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Research Article

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Troubled water: Tracing the plastic tide on Sierra Leone's beaches

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Abstract

This study provides the first investigation into quantities, types, and potential sources of anthropogenic beach litter in Sierra Leone. Beach litter surveys were conducted monthly at four sites over 11 months. A total of 72,901 litter items (1,246 kg dry weight) were categorised. Across all sites, an average of 1,657 items per 100 m (*SD* = 1,639) and 28.32 kg per 100 m (*SD* = 37.48) were recorded. Plastics accounted for 70% of the litter by count and 49% by weight. The three most abundant items by count were plastic bottles (25%), plastic caps and lids (13%), and plastic water sachets (12%). By weight, the three most abundant items were plastic bottles (36%), flip-flops (20%), and shoes (9%). Litter amounts decreased from wet to dry season. We provide the following policy recommendations: improving drinking water access and sanitation, waste management, infrastructure and behaviour change.

Impact statement

This study begins to fill critical plastic pollution data gaps in both Sierra Leone and Africa, offering comprehensive insights into quantities, types, and sources of beach litter. The results highlight a notable prevalence of beverage-related items. As the first beach litter dataset in Sierra Leone, this research is timely, given the evolving global, regional, and national plastic policy landscapes. The findings offer valuable insights for formulating targeted approaches to reduce plastic waste and its environmental impacts. Furthermore, they provide crucial policy recommendations for the effective implementation of strategies in Sierra Leone, supporting progress towards Sustainable Development Goals and the development of a global plastics treaty. Similar strategies could potentially benefit other African countries facing similar infrastructure challenges that are lacking sufficient data on plastic pollution.

Introduction

The pervasive presence of plastic pollution has led to contamination of the planet's ocean and earth cycles, resulting in a wide range of consequences for both human and environmental health (GESAMP, 2021; UNEP, 2021a). This escalating issue is an inevitable outcome of the global consumption rates of plastic materials, coupled with waste management systems that either cannot keep up or do not exist (Wilson and Velis, 2015). Marine plastic pollution predominantly originates from terrestrial sources, but it can also stem from sea-based activities, such as fishing and shipping (GESAMP, 2021; UNEP, 2021a). At a global scale, most plastic waste has been deposited in landfills or the environment (Geyer et al., 2017), with an estimated 12 to 23 million metric tons (Mt) entering aquatic environments every year (Jambeck et al., 2015; Borrelle et al., 2020). Despite a lack of recycling and waste capacity, plastic production is expected to triple by 2050 (Geyer, 2020), particularly in alignment with the growing economies across Africa and Asia (Lebreton and Andrady, 2019). Based on a 'business-as-usual' model, mismanaged plastic waste in Asia will remain significant, while the African continent will become an increasingly problematic region (Nyberg et al., 2023), with waste volumes projected to triple in Sub-Saharan Africa by 2050 and increase tenfold by 2,100 (Hoornweg and Bhada-Tata, 2012; Sila, 2019; UNEP, 2018). Although some countries in Africa and Asia are reported to have some of the largest waste leakages globally (Jambeck et al., 2015; Schmidt et al., 2017), relatively few waste and marine litter studies have been conducted in these regions, particularly considering African countries (Akindele and Alimba, 2021; Alimi et al., 2021). However, despite large data gaps, there is a global consensus that significant knowledge exists for immediate action (Ryan, 2020; Nyberg et al., 2023; UNEP, 2023).

The African continent has a rapidly growing economy, where gross domestic product (GDP) more than tripled between 2016 and 2020 (African Development Bank, 2020). This economic growth, coupled with the highest projected population growth (increasing coastal urbanisation (Barnardo, 2020)), poor waste disposal practices and inadequate waste management will exacerbate marine litter according to models (Abidjan Convention and GRID-Arendal, 2020; Jambeck et al., 2015; Jambeck et al., 2018). The region of West Africa has had the fastest-growing population since the 1950s and is currently home to around 5% of the world's population (Figure 1), which is expected to increase to approximately 10% and exceed 1 billion people by 2059 (United Nations, 2015). Sierra Leone has also had a steadily growing population since the 1960s, reaching an estimated 8.1 million in 2021 (World Bank, 2021), around 37% of which reside in urban areas (EPA-SL,2016). Additionally, Sierra Leone has a densely populated urban centre in the capital city of Freetown (Figure 1), which had an estimated population of 1,055,964 in 2015 (Weekes and Bah, 2017).

Marine litter monitoring has become a powerful tool to improve our understanding of anthropogenic waste volumes (Schulz et al., 2013), distributions (Dixon and Dixon, 1983), sources (Prevenios et al., 2018), impacts (Santos et al., 2005; Costa et al., 2022) and the effectiveness of mitigation measures (Pettipas et al., 2016). Beach litter monitoring is a relatively well-established and cost-effective global indicator for marine pollution (Ryan et al., 2009; GESAMP, 2019; UNEP, 2021b), providing a range of long-term datasets and proposed remediation efforts (Maes et al., 2019). This paper presents the first assessment of marine litter in Sierra Leone, documenting the abundance and distribution across four beach sites during the wet and dry seasons of 2021–2022. The specific objective was to establish a comprehensive baseline dataset, classifying, quantifying, and identifying potential sources of marine litter. This dataset serves as a crucial indicator for pollution, targeted reduction efforts, and supporting recommendations for effective waste management and action plans in Sierra Leone, which are also explored.

Research questions addressed in this paper include:

1) What are the current volumes and compositions of marine litter across Sierra Leone's beaches?
2) Is there a temporal variation of marine litter in Sierra Leone between wet and dry seasons?
3) Are there spatial variations or similarities between marine litter categories across survey sites?
4) What are the main sources and drivers of marine litter in Sierra Leone?
5) How can this monitoring approach be adapted to establish a cost-effective long-term monitoring programme that captures representative data?
6) How can this initial marine litter data set guide and support longer term monitoring and policy decisions?

Methodology

Beach litter monitoring is a cost-effective method that can be supported by trained citizen scientists and provide valuable input towards a range of policy efforts (Addamo et al., 2017; Binetti et al., 2020; Hanke et al., 2019). This monitoring programme approach utilised competent academics and trained citizens as part of a strategy to progress local marine litter specialists. To ensure comparability across sites, all academic and citizen scientists attended two remote training workshops on methodology, followed by a more detailed round-table discussion of the monitoring programme.

The coastal dynamics and ecological profile of Sierra Leone's coastline were important when considering site selection and data analysis (Figure 1). This information is captured in detail in the Supplementary material (SI 1). Identifying beaches near urban and remote areas that could be measured routinely was essential. The number of sites surveyed was based on the oceanography (Figure 1), location of population centres of Sierra Leone and potential leakage (specifically Freetown) (Figure 1), long-term monitoring considerations and funding capacity. Most of the coastline of Sierra Leone is not significantly developed. In contrast, Freetown is significantly developed, around the world's third largest natural harbour (CLISS, 2016). It is believed that marine litter hotspots originate from the unplanned urban and peri-urban areas around Freetown, as well as shipping sources (Environment Protection Agency, 2015). Information regarding the current waste management landscape in Sierra Leone is captured in SI 1.

For this baseline study, four sandy beach sites were chosen to investigate spatial and temporal changes, as well as potential sources and initial recommendations. These sites are beaches located at Bailor, Tintafor, Kent and Chepo (Figure 2). Detailed site descriptions are provided in SI 1. The African Marine Litter Monitoring approach (Barnardo and Ribbink, 2020) is the most relevant beach litter monitoring method for Sierra Leone, allowing for regional (Meakins et al., 2022; Okuku et al., 2020a, 2020b) and global comparison (Wenneker and Oosterbaan, 2010), and therefore utilised in this study. Litter items are categorised based on the African Marine Litter Monitoring Manual (Barnardo and Ribbink, 2020), but adapted to include litter items found locally in the west African region (e.g., water sachets). These categories align with the OSPAR approach (Wenneker and Oosterbaan, 2010), as it allows for the quantification of litter in terms of items and DW 100 m^{-1}. Details regarding the survey approach and data analysis are provided in SI 2. Survey data is also converted to items and DW m^{-2} (SI 3).

Results

Overall litter abundance and composition

Between June 2021 and April 2022, 44 litter surveys were conducted across four sites. There was no evidence of dumping during the surveys. A total of 72,904 items (1,246.06 kg total DW) divided into 11 material categories were recorded. A mean of 1,656.84 items 100 m^{-1} (*SD* = 1,639.02) by count and 28.32 kg 100 m^{-1}(*SD* = 37.48) by DW were documented in the four selected sites for the study period. Linear regression reported a significant relationship between litter count and DW ($F(1,42) = 293.32$, $r^2 = 0.87$, $p = <.001$). Material composition (%) of litter is presented in Table 1. Plastic was the most dominant material by count, with a mean of 1,190.84 items 100 m^{-1} (*SD* = 1,176.12). Plastic was also the most prevalent material by DW, with a mean of 14.97 kg 100 m^{-1} (*SD* = 22.06), contributing an estimated 70% of total litter by count and 49% by weight. Across all survey sites, plastic contributed 42–93% of litter composition by count and 15–90% by DW. Other abundant materials included foam, clothing, rubber and sanitary-related items (Table 1).

A total of 124 different categories of litter were found. Overall, the most abundant items by count and weight were plastic bottles, with a mean of 405 items 100 m^{-1} (*SD* = 632.76)

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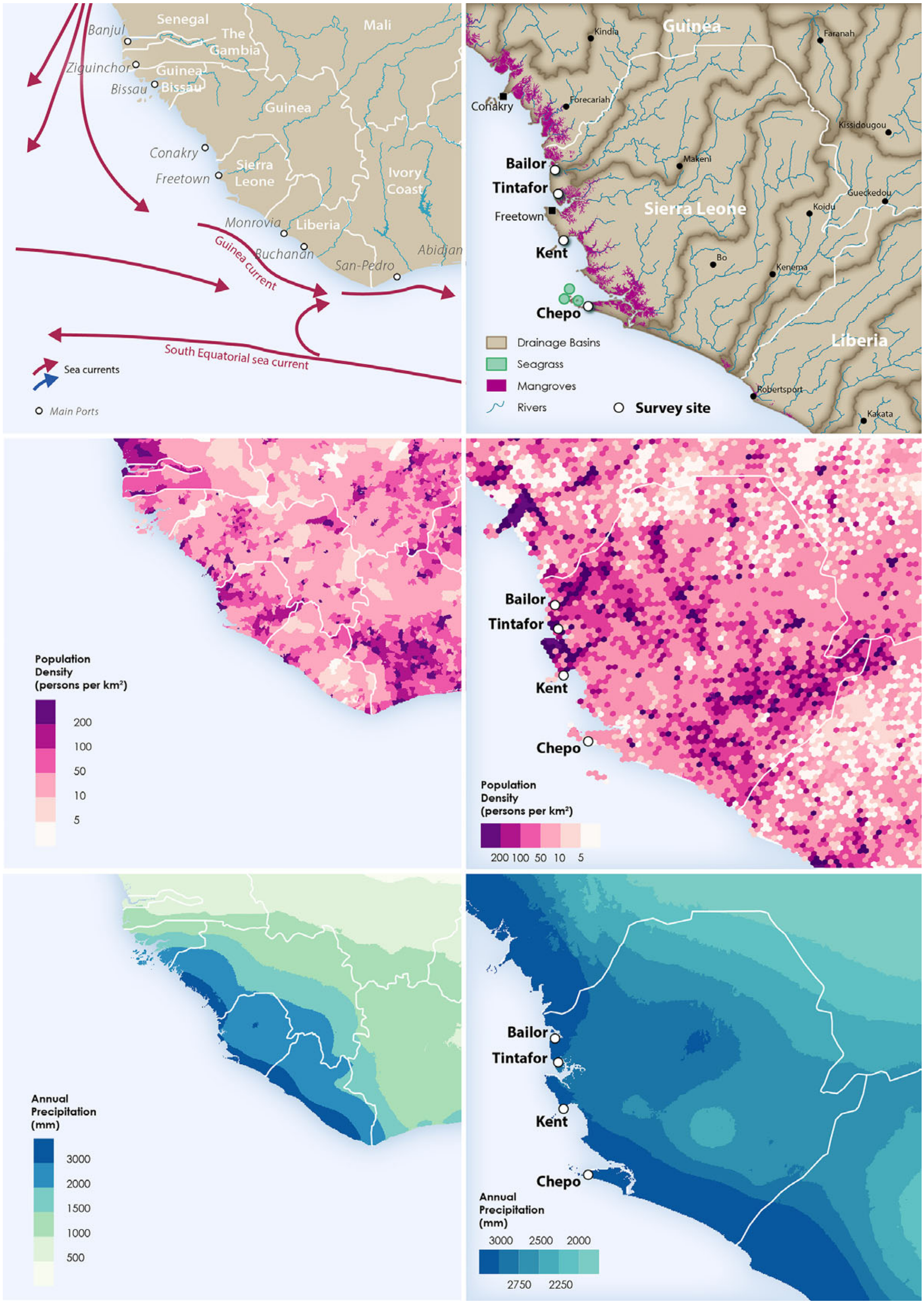

Figure 1. Maps showing coastal ecology and major current systems, population density, and annual precipitation of a) West Africa and b) Sierra Leone (with beach survey sites) (CIESIN, 2009; Dada et al., 2021; Fick and Hijmans, 2017; “Kontur Population,” n.d.; Lehner and Grill, 2013; Spalding et al., 2010; UNEP-WCMC and Short, 2005) Image credit: Georgios Fylakis.

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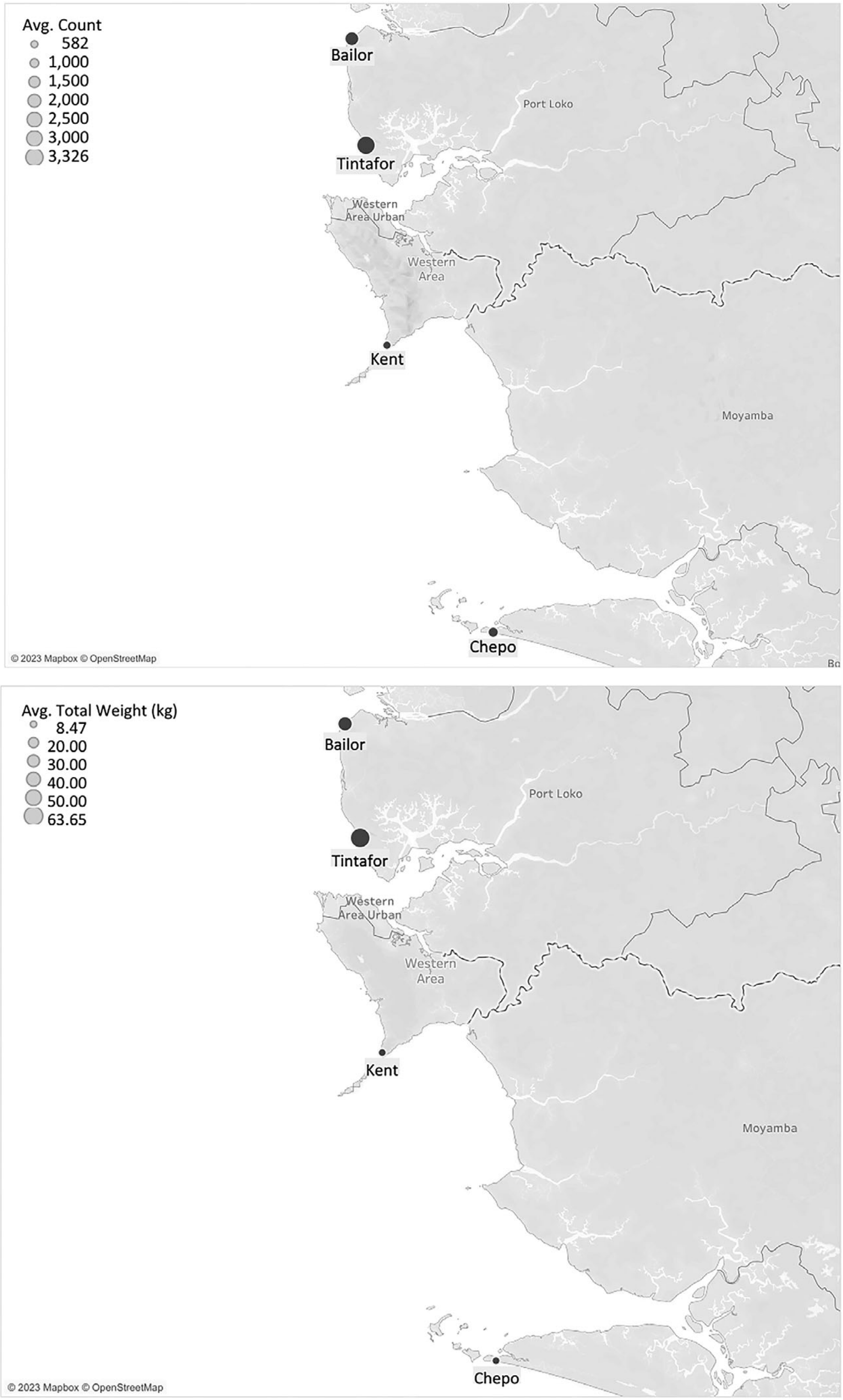

Figure 2. Maps of a) total count of litter (items 100 m^{-1}) and b) total weight of litter (kg 100 m^{-1}) recorded across all sites throughout the duration of the survey.

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Table 1. Counts and weights (kg) of litter material categories reported across all survey sites for the duration of the survey

	Counts				Weights			
Composition (%)	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
Plastic	41.9	92.8	70.1	14.4	14.6	89.6	49.4	20.3
Foam	0	36.9	8.7	9.7	0	9.6	2.2	2.3
Clothing related	0.4	19.7	5.6	3.9	0.5	58.8	26.7	13.6
Rubber	0	38.9	5.6	8.4	0	47.3	4.2	9.1
Sanitary related	0.8	10.2	3.9	2.3	0.3	22.4	5.3	4.4
Fishing related	0	12.1	2.5	2.4	0	16.3	3.5	4.2
Wood	0	16.3	1.9	3	0	34.1	5.4	8.5
Metal	0	6.3	0.9	1.2	0	14.5	1.7	2.5
Paper	0	3	0.4	0.7	0	2.9	0.3	0.7
Glass	0	1.6	0.3	0.4	0	7.9	1.3	2
Ceramic	0	0.2	0	0	0	0.3	0	0

Table 2. Twenty most abundant litter items by count and weight (kg) across all beach survey sites for the duration of the survey

Rank	Item	Avg. items per 100 m	SD	Rank	Item	Avg. weight (kg) per 100 m	SD
1	Bottles – beverage	405.16	632.76	1	Bottles – beverage	10.19	18.2
2	Plastic water sachets	210.16	332.12	2	Shoes – flip flops	5.53	9.43
3	Caps/lids/lid rings	208.25	196.67	3	Shoes – other	2.4	4.14
4	Shoes – flip flops	90.23	175.08	4	Plastic water sachets	1.08	2.75
5	Lollipop sticks	81.41	108.86	5	Bottles – cosmetics/personal care	0.82	0.92
6	Hard foam fragments (e.g., polystyrene): (2.5–5 cm)	62.14	161.2	6	Medical containers/tubes	0.76	1.35
7	Rubber fragments (2.5–5 cm)	54.91	123.72	7	Caps/lids/lid rings	0.68	0.72
8	Plastic fragments (2.5–5 cm) –film	45.11	59.71	8	Bottles – glass	0.43	1.1
9	Wrappers/packaging – food/drink	44.89	51.28	9	Diapers	0.42	0.78
10	Bottles – cosmetics/personal care	40.36	52.12	10	Plastic fragments (5–10 cm) –film	0.41	0.97
11	Medical containers/tubes	36.34	55.98	11	Bags– woven (polypropylene)	0.35	1.13
12	Plastic fragments (5–10 cm) –film	27.68	50.4	12	Rubber fragments (25–50 cm)	0.3	1.3
13	Soft foam fragments (e.g., sponge): (2.5–5 cm)	25.27	48.61	13	Hard foam fragments (e.g., 2.5–5 cm)	0.25	0.64
14	Cushioning/ packaging foam	22.48	60.2	14	Medical glass bottle	0.25	0.71
15	Rubber fragments (5–10 cm)	22.07	57.18	15	Rubber fragments (5–10 cm)	0.25	0.47
16	Cigarette lighters	20.82	30.63	16	Hard foam fragments (5–10 cm)	0.25	0.72
17	Plastic fragments (2.5–5 cm) –hard	15.39	34.68	17	Aerosol/spray cans	0.23	0.56
18	Shoes – other	13.36	22.71	18	Clothing	0.22	0.84
19	Syringes/needles	12.43	13.42	19	Rubber fragments (2.5–5 cm)	0.21	0.35
20	Ice cream cups	11.5	17.01	20	Wrappers/packaging – food/drink	0.21	0.49

(a total of 17,827 items recorded) and 10 kg 100 m^{-1} DW (SD = 18.20) (a total of 448.55 kg recorded) (Table 2). Other abundant items included plastic water sachets, caps/lids/lid rings, flip flops, shoes, lollipop sticks and plastic cosmetics/personal care bottles (Table 2).

The three most abundant litter items by count constitute 50% of all litter recorded (plastic bottles [25%], plastic water sachets [13%] and caps/lids/rings [12%]). The three most abundant litter items categorised by DW constitute 64% of all litter recorded (plastic bottles [36%], flip-flops [20%] and other shoes [9%]).

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Spatiotemporal trends

Litter abundance varied between each site throughout the survey. Tintafor reported the highest abundance overall, with a mean count of 3,326.64 items (*SD* = 1,843.57) and mean DW of 63.65 kg (*SD* = 40.64) (Figure 2, Table 3). Kent reported the lowest abundance of litter items, with a mean count of 581.73 items (*SD* = 506.46) and mean DW of 8.47 kg (*SD* = 6.77) (Figure 2, Table 3). The Levene statistic for homogeneity of variance is significant for litter counts ($F(3,40) = 3.6$, $p = .022$) and weights ($F(3,40) = 6.07$, $p = .002$) between sites. Assuming the distribution of sample means is normal, a Welch test reports a significant difference between sites for counts ($F(3,40) = 8.43$, $p = <.001$) and weights ($F(3,40) = 7.14$, $p = .002$). A post-hoc Games-Howell multiple comparisons test reports a significant difference in litter count and DW between Tintafor and all other sites, except Bailor (Tables in SI 4).

Considering the most abundant items, 93% of plastic bottles and 98% of plastic water sachets were recorded at Tintafor and Bailor by count. Most plastic bottles (58%) were recorded at Tintafor and most plastic water sachets (63%) were recorded at Bailor. Caps/lids/lid rings were the third most abundant item by count, with an average estimate of 208 items 100 m^{-1} across all sites. Most caps/lids/lid rings (67%) were recorded at Tintafor, while 20% were recorded at Chepo and 13% across Bailor and Kent. In terms of litter by DW, over half (55%) of plastic bottles were recorded at Tintafor, which reported an average of 247.54 kg 100 m^{-1}, followed by Bailor with 39% of all bottles recorded and an average of 176.632 kg 100 m^{-1}. Only 5% of all bottles documented by DW were recorded at Kent and <1% at Chepo. Following plastic bottles, flip flops and other shoes were ranked as the second and third most abundant items by DW, 73% and 72% of which were recorded at Tintafor.

Temporal trends of litter counts are apparent throughout the year (Figure 3), with linear regression reporting a significant decrease in litter count ($F(1,42) = 4.89$, $r^2 = 0.1$, $p = .033$) and DW ($F(1,42) = 8.09$, $r^2 = 0.16$, $p = .007$) across all sites from wet to dry season. The mean litter abundance across all sites during the wet season was 2,152.7 items 100 m^{-1} (*SD* = 1,640.83) and 1,243.63 items 100 m^{-1} (*SD* = 1,551.22) during the dry season. The mean litter DW across all sites during the wet season was 42.78 kg (*SD* = 44.12) and 16.27 kg (*SD* = 26.18) during the dry season.

June demonstrates the highest mean litter abundance across all sites (2,841 items 100 m^{-1} [*SD* = 1994.66]), followed by December, which reports a mean count of 2,727 items 100 m^{-1} (*SD* = 3,129.83) across all sites. December also reports the highest individual survey count of 7,421 items 100 m^{-1} at Tintafor (Figure 3), where plastic bottles (2,108), hard foam fragments (e.g., polystyrene) 2.5–5 cm (981), and flip flops (658) were the most prevalent items. The survey at Bailor in June reported the highest abundance by dry weight (157.13 kg 100 m^{-1}), where plastic bottles (96.66 kg), plastic water sachets (17.48 kg) and flip flops (9.71 kg) were most prevalent.

April reports the lowest mean count of litter items across all survey sites (812 items 100 m^{-1} [*SD* = 897.01]). The survey that reported the lowest abundance of litter by count was conducted in April at Kent, with 100 litter items 100 m^{-1} (Figure 3). Temporal analysis of DWs also reports the highest mean across all sites in June (68.67 kg 100 m^{-1} [*SD* = 65.99]), followed by August (51.3 kg 100 m^{-1} [*SD* = 50.87]), then December (40.78 kg 100 m^{-1} [*SD* = 54.55]). Bailor reports the highest DW for one survey in June (157.13 kg 100 m^{-1}) and November reports the lowest mean DW across all sites (6.62 kg 100 m^{-1} [*SD* = 4.48]), with Chepo reporting the lowest weight across all surveys in February (0.8 kg 100 m^{-1}).

The three most abundant litter items by count and DW are the same for each season, although their relative abundance decreases in the dry season (SI 5). Some differences in other prevalent items are observed between seasons, for example, diapers, plastic film fragments (5–10 cm) and plastic bags are identified as some of the most prevalent litter items by weight during wet season, but not dry season (SI 5).

Meteorological data for Sierra Leone is limited, however, survey metadata recorded heavy rain at Tintafor during the surveys conducted in June, July and September (SI 6), which demonstrate some of the lowest observed litter abundances during the wet season at this site (Figure 3). Heavy rain is recorded at Bailor in February, indicating this site's lowest litter abundance across the survey duration. Drizzle was also recorded during the Chepo survey in July, with all other surveys reported as clear days.

Cluster analysis

Figure 4 presents dendrograms to illustrate agglomerative hierarchical clustering (AHC) based on the mean litter counts (items 100 m^{-1}) and weights (kg 100 m^{-1}) recorded for each survey. This analysis of litter categories separates Tintafor when considering both weights and counts, while analysis of the counts of litter categories identifies Bailor and Kent as similar, and analysis of the weights of litter categories identifies Bailor and Chepo as similar.

Principal component analysis (PCA) vector plots (Figure 5) illustrate how two components, PC1 and PC2, account for 64% of the total variance for both count and weight analyses of material categories. Trends are clear between PC1 and Tintafor, as well as PC2 and Chepo. Considering the count analysis; sanitary-related items, plastics, clothing-related, glass, foam and metal are strongly related to PC1, while rubber, paper and wood are strongly correlated with PC2. For weight analysis, a similar trend is observed where clothing-related, sanitary-related, glass, foam, plastic and

Table 3. Litter count and weight (kg) from each survey site for the duration of the survey

	Litter count (items 100 m^{-1})				Litter weight (kg 100 m^{-1})			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Tintafor	989	7,421	3,325.64	1843.57	11	122	63.65	40.64
Bailor	472	5,614	1797.55	1,577.89	3	157	32.48	44.74
Chepo	325	2,610	922.45	675.69	1	27	8.67	9.56
Kent	100	1,505	581.73	506.46	1	22	8.47	6.77

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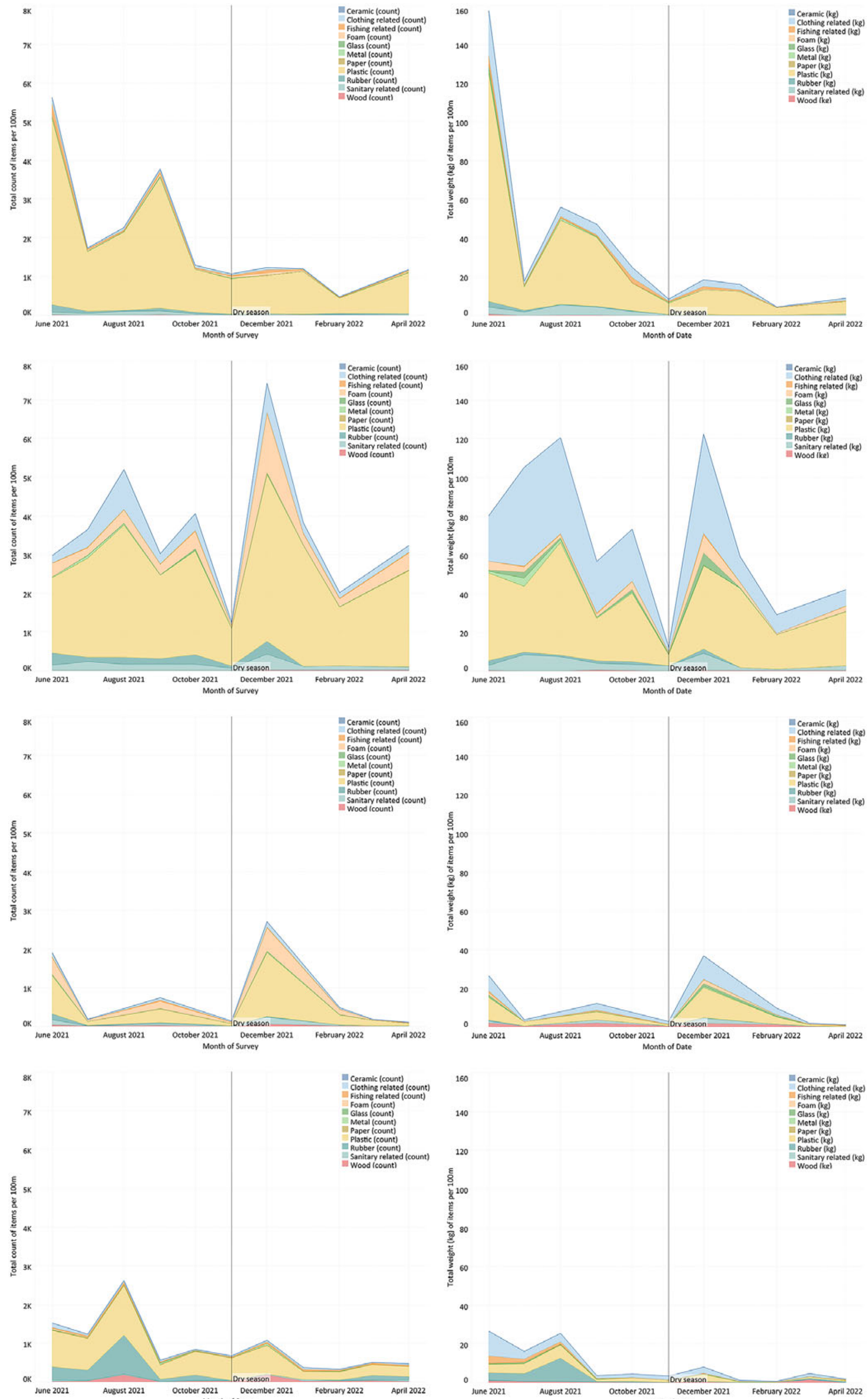

Figure 3. Litter counts and weights throughout the duration of the survey for a) Bailor, b) Tintafor c) Kent and d) Chepo with reference line in bold to indicate the start of dry season in November.

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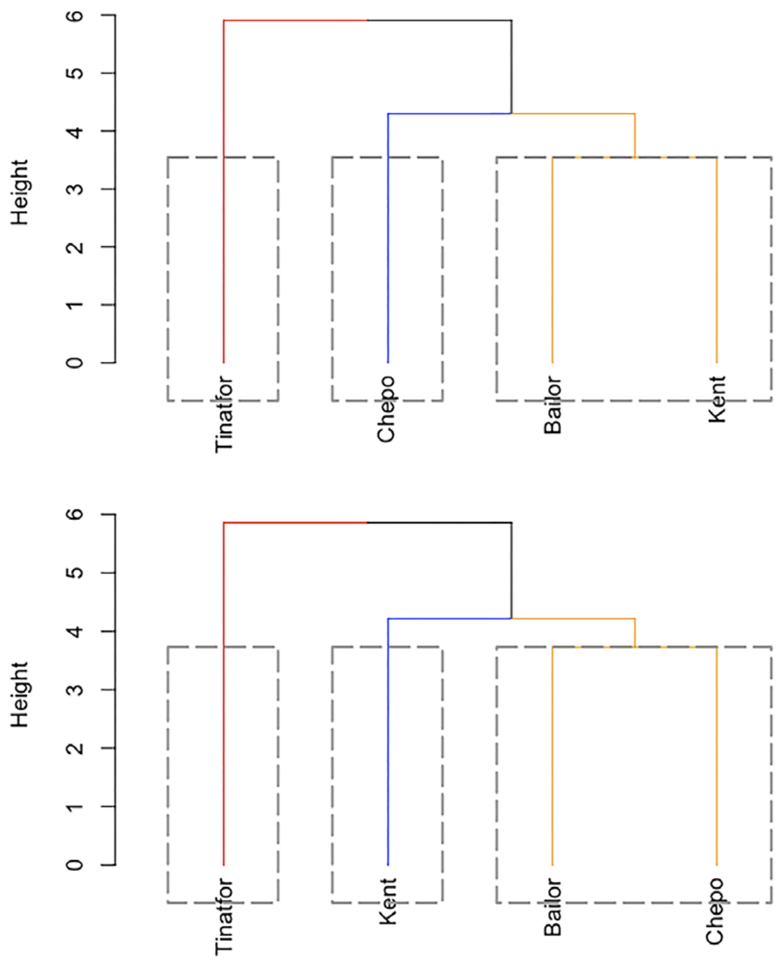

Figure 4. Dendrograms of clustered beaches using the Ward method with Euclidean distances as measures of proximity of litter material categories for a) counts and b) weights, grouped by site.

metal are strongly correlated with PC1, while rubber, paper and fishing gear are strongly correlated with PC2.

PCA was also performed to visualise the relationship between season and litter material category, but this only illustrates a wider range of material types recorded during wet season and no trends are observed between the variance of material and seasonality (SI 5).

Discussion

Summary of results

Plastic bottles were the most abundant litter item by count and weight, surpassing the second-ranked items by almost double. The three most abundant items by count are all directly related to beverage packaging, with an average estimate of 405 plastic bottles 100 m^{-1} (*SD* = 632.76), 210 water sachets 100 m^{-1} (*SD* = 332.12) and 208 caps/lids/lid rings 100 m^{-1} (*SD* = 196.67).

The Tintafor site recorded the highest mean abundance in terms of count (3,325.64 items 100 m^{-1} [*SD* = 1,843.57]) and weight (63.65 kg 100 m^{-1} [*SD* = 40.64]), while Kent had the lowest count (581.72 items 100 m^{-1} [*SD* = 506.46]) and weight (8.47 kg 100 m^{-1} [*SD* = 6.77]). These litter loads are high for both sites when considering the European Union indicator for Good Environmental Status, which has a recommended threshold value of 20 items per 100 m^{-1} (Van Loon et al., 2020). A significant difference in litter load between Tintafor and all sites except Bailor is reported (SI 4), which may be influenced by their proximity to higher populations in urban centres and industrialisation of nearby rivers. Litter abundances also reported a linear decrease from wet season to dry season, both in terms of count ($F(1,42) = 4.89$, $r^2 = 0.1$, $p = .033$) and weight ($F(1,42) = 8.09$, $r^2 = 0.16$, $p = .007$).

Litter abundance and composition linked to spatiotemporal trends

On average, 1,656.91 items 100 m^{-1} (*SD* = 1,639.02) were documented, weighing 28.32 kg 100 m^{-1} (*SD* = 37.48). Plastic was the dominant material category, accounting for 70% (42–93%) of litter by count and 49% (15–90%) by weight. This aligns with previous regional and global studies, demonstrating that plastic is the most prevalent marine litter material (Pham et al., 2014; Jambeck et al., 2015; Maes and Preston-Whyte, 2023). Foam, clothing, rubber, sanitary and fishing-related items were also prevalent, many of which may also be considered plastic. Collectively with plastic, these materials contributed to 96% of litter by count and 91% by weight.

Clothing-related litter items were the second most prevalent material by weight, averaging 26.7 kg 100 m^{-1} (*SD* = 13.6). Global textile production and consumption has doubled over the last two decades reaching around 100 million tonnes, with around 400 billion (USD) worth disposed annually (Shirvanimoghaddam et al., 2020).

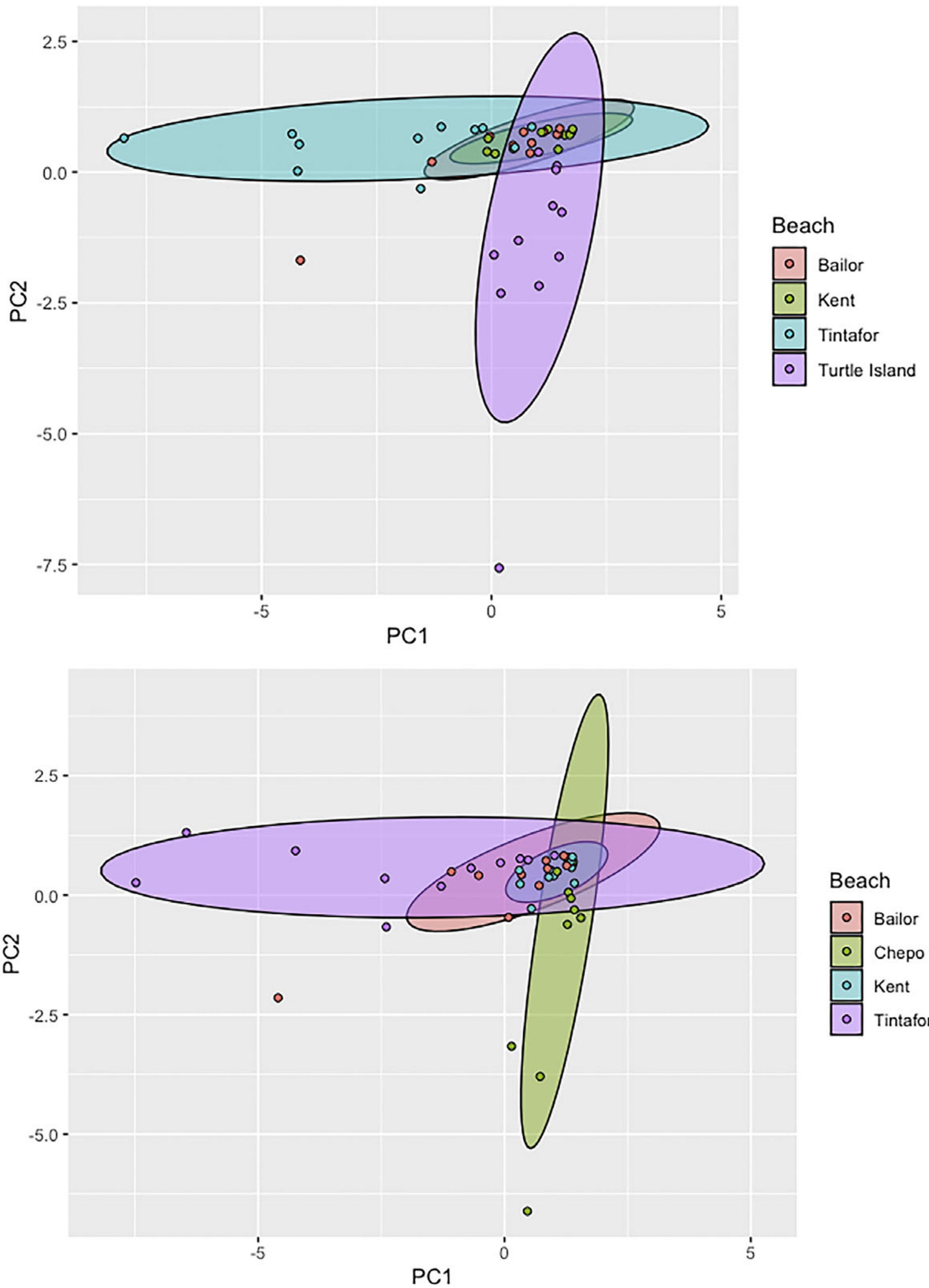

Figure 5. PCA vector plots for litter material categories for a) counts and b) weights, grouped by site.

Textile consumption in Africa is comparatively one of the lowest in the world (Shirvanimoghaddam et al., 2020), but the 'fast fashion' industry has accelerated disposal behaviour globally, and Africa has become the world's destination for second-hand clothes, where poor quality materials can become unmarketable and create environmental challenges (Sumo et al., 2023).

In terms of material count, foam-related items ranked second, with an average of 8.7 items 100 m^{-1} (*SD* = 9.7), followed by clothing-related items with an average of 5.6 items 100 m^{-1} (*SD* = 3.9). Observations suggested many of the foam-related items documented were associated with the fishing industry, such as floats and buoys made locally using imported packaging waste or

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foam from scrapped refrigerators, for example (personal communications). The second and third most abundant items by weight were flip flops (5.53 kg 100 m^{-1} [*SD* = 9.43]) and other shoes (2.4 kg 100 m^{-1} [*SD* = 4.14]), with flip flops also ranking as fourth most abundant by count (90.23 items 100 m^{-1} [*SD* = 175.08]), while shoes ranked at 18 (13.36 items 100 m^{-1} [*SD* = 22.71]). This data demonstrates the importance of considering both count and DW when evaluating litter loads, as the ranking of items may differ. Both datasets are useful for various stakeholders, including policy-makers, municipalities and recyclers.

Around 40% of peer-reviewed beach litter studies in Africa focus on South Africa, although there has been a growing number of studies in other countries and island states over the past two decades (Akindele and Alimba, 2021; Alimi et al., 2021). These studies generally report litter items that originate from local sources, particularly plastic food and drink packaging (Dyck et al., 2016; Maione, 2021; Okuku et al., 2022, 2020b; Ryan and Perold, 2021). However, some studies in the South Atlantic have identified a rapid increase in plastic bottles originating from Asia, particularly in remote oceanic islands, indicating debris inputs from ships (Ryan et al., 2019, 2021). Large quantities of flip-flops have also been observed in Zanzibar and Seychelles, with speculation that their origins are associated with their popularity in countries with poor waste management (Burt et al., 2020; Maione, 2021). The average litter loads reported in this study are similar to the relatively high reports of beach litter from Ghana, Kenya and South Africa (Dyck et al., 2016; Chitaka and von Blottnitz, 2019; Okuku et al., 2022). A list of macrolitter studies from coastal countries around Africa is provided in SI 7, detailing information regarding site, methods, quantification, litter load, abundant items, potential sources and proposed solutions.

Spatial trends

Spatial heterogeneity of litter load was observed across sites in this study. This could be influenced by small-scale differences in hydrodynamics (Ribic, 2011), localised winds (Schulz et al., 2013), proximities to river catchment areas (Ryan et al., 2021), lack of waste infrastructure (Jambeck et al., 2015), littering behaviour (Galgani et al., 2015), and local anthropogenic activities (Bergmann et al., 2015).

The north equatorial counter-current (Figure 1) could potentially facilitate floating litter originating from the Rokel river and Freetown, but additionally, the Canary current could provide a flux of litter from offshore sources, such as illegal dumping from vessels (Herrera et al., 2018) and long-term drift of items, such as bottles (Ryan et al., 2021). The lower litter abundances at Kent and Chepo are likely due to lack of riverine input, although Kent is also a protected/private site with fewer visitors. Overall, current oceanographic, meteorological data and studies on information like river catchment data in Sierra Leone are lacking, making it challenging to discuss potential sources and influences in detail.

Dendrograms did not group beaches that were spatially close together (Figure 4), suggesting geographical position is not a primary driver for observed marine litter trends. Other studies that have applied cluster analysis to beaches have also found beaches are rarely clustered according to spatial proximity, but rather in relation to their degree of pollution (Schulz et al., 2013; Rangel-Buitrago, 2018). PCA analysis revealed that two factors explained 64% of the variance in litter composition between sites for both count and weight data (Figure 5). PC1 showed a clear association with Tintafor, while PC2 was associated with Chepo, indicating distinct litter categories for each site. Tintafor was characterised by sanitary, plastic, clothing, glass, foam and metal-related litter items, while Chepo was associated with rubber, paper, wood and fishing-related items. This information could be useful for turtle conservation efforts in this area, as plastic pollution has been found to have a drastic impact on turtle mortality (Ryan et al., 2016; Aguilera et al., 2018; Sevwandi Dharmadasa et al., 2021).

Temporal trends

A temporal analysis revealed a significant decreasing linear trend in litter counts ($F(1,42) = 4.89$, $r^2 = 0.1$, $p = .033$) and weight ($F(1,42) = 8.09$, $r^2 = 0.16$, $p = .007$) from wet to dry season. This supports existing evidence that weather conditions play a significant role in marine litter trends (Jambeck et al., 2015; Ryan et al., 2009) and aligns with other studies indicating a positive correlation between rainfall and litter loads (Lee et al., 2013; Rech et al., 2014; Ryan and Perold, 2021; Okuku et al., 2022). However, it is worth noting that this study also observed some of the lowest litter loads during heavy rainfall in the wet season, highlighting how weather can have a removal effect and potentially increase litter flux into the ocean environment (Chitaka and von Blottnitz, 2019).

The highest mean litter load by count (2,841 items 100 m^{-1} [*SD* = 1,995) and weight (68.67 kg 100 m^{-1} [*SD* = 1,995]) was recorded in June. This can be attributed to it being the first standing stock survey for all sites (GESAMP, 2019). However, the first seasonal rain may have also influenced these higher litter loads, which can flush litter from sources such as terrestrial runoff and riverine inputs (Okuku et al., 2022; Ryan and Perold, 2021). Rivers have been identified as a major vector for marine litter (Schmidt et al., 2017), particularly in some African countries (Babatunde and Uche, 2018; Moss et al., 2021). Although comparatively under-studied compartments, there is evidence that actively meandering rivers likely retain litter within sedimentary deposits (Nyberg et al., 2023), while rivers can also act as a long-term sink for litter in areas concentrated within river mouths (Ryan and Perold, 2021). Additionally, a recent study of five rivers in Southeastern Nigeria reported a similar composition of macro-debris (>5 mm) to this study, with abundant items including nylon bags/sacs (including water sachets), food packaging, drinks bottles, straws, caps/lids, rope, toys, clothing/shoes and cotton bud sticks (Ebere et al., 2019).

Following June, August in the middle of wet season reports the highest abundance of litter by weight (51.3 kg 100 m^{-1} [*SD* = 51), however, December at the start of dry season is reported as the month with the second most abundant litter load by count (2,727 items 100 m^{-1} [*SD* = 3,130]), a trend observed across all sites. Tintafor also reports the highest individual survey count of 7,421 items 100 m^{-1} in December. This is believed to be due to the influence of travel around the December holiday season, with public holidays and associated higher numbers of beach visitors during this period, accompanied by a lack of available waste infrastructure and clean-up events.

Plastic bottles, although a valuable item for recycling, were the most prevalent litter item in both wet and dry seasons, with an average of 455.08 items 100 m^{-1} [*SD* = 708.52] and 345.25 items 100 m^{-1} [*SD* = 539.91], in terms of count. In terms of weight, the average was 13.07 kg 100 m^{-1} [*SD* = 22.63] during the wet season and 67.49 kg 100 m^{-1} [*SD* = 10.33] during the dry season. Overall, the composition of items was similar throughout wet and dry season, although there was a higher load of diapers observed during wet season, which could be attributed to riverine inputs.

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Research recommendations

In the past two decades, global research on marine litter has significantly increased (Nielsen et al., 2020). Beach litter monitoring is now a relatively well-established global indicator for marine pollution (GESAMP, 2019; Ryan et al., 2009), providing a range of quality long-term datasets and proposed remediation efforts. It has become a powerful tool to improve our understanding of anthropogenic waste volumes (Schulz et al., 2013), distributions (Dixon and Dixon, 1983), sources (Prevenios et al., 2018), impacts (Costa et al., 2022; Santos et al., 2005) and the effectiveness of mitigation measures (Pettipas et al., 2016). However, the complex pathways of litter and additional factors make it challenging to monitor and understand. Therefore, it would be beneficial to modify this monitoring approach by including other relevant upstream settings such as streets, MSW streams and inland waters to obtain more detailed information on waste flows and leakages at a national level (Abidjan Convention and GRID-Arendal, 2020).

Monitoring seagrass and mangrove habitats, known to be particularly vulnerable to plastic pollution (Harris et al., 2021; Walther and Bergmann, 2022), would also provide valuable insight for waste flows and environmental research. However, in this case, the primary objective is to establish a simplified, long-term, and cost-effective monitoring approach that can effectively measure litter trends and evaluate the success of remediation efforts.

The baseline data obtained in this study provides a foundation for future monitoring and allows for the assessment of relevant sites and frequencies to be considered moving forward. Monitoring multiple sites monthly is an administrative and economic burden for most governments, so a balance is needed between available capacity and obtaining representative data. Frequency of sampling is an important factor when designing a monitoring programme. Studies have shown that shorter-term studies tend to report higher abundances compared to less frequent surveys conducted over an annual cycle, which are likely a result of differences in wind and wave action. While some studies have demonstrated 4 weeks to 5 months are an ideal interval between surveys, OSPAR recommend seasonal studies with an interval of 3 months (GESAMP, 2019).

Temporal variability can mask substantial increases in litter, such as the spike in December observed in this study, which could have been missed if monthly surveys were not conducted. Moving forward, a standing stock survey with a monitoring frequency of 4 times a year is proposed for Sierra Leone, taking into consideration the environmental and social impacts observed in this study. Standing stock and accumulation surveys both have their own strengths and weaknesses (Barnardo and Ribbink, 2020; Meakins et al., 2022), but overall standing stock surveys provide a more cost and time effective approach for monitoring and managing marine litter from a policy perspective, to measure mitigation and litter trends over time.

To achieve an even more efficient approach, the number of monitored sites could be reduced. Bailor, being like other sites in terms of litter load and accessibility, could serve as a representative site. Additionally, for a more detailed understanding of the origins of plastic bottles, further investigation into brand labels and markings could be conducted (Okuku et al., 2020a; Ryan et al., 2021), but it's important to note that such an investigation can be resource-intensive in terms of both cost and time.

Focusing on potable water

Plastic bottles accounted for the largest proportion of litter items, contributing 25% by count and 35% by weight. The availability of trusted potable water is a likely factor in their high prevalence. Different marine litter studies have found sites near urban centres tend to have the highest contributions from locally sourced bottles (Okuku et al., 2020b; Ryan et al., 2021). Okuku et al. (2020a,b) found higher contributions from specific manufacturers on beaches near their bottling plants and distribution centres, while Ryan et al. (2021) found more remote beaches to have higher proportions of foreign bottles.

Interestingly, 20% of caps/lids were recorded at Chepo, despite this site only reporting 0.7% of the total number of bottles. This disparity between caps and bottles has also been observed across beaches in South Africa (Ryan et al., 2009; Chitaka and von Blottnitz, 2019). It could be attributed to factors such as polyethylene terephthalate (PET) bottles having a higher density than seawater, whereas caps/lids float in water (Ryan et al., 2009), or the recycling value of bottles, although this is less likely as well-developed recycling schemes for PET bottles are lacking in Sierra Leone.

Access to potable drinking water is severely lacking in Sub-Saharan Africa, including Sierra Leone, which has led to a soaring consumption of packaged drinking water from the private sector (Stoler et al., 2012). This is due to the lack of infrastructure, poor governance and lack of investment (AfDB et al., 2020). The region heavily relies on unreliable and non-piped water supplies, affecting around 750 million people across Africa, most of which are communities in Sub-Saharan Africa (AfDB et al., 2020).

Sanitation also plays a crucial role (WHO, 2017), with poor infrastructure and management leading to water contamination (Dalvie et al., 2003; Sila, 2019). Freetown's lack of central sewage treatment and inadequate sanitation infrastructure contribute to these challenges (Sood, 2004). Considering urban populations, in 2015, Sierra Leone was identified as having one of the lowest proportional increases to improved sanitation across Africa (WHO, 2017), with the country unable to meet their Millennium Development Goal targets on health, food, education, environment and equality in 2016 (EPA-SL,2016).

Policy recommendations

This study indicates a strong link between inadequate clean drinking water and marine litter in Sierra Leone. A range of international and regional policy frameworks exist to support global access to clean water, sanitation and sustainable waste management (SI 8). These frameworks encourage the development of national profiles and action plans, which support strategies including enhancing monitoring, reporting and enforcement capacities. International experts can also assist in developing tools, clarifying best practices, standards, penalties, and standard operating procedures (Maes and Preston-Whyte, 2023).

By improving portable drinking water access, Sierra Leone can address three sustainable development goals (SDGs): clean water and sanitation (SDG 6), life below water (SDG 14), and reduced inequalities (SDG 10). A long-term solution requires an intra-governmental approach and sustainable strategy for municipal planning, emphasising access to clean water and sanitation to improve the quality of life for communities, which will subsequently reduce marine litter. However, there is currently limited information available regarding municipal services in Sierra Leone (SI 9).

Considering the findings of this research, immediate-, short-, medium-, and long-term policy recommendations are described below. Many of these align with the current policy goals and strategic actions of Sierra Leone (MoHS, 2012), additionally highlighting efforts should prioritise addressing clean water and sanitation, as well as municipal solid waste management, plastic pollution remediation and mitigation. In light of the ongoing development of an international legally binding instrument on plastic pollution (UNEP, 2023), mechanisms through which this treaty could support Sierra Leone are also discussed.

Immediate-term

In the immediate-term, a focus on raising awareness and educating communities about the importance of clean water and sanitation access will emphasise their significance. Government groups, non-government organisations (NGOs) and community leaders can play crucial roles in disseminating information and engaging schools in water hygiene and sanitation education programmes. Additionally, the capacities and needs of municipalities to provide water, sanitation, and hygiene (WASH) services should be assessed, and technical support provided to help support planning, service provision, monitoring, reporting, and enforcement.

Efforts also need to be directed towards identifying the capacities and needs of municipalities and the informal waste sector, as well as developing the technical support available for waste management programmes. Local municipalities will need assistance in developing comprehensive strategies for sorting, collection, recycling, and safe disposal of non-reusable and unrecyclable wastes. Private and public sectors also need engagement and awareness raising to support the development and implementation of these strategies. Furthermore, Freetown's main Kingtom and Granville Brook dumpsites should be relocated away from the river/ocean to mitigate environmental risks. The market for recycled waste products also needs to be developed, and local waste recycling technologies should be promoted and invested in.

Sierra Leone should prioritise clean-up and remediation efforts in watershed areas near urban centres. Various stakeholders, including schools, civil society organisations, local communities, and government agencies, should be encouraged to participate in clean-up activities, particularly in areas close to river mouths and beaches after holiday events. Considering implementing technologies like river booms can also help capture litter and prevent its escape into the marine environment. Additionally, efforts could be made to strengthen reporting mechanisms for municipalities, ultimately aiming to explore developing e-government systems.

Collaboration with plastic and recycling industries should be sought to support Extended Producer Responsibility (EPR) and Deposit Return Schemes (DRS), to foster responsible waste management practices and a just transition for the plastic value chain, including the informal sector. Investing in research and innovation across the plastic value chain is also crucial to improving municipal services, where pilot and demonstration programmes can promote reduction, reuse, repair, recycling, and alternatives across private and public sectors. The introduction of initiatives such as a 'No Plastic Day,' aiming to reduce unnecessary and avoidable plastics, could also be explored.

Sierra Leone should align existing policies into an overarching plastic policy and National Action Plan, considering market-based instruments, regulatory control measures, green taxonomy, standards, procurement processes, and targets for plastic pollution reduction, recycling, and recycled content. The development of financial mechanisms to support municipal services and the informal sector needs to be explored, ensuring equitability and considering the capacity and needs of municipalities, the informal sector, and businesses to deliver effective services. Collaboration with international development groups and NGOs can also provide platforms to share relevant monitoring data, help leverage resources and expertise, and support the continued progress of the international treaty to define goals and strategies aligned with Sierra Leone's specific needs and capabilities (Shomuyiwa et al., 2023).

Short-term

During the short-term, the focus should shift towards improving WASH and waste management services in urban areas, enhancing collaboration with the private sector, and promoting public-private partnerships. A comprehensive approach should be developed to make water delivery, sanitation, and hygiene services more affordable and reliable. The efforts to raise awareness and educate communities on clean water and sanitation access should continue and extend to rural areas. A comprehensive strategy and framework also need to be established for coordinating and implementing plastic material management policies. Additionally, the phase-out of unnecessary, avoidable, and problematic plastics (UAPP) should be pursued, along with evaluating incentives and disincentives for reduction, recycling, and sustainable alternatives.

Collaboration with industry and promotion of public-private partnerships should continue, focusing on a just inclusion of the informal sector in waste management and recycling. Partnerships should be fostered to expand access to clean drinking water through reusable and recyclable containers, while maintaining affordability. The implementation of strategies, policies, and action plans for water, sanitation, and plastic material management at a national level should also continue, expanding to reach rural communities. Institutional responsibility, coordination, and reporting for national and municipal agencies should be defined, while enhancing the monitoring of pollution and water quality under a policy framework(s). Frameworks for extended producer responsibility (EPR) and public-private partnerships to ensure a just transition should be institutionalised, and measures should be identified to support municipalities to increase their own revenue streams. Furthermore, measures need to be defined to ring-fence revenue and evaluate the viability of incentives and disincentives to ensure sustainability.

Medium-term

In the medium-term, investments should prioritise water and sanitation infrastructure, including repairing and replacing outdated infrastructure, constructing new wells, and improving sanitation services. Waste collection and disposal in urban areas should be established through the implementation of strategies, with a focus on improving waste collection, material recovery, and disposal infrastructure. Efforts should also consider improving rural access to WASH and waste services. The use of new technologies, such as solar-powered pumps, could be explored to enhance the affordability and reliability of water delivery in remote regions. The effort to phase out UAPP should continue, evaluating incentives and disincentives for sustainable alternatives and technical support for innovations. Institutional structures and multi-stakeholder engagement platforms should be well established to strengthen data-driven sustainable financing mechanisms for municipal services.

Long-term

In the long-term, transparency, accountability, and stakeholder engagement should be further enhanced to establish clear roles and responsibilities in WASH services, waste management and plastic pollution reduction. Public awareness and behaviour change campaigns should continue to promote sustainable practices. Data-driven decision-making systems should be implemented to track progress and support effective policy implementation. The establishment of extended producer responsibility (EPR) programmes should be coordinated with national plastic reduction and management strategies, helping foster regional and international cooperation on plastic.

In the scope of the international plastics treaty

A draft resolution, ensuring a full-life-cycle approach to plastics, was adopted for negotiating an internationally legally binding instrument in March 2022. A revised zero draft document is the basis for ongoing discussions and includes sections dedicated to options around financing mechanisms, capacity building, technology transfer, national planning, implementation, reporting, enforcement, and governing bodies for the subsequent treaty. The draft text also offers a range of options targeted towards identifying and transitioning away from chemicals, polymers and products of concern, improving material and product design, addressing existing plastic pollution, waste management, trade, monitoring, and supporting a just transition.

Understanding how the new agreement connects with current global, regional, national, and local efforts to address plastic pollution, fostering synergies while respecting existing processes, is crucial but not fully explored for effective implementation (Maes et al., 2023). Similar to its environmental treaty counterparts, the plastics treaty is expected to serve as a structural legal framework for developing and implementing policies, legislations, and action plans to address plastic leakage into the environment. Additionally, it can function as a practical guiding instrument that can be mainstreamed into national programmes to curb plastic pollution, especially in the marine environment. With consideration to Sierra Leone and the findings in this study, a global plastics treaty could provide a strong framework and much-needed support for the country's fight against plastic pollution in the following ways:

- The treaty can establish international standards for the entire plastic lifecycle, from production and design to waste management and disposal. This would provide a clear roadmap for Sierra Leone to develop or revise national policies and legislation to effectively regulate plastic use and promote responsible practices.
- A global agreement could lead to restrictions or bans on specific types of plastic known to be particularly harmful, like single-use plastics or microplastics. This would directly address a major source of plastic pollution in Sierra Leone.
- The treaty can create mechanisms for nations to share best practices and technical expertise, fostering international cooperation and a just transition for the entire plastics life cycle. This could involve knowledge transfer on implementing effective waste collection systems, promoting recycling technologies, and educating communities about responsible plastic use.
- The treaty process itself can be a capacity-building exercise. International support can help train Sierra Leonean negotiators to effectively participate in future discussions and secure provisions that best address the country's needs.
- The treaty can establish a framework for creating an international fund to support developing countries in implementing their obligations under the agreement. This could provide Sierra Leone with much-needed financial resources to invest in critical infrastructure for WASH services, waste management, recycling facilities, and public awareness campaigns.
- The treaty can encourage sustainable green investments towards innovative solutions for plastic pollution. This could incentivise companies to develop new technologies for plastic recycling or biodegradable alternatives, benefiting both the environment and Sierra Leone's economy.
- The treaty can foster international collaboration on research and development of new materials and technologies to address plastic pollution. Sierra Leone could benefit from knowledge exchange and potential access to these advancements to improve waste management practices.
- The treaty can encourage research into sustainable alternatives to traditional plastics. This could open doors for Sierra Leone to explore and potentially develop eco-friendly materials suitable for local needs.
- A well-designed and aligned treaty could include provisions to address transboundary plastic pollution and promote a unified approach to dealing with pollution impacts. This would be particularly relevant for Sierra Leone, which imports a significant amount of plastic waste (personal communications).
- The success of any plan to tackle plastic pollution relies heavily on public awareness and participation. The treaty can emphasise the importance of engaging local communities in waste management initiatives and promoting behavioural change.
- Establishing localised and comparable datasets, as outlined in this study, is pivotal in supporting mitigation efforts and facilitating the treaty's implementation towards a significant reduction in the widespread distribution of harmful plastic products, consequently lessening the environmental and biodiversity impacts, especially for vulnerable countries like Sierra Leone.

Conclusions

The data from this study suggests that by tackling access to clean drinking water, Sierra Leone will also be able to tackle a substantial part of their marine litter leakage by reducing the current need for clean water access through bottles and water sachets. Investment in improved freshwater infrastructure, sanitation infrastructure, wastewater practices, and regular monitoring of water sources is vital for ensuring access to clean drinking water and reducing contamination risks. Furthermore, effective monitoring, management, infrastructure and improved disposal behaviour are crucial for preventing marine litter (Sankoh, 2013; Jambeck et al., 2018; Maes and Preston-Whyte, 2023).

The government must adopt strategies that strengthen institutions, increase transparency, and build awareness and trust within local communities. Promoting a clean-up culture through education, campaigns, and social mobilisation, as well as empowering civil society and government groups for monitoring, can help target issues like illegal dumping. Leveraging technology and international cooperation will also support efficient progress. Sustainable waste management systems and services are crucial for economic growth, but exceed the capabilities of any government alone, requiring tightly coupled partnerships involving the private sector, development agencies and local communities to achieve sustainable development.

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