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Are tropical estuaries a source of or a sink for marine litter? Evidence from Sabaki Estuary, Kenya

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ABSTRACT

Litter surveys were carried out in August and September 2020 to determine the contribution of Sabaki River and estuary in modifying the quantities of litter entering the oceans. The river discharged 0.035 items $m^{-3}s^{-1}$ translating to an estimated annual litter flux of between 6,622,560 and 614,952,000. The surveys in the estuary revealed that plastics contributed 90.8% of the total litter. Wet and dry zones had mean litter accumulation rates of 2.7 ± 1.1 and 4.4 ± 3.5 items m^{-1} day^{-1} respectively. 69.8% and 77.4% of branded litter were of Kenyan origin and food packaging material respectively. The litter turnover was slightly higher in the dry beach zone compared to the wet zone with a Whitakker Beta diversity of 0.36 and 0.33 respectively. Sabaki estuary acted as a sink for litter during flooding (through burial) and as a source (through exposure of buried litter due to wind and rain action).

1. Introduction

Marine litter pollution is a growing global problem that has recently gained scientific attention due to its detrimental effects at ecological, economic and societal scales (Galloway, 2015; GESAMP, 2015; Newman et al., 2015; La Beur et al., 2019; Núñez et al., 2019). Marine litter is defined as any processed item that is subsequently discarded or abandoned thus ending up in the coastal and marine environments (Buhl-Mortensen and Buhl-Mortensen, 2017). There are three size classes of marine litter: macro-litter (>25 mm), meso-litter (5–25 mm) and micro-litter (<5 mm) (Haseler et al., 2018). Previous studies have found that 40–80% of macro-marine litter is plastic, most of which is associated with food products (Venter et al., 2011; Okuku et al., 2020b).

Globally, Africa and Asia are the largest contributors of marine litter discharge into the ocean (Korshenko et al., 2020), contributing approximately 70% of the global quantities (Lebreton et al., 2017; Kiessling et al., 2019). Land-based sources contribute an estimated 80% of marine litter (Jambeck et al., 2018) which may be transported to the ocean through various pathways such as rivers, estuaries, storm drains, surface run-off and sewage plant effluents (Rech et al., 2014) compared to ocean-based activities such as the fishing & maritime industry and offshore installations.

Rivers act as conduits connecting terrestrial, freshwater, transitional and marine systems thus providing a long-range transport pathway as well as storage opportunities in floodplains or riparian habitats (Horton and Dixon, 2018; Windsor et al., 2019). In marine systems, river floodplains constitute estuarine habitats (such as sandbanks, mudflats, salt marshes and coastal dunes) that offer important ecosystem services, such as fisheries support, carbon sequestration and coastal protection (Núñez et al., 2019). Both rivers and estuaries are reported as major pathways (Núñez et al., 2019) of litter into the oceans but little is known on the exchange between rivers and coastal waters. Estuarine hydrodynamics determined by tides, riverine flow, wind, and the interactions with estuarine bathymetry and morphology, may determine the retention time of litter within the estuary (Browne et al., 2010) thus posing a significant threat to their ecosystem services.

Globally, rivers transport an annual estimate of 2.7 × 10^6 t/y^{-1} of plastics into the ocean (Schmidt et al., 2017.) with high accumulation in areas identified as sinks such as river shores, estuaries and benthic sediments (van Emmerik and Schwarz, 2020), strandlines, in the open

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ocean and seafloor (Browne et al., 2010). Past studies have attributed the abundance and distribution of plastic debris in estuarine habitats to wind, wave-action, and litter density (Browne et al., 2010), timing of floods and seasons (Lebreton et al., 2017; Liro et al., 2020), hydrological processes, riparian vegetation, anthropogenic characteristics of river catchments and channel morphology (Liro et al., 2020; van Emmerik et al., 2020), and tides (van Emmerik and Schwarz, 2020).

Kenya is implementing different initiatives to fight plastic pollution including clean-up activities, outreach programs, revision of policies and laws and enforcement of the ban on single-use plastics. Despite these efforts, no baseline data exists for monitoring the effectiveness of these efforts in the fight against plastic pollution in Kenyan estuaries. Additionally, developing countries are undergoing rapid urbanization estimated at 25% in 2014 (Review, 2016) with the Kenyan population having increased from 38,610,097 in 2009 (KNBS, 2010) to 47,564,296 in 2019 (KNBS, 2019). The majority of this population is concentrated in urban settlements which are characterized by inadequate waste management infrastructure resulting in an increase in plastic leakage into the environment (Deloitte, 2014). The leakage of plastic into the environment is further expected to increase due to the increasing population of the middle class (Deloitte, 2014; Jambeck et al., 2018) and the associated increase in consumption of plastic and waste production (Okuku et al., 2020b).

To address the challenge of marine litter, there has been increased attention towards monitoring of marine litter in Kenya. However, these studies have focused majorly on the peri-urban creeks and other coastal areas (Okuku et al., 2020a, 2020b, 2021). No known study has determined the contribution of Kenyan rivers and estuaries to the quantities of marine litter entering the oceans even though rivers are major pathways that are key in understanding marine litter flow. This study was, therefore, conducted to quantify the contribution of River Sabaki in transporting litter to the ocean and the role of Sabaki estuary in modifying the quantities, composition and distribution of litter delivered in the Indian Ocean. The data generated will be key in calibrating the global models that quantify the contribution of global rivers to marine litter pollution given that past contribution of rivers to marine litter were determined in developed countries but the results cannot be extrapolated on a wider scale due to the dependence of riverine litter fluxes on local watershed characteristics (Jambeck et al., 2015; Schmidt et al., 2017). The study also determined the Clean Coast Index of Sabaki Estuary to enable comparison of the pollution status of Sabaki estuary to other documented studies. Clean Coast Index as proposed by Alkalay et al. (2007) provides a suitable and objective tool to reveal litter densities and hence assess the level of cleanliness of beaches, the success of cleanups and create public awareness. This index categorizes beaches as very clean, clean, moderately clean, dirty and extremely dirty with an index of 0–2, 2–5, 5–10, 10–20 and >20 respectively.

2. Study area and methodology

2.1. Study area

The study was carried out between 31st August and 11th September 2020 in the lower part of the River Sabaki estuary in Kenya (−3.167146, 40.145548) in an area of approximately 204,358 m^2 (Fig. 1). Athi-Galana-Sabaki River is the second-largest drainage basin (~46,600 km^2) in Kenya. The river arises in the Gatamaiyu forest as Athi River and flows across Athi plains, through Athi river town, then takes a northeast direction where it is met by the Nairobi River (Kahara, 2002; Kitheka and Mavuti, 2016) which flows through the Kenyan capital, Nairobi. The headwaters in the vicinity of Nairobi drain agricultural, industrial areas and informal settlements and further flows through livestock and small-scale irrigation areas before discharging into the Indian Ocean (Marwick et al., 2014). Sabaki River estuary is characterized by intertidal mud and sand flats as well as saline water floods, salt marshes, dunes, shrubs, sandbanks, mangroves and seasonal and permanent freshwater pools

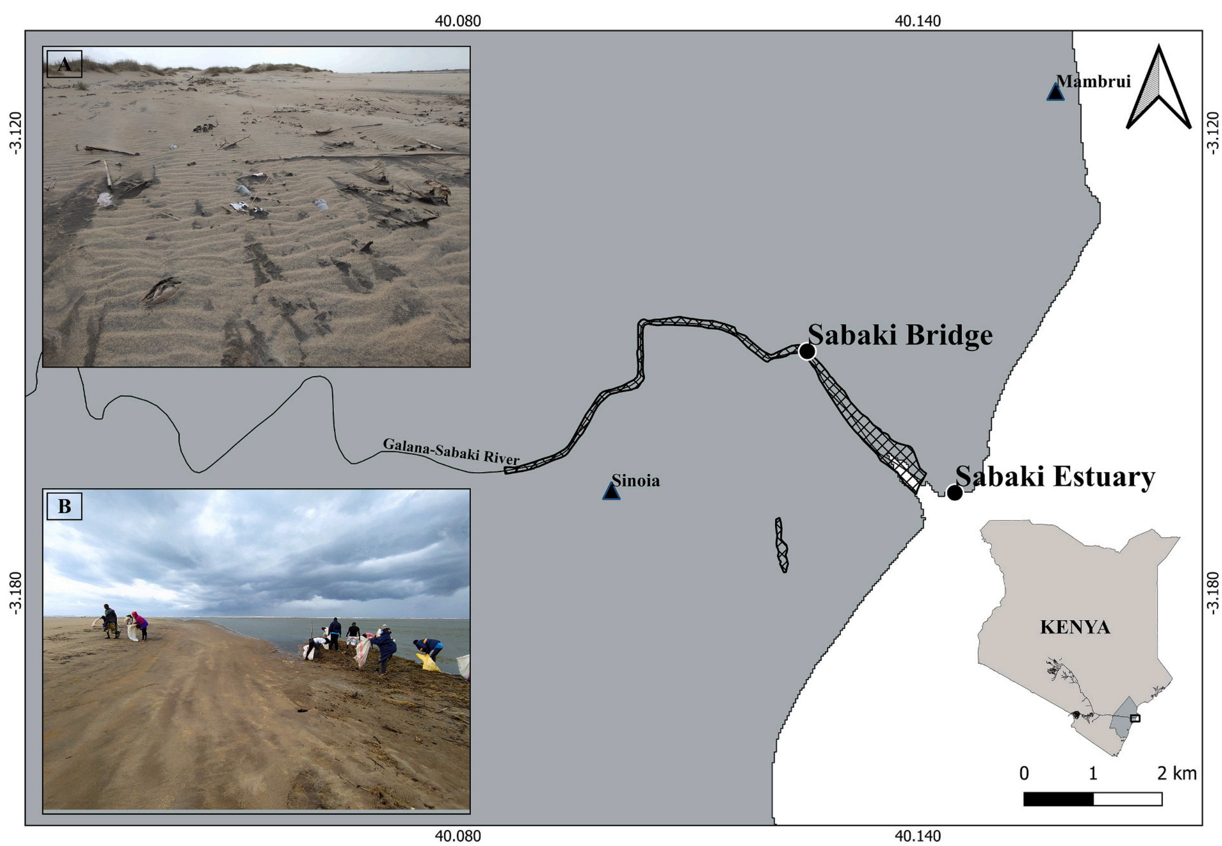

Fig. 1. Map of the study area showing Sabaki estuary sampling site.

(Abuodha, 2003). The tidal range during spring tide is 3.0 m and 1.5 m during neap tide penetrating about 2–3 km into the estuary (Kamau et al., 2015).

River Sabaki experiences semidiurnal tides with south south-east monsoon and northeast monsoon winds prevailing between April and October and November to March respectively. Precipitation range between 800 and 1200 mm yr^{-1} in the central highlands surrounding Nairobi, and between 400 and 800 mm yr^{-1} in the low-lying south-eastern areas of Kenya.

The Sabaki estuary is recognized as an Important Bird Area (IBA) by Bird Life International under the Important Bird Area programme (Valle et al., 2012). The area is an extensive feeding ground for over 180 species of large migratory and wintering shorebirds, terns and gulls (Houte-howes, 2003). Despite the importance of the river, it receives litter, raw sewage, industrial and domestic waste and agricultural fertilizer from its watershed (Kahara, 2002), which compromises the ecological and economic value of the Sabaki estuary.

2.2. Methodology

2.2.1. Riverine survey

The survey was conducted for 10 days in Sabaki River, from Sabaki Bridge since it is close to the outflow to the ocean. Information including weather, water depth, and river velocity of the study site were recorded daily. The river flow rate was determined as described by Ribbink et al. (2019) and Crosti et al. (2018). In brief, a disposable floating object was released a distance away at the center of the river corresponding to the point of net deployment. The object was observed from the bridge vantage point, and time taken to disappear and emerge from view under the bridge was noted. The calculated speed using the noted time and the distance traveled averaged 0.37 ms^{-1}. Thereafter a STOP net was set up by tying four ropes to the top and bottom corners of the net. Weights were attached to the bottom edges of the net to ensure an upright position in the water column. The net was deployed vertically by lowering off the edge of the bridge and firmly securing it by four ropes on the bridge railings. The sampling was carried out for 30 min. The trapped litter in the net were collected, placed in sample bottles and transported to the laboratory for further analysis as recommended by Ribbink et al. (2019).

The litter load by weight and count of the riverine survey was calculated using the formula

$$\text{Litter load}\left(\text{Items or weight m}^{-3}\right) = \frac{\text{Litter collected}\left(\text{number collected per hr}\right)}{\text{Net area}\left(m^2\right) \times \text{Flow rate}\left(ms^{-1} \times 3600\right.}$$

where:

Litter collected = the number or weight of litter items collected per hour of sampling.
Net area = the area of the mouth of the sampling net (m^2).
Flow rate (ms^{-1}) = the rate of flow of water into the net

Riverine litter discharge into the estuary was estimated based on the litter flow rate and river discharge.

$$\text{Litter Discharge}\left(\text{Items}\cdot\text{s}^{-1}\right) = \text{Litter Flow rate}\left(\text{items}/\text{m}^3\right) \times \text{River Discharge}\left(\text{m}^3\ \text{s}^{-1}\right)$$

where River Discharge is estimated at 7 $m^3\ s^{-1}$ and 650 $m^3\ s^{-1}$ (low and high flows respectively) as reported by UNEP/Nairobi Convention Secretariat and WIOMSA (2009).

Survey time diurnal precipitation and wind speed data for the study area was obtained from online logs (https://en.tutiempo.net/climate/08-2020/ws-637990.html) to complement climatic information in the literature.

2.2.2. Standing stock and accumulation surveys

The surveys were carried out following guidelines provided in the African Marine Litter Monitoring Manual (Ribbink et al., 2019). Briefly, onsite characterization of the River Sabaki estuary was carried out to establish the substrate type, weather, slope aspect and back of the beach. A buffer zone of 10 m was designated on one side of the surveyed site and cleaned daily to minimize litter movement from outside into the survey area.

2.2.2.1. Standing stock survey. The standing stock for the surveyed area in the Sabaki River estuary was carried out for the first two days of the survey. All visible macro-litter (>25 mm size) were collected and analyzed as described by Ribbink et al. (2019). Standing stock densities were calculated by category and expressed as counts and weights per square meter using the formula below (Lippiatt et al., 2013).

$$\text{Standing stock densities }(SS) = n/A$$

where

SS = Standing Stock densities.
n = number of items or weight of items in a category
A = area surveyed (m^2).

2.2.2.2. Accumulation survey. Following the standing stock survey, a 10-day accumulation survey was carried out (starting at 7.30 am every day) in both wet and dry beach zones on a stretch of 513 m parallel to the beach equivalent to an area of 204,358 m^2. The wet section was defined as the area from the edge of water up to the recent highest watermark/strandline, whereas the dry section was defined as the area from the recent highest watermark/strand line up to the back of the beach (2 m into back vegetation). Noteworthy, the back of the beach was a floodplain with a background of sand dunes and mangroves.

All macro-litter were collected, separated, cleaned and thereafter sorted based on litter categories (plastic, glass, metal, processed wood, foam, textiles, rubber, construction material and ceramics, fishing-related gears and others). Litter counting and weighing were done per item type (lollipop sticks, diapers, aluminium cans and others). Smaller litter items that could not be weighed by the digital scales were put in separate labeled bags, taken to the laboratory and weighed using an analytical weighing balance.

Daily accumulation rates were calculated for both weights and counts and expressed as the number and weights of items per linear meter per day.

$$Accumulation\ rate = \frac{n/L}{D}$$

where

n = No. of items or weight of items in a category,
L = Length of beach surveyed (m),
D = No. of days surveyed

2.2.3. Waste brand audit

Brand audit was also carried out to determine the polluting brands, type of packaging, manufacturers and countries of origin. Types of products included household products (detergents, cleaning tools etc.), food packaging (food wrappers, beverage bottles etc.), smoking material (cigarette butts, cigarette packets etc.), and personal care products (soap, shampoo packaging, toothpaste etc.). Items were further classified into the type of material such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), single layer (SL) or multi-layer (ML) and other materials (O). Magnifying lenses were used to read labels on the litter and data recorded on datasheets.

2.2.4. Litter indices

Shannon–Wiener diversity index (H′) was used to estimate the estuary litter diversity indices, a non-parametric measure of diversity based on a number of species and their relative frequency and species richness and evenness. The Whittaker Beta diversity was used to display the differences in litter categories (species) between dry and wet zones of the estuary and calculated as described in Battisti et al. (2018).

Litter diversity Index $H' = -\sum fr \times ln(fr)$

where; *fr* is the proportion of total sample represented by litter categories. It is obtained by dividing the number of litter categories by total number of litter items

Evenness index $E = H'/H'max$

where: H′ = litter diversity index, H′ max = ln(S) and S is litter richness (number of categories)

From the standing stock data, a Clean-Coast Index (CCI) was applied to assess the level of cleanliness of Sabaki estuary using the formula described by Vlachogianni et al. (2018).

$CCI = CM \times K$

where:

CM is the density of litter items per square meter given by

$CM = n/(w \times l)$

n is the number of litter items recorded;
w and *l* are the width (m) and length (m) of the sampling unit
K is a constant that equals 20

2.2.5. Burial and exposure rates experiment

The burial/exposure rate experiment was conducted in four randomly placed geo-referenced stations at the dry zone of the river Sabaki estuary. Three pegs were pushed into the ground at each site and the initial ground level on the sticks marked. The ground level was then marked after every 24 h with a different colour at 1000 h EAT, and the difference (in cm) between the markings per day measured using a desk ruler. Burial and exposure rates were calculated by dividing the buried or exposed length in each of the 4 sites by the number of days of the experiment.

3. Results and discussion

3.1. Riverine contribution of marine litter

The mean amount of litter flowing downstream Sabaki estuary based on our estimates is 0.035 items m^{-3} s^{-1}. This translates to an annual estimate of between 6,622,560 and 614,952,000 litter items assuming minimum and maximum annual river discharge of 7 m^3 s^{-1} and 650 m^3 s^{-1} reported by UNEP/Nairobi Convention Secretariat and WIOMSA (2009).

Litter categories encountered were plastics (hard plastics, soft plastics, plastic lines/fibres) foam/styrofoam, rubber, wood and paper. The most abundant were soft plastics with a mean of 0.032 ± 0.005 items m^{-3} accounting for 91% of riverine litter. This could be explained by their: (a) widespread use prior to the Kenyan ban on plastic carrier bags in 2017 which may still be in the river system and are being broken into small fragments and (b) durability and buoyancy (Crosti et al., 2018) that facilitates their transport from upstream to flood plains downstream where they are buried. The finding of Liro et al. (2020) shows that the storage and remobilization cycles of macroplastic debris in fluvial systems may last for decades or centuries even when the input of new plastic debris to the fluvial systems is decreased. This could confirm the presence of soft plastic during the survey after it was banned in Kenya in 2017. Soft plastics registered the highest mean weight (2.34 ± 0.63 g) compared to the other captured litter which is due to their higher abundance (Fig. 2).

3.2. Standing stock survey

General litter density was 0.044 items m^{-2} weighing 0.0007 g m^{-2}. The major proportion of litter found in the study was plastic (0.040 items m^{-2}; weighing 0.0005 g m^{-2}) which contributed 90.8% of the total litter collected. Hygiene and clothing contributed 3.1 and 2.9% respectively (Fig. 3a). Plastic and clothes were also the most abundant by weight (Fig. 3b). The high levels of plastics in the river could be attributed to illegal dumping in the Nairobi River and areas around the Athi River. Illegal dumping along Chilean Rivers has similarly been reported by Rech et al. (2015) to contribute to plastics along the rivers. Similarly, plastics have been reported to be the predominant litter items in rivers (Rech et al., 2014), estuaries (Possatto et al., 2015; Gonçalves et al., 2020) and on coastal beaches (Okuku et al., 2020a, 2020b, 2021). The predominance of plastic litter has been attributed to its widespread use, durability, persistence, buoyancy (Crosti et al., 2018) and remobilization (Kiessling et al., 2019; Liro et al., 2020).

The 3.1% contribution of hygiene items observed in this study could be due to laundry in the river by communities living along the Athi-Sabaki-Galana River leading to the reported litter leakage as witnessed by several soap wrappers encountered. Osadebe et al., 2018 similarly reported the prevalence of laundry activities along the riverbanks of the New Calabar River.

Plastic bottle tops/caps/lid rings contributed 40.1% of total plastics. Soft and hard plastic fragments contributed 18.3 and 10.3% respectively which could be as a result of fragmentation of larger plastics along the river continuum. Plastic debris in river systems are usually subjected to mechanical degradation (through physical contact with other plastics or with objects), thermal and UV degradation/photo-degradation (Andrady, 2015). This degradation process is particularly significant in tropical African countries due to higher rates of rainfall and higher temperatures and UV.

Brands of Kenyan origin constituted 70% of the total branded litter whereas 11% of the litter were of Tanzania origin mostly dominated by Azam energy drinks. Food packaging materials recorded up to 75% of the total litter consisting mainly of big daddy and Daima yoghurt's packaging. Other litter collected including personal care and household products contributing 17 and 7%, respectively. PET contributed the highest percentage (38.2%) of the branded litter while PP, SL, ML and HDPE contributed 17.7, 11.8, 5.7 and 5.7% respectively. Among the branded litter included valon and blue band containers that dated back to 2015 and 1998 respectively (Fig. 4) confirming the possibilities of exposure of previous buried litter during flood events. Most of the litter were typically of small packaging quantities e.g., 15 g, 30 g of colgate toothpaste and 100 g valon. Colgate tabs cut in the middle to allow for

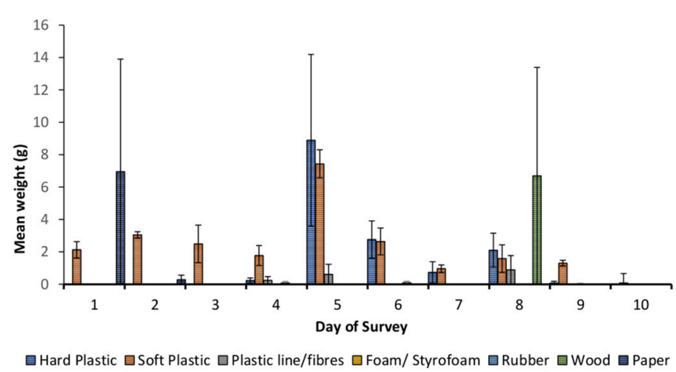

Fig. 2. Riverine litter composition encountered during the survey.

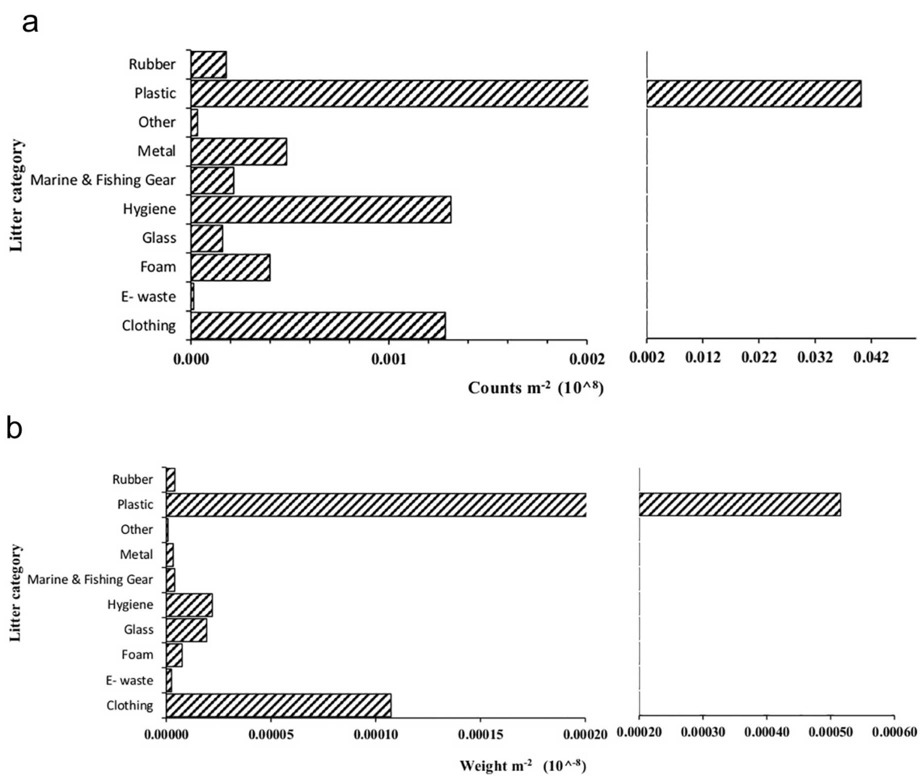

Fig. 3. Litter abundance (by count) and composition during the survey in Sabaki estuary. b: Litter density (by weight) and composition during the survey in Sabaki estuary.

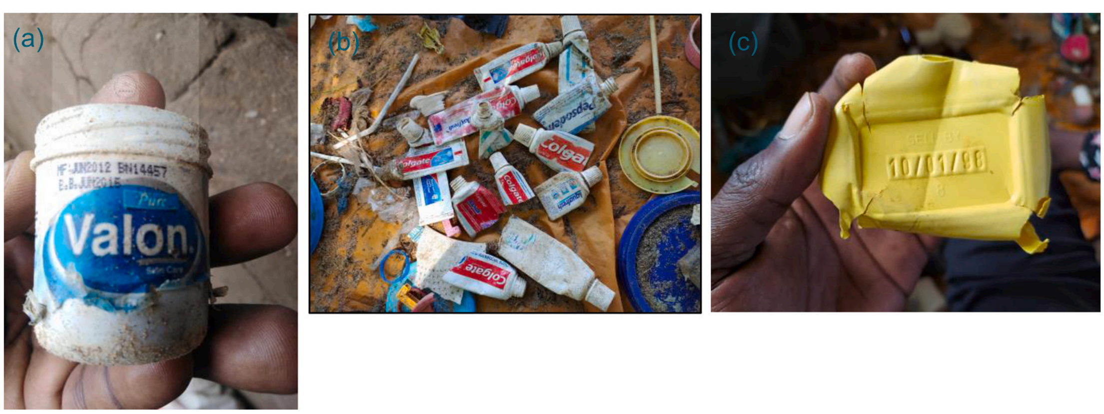

Fig. 4. Pictures of plastics (a) valon container, (b) toothpaste tubes and (c) blue band containers recovered during the survey in Sabaki estuary.

full utilization of the content were also encountered. Such litter are characteristic of litter from low-income settlement particularly Kibera slums in Nairobi thus attesting to the poor waste infrastructure upstream and range transportation of litter by Sabaki River.

3.3. *Marine litter accumulation rates*

The mean accumulation rates in this study was 2.7 ± 1.1 items m^{-1} day^{-1} in the wet zone and 4.4 ± 3.5 items m^{-1} day^{-1} in the dry zone while the accumulation rates by item weight was 0.01 ± 0.005 g m^{-1} day^{-1} in the wet and 0.13 ± 0.011 g m^{-1} day^{-1} dry zones respectively. Okuku et al. (2020b) reported higher mean accumulation rates between 2.69 and 8.93 items m^{-1} day^{-1}; 0.03 to 0.18 g m^{-1} day^{-1} in the wet zone and 1.54 to 11.46 items m^{-1} day^{-1}; 0.007 to 0.090 g m^{-1} day^{-1} in the dry zone in selected beaches in Kenya.

Litter count for the dry zones was higher than the wet zone which could be as a result of exposure of buried litter by wind, tides and slight

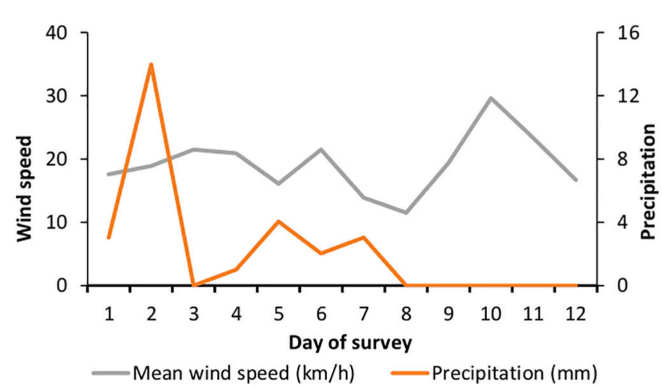

Fig. 5. Wind and precipitation during the survey period for Athi-Galana-Sabaki watershed.
Data (source https://en.tutiempo.net/climate/08-2020/ws-637990.html).

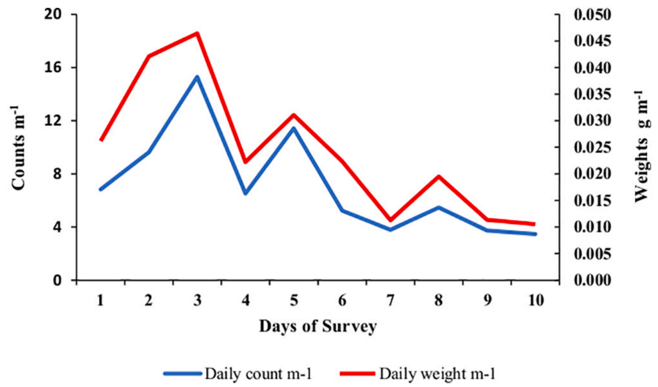

Fig. 6. The general density of litter collected during the survey in Sabaki estuary.

rains experienced in the sampling area during the survey (Fig. 5) this was similarly explained in Saigon river in Vietnam, Seine river in Northern France and Adour river in Southwest France by Emmerik and Schwarz (2020). Liro et al. (2020) further reported that storage–remobilization cycles of macroplastic debris preserved in the fluvial systems may last for decades or centuries thus continuing to provide litter even when the input of new plastic debris to the fluvial systems is decreased. The role of wind in litter exposure was evident in this study that reported an exposure rate of 0.68 cm per day which was a result of the wind speed range of 11.5 and 29.6 km/h experienced during the survey. This suggests Sabaki estuary as both a sink and source of marine litter.

The general density of litter collected during the survey showed a rising trend from day 1 (6.83 items m^{-1}) to day 3 (15.30 items m^{-1}) and could be attributed to the short rainfall and windy conditions experienced during the first two days (Figs. 5 and 6) of the survey which exposed litter that was buried in the sediment on the third day of the survey. Despite a downward trend in the quantity and weight of litter as the accumulation survey progressed, slight increases were recorded on the fifth and eighth days which could be as a result of exposure of buried litter by strong winds experienced on these days (Fig. 5). Only day 6 and 7 had more litter in the wet intertidal zone compared to the dry zone (Fig. 6) and this could be due to change in water tides from spring to neap tide.

The litter in the wet zone was predominantly plastic (94.1%) and hygiene (1.7%) while the dry zone was dominated by plastics (96.2%) and hygiene (0.8%) (Fig. 7a). The dominance of plastic was similarly reported by Mansui et al. (2020) in the Mediterranean basin. The high litter densities (4.58 items m^{-1} weighing 0.017 g m^{-1}) show the important role that Sabaki estuary plays as a conduit of litter to the ocean (Fig. 7a, b). This finding is in agreement with studies done by Ivar do Sul et al. (2014); Corcoran (2015) and Faure et al. (2015) who reported a significant contribution of wind and hydrology on plastic transportation with low-density plastics expected to easily travel far in the river continuum and with a higher tendency to easily beach in estuaries. Vermeiren et al. (2016) and Gray et al. (2018) similarly reported

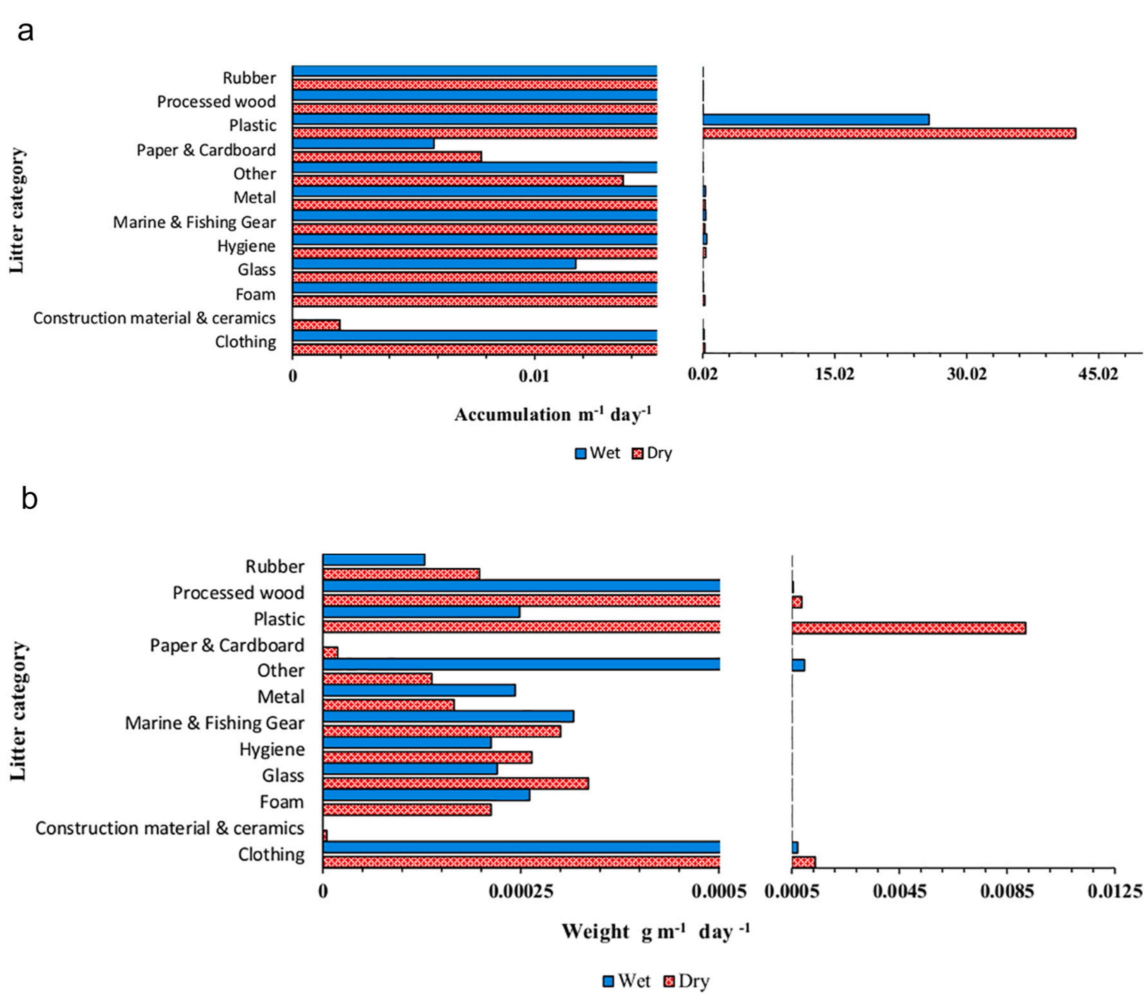

Fig. 7. (a): Litter densities by category in the wet and dry zones collected during the survey in Sabaki estuary. (b): Litter weight by category in the wet and dry zones collected during the survey in Sabaki estuary.

estuarine systems as pollution hotspots that receive litter from fluvial discharge, tidal and coastal currents. Liro et al. (2020) attributed the transport and storage of macroplastic debris in rivers, to plastic's relatively low densities and large surface area, river hydrodynamics (including river flow), morphology and types of aquatic vegetation.

The high number of litter categories (11) were recorded on day 6 while the least number of categories (8) recorded on day 1, 2 and 3. The categories were however more diverse on day 7 with an index of 0.6 and less diverse on days 1, 3, 4 and 8 of the accumulation survey with an index of 0.2. The evenness index (0.1) tending to zero indicates heterogeneity of the litter categories across the ten days of the survey. The litter turnover (Whitakker Beta diversity) was slightly higher in the dry zone 0.364 compared to the wet zone 0.325. Sabaki estuary had a Clean Coast Index (CCI) of 0.923 and could be considered 'very clean'.

In the 10 days of accumulation surveys, plastic fragments recorded the highest accumulations rate (0.13 items m^{-1} day^{-1} weighing 0.0003 g m^{-1} day^{-1}) as compared to the other litter categories which could be due to the breaking down of the large plastics into small fragments due to biodegradation during the burial of the plastic litter.

The accumulation survey revealed that only 3.14% of litter collected were branded with most products (69.84%) being of Kenyan origin. Most of the products collected from the estuary were unique to manufacturers from Nairobi and its environment. This could be explained by the high levels of urbanization in Nairobi with poor waste management infrastructure leading to leakage of litter into Nairobi River which drains into Athi/Sabaki River.

Food packaging material (FP) recorded up to 77.42% of the total litter mostly consisting of yoghurt and small 100 g cooking oil tubs. Other litter products collected included personal care (PC) packaging material (15.48%). ML contributed 21.78% of the branded litter while HDPE, SL, PP, PET (clear or tinted plastic drink bottles) and others accounted for 20.75, 19.59, 18.15, 9.11 and 10.62% respectively.

4. Conclusion

This study aimed at quantifying the contribution of River Sabaki to the influx of marine litter into the ocean and the role of Sabaki estuary in modifying the quantities, composition and distribution of litter delivered into the Indian Ocean. Our findings concluded that River Sabaki discharges litter into the Indian Ocean at the rate of 0.035 items m^{-3} s^{-1} with plastic litter constituting the highest proportion.

The study further reports marine litter pollution in Sabaki River with a standing stock litter density of 0.044 items m^{-2} and an average daily litter accumulation rate of 3.55 litter items per linear meter of the estuary. Litter brand audit during the surveys reports most of the litter to be unique to Nairobi compared to those collected during previous marine litter surveys along the Kenyan Coast indicating the contribution of River Sabaki to marine litter pollution in Sabaki estuary. Sabaki estuary therefore acted as a sink for litter during flooding evidenced from macroplastic litter buried in the fluvial system and as a source of litter due to exposure by wind and rain (exposure rate of 0.68 cm/day) which remobilized buried litter.

Recommendations

1. Additional research is needed to understand the contribution of estuaries to the transport of marine litter.
2. Participating in estuary/river cleanup to remove plastics and prevent them from getting into the ocean.
3. Strengthen monitoring to provide information on trends and status
4. Reduce single-use plastic, use more sustainable alternatives and rethink the way we produce, consume and dispose of plastic.

CRediT authorship contribution statement

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Declaration of competing interest

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

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References

Abuodha, J.O.Z., 2003. Grain size distribution and composition of modern dune and beach sediments, Malindi Bay coast, Kenya. J. African Earth Sci. 36, 41–54. https://doi.org/10.1016/S0899-5362(03)00016-2.
Alkalay, R., Pasternak, G., Zask, A., 2007. Clean-coast index—a new approach for beach cleanliness assessment. Ocean Coast. Manag. 50 (5–6), 352–362.
Andrady, A.L., 2015. Persistence of plastic litter in the oceans. In: Marine Anthropogenic Litter. Springer, Cham, Switzerland, pp. 57–72.
Battisti, C., Malavasi, M., Poeta, G., 2018. Applying diversity metrics to plastic litter 'communities': a first explorative and comparative analysis. Rendiconti Lincei. Scienze Fisiche e Naturali 29 (4), 811–815.
Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44 (9), 3404–3409.
Buhl-Mortensen, L., Buhl-Mortensen, P., 2017. Marine litter in the Nordic seas: distribution composition and abundance. Mar. Pollut. Bull. 125, 260–270.
Corcoran, P.L., 2015. Benthic plastic debris in marine and freshwater environments. Environ. Sci.: Processes Impacts 17 (8), 1363–1369.
Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., González-Fernández, D., 2018. 'Down to the river': amount, composition, and economic sector of litter entering the marine compartment, through the Tiber River in the Western Mediterranean Sea. Rendiconti Lincei. Scienze Fisiche e Naturali 29 (4), 859–866.
Deloitte, 2014. The Deloitte Consumer Review Africa: A 21st-century View. London.
Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7 (1). https://doi.org/10.1002/wat2.1398.
van Emmerik, T., van Klaveren, J., Meijer, L.J.J., Krooshof, J.W., Palmos, D.A.A., Tanchuling, M.A., 2020. Manila River mouths act as temporary sinks for macroplastic pollution. Front. Mar. Sci. 7 (October), 1–8. https://doi.org/10.3389/fmars.2020.545812.
Faure, F., Demars, C., Wieser, O., Kunz, M., De Alencastro, L.F., 2015. Plastic pollution in swiss surface waters: nature and concentrations, interaction with pollutants. Environ. Chem. 12 (5), 582–591.
Galloway, T.S., 2015. Micro- and nano-plastics and human health. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin.
GESAMP, 2015. Sources, Fate and Effects of Microplastics in the Marine Environment: A Global Assessment, Reports and Studies. International Maritime Organization, London. https://doi.org/10.13140/RG.2.1.3803.7925.

Gonçalves, M., Schmid, K., Andrade, M.C., Andrades, R., Pegado, T., Giarrizzo, T., 2020. Are the tidal flooded forests sinks for litter in the amazonian estuary? Mar. Pollut. Bull. 161, 111732.

Gray, A.D., Wertz, H., Leads, R.R., Weinstein, J.E., 2018. Microplastic in two South Carolina estuaries: occurrence, distribution, and composition. Mar. Pollut. Bull. 128, 223–233. https://doi.org/10.1016/j.marpolbul.2018.01.030.

Haseler, M., Schernewski, G., Balciunas, A., Sabaliauskaite, V., 2018. Monitoring methods for large micro-and meso-litter and applications at Baltic beaches. J. Coast. Conserv. 22 (1), 27–50.

Horton, A.A., Dixon, S.J., 2018. Microplastics: an introduction to environmental transport processes. Wiley Interdiscip. Rev. Water 5, e1268. https://doi.org/10.1002/wat2.1268.

Houte-howes, K.S.S.Van, 2003. Macroinvertebrate communities in intertidal mudflats at the Sabaki River Estuary. In: Kenya: An Important Habitat for Resident and Migratory Shore Birds.

Ivar do Sul, J.A., Costa, M.F., Silva-Cavalcanti, J.S., Araújo, M.C.B., 2014. Plastic debris retention and exportation by a mangrove forest patch. Marine Pollution Bulletin 78 (1–2), 252–257.

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 (6223), 768–771.

Jambeck, J., Hardesty, B.D., Brooks, A.L., Friend, T., Teleki, K., Fabres, J., Beaudoin, Y., Bamba, A., Francis, J., Ribbink, A.J., Baleta, T., Bouwman, H., Knox, J., Wilcox, C., 2018. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Mar. Policy 96, 256–263. https://doi.org/10.1016/j.marpol.2017.10.041.

Kahara, S.N., 2002. Characterizing anthropogenic sources management: a proposed case study of pollution for tropical urban river of the Nairobi River Basin. In: Discharged Urban Waters : Resource or Risk? - First World Wide Workshop for Junior Environmental Scientists (21-24 May 2002). Université de Lyon, Vitry sur Seine, pp. 87–99.

Kamau, Joseph Nyingi, Wayaki, Edward, Mathendu, Patric, Ogongo, Benard, Kilonzi, Joseph, 2015. In: Technical Report on the Pollution Status of River Galana/Sabaki/Athi, KMFRI NRM Report Series, Mombasa, p. 15.

Kiessling, T., Knickmeier, K., Kruse, K., Brennecke, D., Nauendorf, A., Thiel, M., 2019. Plastic pirates sample litter at rivers in Germany –Riverside litter and litter sources estimated by schoolchildren. Environ. Pollut. 245, 545–557.

Kitheka, J.U., Mavuti, K.M., 2016. Tana Delta and Sabaki Estuaries of Kenya: freshwater and sediment input, upstream threats and management challenges. In: Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean. Springer, Cham, pp. 89–109.

Kenya National Bureau of Statistics (KNBS), 2010. The 2009 Kenya Population and Housing Census, 1. Kenya National Bureau of Statistics, Nairobi.

KNBS, 2019. Volume 1: Population by County and Sub-County, 2019 Kenya Population and Housing Census. Kenya National Bureau of Statistics, Nairobi.

Korshenko, E., Zhurbas, V., Osadchiev, A., Belyakova, P., 2020. Fate of river-borne floating litter during the flooding event in the northeastern part of the Black Sea in october 2018. Mar. Pollut. Bull. 160, 111678 https://doi.org/10.1016/j.marpolbul.2020.111678.

La Beur, L., Henry, L.A., Kazanidis, G., Hennige, S., McDonald, A., Shaver, M.P., Roberts, J.J.M., 2019. Baseline assessment of marine litter and microplastic ingestion by cold-water coral reef benthos at the east mingulay marine protected area (Sea of the Hebrides, western Scotland). Front. Mar. Sci. 6, 1–13. https://doi.org/10.3389/fmars.2019.00080.

Lebreton, L.C.M., Zwet, J.Van Der, Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 1–10. https://doi.org/10.1038/ncomms15611.

Lippiatt, S., Opfer, S., Arthur, C., 2013. Marine Debris Monitoring and Assessment. Available online at. In: NOAA Technical Memorandum NOS-OR&R-46. U.S. Department of Commerce. https://marinedebris.noaa.gov/protocol-documents/technical-memo-marine-debris-monitoring-and-assessment.

Liro, M., van Emmerik, T., Wyzga, B., Liro, J., Mikuś, P., 2020. Macroplastic storage and remobilization in rivers. Water (Switzerland) 12, 22–29. https://doi.org/10.3390/w12072055.

Mansui, J., et al., 2020. Predicting marine litter accumulation patterns in the Mediterranean basin: spatio-temporal variability and comparison with empirical data. Prog. Oceanogr.

Marwick, T.R., Tamooh, F., Ogwoka, B., Teodoru, C., Borges, A.V., Darchambeau, F., Bouillon, S., 2014. Dynamic seasonal nitrogen cycling in response to anthropogenic N loading in a tropical catchment, Athi–Galana–Sabaki RiverKenya. Biogeosciences 11, 443–460. https://doi.org/10.5194/bg-11-443-2014.

Newman, S., Watkins, E., Farmer, A., Ten Brink, P., Schweitzer, J.P., 2015. The economics of marine litter. In: Marine Anthropogenic Litter. Springer, Cham, pp. 367–394.

Núñez, P., García, A., Mazarrasa, I., Juanes, J.A., Abascal, A.J., Méndez, F., Castanedo, S., Medina, R., 2019. A methodology to assess the probability of marine litter accumulation in estuaries. Mar. Pollut. Bull. 144, 309–324. https://doi.org/10.1016/j.marpolbul.2019.04.077.

Okuku, E.O., Kiteresi, L.I., Owato, G., Mwalugha, C., Omire, J., Otieno, K., Mulupi, L., 2020. Marine macro-litter composition and distribution along the Kenyan coast: the first-ever documented study. Mar. Pollut. Bull. 159, 111497.

Okuku, E.O., Kiteresi, L.I., Owato, G., Mwalugha, C., Omire, J., Mbuche, M., Chepkemboi, P., Ndwiga, J., Nelson, A., Kenneth, O., Lilian, M., Brenda, G., 2020. Baseline meso-litter pollution in selected coastal beaches of Kenya: where do we concentrate our intervention efforts? Mar. Pollut. Bull. 158, 111420 https://doi.org/10.1016/j.marpolbul.2020.111420.

Okuku, E., Kiteresi, L., Owato, G., Otieno, K., Mwalugha, C., Mbuche, M., Gwada, B., Nelson, A., Chepkemboi, P., Achieng, Q., Wanjeri, V., Ndwiga, J., Mulupi, L., Omire, J., 2021. The impacts of COVID-19 pandemic on marine litter pollution along the kenyan coast: a synthesis after 100 days following the first reported case in Kenya. Mar. Pollut. Bull. 162, 111840 https://doi.org/10.1016/j.marpolbul.2020.111840.

Osadebe, A.U., Onyiliogwu, C.A., Suleiman, B.M., Okpokwasili, G.C., 2018. Microbial degradation of anionic surfactants from laundry detergents commonly discharged into a riverine ecosystem. J. Appl. Life Sci. Int. 16 (4), 1–11. https://doi.org/10.9734/JALSI/2018/40131.

Possatto, F.E., Spach, H.L., Cattani, A.P., Lamour, M.R., Santos, L.O., Cordeiro, N.M., Broadhurst, M.K., 2015. Marine debris in a world heritage listed Brazilian estuary. Mar. Pollut. Bull. 91 (2), 548–553.

Rech, S., Macaya-Caquilpán, V., Pantoja, J.F., Rivadeneira, M.M., Jofre Madariaga, D., Thiel, M., 2014. Rivers as a source of marine litter - a study from the SE Pacific. Mar. Pollut. Bull. 82 (1–2), 66–75. https://doi.org/10.1016/j.marpolbul.2014.03.019.

Rech, S., Macaya-Caquilpán, V., Pantoja, J.F., Rivadeneira, M.M., Campodónico, C.K., Thiel, M., 2015. Sampling of riverine litter with citizen scientists — findings and recommendations. Environ. Monit. Assess. 187 https://doi.org/10.1007/s10661-015-4473-y.

Review, U., 2016. Kenya Urbanization Review_WB_2016.

Ribbink, T., Baleta, T., Martin, S., Mbongwa, N., Bray, D., 2019. Guideline to marine litter monitoringWest. Indian Ocean Mar. Sci. Assoc. 1–80.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol. 51 (21), 12246–12253.

UNEP/Nairobi Convention Secretariat and WIOMSA, 2009. An Assessment of Hydrological and Land Use Characteristics Affecting River-coast Interactions in the Western Indian Ocean Region. UNEP, Nairobi Kenya, 109p.

Valle, S., Boitani, L., Maclean, I.M.D., 2012. Seasonal changes in abundances of waterbirds at Sabaki River mouth (Malindi, Kenya), a key stopover site on the west Asian-east African flyway. Ostrich 83, 19–26. https://doi.org/10.2989/00306525.2012.680262.

Venter, K., Van der Merwe, D., De Beer, H., Kempen, E., Bosman, M., 2011. Consumers' perceptions of food packaging: an exploratory investigation in Potchefstroom, South Africa. Int. J. Consum. Stud. 35, 273–281. https://doi.org/10.1111/j.1470-6431.

Vermeiren, P., Muñoz, C.C., Ikejima, K., 2016. Sources and sinks of plastic debris in estuaries: a conceptual model integrating biological, physical and chemical distribution mechanisms. Mar. Pollut. Bull. 113, 7–16. https://doi.org/10.1016/j.marpolbul.2016.10.002.

Vlachogianni, T., Fortibuoni, T., Ronchi, F., Zeri, C., Mazziotti, C., Tutman, P., Varezić, D.B., Palatinus, A., Trdan, Š., Peterlin, M., Mandić, M., Markovic, O., Prvan, M., Kaberi, H., Prevenios, M., Kolitari, J., Kroqi, G., Fusco, M., Kalampokis, E., Scoullos, M., 2018. Marine litter on the beaches of the Adriatic and Ionian seas: an assessment of their abundance, composition and sources. Mar. Pollut. Bull. 131, 745–756. https://doi.org/10.1016/j.marpolbul.2018.05.006.

Windsor, F.M., Durance, I., Horton, A.A., Thompson, R.C., Tyler, C.R., Ormerod, S.J., 2019. A catchment-scale perspective of plastic pollution. Glob. Chang. Biol. 25, 1207–1221. https://doi.org/10.1111/gcb.14572.