3) Makongeni village, and (4) upstream industries (*i.e.* the Base Titanium Mine). (Image source: CNES Airbus, dated 2 Jan 2022, via Google Earth Pro (2022))

the trees per square metre (items m^{-2}), (ii) the number of plastic items covering the branches and roots of each mangrove tree (items $tree^{-1}$), (iii) the macroplastic cover, quantified as the percentage area covered by plastic debris (%), and (iv) the mass of plastic recovered per square metre (g m^{-2}).

The data from these measurements were compared between different zones: the beach, the landward zone of the mangrove forest, the intermediate zone, and the seaward/creekward zones adjacent to the bay and the river. The seaward zone was defined as the area of the mangrove forest directly exposed to the water, while the landward zone marked the transition from mangrove to terrestrial vegetation.

In total, 21 transects were completed, with the number of sampled sections per transect ranging from 1×25 m to 6×25 m (Fig. 1.C and Table S.1).

Mangrove Transects

All macroplastics (> 5 mm) were collected using belt transects that stretched the entire width of the mangrove forest (Fig. 1.C), according to a procedure suggested by Luo et al. (2022). Transects were measured using a tape measure to delineate the sampling area (Fig. 2.C), with each transect subdivided into sections of 1×25 m^2 at 100 m intervals (Figure S.1.A and S.1.B). Plastic items larger than 5 mm within 50 cm on either side of the transect line were collected manually.

Plastic items found on trees were quantified using a random sampling generator. All trees within each transect area (from saplings to mature trees) were counted, and five trees were randomly selected. The abundance of plastic on these trees was then measured in terms of items per tree (items $tree^{-1}$) and items per square metre (items m^{-2}), as well as the percentage area of the tree covered by macroplastics (%) by manually measuring the surface of the plastic items covering the trees in the field per square metre with a tape measure.

In the mangrove forest west of the Kidogoweni River, six transects (T1–T6) were completed, extending from the riverside to the landward side to detect a potential gradient of macroplastic accumulation (Fig. 1.C and Figure S.1.A). Along the bay, transects (T7–T15) were sampled parallel to the shoreline to identify potential plastics transported from the ocean (Fig. 1.C and Figure S.1.B).

Transects within the mangrove forest were surveyed during both low-water neap tide (LWNT) and low-water spring tide (LWST) to ensure maximal accessibility and proper collection of the debris. Transects along the bay were completed only during LWST, as these areas were only accessible at that time. In total, fifteen transects were sampled within the mangrove forest, with the number of subsections ranging from 1×25 m to 6×25 m (Table S.1).

Beach Transects

Six 25 m transects (T16–T21) were sampled along the beach (parallel to the shoreline), at 400 m intervals, extending from the Kidogoweni River to the Mkurumuji River (Fig. 1.C). The transects covered the area from the low-water mark of neap tide to the vegetation line, following a modified procedure based on Van Cauwenberghe et al. (2013b) (Figure S.1.C). The first beach transect was completed during LWNT, with the low-water mark serving as the baseline for the remaining transects. Since the beach transects all differed in width (ranging from 10.2 m to 21.2 m), the total sampling area was recalculated to 1×25 m^2 to facilitate comparison with other transects.

Microplastic Sampling

Sediment samples were collected along the transects to assess the presence of large microplastic debris (LMPs: 1–5 mm). Due to potential contamination by smaller airborne MPs, only LMPs were targeted to minimise sampling inaccuracies. Sediment was collected using 50×50 cm^2 quadrats, down to a depth of 5 cm (12,500 cm^3), with a stainless-steel scoop. The sediment samples were placed into stainless-steel buckets and sieved through a 0.5 mm mesh to recover the LMPs. All equipment used was rinsed three times with water filtered through a 500-mesh (25-micron) phytoplankton net before use to avoid cross-contamination.

At each beach transect, nine replicate samples were collected following EPA protocols (EPA, 2021). Three perpendicular lines were drawn randomly along the beach, extending from the high neap tide mark to the vegetation line, with three replicates sampled along each line (Figure S.2.A). In the mangrove forest transects, three sediment replicates were taken randomly within each 25 m^2 section (Figure S.2.B).

In addition to the sediment samples, four water and sediment sampling points were established within the bay (Fig. 1.C). Water samples were collected weekly for three consecutive weeks using stainless-steel buckets, with 100

Fig. 2 Photos documenting plastic pollution during transect surveys in the Gazi mangrove forest. (**A** & **B**) Main village waste disposal sites adjacent to *Avicennia*-dominated mangroves. (**C**) Transects through *Ceriops*-dominated mangroves. (**D**) Example of macroplastic debris (ropes) found during the survey. (Photos by Elissa Pelsmaekers, Kenya)

L of water filtered through a 0.5 mm sieve at each sampling point. Sediment samples were taken at low-water spring tide (LWST), with wet sediment sieved (0.5 mm) after adding filtered water to facilitate microplastic recovery.

Plastic Identification and Chemical Characterisation

Following the sampling process, both macro- and microplastics were sorted and categorised based on type, use, chemical composition and potential source, following the OSPAR

(Wenneker et al., 2010) and UNEP (UNEP, 2009) classification systems. Microplastics were classified by shape (*e.g.*, fragments, pellets, films, foams and fibres), using categories suggested by GESAMP (GESAMP, 2019) and OSPAR (Wenneker et al., 2010). Both the macro- and microplastic items were measured, and for each macroplastic item, a 1 cm^2 fragment was cut and stored separately in aluminium foil for further analysis. The percentage of ground area covered by macroplastics was calculated by measuring the surface area (cm^2) of each plastic item collected within the 1×25 m^2 transect. The total surface area of all items in a transect was summed and then standardised to 1 m^2. This value was then expressed as a percentage of the ground area.

Weighing all macroplastic debris in the field was infeasible due to size and adhesion of other materials, only the collected microplastics and cut-off macroplastic fragments were weighed in the laboratory. To estimate the weight of the full plastic items, we used the data on surface area, weight, and polymer type of each fragment for the calculation. Based on the known density of the polymers, we deduced the total weight of the items by calculating the estimated volume and multiplying it by its material density.

A Fourier-transform infrared (FTIR) spectrometer (Thermo Scientific™ Nicolet™ iSTM 10 with Smart iTX™ accessory) was used for chemical characterisation of the plastic samples, controlled with the Thermo ScientificTM OMNIC™ Spectra software. Mid-infrared range spectra (4000–400 cm^{-1}) were recorded with 16 scans per sample. Samples were handled with metal tweezers and positioned directly under the interferometer. For pieces thicker than 1 mm, a smaller section was cut for analysis. To prevent contamination, the FTIR instrument was cleaned with paper cloths between scans.

Data Analysis

To analyse the macro- and microplastic cover data, non-parametric statistical methods were used with a significance level of $\alpha = 0.05$. The Kruskal–Wallis (KW) tests enabled to analyse differences in the response variable across the sampling zones.

A post hoc Dunn test with Bonferroni correction was used to determine which groups significantly differed from each other, using the'FSA'package in R (Ogle et al., 2023).

A generalised additive model (GAM) was used to examine non-parametric relationships between plastic debris abundance in the field and:

i. The distance from Gazi village.
ii. Potential river-based plastic sources along the Kidogoweni River (*i.e.* Gazi Village, Makongeni village bordering the river, the Mombasa-Lunga Lunga Road that crosses the river, which may contribute roadside litter to the river system, and upstream industries (*i.e.* the Base Titanium Mine) (Fig. 1.C)).

The GAM output was used in ArcGIS to produce a gradient map illustrating plastic abundance and cover for both the sediment and the roots and branches of trees in the mangrove forest.

Social Questionnaire Survey

A social survey was conducted to gather insights into plastic use, disposal habits and perceptions of plastic pollution among the residents and fishermen in Gazi village. The questionnaire contained both open- and closed-ended questions, designed to (i) assess household and fishing-related plastic use and disposal practices, and (ii) explore knowledge and perceptions of plastic pollution, recycling and waste reduction efforts within the community.

Interviews were conducted in March and April 2022, across 60 households in Gazi village. To avoid data repetition, only one person per household was interviewed, though other family members were allowed to contribute. Households were selected by choosing five to six residences per street. A translator helped translate the questions into Kiswahili and responses into English when needed. Fishermen were asked additional questions regarding the plastic items they used aboard their boats.

Results

Spatial Distribution of Macroplastic Pollution

A total of 1269 macroplastic items were identified across all transects, including those entangled in the roots and branches of mangrove trees. The average abundance of plastics on the ground was 0.79 ± 0.35 items m^{-2}, while the average number of plastic items found on trees was 0.17 ± 0.05 items $tree^{-1}$ (0.1 ± 0.04 items m^{-2}). Plastic abundance on the ground varied greatly across transects, ranging from no plastics to a maximum of 11.12 items m^{-2}. On the trees, plastic abundance ranged from 0 to 0.8 items $tree^{-1}$ (0 to 1.32 items m^{-2}) (Table S.1). An average macroplastic ground cover of $1.15 \pm 0.45\%$ was observed across all transects and ranged from 0 to 15%. Similarly, macroplastic cover on the trees ranged from 0% to 11.64%, with an average of $0.87 \pm 0.36\%$ (Table S.1). The total estimated weight of macroplastic on the ground was 21.76 kg, corresponding to an average of 21.62 ± 12.59 g m^{-2}. The highest recorded weight on a single 25 m transect was 11.65 kg (0.47 kg m^{-2}). For plastics found on tree roots and branches, the total weight was estimated at 4.05 kg, with a range of 0 to 51.07 g m^{-2}, and an average of 4.63 ± 2.11 g m^{-2} (Table S.1).

Comparison of Plastic Debris Between Zones

Plastic abundance on the forest floor was highest in the landward zone, with an average of 1.78 items m^{-2} (± 3.57, n = 9), followed by the seaward (0.58 ± 2.20, n = 18), intermediate (0.56 ± 0.73, n = 8), and beach zones (0.22 ± 0.19, n = 6) (Table S.1). A Kruskal–Wallis test detected a difference in plastic abundance across zones (χ^2 = 10.311, df = 3, p = 0.0161, n = 41). The post hoc Dunn tests indicated that plastic abundance in the landward zone was higher than in the seaward zone (p = 0.039), although variation was high in both zones.

The average plastic ground cover was highest in the landward zone at 2.93% (± 0.84, n = 9), compared to 1.08% (± 0.88, n = 18) in the seaward zone, 0.60% (± 0.13, n = 8) in the intermediate zone, and 0.26% (± 0.06, n = 6) on the beach (Table S.1). The Kruskal–Wallis test (χ^2 = 5.327, df = 3, p = 0.1494, n = 41) did not detect strong evidence of a difference in plastic cover among zones, although the landward zone showed the highest average.

Plastic on the trees was highest in the seaward zone (0.3 ± 0.32 items $tree^{-1}$; 0.19 ± 0.07 items m^{-2}, n = 18) compared to the landward (0.004 ± 0.0013 items $tree^{-1}$; 0.02 ± 0.02 items m^{-2}, n = 9) and intermediate zones (0.025 ± 0.085 items $tree^{-1}$; 0.03 ± 0.03 items m^{-2}, n = 8) (Table S.1). The Kruskal–Wallis test detected differences among zones (χ^2 = 12.27, df = 2, p = 0.0022, n = 35). Dunn post hoc comparisons showed a lower abundance in the intermediate zone (p = 0.0166) and the landward zone (p = 0.074) compared to the seaward zone.

Similarly, plastic cover on trees was highest in the seaward zone (1.69% ± 0.70, n = 18), while both the landward and intermediate zones had average cover values below 0.01% (landward: ± 0.0007, n = 9; intermediate: ± 0.003, n = 8) (Table S.1). Differences among zones were detected (χ^2 = 14.629, df = 2, p = 0.0006, n = 35). Pairwise comparisons showed that plastic cover in the seaward zone was higher than in the landward (p = 0.0039) and intermediate zones (p = 0.0056).

Origin of Plastic Input

The generalised additive model (GAM) revealed that the plastic abundance on the mangrove forest floor increased with proximity to Gazi village (p = 0.0283), explaining 22.3% of the variability (n = 41). This trend was also visible in the field, where higher plastic concentrations were confirmed closer to Gazi village on the plastic abundance gradient map (Fig. 3.A). In the northmost section of the mangrove, the transect adjacent to the Mombasa-Lunga Lunga Road showed a sudden increase in plastic abundance and ground cover (1.4 items m^{-2}; 6.54% cover), in contrast to nearby transects further from the road (0.04 to 0.28 items m^{-2}; < 0.01–0.5% cover) (Fig. 3.A and 3.C). Plastic cover on the ground showed little evidence of a relationship with distance to Gazi (p = 0.135, 10.1% deviance explained), and plastic items on trees were not meaningfully explained by proximity to the village (p = 0.493, < 0.001% deviance explained, n = 35) (Fig. 3.C). Tree cover showed a modest trend (p = 0.0698, 14.1% deviance explained), but with substantial unexplained variability (Fig. 3.D).

Models focused on beach transects and riverbank areas did not reveal strong spatial trends. For beach transects, p-values exceeded 0.5 and the models explained less than 0.001% of the deviance (n = 6). Similarly, models for riverside plastic abundance and cover had low explanatory power and high p-values (p > 0.5, deviance < 0.001%, n = 4), suggesting no detectable pattern within this small subset of the data.

Macroplastic Identification and Chemical Characteristics

Unidentifiable plastic fragments constituted the largest proportion of debris, representing 28.84% of all items recorded. Other major items included bottles, caps, plastic sheets, packaging, ropes, candy wrappers and pieces of fishing nets (Fig. 4). Various other items, such as toothbrushes, toothpaste tubes, food containers, slippers and building materials, were also recovered in very limited numbers, with each category comprising less than 0.1% of the total items found. Only eight single-use polyethylene (SUP) bags (0.63%) and one polypropylene (PP) bag (0.08%) were identified across the sampling area.

Plastic debris in the landward zone mainly consisted of domestic waste (*e.g.,* bread wrappers, household items, slippers, food containers), while debris near the bay was predominantly related to marine activities (*e.g.*, ropes, fishing nets, buoys, tarps, buckets). The landward zone transects (21.56 ± 16.18 items) and beach (12.67 ± 4.28 items) had higher plastic fragment counts than the intermediate (3.5 ± 2.42 items) and seaward zones (3.78 ± 3.44 items). Rope and tarp were more frequent in the beach (7 ± 2.57 and 2.67 ± 1.15 items) and seaward zones (2.56 ± 1.36 and 1.39 ± 0.68 items) compared to the landward (0.44 ± 0.24 and 0.22 ± 0.15 items) and intermediate zones (0.75 ± 0.49 and 0 items). Fishing nets were five times more prevalent in the seaward zone (1.61 ± 1.11 items) than in the landward (0.11 ± 0.11 items) and intermediate zones (0.13 ± 0.13 items) and twice as frequent as on the beach (0.83 ± 0.31 items) (Table S.2).

Polypropylene was the most common material, accounting for 42.62% of all plastic items, followed by polyethylene (35.95%) and polyethylene terephthalate (14.83%). Lesser quantities of polystyrene and polyacrylamide were also identified (1.79%), while polyvinyl chloride, polyester, nylon,

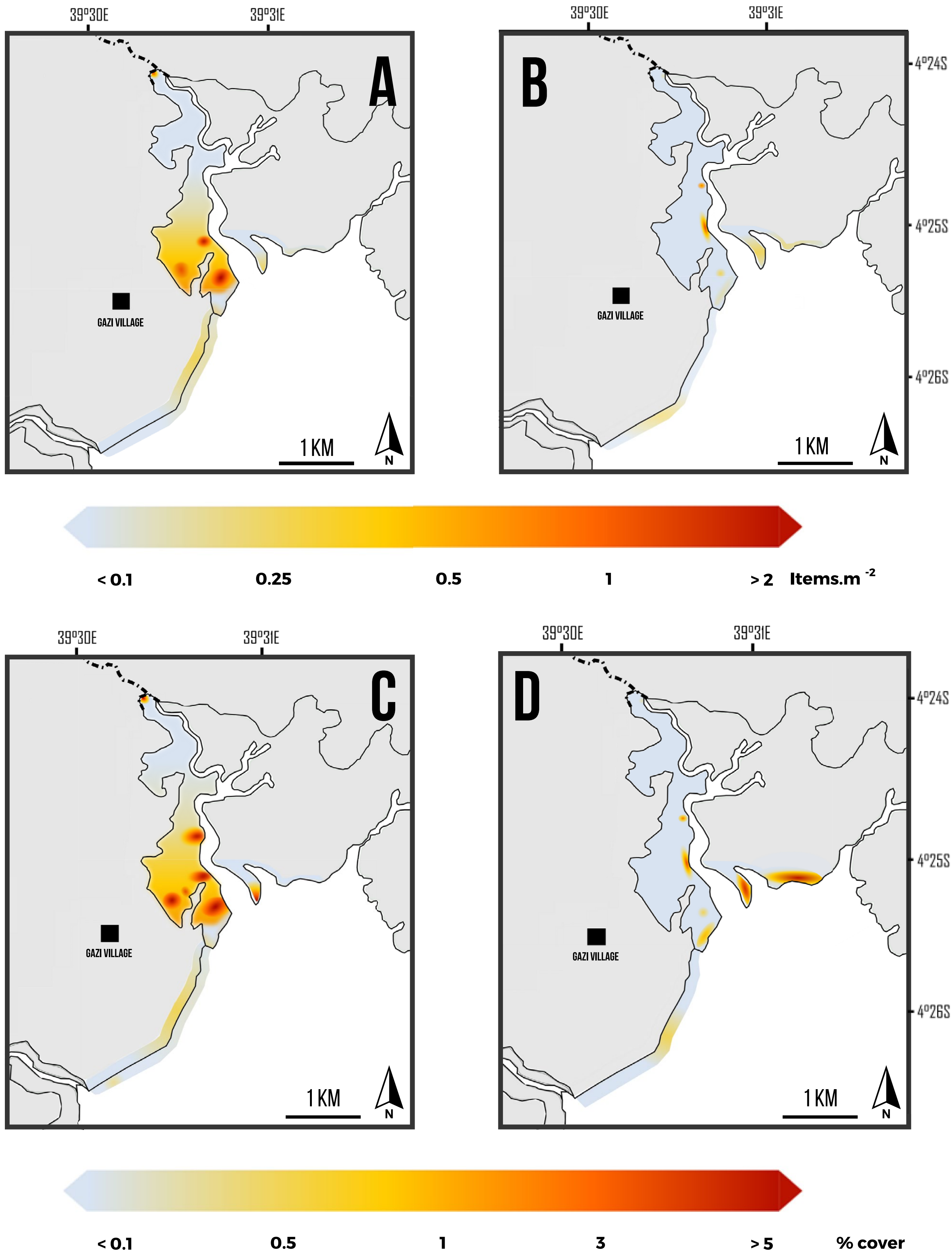


Fig. 3 Representation of plastic abundance and ground cover in Gazi Bay. (**A**) Plastic abundance on the ground (items m^{-2}). (**B**) Plastic abundance in tree roots and canopy (items tree.$^{-1}$). (**C**) Ground plastic cover (%) and (**D**) Plastic cover in trees (%)

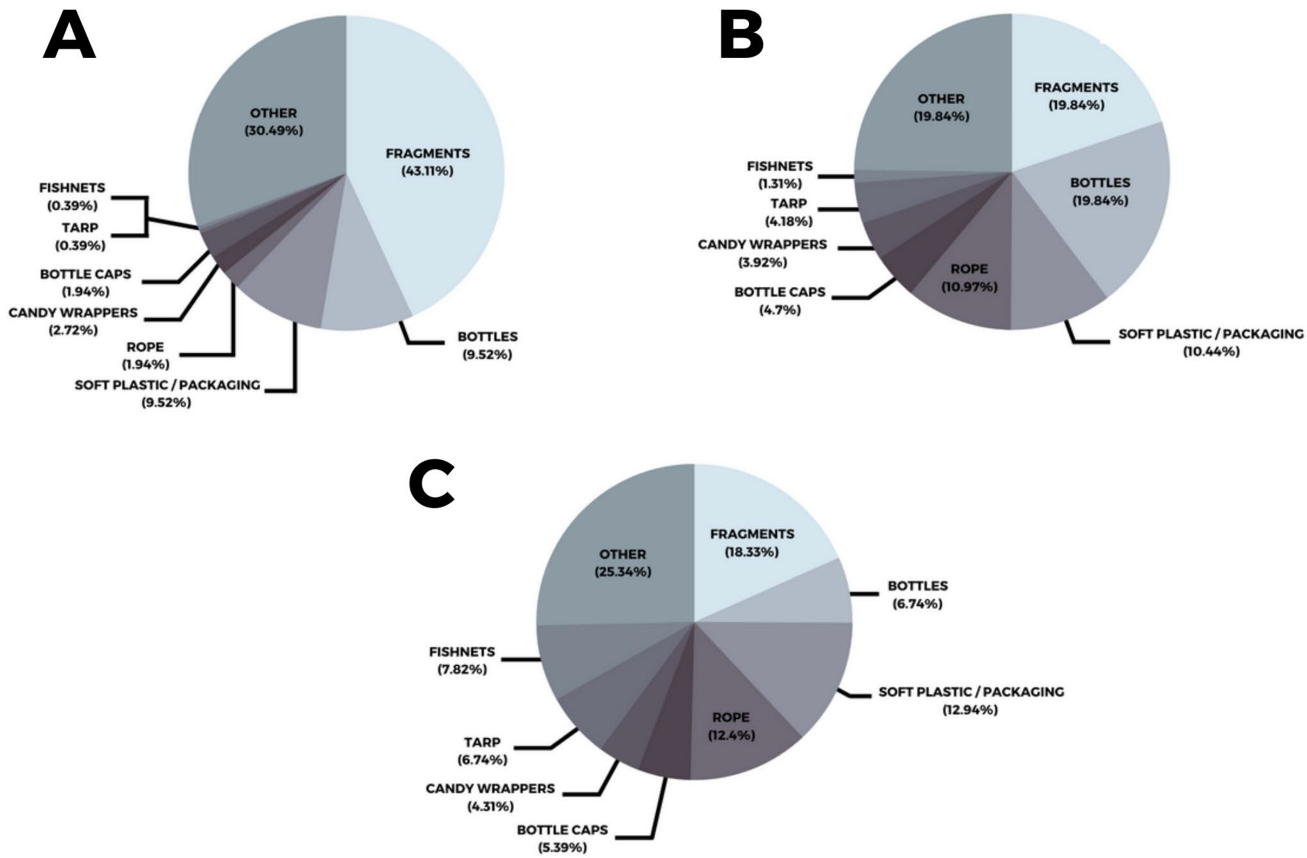


Fig. 4 Total percentage (%) of most common plastic items recovered during completion of the landward (**A**), beach (**B**) and seaward transects (**C**)

ethylene-propylene rubber, polyisoprene, and polybutylene terephthalate were present in concentrations of less than 1%.

Spatial Distribution of Microplastic Pollution

A total of 270 large microplastic items (LMPs, 1–5 mm) were identified across all transects. Out of all 183 sample replicates, only 21 contained LMPs. The landward zone had a detection rate of 9.25% for LMPs, while the seaward zone recorded 3.92%, and the beach zone exhibited the highest contamination rate at 25.93%. No LMPs were detected in the intermediate zone or in the sediment and water of the bay itself.

The Kruskal–Wallis test identified differences among zones ($\chi^2 = 15.574$, df = 3, p = 0.0014, n = 183), with post hoc Dunn tests indicating a higher LMP detection rate on the beach compared to the seaward zone (p = 0.006). Other pairwise comparisons did not show strong differences.

The concentration of LMPs ranged from 0 to 12.39 LMPs per kg of dry sand, with an average of 0.24 ± 0.11 LMPs kg^{-1}. The landward zone had the highest average concentration of LMPs at 1.25 ± 0.66 LMPs kg^{-1} dry sand, which was considerably higher than both the seaward (0.014 ± 0.01 LMPs kg^{-1}) and beach zones (0.13 ± 0.04 LMPs kg^{-1}) (Table 1).

Microplastic Identification and Chemical Characteristics

Among the LMPs identified, the majority were fragments (63.33%), followed by films (19.63%) and fibres (12.96%). Only small quantities of foam fragments (2.22%) and pellets (1.85%) were found. The landward zone exhibited the highest average concentrations of fragments (0.78 ± 0.43 items kg^{-1} dry sand), films (1.56 ± 0.12 items kg^{-1}), and fibres (0.2 ± 0.14 items kg^{-1}). Pellets (0.03 ± 0.02 items kg^{-1} dry sand) were also exclusively found in the landward zone of the mangrove. In contrast, the seaward zone had an average of 0.014 ± 0.06 fragments kg^{-1} dry sand, while the beach zone recorded 0.09 ± 0.03 fragments kg^{-1}. Foam fragments were only detected in the beach transects (0.02 ± 0.01 items kg^{-1} dry sand) (Table S.3).

In terms of plastic type, four main polymers were identified. Polypropylene was the most prevalent, accounting for 64.07% of all plastics found, followed by polyethylene

Table 1 Average microplastic (1–5 mm) concentrations detected and microplastic concentration range in different sampling zones (LMPs.kg^{-1} dry), with given standard error (SE)

Sampling Location	Number of Samples	Mean Concentration (LMPS.kg^{-1} dry)	SE	Concentration Range (LMPS.kg^{-1} dry)
Mangrove Landward Zone	27	1.25	0.66	0–10.35
Mangrove Intermediate Zone	24	0	-	-
Mangrove Seaward/Creekward Zone	51	0.014	0.01	0–0.65
Beach	54	0.13	0.04	0–1.19
Bay (Sediment)	12	0	-	-
Bay (Water)	12	0	-	-

at 32.96%. Minor amounts of polyacrylamide (2.59%) and polyvinyl chloride (0.37%) were also detected.

Social Questionnaire Survey

The age of the interviewees ranged from 15 to 80 years, and the female-to-male ratio was 1:1.2. Education levels varied, with 38.33% of the respondents having a primary level education, 36.67% having obtained a secondary degree, 15% having obtained a college or university degree while the remaining respondents had no formal education. Of the respondents, 22.3% worked as fishermen.

When asked about the plastic items used in daily life, plastic beverage bottles (91.67% of all respondents), buckets (93.33%), toothbrushes (85%) and other sanitary items (71.67% – 76.67%), disposable face masks (73.33%) and plastic household bowls (68.33%) were mostly listed. All fishermen reported using fishing nets, and other items frequently brought on fishing trips included bottles, buckets, fishing lines, gas jerrycans, cool boxes, fish lures, phones, flashlights and plastic sheets for protection against rain.

Fishermen reported losing an average of 14 nets per boat per month, primarily during storms or when nets became entangled in rocks. The majority of the fishermen repaired the nets when damaged. When unrepairable, the nets were burned or discarded in the ocean. Additionally, 55% of respondents admitted to habitually littering plastics, while 20% resorted to burning, and 21.67% disposed of their plastics at nearby dumpsites (Fig. 1.C). Only two respondents (3.33%) ensured that their waste was recycled, either by repurposing items or by sending waste to recycling facilities. Most respondents argued there were no trash cans available and recycling options were non-existent, or the plastic items simply had no use for them anymore.

The majority of respondents (88.33%) noted the lack of recycling options in Gazi village, although 30% made efforts to reuse beverage bottles or deliver them to local businesses. Some respondents viewed burning plastic as a form of recycling. Since the 2017 ban on single-use polyethylene bags, 66.67% of participants reported observing less plastic pollution. Nearly half (46.67%) viewed the ban as a positive change, improving the environment for both people and livestock, while 16.67% perceived the ban negatively, 10% recognised both positive and negative aspects, and the remaining participants had no opinion. Many respondents called for stricter regulations and more public awareness campaigns to address plastic pollution, as other forms of plastic waste still dominated the environment. The newly induced woven polypropylene (PP) bags, which replaced single-use plastic bags, were criticised for being more expensive and less practical.

Interestingly, 66.67% of respondents believed that the government had taken adequate measures to reduce plastic waste in the village, but political leaders were still expected to take more action against environmental pollution. The majority of respondents (60%) felt that the inhabitants of Gazi village were doing enough to reduce plastic pollution, and 61.67% claimed to have personally taken measures to reduce plastic waste. Examples of local initiatives included groups organised to collect plastic, the use of alternative materials, clean-up events on Environmental Day, and even turning plastic collection into a competitive team sport.

Despite the progress, some respondents remained sceptical, arguing that clean-ups were ineffective unless the entire community participated. Nonetheless, 90% of respondents expressed a willingness to reduce their use of plastics, adopt alternatives and engage in more environmental clean-ups and actions against plastic pollution.

Discussion

Environmental Macroplastic Pollution in Gazi Bay

Our findings indicate that the mangrove forest in Gazi Bay shows considerable plastic contamination, with plastics recovered from 87.81% of sampled transects.

The highest overall recorded plastic abundances on the forest floor were on the landward side, reaching 11.12 items m^{-2} (Table S.1). Yet, a significantly higher plastic abundance and cover in the mangrove tree branches and roots were recorded on the seaward transects. This supports the hypothesis that mangroves act as traps for marine debris

(Kesavan et al., 2021; Luo et al., 2021), as ocean-borne plastics are pushed into the forest by tides (Chee et al., 2020). Environmental factors such as seasonality, wind patterns, tidal range, hydrodynamics, and forest structure (*e.g.,* tree density, zonation patterns) tend to influence plastic transport and deposition within mangroves (Ivar do Sul et al., 2014; Luo et al., 2021; Vorsatz et al., 2023). This study was conducted during the dry season, when calmer wind and current patterns, and reduced river discharge may influence plastic distribution differently compared to the wet season. Seasonal variations in tidal action, rainfall, and wind direction could therefore change the contributions of land- versus sea-based plastic sources, as shown by Vorsatz et al. (2023). Additional studies across seasons would be useful to analyse these environmental drivers.

Plastic items associated with fishing, such as ropes and fishnets, were more frequently found in transects near the bay and the mouth of the River Kidogoweni. This pattern is consistent with findings from the Philippines and Hong Kong, where landward sites contained more household waste, while seaward zones had a higher proportion of fishing-related waste (Abreo et al., 2020; Luo et al., 2022; Paler et al., 2022). According to Cappa et al. 2023, denser canopy and root structure of seaward mangroves contribute to the higher plastic entrapment in these areas, and due to the coastal elevation gradient, the water does not reach the canopies of the trees at the landward zone at higher elevation during high tide (Robertson & Alongi, 1992). This explains why plastic cover and abundance on the trees were higher as items are more easily trapped and why less plastic from marine origin was recovered in the landward zone. However, the statistical models did not detect a spatial trend along the river itself. Consequently, our data do not provide strong support for river-based plastic input as a major source within the sampled area. The Kidogoweni River transitions from a freshwater system inland to a tidally influenced creek near the mouth (Bosire et al., 2003) (Fig. 1.C). Since this study was conducted during dry season, the freshwater inflow was possibly reduced, which could have decreased the transport of debris from upstream sources. The accumulation of debris near the river mouth could be explained by hydrodynamic retention, which was already documented by Duarte et al. (2023). In tidal creeks, ebb tides may not have sufficient energy to carry the plastic back out (Ivar do Sul et al., 2014; Duarte et al., 2023), and mangrove roots further decrease water flow and act as a barrier increasing plastic retention (Mazda et al., 2006). Similar patterns of plastic accumulation due to tidal retention have been observed in other estuarine and bay environments (Ivar do Sul et al., 2014: Rahim et al., 2020). These findings strengthen our observations that the debris near the river mouth might be more influenced by local deposit and tidal trapping than by input from the river system. Additional research during the rainy season, and with wider spatial coverage would be helpful in explaining the contribution of riverine plastic transport compared to hydrological retention.

Despite this, the GAM confirmed plastic abundance to be higher in proximity to Gazi village, regardless of the sampling zone, suggesting that a significant portion of this debris is of domestic origin, likely linked to improper waste management. In fact, Phelan et al. (2020) found that mangroves are commonly used as dumping grounds for domestic rubbish. Various studies already demonstrated that mangroves near urbanised areas accumulate more mismanaged land-based domestic and municipal debris, while mangroves further from urban centres tend to trap more marine-originated debris (Riascos et al., 2019; Chee et al., 2020; Luo et al., 2022). This is also consistent with the behaviour reported by local residents, with 55% indicating they habitually discard plastic waste on the ground or dump their waste on dumpsites in proximity to the mangrove forest (21.67%).

The average macroplastic pollution levels in Gazi Bay (0.79 items m^{-2}) were lower than those reported in several heavily urbanised mangrove areas, such as Biscayne Bay, Florida (Paduani et al., 2024), and the Central Region of Ghana (Gonçalves et al., 2025), and multiple Southeast Asian sites (Table 2). In contrast, plastic levels in Gazi Bay were comparable to those found in smaller, rural, or less densely populated coastal areas, such as Tunda Island, Indonesia (Maharani et al., 2018), Pujada Bay, Philippines (Abreo et al., 2020), and the Red Sea, Saudi Arabia (Martin et al., 2019) (Table 2). These comparisons highlight how factors such as proximity to settlements and local activities (*e.g.* fishing) influence plastic accumulation within the mangrove forests. However, none of the reviewed studies incorporated community-level data on waste practices, reinforcing the need for interdisciplinary approaches that combine environmental and social dimensions. Within Africa specifically, the scarcity of published data limits regional comparisons and highlights the need for more region-specific studies.

Environmental Microplastic Pollution in Gazi Bay

Higher concentrations of LMPs were found in transects with elevated levels of macroplastic debris, particularly in areas close to village garbage disposal sites (Fig. 1.C). This suggests that LMPs in Gazi Bay largely originates from the fragmentation of larger plastics in these areas. The degradation of plastics in mangroves is likely facilitated by environmental factors such as high temperatures and UV radiation in tropical climates, and the fluctuations in oxygen levels and salinity in intertidal zones (Weinstein et al., 2016; Deng et al., 2021).

The landward zones of the mangroves and the beach displayed the highest concentrations of LMPs, which is

Table 2 Summary of previous mangrove macroplastic studies

Site/Country	Methodology	Debris Size Threshold	Items m^{-2} (Avg.)	Items m^{-2} (Range)	Authors
São Vicente Estuary, SP, Brazil	10 m^2 quadrats	-	1.33	-	Cordeiro & Costa (2010)
Mutupore Island, Papua New Guinea	1 m× 2 m plots	> 5 mm	21.23	1.2—78.3	Smith (2012)
Lac Bay, Bonaire Island, Caribbean	5 m wide belt transects	> 50 mm	11.76	5.8—23.2	Debrot et al. (2013)
Pantai Indah Kapuk, Jakarta, Indonesia	1 m^2 quadrats	> 2 mm	-	20—533	Hastuti et al. (2014)
Tunda Island, Indonesia	100 m× 1 m transect	-	0.75	-	Maharani et al. (2018)
Red Sea, Saudi Arabia	Belt transects, between 2—8 m wide, and 4—60 m long	> 25 mm	0.66	0.02—3.7	Martin et al. (2019)
Buenaventura, Colombia	Plots (154 m^2)	> 5 mm	9.42	0.22—35.4	Riascos et al. (2019)
Pajuda Bay, Philippines	5 m× 5 m subplots within 50 m× 50 m transects	-	0.62	0.18—62.09	Abreo et al. (2020)
Penang, Malaysia	10 m× 10 m quadrats	> 25 mm	-	2.15—73.1	Chee et al. (2020)
Kendari Bay, Indonesia	5 m× 5 m plots	-	-	159—234	Rahim et al. (2020)
Ambon Island, Indonesia	540 m line transects	> 5 mm	-	10—230	Suyadi & Manullang (2020)
Mumbai, India	20 m× 2 m plots	> 5 cm	8.82	-	Kesavan et al. (2021)
Java, Indonesia	50 cm ×50 cm quadrats	-	27	-	Van Bijsterveldt et al. (2021)
Hong Kong	1 m× 25 m transects	> 5 mm	1.45	-	Luo et al. (2022)
Cebu Island, Philippines	10 m× 10 m plots	> 1 cm	1.29	-	Paler et al. (2022)
Ciénaga de Mallorquín, Colombia	9 m× 9 m plots	-	23.89	1.67—57.11	Velez-Mendoza et al. (2023)
Biscayne Bay, Florida, USA	Transects	> 5 mm	17.1	-	Paduani et al. (2024)
The Central Region of Ghana	50 cm ×50 cm quadrats	-	79	-	Gonçalves et al. (2025)

consistent with other studies that report higher microplastic accumulation in these areas (Zhang et al., 2020). These zones are more exposed to UV radiation due to lower-density foliage (Neukermans et al., 2008) and experience more extreme variations in salinity as they are only inundated by seawater during spring tides (Lugo & Snedaker, 1974; Di Nitto et al., 2014). The interaction of plastics with biota can also result in their fragmentation through chewing, biting, contractions by their digestive tracts, gut associated microbiota and even burrowing behaviour. Mangrove crabs have been identified as key bioengineers, contributing to plastic fragmentation through their foraging and burrowing activities (So et al., 2022). A large abundance of burrowing sesarmid crabs are present on the landward side of the mangroves in Gazi (Dahdouh-Guebas et al., 2005; Andreetta et al. 2014). Consequently, larger plastic items could have been broken down into smaller pieces due to all these disintegrative forces at play.

The presence of LMPs along the beach may also result from both debris fragmentation and ocean transport. Mechanical degradation of plastic by wave action generates microplastics, which are then deposited along the shoreline (Andrady, 2017). The eroded fragments observed suggest oceanic origin for some of the debris. However, no LMPs were observed in the mangrove seawater and sediment in the bay (Table 1), possibly due to limitations in our sampling methods. If smaller size categories had been included, more MPs might have been detected, as some particles under 1 mm were observed in the water samples. Additionally, the sieves used for MP extraction may have retained other materials, including organic-rich matter, which requires more complex techniques to remove (*i.e.* digestion, followed by an extraction protocol). However, these sampling approaches were not feasible due to practical and sampling site limitations, particularly the high risk of external microplastic contamination in the field and field-laboratory. Consequently, without more refined techniques and broader particle size inclusion, the precision of MP concentration estimates is limited.

Plastic Attitude and Practices in Gazi village

Despite Kenya's 2017 ban on single-use plastic (SUP) bags, many respondents still reported the use of these bags, mentioning the higher cost of polypropylene alternatives as a barrier. However, relatively few SUP and PP bags were recovered during field surveys (n = 8), which may indicate reduced usage or improved reuse of plastic bags following the ban. While most respondents perceived a decline in plastic pollution post-ban, waste management remains a major challenge. 55% of villagers admitted to littering, and only 3.33% actively recycling, highlighting gaps in plastic pollution management. However, 90% of the respondents expressed willingness to reduce plastic consumption if better waste management and recycling options were available. This supports previous studies suggesting that behavioural change is strongly influenced by access to resources, alongside personal motivation (Oguge et al., 2021).

Policy Effectiveness and Local Engagement

Government regulations, such as the SUP bag ban, were generally viewed positively by approximately half of the interviewees. However, respondents believe that local-level support for waste management initiatives is still lacking. Key challenges remain bans being implemented without fully considering their impact on local communities. According to the survey, many residents depend on plastic bags in their daily lives, making it difficult to comply with such bans when recycling, waste management and alternatives to plastics are still limited.

The people in Gazi were aware of the plastic pollution issue but were reluctant to follow restrictive policies that do not address their practical needs. While bans can be beneficial, strengthening infrastructure, recycling programs and regulatory enforcement would enhance policy effectiveness, particularly since such measures have not yet been widely implemented across Kenya (Okuku et al., 2011; Oyake-Ombis et al., 2015; Hardesty et al., 2016). To ensure long-term effectiveness, it is important to work directly with communities to develop more targeted solutions at a local level.

Similar to trends in restoration ecology, where social dimensions are increasingly recognised as crucial for successful conservation efforts (Martínez-Espinosa et al., 2020), plastic pollution mitigation should incorporate local perspectives. This could include co-designing policies with local stakeholders to ensure that waste management solutions are not only ecologically sound but also socially and economically feasible. While much research has focused on plastic accumulation, transport and chemical degradation, fewer studies have examined the social factors influencing plastic waste generation and management.

This study highlights that understanding community behaviour, economic constraints and local perceptions is key to developing more effective policies. Future research on plastic pollution should integrate more social studies to ensure that potential future conservation strategies are socially inclusive.

Conclusions

This study provides the first comprehensive assessment of plastic pollution in the mangroves of Gazi Bay, Kenya, integrating both environmental sampling and socio-economic insights. While plastic pollution levels were lower than in some other regions globally, improper waste disposal practices and limited recycling infrastructure contribute significantly to environmental contamination. Domestic waste was identified as the primary land-based plastic source, particularly from Gazi village and the Kidogoweni River. Although the number of plastic bags was relatively low, suggesting the implementation of Kenya's 2017 ban on single-use plastic bags might have a positive impact, overall plastic pollution remains high. This indicates broader improvements in local waste management are still needed.

Public awareness alone is insufficient if policies do not align with community needs and economic realities. Given that 55% of respondents admitted to littering but 90% expressed willingness to reduce plastic use if better options were available, a collaborative approach is needed. Involving stakeholders and local communities in co-developing sustainable waste reduction and recycling programs could improve compliance and long-term effectiveness.

Furthermore, plastic retention in mangroves is influenced by both ecological and socio-economic factors, emphasising the need for interdisciplinary research that combines environmental, chemical and social sciences. Future studies should explore how socio-economic drivers shape plastic pollution trends by including social studies into the research.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-025-01573-6.

Acknowledgements We acknowledge the Erasmus Mundus Joint Master Degree in Tropical Biodiversity and Ecosystems – TROPIMUNDO (European Commission 2019-1451) for financial support. We thank the Ba'alawy family (especially Sauda S. Abdulrahman and Zwena Khalfan) for accommodation and care in Gazi and Emmy Pequeur for her help at the GhEnToxLab Facilities. Finally, we thank Glutton, Prudence, Maximilian, Destiny and Bublé, and the Pelsmaekers and Peeters families for all support, especially Chris Peeters. This research was presented at the Flanders Marine Institute (VLIZ) Marine Science Day in Belgium (1 March 2023) and the Mangrove Macrobenthos and Management (MMM6) Conference in Colombia (24–28 July 2023). I am also honoured to have received the Lorenzo Borella Memorial Award for Best M.Sc. Thesis (July 2023) and sincerely thank everyone involved in presenting me with this award.

Authors Contribution **Elissa P.B. Pelsmaekers:** Conceptualization, Methodology, Formal Analysis, Investigation, Writing-Original Draft, Visualization, Writing – Review & Editing. **Colin R. Janssen:** Conceptualization, Methodology, Resources, Supervision, Writing – Review &

Editing. **Stefano Cannicci:** Conceptualization, Supervision, Writing – Review & Editing. **Cosmas N. Munga:** Conceptualization, Resources, Supervision, Writing – Review & Editing. **Farid Dahdouh-Guebas:** Conceptualization, Methodology, Validation, Supervision, Writing – Review & Editing, Project administration, Funding acquisition.

Funding E.P.B.P., C.N.M. and F.D.G. were funded by the Erasmus Mundus Joint Master Degree in Tropical Biodiversity and Ecosystems – TROPIMUNDO (European Commission 2019–1451). SC also acknowledges funds from the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 – Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of university and Research funded by the European Union – NextGenerationEU. Project code CN_00000033. Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of university and Research, CUP: B83C22002910001 (Spoke 3). Project title "National Biodiversity Future Center – NBFC".

Data Availability The datasets generated and/or analysed during the current study are not yet publicly available as they are being prepared for upload to an online repository. They will be made available following publication. In the meantime, the data can be obtained from the corresponding author upon request.

Declarations

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.

References

Abd Rahim, N. H., Cannicci, S., Ibrahim, Y. S., Not, C., Idris, I., Jani, J. M., Dahdouh-Guebas, F., & Satyanarayana, B. (2023). Commercially important mangrove crabs are more susceptible to microplastic contamination than other brachyuran species. *Science of the Total Environment, 903*, 166271. https://doi.org/10.1016/j.scitotenv.2023.166271

Abreo, N. A. S., Siblos, S. K. V., & Macusi, E. D. (2020). Anthropogenic marine debris (AMD) in mangrove forests of Pujada Bay, Davao Oriental, Philippines. *Journal of Marine and Island Cultures, 9*(1), 25–35. https://doi.org/10.21463/jmic.2020.09.1.03

Andrady, A. L. (2017). The plastic in microplastics: A review. *Marine Pollution Bulletin, 119*(1), 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082

Andreetta, A., Fusi, M., Cameldi, I., Cimò, F., Carnicelli, S., & Cannicci, S. (2014). Mangrove carbon sink. Do burrowing crabs contribute to sediment carbon storage? Evidence from a Kenyan mangrove system. *Journal of Sea Research, 85*, 524–533. https://doi.org/10.1016/j.seares.2013.08.010

Barnes-Mauthe, M., Oleson, K., & Zafindrasilivonona, B. (2013). The total economic value of small-scale fisheries with a characterisation of post-landing trends: An application in Madagascar with global relevance. *Environmental Science, Economics & Fisheries Research, 147*, 175–185. https://doi.org/10.1016/j.fishres.2013.05.011

Bornscheuer, U. T. (2016). Feeding on plastics. *Science, 351*(6278), 1154–1155.

Bosire, J. O., Dahdouh-Guebas, F., Kairo, J. G., & Koedam, N. (2003). Colonization of non-planted mangrove species into restored mangrove stands in Gazi Bay. *Kenya. Aquatic Botany, 76*(4), 267–279. https://doi.org/10.1016/S0304-3770(03)00054-8

Browne, M. A., Chapman, M. G., Thompson, R. C., Amaral Zettler, L. A., Jambeck, J., & Mallos, N. J. (2015). Spatial and temporal patterns of stranded intertidal marine debris: Is there a picture of global change? *Environmental Science & Technology, 49*, 7082–7094. https://doi.org/10.1021/es5060572

Bunting, P., Rosenqvist, A., Lucas, R. M., Rebelo, L., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., & Finlayson, C. M. (2018). The global mangrove watch, a new 2010 global baseline of mangrove extent. *Remote Sensing, 10*(10), 1669. https://doi.org/10.3390/rs10101669

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R. M., Thomas, N., Tadono, T., Worthington, T. A., Spalding, M., Murray, N. J., & Rebelo, L. (2022). Global mangrove extent change 1996-2020: Global Mangrove Watch Version 3.0. *Remote Sensing, 14*(15), 3657. https://doi.org/10.3390/rs14153657

Cannicci, S., Burrows, D. W., Fratini, S., Smith, T. J., III., Offenberg, J., & Dahdouh-Guebas, F. (2008). Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. *Aquatic Botany, 89*(2), 186–200. https://doi.org/10.1016/j.aquabot.2008.01.009

Cappa, P., Walton, M. E., Paler, M. K. O., Taboada, E. B., Hiddink, J. G., & Skov, M. W. (2023). Impact of mangrove forest structure and landscape on microplastics capture. *Marine Pollution Bulletin, 194*, 115434.

Chee, S. Y., Yee, J. C., Carey, D., Yusup, Y., & Gallagher, J. B. (2020). Anthropogenic marine debris accumulation in mangroves on Pengang Island, Malaysia. *Journal of Sustainability Science and Management, 15*(6), 36–60. https://doi.org/10.46754/jssm.2020.08.004

Coppejans, E., & Beeckman, H. (1989). The mangrove vegetation of Gazi Bay (Kenya). *Bulletin De La Societe Royale De Botanique De Belgique, 122*(2), 197–207.

Cordeiro, C. A., & Costa, T. M. (2010). Evaluation of solid residues removed from a mangrove swamp in the São Vicente Estuary, SP. *Brazil. Marine Pollution Bulletin, 60*(10), 1762–1767. https://doi.org/10.1016/j.marpolbul.2010.06.010

Crona, B., & Rönnbäck, P. (2007). Community structure and temporal variability of juvenile fish assemblages in natural and replanted mangroves, Sonneratia alba Sm., of Gazi Bay, Kenya. *Estuarine Coastal and Shelf Science, 74*(1), 44–52. https://doi.org/10.1016/j.ecss.2007.03.023

Dahdouh-Guebas, F., Verneirt, M., Tack, J. F., Van Speybroeck, D., & Koedam, N. (1998). Propagule predators in Kenyan mangroves and their possible effect on regeneration. *Marine and Freshwater Research, 49*(4), 345–350.

Dahdouh-Guebas, F., Jayatissa, L. P., Di Nitto, D., Bosire, J. O., Lo Seen, D. & Koedam, N. (2005). How effective were mangroves as a defence against recent tsunami? *Current Biology 15*(14): 1337–1338.

Dahdouh-Guebas, F., Friess, D. A., Lovelock, C. E., Connolly, R. M., Feller, I. C., Rogers, K., & Cannicci, S. (2022). Cross-cutting research themes for future mangrove forest research. *Nature Plants, 8*, 1131–1135. https://doi.org/10.1038/s41477-022-01245-4

Debrot, A. O., van Rijn, J., Bron, P. S., & de León, R. (2013). A baseline assessment of beach debris and tar contamination in Bonaire. *Southeastern Caribbean. Marine Pollution Bulletin, 71*(1–2), 325–329.

Deng, H., Feng, He, J., Feng, D., Zhao, Y., Sun, W., Yu, H., & Ge, C. (2021). Microplastics pollution in mangrove ecosystems: A critical review of current knowledge and future directions. *Marine Pollution Bulletin, 753*, 142041. https://doi.org/10.1016/j.scitotenv.2020.142041

Di Nitto, D., Neukermans, G., Koedam, N., Defever, H., Pattyn, F., Kairo, J. G., & Dahdouh-Guebas, F. (2014). Mangroves facing climate change: Landward migration potential in response to projected scenarios of sea level rise. *Biogeosciences, 11*, 857–871. https://doi.org/10.5194/bg-11-857-2014

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, S., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience, 4*, 293–297. https://doi.org/10.1038/ngeo1123

Duarte, L. F., Ribeiro, R. B., Val de Nedeiros, T., Scheppis, W. R., & Gimiliani, G. T. (2023). Are mangroves hotspots for marine litter for surrounding beaches? Hydrodynamic modeling and quali-quantative analyses of waste in southeastern Brazil. *Regional Studies in Marine Science, 67*(20), 103177. https://doi.org/10.1016/j.rsma.2023.103177

EPA. (2021). *EPA's microplastic beach protocol*. Environmental Protection Agency.

Friess, D. A., Rogers, K., Lovelock, C., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The state of the world's mangrove forests: Past, present, and future. *Annual Review of Environment and Resources, 44*(1), 1–27. https://doi.org/10.1146/annurev-environ-101718-033302

Friess, D. A., Yando, E., Abuchahla, G., Adams, J. B., Cannicci, S., Canty, S., Cavanaugh, K. C., Connolly, R. M., Cormier, N., Dahdouh-Guebas, F., Diele, K., Feller, I. C., Fratini, S., Jennerjahn, T. C., Lee, S. Y., Ogurcak, D., Ouyang, X., Rogers, K., Rowntree, J. K., … Wee, A. (2020). Mangroves give cause for conservation optimism, for now. *Current Biology, 30*(4), R153–R154.

GESAMP. (2019). *Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean*. United Nations Environment Programme.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7), e1700782.

Gonçalves, G. R. L., Grey, C., Koomson, A., Aggrey-Fynn, J., Nyarko, B. K., & Narayanaswamy, B. E. (2025). Patterns and implications of plastic accumulation in mangrove ecosystems and sandy beaches in Western and Central regions of Ghana, West Africa. *Environmental Science and Pollution Research, 32*, 11996–12012. https://doi.org/10.1007/s11356-025-36359-7

Google Earth Pro 7.3.6.9345. (2022). *Gazi Bay Region, Kenya*. 04°25'S, 039°30'E, Eye alt 8.57km. NOAA, GEBCO, U.S. Navy, SIO, NGA. Retrieved April 14, 2023, from http://www.google.com/earth/index.html

Gorman, D., & Turra, A. (2016). The role of mangrove revegetation as a means of restoring macrofauna communities along degraded coasts. *Science of the Total Environment, 566–567*, 223–229. https://doi.org/10.1016/j.scitotenv.2016.05.089

Griffin, M., & Karasik, R. (2022). *Plastic polution policy country profile: Kenya*. Duke University.

Hardesty, B.D., Schuyler, Q., Lawson, T.J., Opie, K., & Wilcox, C. (2016). *Understanding debris sources and transport from the coastal margin to the ocean*. Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Harris, P. T., Westerveld, L., Nyberg, B., Maes, T., Macmillan-Lawler, M., & Apperlquist, L. R. (2021). Exposure of coastal environments to river sourced plastic pollution. *Science of the Total Environment, 769*, 145222. https://doi.org/10.1016/j.scitotenv.2021.145222

Hastuti, A.R., Yulianda, F., & Wardiatno, Y. (2014). Spatial distribution of marine debris in mangrove ecosystem of Pantai Indah Kapuk, Jakarta. *International Journal of Bonorowo Wetlands, 4*(2). https://doi.org/10.13057/bonorowo/w040203

Ivar do Sul, J. A., Costa, M. F., Silva-Cavalcanti, J. S., & Araújo, M. C. (2014). Plastic debris retention and exportation by a mangrove forest patch. *Marine Pollution Bulletin, 78*, 252–257. https://doi.org/10.1016/j.marpolbul.2013.11.011

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347*, 768–771.

Kershaw, P.J. (Ed.) (2015). *Sources, fate and effects of microplastics in the marine environment: part one of a global assessment.* (GESAMP Report No. 90). Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP).

Kesavan, S., Xavier, K. M., Deshmukhe, G., Jaiswar, A. K., Bhusan, S., & Sukla, S. P. (2021). Anthropogenic pressure on mangrove ecosystems: Quantification and source identification of surficial and trapped debris. *Science of the Total Environment, 794*, 148677. https://doi.org/10.1016/j.scitotenv.2021.148677

Kimani, E. N., Mavuti, K., & Mukiama, T. (2006). The reproductive activity of the pearl oyster *Pinctada imbricata* Röding 1798 (Pteriidae) in Gazi Bay. *Kenya. Tropical Zoology, 19*(2), 159–174.

Law, K. L. (2017). Plastics in the marine environment. *Annual Review of Marine Science, 9*, 205–229.

Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., & Reddy, C. M. (2010). Plastic accumulation in the North Atlantic Subtropical Gyre. *Science, 329*(5996), 1185–1188.

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications, 5*(6). https://doi.org/10.1057/s41599-018-0212-7

Lugo, A. E., & Snedaker, S. C. (1974). The ecology of mangroves. *Annual Review of Ecology and Systematics, 5*, 39–64.

Luo, Y. Y., Not, C., & Cannicci, S. (2021). Mangroves as unique but understudied traps for anthropogenic marine debris: A review of present information and the way forward. *Environmental Pollution, 271*, 116291. https://doi.org/10.1016/j.envpol.2020.116291

Luo, Y. Y., Vorsatz, L. D., Not, C., & Cannicci, S. (2022). Landward zones of mangroves are sinks for both land and water borne anthropogenic debris. *Science of the Total Environment, 818*, 151809. https://doi.org/10.1016/j.scitotenv.2021.151809

Maharani, A., Purba, N. P., & Faizal, I. (2018). Occurrence of beach debris in Tunda Island, Banten Indonesia. *E3S Web of Conferences, 47*, 12. https://doi.org/10.1051/e3sconf/20184704006

Martin, C., Almahasheer, H., & Duarte, C. M. (2019). Mangrove forests as traps for marine litter. *Environmental Pollution, 247*, 499–508. https://doi.org/10.1016/j.envpol.2019.01.067

Martin, C., Baalkhuyur, F., Valluzi, L., Saderne, V., Cusack, M., Almahasheer, H., Krishnakumar, P. K., Rabaoui, L., Qurban, M. A., Arias-Ortiz, A., Masqué, P., & Duarte, C. M. (2020). Exponential increase of plastic burial in mangrove sediments as a major plastic sink. *Science Advances, 6*(44), eaaz5593.

Martínez-Espinosa, C., Wolfs, P., Vande Velde, K., Satyanarayana, B., Dahdouh-Guebas, F., & Huge, J. (2020). Call for a collaborative management at Matang Mangrove Forest Reserve, Malaysia: An assessment from local stakeholders' view point. *Forest Ecology and Management, 458*, 117741. https://doi.org/10.1016/j.foreco.2019.117741

Mazda, Y., Magi, M., Ikeda, Y., Kurokawa, T., & Asano, T. (2006). Wave reduction in a mangrove forest dominated by Sonneratia sp. *Wetlands Ecology and Management, 14*, 365–378.

Mendes, D. S., Beasly, C. R., Silva, D. N. N., & Fernandes, M. E. B. (2023). Microplastic in mangroves: A worldwide review of contamination in biotic and abiotic matrices. *Marine Pollution Bulletin, 195*, 115552. https://doi.org/10.1016/j.marpolbul.2023.115552

Morét-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, G. K., Peacock, E., & Reddy, C. M. (2010). The size, mass, and composition of plastic debris in the western North Atlantic Ocean. *Marine Pollution Bulletin, 60*(10), 1873–1878. https://doi.org/10.1016/j.marpolbul.2010.07.020

Moss, E., Eidson, A., & Jambeck, J. (Eds.). (2017). *Sea of opportunity: supply chain investment opportunities to address marine plastic pollution*. Encourage Capital, on behalf of Vulcan Inc.

Mukherjee, N., Sutherland, W. J., Kan, Md. N., Berger, U., Schmitz, N., Dahdouh-Guebas, F., & Koedam, N. (2014). Using expert

knowledge and modeling to define mangrove composition, functioning, and threats and estimate time frame for recovery. *Ecology and Evolution, 4*(11), 2247–2262.
Ndarathi, J., Munga, C., Hugé, J., & Dahdouh-Guebas, F. (2020). A Socio-ecological system perspective on trade interactions with artisanal fisheries in coastal Kenya. *Journal of Marine Sciences, 19*(2), 29–43.
Neukermans, G., Dahdouh-Guebas, F., Kairo, J. G., & Koedam, N. (2008). Mangrove species and stand mapping in Gazi Bay (Kenya) using Quickbird satellite imagery. *Spatial Science, 52*(1), 75–86.
Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding – a global assessment. *PLoS ONE, 10*, 6. https://doi.org/10.1371/journal.pone.0118571
Ogle, D. H., Doll, J. C., Wheeler, A. P., & Dinno, A. (2023). *FSA: Simple fisheries stock assessment methods* (Version 0.9.4) [R package]. https://cran.r-project.org/package=FSA
Oguge, N., Oremo, F., & Adhiambo, S. (2021). Investigating the knowledge and attitudes towards plastic pollution among the youth in Nairobi Kenya. *Social Sciences, 10*, 408. https://doi.org/10.3390/socsci10110408
Okuku, E. O., Ohowa, B., Mwangi, S. N., Munga, D., Kiteresi, L. I., Wanjeri, V. O., Okumu, S., & Kilonzo, J. (2011). Sewage pollution in the coastal waters of Mombasa city, Kenya: A norm rather than an exception. *International Journal of Environmental Research, 5*(4), 865–874.
Ouyang, X., Duarte, C. M., Cheung, S., Tam, N. F., Cannicci, S., Martin, C., Lo, H. S., & Lee, S. Y. (2022). Fate and Effects of Macro- and Microplastics in Coastal Wetlands. *Environmental Science & Technology, 56*, 2386–2397. https://doi.org/10.1021/acs.est.1c06732
Oyake-Ombis, L., van Vliet, B. J. M., & Mol, A. P. J. (2015). Managing plastic waste in East Africa: Niche innovations in plastic production and solid waste. *Habitat International, 48*, 188–179. https://doi.org/10.1016/j.habitatint.2015.03.019
Paduani, M., Ross, M., & Odom, G. (2024). Mangrove forests of Biscayne Bay, FL, USA may act as sinks for plastic debris. *Wetlands, 44*, 32. https://doi.org/10.1007/s13157-024-01785-9
Paler, M. K., Tabanag, I. D., Siacor, F. D., Geraldino, P. J., Walton, M. E., Dunn, C., Skov, M. W., Hiddink, J. G., & Taboada, E. B. (2022). Elucidating the surface microplastic load, types and distribution in mangrove areas around Cebu Island, Philippines and its policy implications. *Science of the Total Environment, 838*(1), 1560408. https://doi.org/10.1016/j.scitotenv.2022.156408
Paler, M. K. O., Tabañag, I. D. F., Siacor, F. D. C., Geraldino, P. J. L., Walton, M. E. M., Dunn, C., Skov, M. W., Hiddink, J. G., & Taboada, E. B. (2022). Elucidating the surface macroplastic load, types and distribution in mangrove areas around Cebu Island, Philippines and its policy implications. *Science of the Total Environment, 838*, 156408. https://doi.org/10.1016/j.scitotenv.2022.156408
Phelan, A., Ross, H., Setianto, N. A., Fielding, K., & Pradipta, L. (2020). Ocean plastic crisis-Mental models of plastic pollution from remote Indonesian coastal communities. *PLoS ONE, 15*(7), e0236149. https://doi.org/10.1371/journal.pone.0236149
PlasticsEurope. (2023). *Plastics – the fast facts 2022*. PlasticsEurope.
Pranchai, A., Jenke, M., & Berger, U. (2019). Well-intentioned, but poorly implemented: Debris from coastal bamboo fences triggered mangrove decline in Thailand. *Marine Pollution Bulletin, 146*, 900–907. https://doi.org/10.1016/j.marpolbul.2019.07.055
Rahim, S., Widayati, W., Analuddin, K., Saleh, F., Alfirman, A., & Sahar, S. (2020). Spatial distribution of marine debris pollution in mangrove-estuaries ecosystem of Kendari Bay. *IOP Conference Series: Earth and Environmental Science, 412*, 012006. https://doi.org/10.1088/1755-1315/412/1/012006
Riascos, J. M., Valencia, N., Pena, E. J., & Cantera, J. R. (2019). Inhabiting the technosphere: The encroachment of anthropogenic marine litter in neotropical mangrove forests and its use as habitat by macrobenthic biota. *Marine Pollution Bulletin, 142*, 559–568. https://doi.org/10.1016/j.marpolbul.2019.04.010
Ribeiro, F., O'Brien, J. W., Galloway, T., & Thomas, K. V. (2019). Accumulation and fate of nano- and micro-plastics and associated contaminants in organisms. *TrAC Trends in Analytical Chemistry, 111*, 139–147. https://doi.org/10.1016/j.trac.2018.12.010
Richardson, K., Hardesty, B. D., & Wilcox, C. (2019). Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. *Fish and Fisheries, 20*(6), 1218–1231. https://doi.org/10.1111/faf.12407
Robertson, A. I., & Alongi, D. M. (1992). *Tropical mangrove ecosystems*. American Geophysical Union.
Ryan, P. G. (2020). Land or sea? What bottles tell us about the origin of beach litter in Kenya. *Waste Management, 116*, 49–57. https://doi.org/10.1016/j.wasman.2020.07.044
Ryan, P. G., Dilley, B. J., Ronconi, R. A., & Connan, M. (2019). Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships. *Environmental Sciences, 116*(42), 20892–20897. https://doi.org/10.1073/pnas.1909816116
Smith, S. D. A. (2012). Marine debris: A proximate threat to marine sustainability in Bootless Bay, Papua New Guinea. *Marine Pollution Bulletin, 64*, 1880–1883. https://doi.org/10.1016/j.marpolbul.2012.06.013
Smith, S.D.A., & Edgar, R.J. (2014). Documenting the density of subtidal marine debris across multiple marine and coastal habitats. *PloS One, 9*. https://doi.org/10.1371/journal.pone.0094593
So, M. W. K., Vorsatz, L. D., Cannicci, S., & Not, C. (2022). Fate of plastic in the environment: From Macro to nano by macrofauna. *Environmental Pollution, 300*, 118920. https://doi.org/10.1016/j.envpol.2022.118920
So, M. W. K., Vorsatz, L. D., Cannicci, S., & Not, C. (2023). The role of mangrove crabs, the key macrofaunal bioengineers, in microplastic production in tropical coastal forests. *Regional Studies in Marine Science, 63*, 103012. https://doi.org/10.1016/j.rsma.2023.103012
Suyadi, & Manullang, C. Y. (2020). Distribution of plastic debris pollution and its implications on mangrove vegetation. *Marine Pollution Bulletin, 160*, 111642. https://doi.org/10.1016/j.marpolbul.2020.111642
Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., Mcgonigle, D., & Russel, A. E. (2004). Lost at sea: Where is all the plastic? *Science, 304*(5672), 838.
United Nations Environment Programme. (2015). *Global waste management outlook*. https://www.unep.org/resources/report/global-waste-management-outlook
United Nations Environment Programme. (2018a). *Africa waste management outlook*. https://www.unep.org/resources/report/africa-waste-management-outlook
United Nations Environment Programme. (2018b). *Single-use plastics: A roadmap to sustainability*. https://www.unep.org/resources/report/single-use-plastics-roadmap-sustainability
United Nations Environment Programme. (2009). *UNEP guidelines on survey and monitoring of marine litter* (Regional Seas Reports and Studies No. 186; IOC Technical Series No. 83). https://uneplive.unep.org/media/docs/markdown/Litter/UNEP_2009_Marine_Litter_Survey_and_Monitoring.pdf
United Nations Environment Programme. (2023). *Decades of mangrove forest change: What does it mean for nature, people and the climate?* https://www.unep.org/resources/report/decades-mangrove-forest-change
van Bijsterveldt, C. E., 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. *Science of the Total Environment, 756*, 143826. https://doi.org/10.1016/j.scitotenv.2020.143826

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B. D., Van Franeker, J. A., Eriksen, M., Siegel, D. A., Galgani, F., & Law, K. L. (2015). A global inventory of small floating plastic debris. *Environmental Research Letters, 10*(12), 124006.

Van Cauwenberghe, L., Vanreusel, A., Mees, J., & Janssen, C. R. (2013a). Microplastic pollution in deep-sea sediments. *Environmental Pollution, 182*, 495–499. https://doi.org/10.1016/j.envpol.2013.08.013

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M. M., Mees, J., & Janssen, C. R. (2013b). Assessment of marine debris on the Belgian Continental Shelf. *Marine Pollution Bulletin, 73*(1), 161–169. https://doi.org/10.1016/j.marpolbul.2013.05.026

Vélez-Mendoza, A., Villamil, C., Castellanos, K., & Domínguez-Haydar, Y. (2023). Assessment of marine litter in the mangrove forest in the Ciénaga de Mallorquín, Colombian Caribbean region. *Boletín De Ciencias De La Tierra, 53*, 23–37.

Vorsatz, L. D., So, M. W. K., Not, C., & Cannicci, S. (2023). Anthropogenic debris pollution in peri-urban mangroves of South China: Spatial, seasonal and environmental drivers in Hong Kong. *Marine Pollution Bulletin, 195*, 115495. https://doi.org/10.1016/j.marpolbul.2023.115495

Weinstein, J.E., Crocker, B., & Gray, A. (2016). From macroplastic to microplastic: degradation of high density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. *Environmental Toxicology and Chemistry*, *35*(7). https://doi.org/10.1002/etc.3432

Wenneker, B., Oosterbaan, L. & Intersessional Correspondence Group on Marine Litter (ICGML). (2010). *Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area* (Edition 1.0). OSPAR Commision. https://doi.org/10.25607/OBP-968

Willis, K., Denise Hardesty, B., Kriwoken, L., & Wilcox, C. (2017). Differentiating littering, urban runoff and marine transport as sources of marine debris in coastal and estuarine environments. *Scientific Reports, 7*, 44479. https://doi.org/10.1038/srep44479

Zhang, L., Zhang, S., Guo, J., Yu, K., Wang, Y., & Li, R. (2020). Dynamic distribution of microplastics in mangrove sediments in Beibu Gulf, South China: Implications of tidal current velocity and tidal range. *Journal of Hazardous Materials, 399*, 122849. https://doi.org/10.1016/j.jhazmat.2020.122849

Zu Ermgassen, P. S. E., Mukherjee, N., Worthington, T. A., Acosta, A., Rocha Araujo, A. R. D., Beitl, C. M., Castellanos-Galindo, G. A., Cunha-Lignon, M., Dahdouh-Guebas, F., Diele, K., Parrett, C. L., Dwyer, P. G., Gair, J. R., Johnson, A. F., Kuguru, B., Savio Lobo, A., Loneragan, N. R., Longley-Wood, K., Mendonça, J. T., … Spalding, M. (2021). Fishers who rely on mangroves: Modelling and mapping the global intensity of mangrove-associated fisheries. *Estuarine, Coastal and Shelf Science.* https://doi.org/10.1016/j.ecss.2020.107159

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.