

Environmental Forensic Analysis and Risk Assessment of the Shoreline Microplastics Debris on the Limbe-Idenau Coastline, Cameroon

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Abstract

The incidence and unpleasant quality of plastic pollution, regularly witnessed on beach shores, has prompted researchers around the world to theses on the scale of the problem. The morphological features of waste plastics are important in understanding the nature of pollution, identifying sources, estimating dangers, and developing remediation strategies. The goal of this research is to detect, quantify, and forensically characterize the distribution of each MP/polymer composition and its associated risk on the Limbe shoreline in Cameroon. Over an 8-month period, duplicates of 4 m² quadrants were collected at five purposive beaches. Plastic samples were thoroughly washed and sorted using a 2 mm sieve. Only particles < 2 mm were included for examination. The samples were subjected to an established step-by-step scientific procedure such as particle filtration, organic matter digestion, density separation, particle extraction, and polymer identification, all aided by particle image magnification. In total, 241 particles weighed 89.15 g and had a mean abundance of 2 particles/m² (0.69 g/m²) and 6 particles/month (2.0 g/m²), accounting for 75% of beach contamination in LDB 2, LDB 1, and IDN. May and June had 39% abundance, making them the most contaminated months. The buildup of MPs on beaches varied greatly spatially and temporally. ANOVA and Spearman's rank correlation reveals linear correlations among the size categories. From the polymer MPs analysis, the dominant colour, shape, MPs type, size ranged, and weigh class in particle/number recorded white coloured, 50 (22.25 g) with PP (25), PE (15) and PS (5); irregularly shaped, 98 (30.5 g) with PP (39), PE (33), and PS (11); fragmented type, 80 (25.25 g) with PP (30),

PE (28) and PS (15); 1.5 - 1.99 mm sized ranged, 102 (51.77 g) with PP (47), PE (41), and PS (7) and 0.01 g weighs, 98 (56.57 g) with PP (49), PE (29) and PS (13) with 65.5% of the MP's being of old weathered plastic particles (OWPP). According to the environmental risk model, CF, PLI, PHI, and PERI pose the greatest danger of contamination to both marine life and beach tourists due to their category III polluting capacity. Similarly, the PET polymer material poses a Level III risk in both seasons. Forensic research revealed that the majority of beach MPs are heavily influenced by beach structure/water behaviour, while the risk provides critical insight into management, pollution monitoring efforts, and sustainable methods for MPs throughout the Limbe coastline as it serves as baseline monitoring materials and other methods could use for deeper investigations.

Keywords

Forensic Analysis, Beach MPs, Ecological Risk Assessment, Particle/Number, Polymer Composition, Limbe-Cameroon

1. Introduction

Global concerns over the polluting effects of plastics are of major concern in the marine environment. Plastics are introduced into the oceans principally from land-based sources such as rivers, wastewater discharges, floods, coastal activities, fishing and aquaculture. Plastic production and use are increasing globally. The total amount of resins and fibers manufactured from 1950 through 2015 is 7800 Mt, and half of this 3900 Mt—was produced in just the past 13 years [1]. [2] and [3] reported that in 2010 between 4.8 and 12.7 million metric tons of plastic litter reached the oceans and an estimated 5 trillion pieces of plastic are currently floating in the ocean. Unsustainable uses, low recycling rates and poor waste disposal practices, coupled with the non-degradability of plastics imply rapid increases in their rate of accumulation in the oceans.

Plastics in the marine environment are transformed by complex physical and chemical processes. Fragmentation and particle size reduction are some of the most visible products of this transformation. Researchers classify plastic debris into four major categories based on particle size: three classes: macro debris (>20 mm in diameter), meso debris (2 - 20 mm), and micro debris (<2 mm) [4] [5]. The effects of plastics on the marine environment can also be described by following this classification system. Microplastics are significantly concentrated in beach sands and sea sediments [6] [7] ranging from 1 piece/kg dry weight to more than 2000 pieces/kg dry weight [8] [9]. Microplastics are heterogeneous in nature and exhibit distinct behavior, depending on their physical properties, such as particle density, shape, and size [10] [11]. Microplastics have attracted a lot of attention in environmental research because of their higher potential for bioaccumulation and biomagnification.

Sandy beaches and shorelines in coastal environments around the world are

particularly vulnerable to microplastic pollution [12] [13]. Globally, these are some of the most densely populated coastal areas in the world. Shorelines support ecological processes and humans' sustainable use. Crashing waves, tidal movements and current actions render beaches highly dynamic and turbulent environments. These environments harbor very specialized flora and fauna. Many species that require multiple habitats spend different parts of their life cycle between the beach and the open waters (e.g., sea turtles). Some species feed on plankton and other organisms found in this environment [13].

Environmental forensics involves the investigation of a diverse range of pollutants that have been accidentally or deliberately released into the environment, to understand their origin, and distribution and aid the authorities in attributing responsibility for those concerns [14]. A forensic understanding of the weight, polymeric chemical composition, and shape distribution of MPs can guide and help us focus on the kind of possible remediation [15] [16].

Around the world, many approaches and models have been developed to estimate the danger of MP pollution in aquatic environments. For example, [17], used a species sensitivity distribution (SSD) method to assess the ecological risk of MP pollution by evaluating the susceptibility of soil biota to microplastics [17]. [18] used a pollutant load index (PLI) methodology to assess the danger presented by MPs in Dongshan Bay, China [19]. In a separate investigation, [20], used a polymer risk index (RI) model to quantify the degree of MP pollution in Chagan Lake and Xianghai Lake, China and was supported by [21]. By using several models, researchers paved the ground for comprehensive ecological risk evaluations of MP pollution in marine settings. These assessments, in turn, give useful information about viable preventative strategies and controls for MP contamination.

Thus, this paper aims to morphologically identify microplastics (MPs), quantify them, and forensically understand the distribution of each plastic polymer composition (in terms of size, color, shape, and weight) and their risk potential on the beach shore along the Limbe coastline, Cameroon. To this end, a quadrant sampling method combined with hand-picking collection techniques was developed and applied using a well-established stepwise methodological laboratory procedure, taking all necessary precautions.

2. Materials and Methods

2.1. Location of Study Area

Samples were collected on beaches found within a stretch of 42.9km along the Cameroon's coastline in from Limbe to Idenau Falls within the Fako Division of the south-west province of Cameroon, located between 3°90' and 4°05'N latitude and 9°29' and 9°06'E longitude (Figure 1) with a coastline of approximately 50.5 km. This area falls within the lowest reaches of Mt. Cameroon, marking the surface of contact between the Sea and the massif. The geographical coordinates of the beaches are as follows; 9°16'18.30"E, 4°1'8.2"N Limbe Down Beach 1 (LDB1), 9°14'18.24"E, 4°2'8.19"N Limbe Down Beach 2 (LDB2), 9°8'17.10"E, 4°5'8.5"N Ba-

toke (BTK), 9° 4'18.10"E, 4° 15'8.10"N Seme (SEM), and 8° 90'17.50"E, 4° 14'8.30"N Idenau (IDN). **Table 1** is a summary of relevant features of the studied beaches that influence MP distribution. Slope structure, land drainage and wind and wave direction can influence MP transport processes. The bioaccumulation of sediments and materials is influenced by factors that are inherent on the nature of the coastline/beach morphology and the wave action. Human-induced activities significantly affect the cleanliness of beaches, particularly through waste disposal and beach cleaning activities. For instance, locations LBD1, LBD2, and IDN are in close proximity to human settlements and serve as recipients of river discharges and drainage systems.



Figure 1. Map of the study area showing sampling sites on Limbe-Idenau Coastline.

Table 1. Characteristic feature of the studied beaches.

Physical parameter	LDB 1	LDB 2	BTK	SEM	IDN
Beach coastline space	0.8 km	1 km	1.4 km	2.2 km	2.5 km
Substrate nature	-Sandy (<2 mm)	-Sandy (<2 mm) -Stony, 1 m offshore	Sandy (<2 mm)	-Sandy (<2mm) + gravel nature	-Sandy (<2 mm) -Stony, 1 m offshore
Beach slope height	0.7 m	0.6 m	0.2 m	0.2 m	0.4 m
Slope Structure	-Open on both side	-Open on the sea end -Embankment, 10 m from the shoreline	-Open on the sea end -Tree, built 7 m from the shoreline	-Open on the sea end -Embankment, 8 m from the shoreline	-Open on the sea end -Sand rose, at 8 m from the shoreline
Land drainage/ gutters/streams	Present	Present	None	None	Present
Average water temperature	29.9°C	29.4°C	28.0°C	28.5°C	27.8°C

Continued

Proximity to settlement	Very close	Very close	≈200 m	≈2.5 km from town	Very close
Wind and/wave direction	Towards the shore	Towards the shore	South to East direction	South to East direction	North to South direction
Average tide height/beach	1.46	1.65	0.49	1.28	1.38
Av. Strandline/ stormy event/beach/ month	4	5	2	3	4

Geologically, the basaltic rock in this region has given rise to black beach sands rich in olivine, magnetite, amphibole and pyroxene. Two of the beaches, LDB sites 1 and 2, are very close to 0.7 km while the others are spread within a distance of 3.5 km. The study area falls within the equatorial climate characterized by high rainfall and high temperature. The area experiences heavy torrential rains during the rainy season (3000 - 4000 mm per year) from March-October with a peak of 10160 mm in Debunscha [22], considered the second wettest place in the world, after Cherrapunji in India. The low elevation (1 - 2 m asl) of the city of Limbe and the torrential rains in the rainy season and cause the rivers to overflow their banks causing floods [23].

The composition of sediments and deposits within beaches and shorelines is influenced by land-based sources and offshore processes. The town of Limbe with an estimated population of 300,000 living in an area of 1,596 km², hosts two of the beaches studied (LDB1 and LDB2). Serving as the major centre of economic growth in the Southwest Region, the town is also besieged with the problem of solid waste management. The almost 200 tonnes of solid waste generated daily is managed using the rudimentary practice of collecting and dumping. Low collection efficiency coupled with irregular waste collection of wastes disposed along the streets, open spaces and overflowing waste bins exposes these materials to spatial dispersal by agents of weathering, particularly flood waters. The many small streams that drain the area flow into larger drainage systems that converge into two main rivers (Limbe and Jengele) that empty into the Atlantic Ocean [23]. Along the beach, restaurants, mobile vendors, fishermen, and tourists discharge their waste directly into the beaches. The fishing communities use the sea and the beach for the disposal of household waste, including human waste. Workshops, boat-building and maintenance at the dockyard located in the LDB1 constitute an important source of solid waste that is introduced into the sea.

The study area is part of the coastal waters of the Bight of Biafra, located in the Eastern part of the Gulf of Guinea. The ocean circulation and the hydrodynamics of the eastern part of the Gulf of Guinea have been ascribed to be complex and highly variable and not well documented [24]. [25] intimated that the southerly flowing Guinea currents and the enormous sediment load from the many distributaries in the area, coupled with high rainfall discharges, contribute to a major

lobe of suspended matter. Findings of a region-wide coastal pollution sources assessment undertaken by 6 countries indicated that households produce 90% of all solid waste. The study further suggests that the industry is responsible for substantial amounts of hazardous waste, specifically the Nigerian petroleum industry. Offshore activities are dominated by petroleum exploration, transportation and fishing.

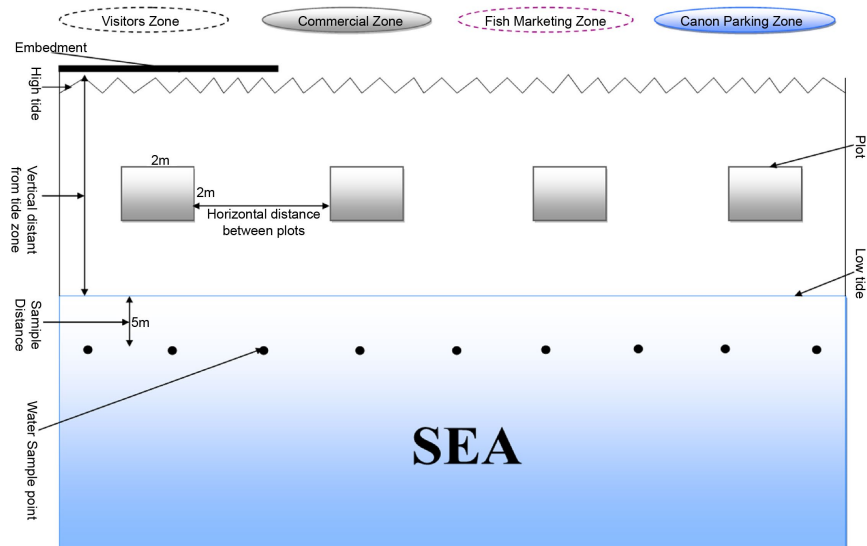


Figure 2. Sampling design within the Limbe-Idenau Coastline.

2.2. Sampling Designs

This work was carried out over eight (8) months (from March-October) in 2020. Before field collection, a reconnaissance survey was conducted and tide prediction was acquired from online admiralty charts (<http://www.tide-forecast.com/>) simultaneously before every sampling day during the sampling week to know the low tide level [26]. Five purposive sampling plots were selected along the coast, viz, Limbe down 1&2 (at least 0.7 km stretch length), Batoke, Seme, and Idenau beaches based on their potential in terms of beach activities, fishing, sloping and tide height as detailed in **Table 1**. A 2.0 m by 2.0 m sampling plot with four 1.5 m iron rods, each painted 1 m red and 0.5 m black was laid with the black end on the sandy ground on each studied beach pathway between high and low tide levels (**Figure 2**) [27] [28]. Also, the landward edge of each studied beach was determined by either natural vegetation, sharply rising sand dunes or man-made structures (such as walls, pavements, steps, etc.) depending on the sampling path chosen for the beach. Additionally, the implementation of beach clean-ups by the local authorities and the accessibility of the sampling sites were also considered.

2.3. Sample Collection

Beach plastic litter visible to the naked eyes was collected, in each sampling plot/ day/ beach within five days/week respectively, with a systematic sampling done on the first

week and the third week, for each month for over an eight (8) month study period. To keep the sampled area constant, red and black ink paint was marked on any permanent sign post/structure mentioned above adjacent to the lay plot. Each beach was sampled 16 times, making a total of 80 samples. At low tide, plastic debris within each quadrant was collected by hand-picking and placed in a 10L labeled glass bowl to minimize contamination by post-collection fragmentation impact. It was immediately closed and carried to the laboratory. We tried to keep the sampling depth as constant as possible at 0.1 cm and ensured that hands were rinsed with seawater into a 5L bowl. Plastics particles < 1 mm on the beach surface and within the plot were included in the survey [29], as they were visible to the naked eye.

2.4. Sample Analysis and Calculations

In the laboratory, the plastic debris was washed and rinsed thoroughly with fresh water to remove sand, shells and other organic debris, in a glass bowl. In addition, a 2 mm stainless sieve was used to separate plastics particle into < 2 mm and ≥ 2 mm size classes, but only particles < 2 mm were considered for further analysis, which went through the surface water microplastics analytical stepwise procedure as mentioned in 2.5.

2.5. Laboratory Analysis

Firstly, in the laboratory, the 0.05M Fe(II) catalyst for use in the wet peroxide oxidation process was prepared in the laboratory as follows: in a 250 ml beaker, 9.80 g of aluminum iron(II) sulphate, $(\text{NH}_4)_2\text{Fe}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$, was mixed with 250 ml of $\text{H}_2\text{O}(\text{aq})$ + 5 ml $\text{H}_2\text{SO}_4(\text{conc})$. The mixture was transferred to a 250 ml volumetric flask. When the catalyst was not in use, it was kept in a closed volumetric flask. [12].

The beach water sample from the 5L bowl was filtrated through a clean rinsed and dry standard sieve of 0.0063 mm (63 μm) to isolate all microplastics content. The sieved content was then transferred using squirt-bottled distilled water (to ensure total removal of all materials) into a clean and empty weighed 50 ml beaker.

The mixture was heated under a control hotplate and then the oven dried at 60°C. The dried content was weighed again at the end of the process. Furthermore, 25 ml of 0.05M Fe (II) solution and 25 ml of hydrogen peroxide, (H_2O_2) were added simultaneously to the beaker containing the dried solid content and the wet peroxide oxidation, WPO mixture and left standing on the Lab bench for 5 minutes and a stirring bar was added. The beaker was again placed on the hotplate and allowed to heat for 60°C with close observation for a few minutes while stirring to homogenize the mixture and this also helped break down any organic matter present [30]. For complete digestion, H_2O_2 was added 2 to 3 times (in cases where bubbles of gas were seen rising from within the beaker, distilled water was added immediately followed by continuous heating for atleast 30 minutes). After 2 minutes, 6 g of $\text{NaCl}_{(s)}$ salt was measured and added to the mixture in the beaker

per hydrogen peroxide addition after the first pipetting and heated again continuously. The mixture was further transferred into the density separator, covered loosely with aluminium foil and allowed to settle overnight. Clean white folded 500 cm² grade 90 cheesecloth firmly tied with a woody rope around the mouth of the 250 ml beaker was used to collect floating solids under the density separator and rinsed severally with distilled water to transfer all particles on the cheesecloth and allowed air dry while loosely covered with aluminum foil for 24 hours. Samples in the cheesecloth oven were dried at $\leq 50^{\circ}\text{C}$ to ease separation and were then placed under a magnifier at 40 \times for visual sorting.

- Microplastic classification and quantification: Forceps were used to count all identifiable microplastics, and they were quantified by abundance/count, /gram, /beach and separately transferred onto a different labeled watch glass [31].

2.6. Contamination Control

Before analyzing the samples, the workplace was cleaned with clean water and followed by 70% alcohol. All apparatuses were rinsed three times with distilled water and covered with tin foil and some head down to avoid airborne contamination. A cotton lab coat and nitrile gloves were worn from the beginning to the end of the procedure.

2.7. Polymer Identification

Fourier transform infrared spectroscopy, FTIR was carried out on the beach shoreline microplastic to clearly identify the chemical identity of the polymer types of present. This FTIR analysis was carried out in the Analytical Laboratory of the Department of Applied and Analytical Chemistry, University of Yaounde 1, Ngoa-Nkwelle. The instrument used was the Bruker Alpha Spectrometer with specifications set at spectra range; 45,000 - 4 cm⁻¹ (data spacing of 0.483 cm⁻¹) using 32 scans, hardness; 9,000 (Knoop), refractive index; 2.40, penetration depth; 1.66 μm (at 45 $^{\circ}\text{C}$ and 1000 cm⁻¹) and with chemical/physical inertness; very high.

The samples were directly analyzed using the ATR-FTIR (Attenuated Total Reflection Fourier Transform Infrared Spectroscopy) technique on a diamond crystal. The resolution during the collection of the spectra was fixed at 4 cm⁻¹. Between samples, the ATR-crystal was cleaned with isopropanol and the background signal was updated. Hence, the spectra diagram was obtained based on the absorbance mode. Polymer identification was made by comparing the particle spectra to a reference library provided by the manufacturer. The minimum matching for positive identification was set at 80% as recommended elsewhere [32]. In addition to the identification of polymers, FTIR-ATR was also used to determine the relative levels of surface oxidation of some specific polymers. For this, the carbonyl index of each particle was calculated individually for the microplastics of polyethylene (PE) (n = 76), polypropylene (PP) (n = 90), polystyrene (PS) (n = 39), polyvinylchloride (PVC) (18) and polyethylene terephthalate (PET) (n = 18) using the following equation (Equation (1)):

$$\text{Carbonyl Index (CI)} = \frac{\text{Absorbance carbonyl peak}}{\text{Absorbance peak}} \quad (1)$$

The index was determined based on the absorbance between 1715 and 1735 cm^{-1} for carbonyl groups and the reference peaks used for polyethylene (PE) at 1471 cm^{-1} , polypropylene (PP) at 1460 cm^{-1} and polystyrene (PS) at 1452 cm^{-1} (Rodrigues et al., 2018). This is because the carbonyl group is not characteristic in the spectra of these polymers, being formed from the introduction of oxygen in the polymeric chain after exposure to UV radiation and/or atmospheric and aquatic oxygen [33]. The relative level of surface oxidation was also expressed as a low surface oxidation rate (with CI between 0 and 0.15); medium (CI between 0.16 and 0.30) and high (with CI \geq 0.31) [33]. Each polymer type was forensically analysis (in terms of abundance) in colour and shape, size, and weight classes aided by a 40X magnifier (and/ microscope), sieve (0.063 mm, 1 mm and 1.5 mm based on size category) and an electronic balance respectively.

2.8. Potential MPs Ecological Risk Model

There is currently no standardized model to estimate the environmental impact of microplastics. Researchers have assessed the ecological consequences of microplastic contamination using a risk-assessment approach similar to that used for other contaminants [14]. Four alternative methodologies were employed in the current investigation to estimate the possible risks posed by microplastic pollution in a stepwise mathematical assessment model as depicted in **Table 2**.

Pollution load index: The pollution/pollutant load index (PLI) is the first approach and was used to determine the overall degree of MP pollution in beach sediment. According to the PLI model first provided by [34], MP abundances at regional sample locations were employed as key indices. The mathematical procedure has been defined as follows:

$$\text{MP abundance/sampling beach} = C_i$$

$$\text{Minimum MP abundance/beach} = C_{i0}$$

$$\text{Contamination factor} = CF_i$$

Table 2. Various categories of pollution load index, polymer risk index, potential ecological hazard (single polymer effect), and risk index (combined polymer effects) [36] and [37].

Contamination factor (CF)		Pollution load index (PLI)		Polymer hazard index (PHI)		Potential ecological risk index (PERI _{Single})		Risk index (Combined effects), RI	
Range	Category	Range	Category	Range	Category	Range	Category	Range	Category
< 1	Minor	< 1	I	< 1	I	< 40	Minor	< 150	Minor
1 - 3	Medium	1 - 2	II	1 - 10	II	40 - 80	Medium	150 - 300	Medium
3 - 4	High	2 - 3	III	10 - 100	III	80 - 160	High	300 - 600	High
4 - 5	Danger	3 - 4	IV	100 - 1000	IV	160 - 320	Danger	600 - 1200	Danger
>5	Extremely danger	>4	V	>1000	V	>320	Extremely danger	>1200	Extremely danger

Then

$$CF_i = \frac{C_i}{C_{i0}} \quad (2)$$

Implies that,

$$PLI_i = \sqrt{CF_i} \quad (3)$$

Therefore,

$$PHI_{zone} = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n} \quad (4)$$

PLI_i is the pollution load index of MPs for a single sample, while PHI_{zone} it represents the pollution load index of MPs along the beach coastline.

Polymer hazard index: The polymer hazard index (PHI) is the second approach of this model and was used to evaluate the polymer-related risks associated with MPs pollution in beach sediment. The eco-risk index ($H_{(PHI)}$) of MP polymers was derived as adopted by [35], and the mathematical procedure is:

MP type in the samples/beach = P_i

Risk score/MP polymers = S_i

Number of sampling beaches = n

Polymer hazard index = H_{PHI}

$$H_{PHI} = \sum_{i=1}^{n=Beach\ present} P_i \times S_i \quad (5)$$

Potential ecological risk index: The potential ecological risk index, PERI, is the third approach that was used to evaluate the risk extent possessed by each MP polymer on the beach shore of the Limbe Atlantic Coast of Cameroon. The mathematical assessment is as follows:

Contamination factor = CF

Polymer hazard index = H_{PHI}

Potential ecological risk index = $PERI_{Single}$

$$PERI_{Single} = CF \times H_{PHI} \quad (6)$$

Risk index: The risk index (RI) is the fourth approach that is used to examine the combined potential ecological risk from these polymers within the coastline. The formula for the combined effects is:

If

Single effect of the potential ecological risk index = $PERI_{Single}$

Combined effects of the potential ecological risk index = RI

$$RI = \sum_{i=0}^n PERI_{Single} \quad (7)$$

3. Data Analysis

ArcGIS version 21 was used to map the monitoring beach sampling sites (Figure 1) and with the help of Microsoft Word, the sampling design was also developed. The total abundance of the beach surface microplastic distributions was performed using Microsoft Excel 2010 and drawn using SPSS version 16.0 [38]. Statistical

analyses were carried out at a significant level of $p < 0.05$ for each correlation analysis. Also, for significant effects, the temporal and spatial differences in mean abundance on each polymer type identified (in terms of size, colour shape, and weight) were analyzed with a factorial analysis of variance (ANOVA) test followed by Tukey Pairwise Comparisons test. The mean abundance /concentration of the different parameters (such colours, types, sizes, shapes and weights class) were expressed in Mean \pm STD and in terms of particle/number and particles/gram and as well in percentages.

4. Results and Discussions

4.1. Microplastic Abundance

Microplastic contamination was observed on all the beaches studied. In total, 241 microplastic particles weighing 89.15 g were recorded. LDB 2 had the highest polymer mixture abundance of 74 (30.7%) with PP (31, 9.5%), PE (22, 6.8%) and PS (15, 4.6%) followed by LDB 1 63 (26.1%) with PE (31, 8.1%), PP (17, 4.4%) and PS (10, 2.6%). BTK was the least of 28 (11.6%) with PP (14, 1.2%), PE (08, 0.9%) and PS (03, 0.3%). ANOVA results show a highly significant relationship between beach MP abundance and tidal height (f -value = 6.19, $p = 0.000$ at $p < 0.05$) with LDB1 significantly different from the other beaches. High MP rates in LDB1 and 2 can be attributed to their location in an urban area coupled with the prominence of rivers and drains discharging into this area (**Figure 3**). The beachfront in Limbe is a popular touristic site, hosting restaurants and small vendors selling food and a variety of goods. It was observed that waste from these activities was directly discharged into the sea. The area also plays host to fishing communities and fishermen who dispose of almost all of their wastes into the sea. The assertion that MP found here is primarily sourced from urban activities is supported by the results of an assessment of pollution sources undertaken by six countries in the Gulf of Guinea region (including Cameroon) which reported that over 80% of pollution comes from land-based activities [39]. Furthermore, the State of the Marine Environment Regional Assessment (SMERA) reported disturbing high quantities of litter/km collected from beaches in Cameroon some of which they attributed to current countries, transported through longshore drift to the Cameroon coast. The Limbe coastline can best be described as a cove. Coves are sheltered from the turbulent currents and waves of the open sea and are consequently less disturbed, promoting particle accumulation. May and June had the highest microplastic abundance in terms of both number and weight, with 44 particles/m² (18.19 g) and 50 particles/m² (25.02 g) respectively. These months represent the beginning of the rainy season, when heavy rain typically washes away all the debris accumulated during the dry season into the rivers, drains and canals into the sea. March month had the least microplastic abundance of 9 particles/m² but not in terms of weight, at 3.42 g with a mean concentration of 1.8 ± 1.1 particles/m². Exceptionally, SEM was the most contaminated beach in July, with 45.2%, despite the fact that July was one of the beaches with the least accumulation in terms of

particles, 31 particles/number also the least in terms of weight (12.5%) (**Figure 4(a)** and **Figure 4(b)**). This may indicate the influence of other sources of debris, most likely up currents. Previous studies [40]-[42] have reported that MP can be potentially ingested by sand-dwelling organisms such as crabs, polychaetes, and bivalves, which could be further transferred along food chains and affect human health; LBD1 and LBD2 beaches present the highest risks of this happening (see **Table 3**).

Table 3. Summary statistics on beach type abundance variation of the tide height.

Beach	Mean	STD	One-way ANOVA		Tukey-pairwise comparison test
			F-value	χ -value	Grouping
LDB1	20.53	7.20			A
LDB2	12.06	3.54			B
BTK	8.72	2.16	6.19	0.000	B
SEM	3.819	1.95			B
IDN	5.47	2.34			B

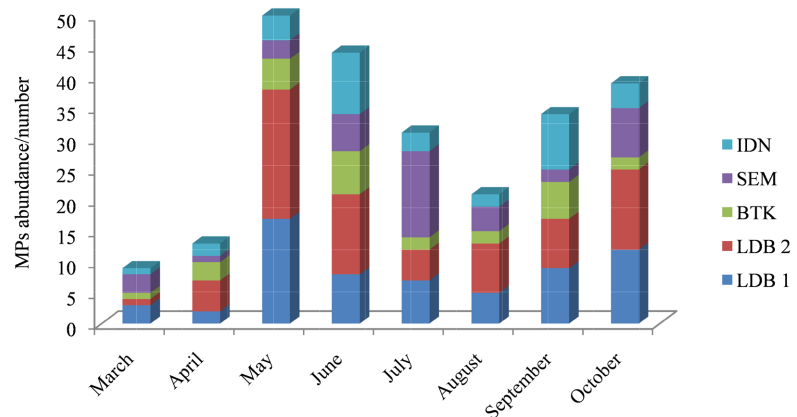


Figure 3. Distribution of the monthly MPs composition along the Limbe-Ide-anu Coastline.

4.2. Microplastic Size Class

MP size analysis indicated a range in size from 0.063 to 1.99 mm dominated by the 1.5 - 1.99 mm size class in terms of particle/number and weight with 102 particles/number and 51.77 g accounting for ~46%. The dominance of a similar class range (1 and 2.8) was reported in a study in California by [43] corresponding to ~61% of the total microplastics. Particle size analysis helps in assessing the shoreline MP threats to biota (/and aesthetic quality), as smaller MPs can be easily engulfed by both terrestrial and aquatic organisms and may also cost billion dollars in remediation [44]. Additionally, these small particles are a cause for concern because their relatively large surface-to-volume ratio makes them capable of adsorbing a wide variety of pollutants [45].

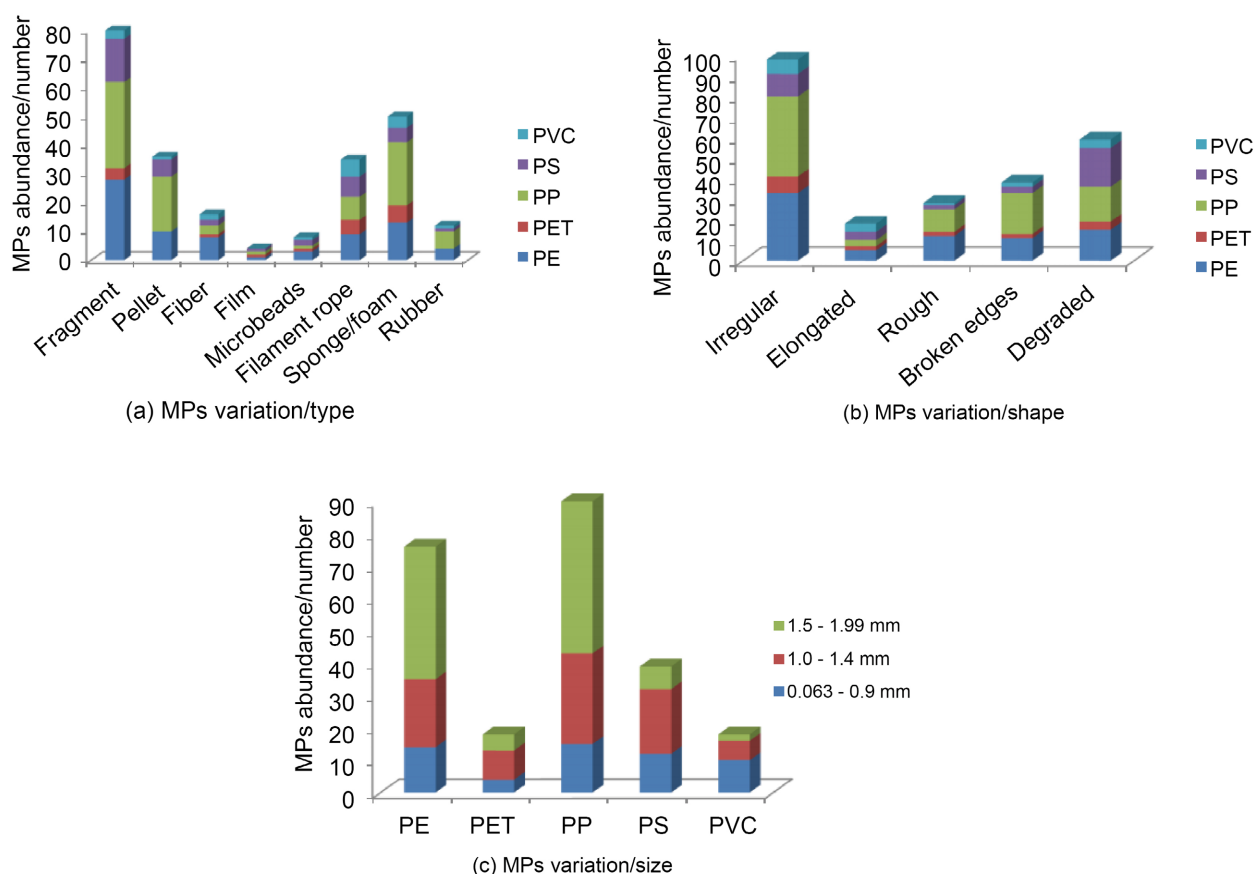


Figure 4. Beach polymer composition in type (a), shape (b), and size (c) along the Limbe-Idenau Coastline.

4.3. Microplastic Shape Class

In total, the irregularly shaped followed by degraded shaped MPs particles had the highest abundance in terms of particles and weight, 98 particles/number (30.5 g) and 59 particles/number (24.98 g) accounting for 40% and 24% respectively. MPs with elongated shapes had the least particle count of 18 (8.51 g) and a mean concentration of 3.6 ± 1.1 particles/number. The highest abundance in irregular and degraded shaped MPs could be due to the disintegration of plastic debris derived from tourism-related activities, household materials, and fishing activities through a combination of mechanical breakdown, photodegradation, and possibly microbial degradation processes along the surf zone. Photodegradation of the polymer matrix leads to bond cleavage which makes plastics brittle, causing them to disintegrate most often into irregularly shaped particles with different fading colours as reported in previous studies [46] [47]. The degraded-shaped plastic is an indication that the fragment has been present in the marine environment for some time and has thus been polished by mechanical and chemical actions. Fragments have been defined as particles with irregular shapes and edges, suggesting an origin in the fragmentation of larger particles, although this is not necessarily true [48]. Adsorption, desorption and ecological effects of MP are influenced by different shapes.

4.4. Microplastic Type Class

Terminologies used in identifying different variations within this category point towards the origin of the particles, for instance, beads and pellets which allude to the use of primary in cosmetics and plastic manufacturing respectively. In terms of beach microplastic type morphology, fragments and sponge/foam typed MPs particles had the highest particle/number abundance, with 80 particles/number (25.25 g) and 50 particles/number (7.59 g), representing 33% and 21% respectively. Fragments were found to be angular, sub-angular, rounded, or sub-rounded with jagged edges or sharp corners, indicating that they are likely to be secondary MPs that had broken off from larger products. Previous studies worldwide have reported the dominance of fragments and fibre [8] [12] [49]. The occurrence of foam/sponge is attributed to the leaching of styrene oligomers present in single-use Styrofoam products (such as cups, plates and plates) used in local food businesses and possibly from the buoys in the ocean, which may detach small amounts of foam debris into the ocean [49] [50]. According to [51] and [52] foams present in the sandy beaches of South Korea and Russia are derived from expanded polystyrene used in aquaculture floats. It is worth noting that only BTK and SEM beaches had substantial amounts or numbers of pellets (**Figure 4(b)**), and these beaches are in close proximity to a petroleum refinery plant (Limbe). Petrochemicals constitute a major source of pellets in the marine environment. Incidentally, MPs as film, fiber and microbeads were more dominant in the <1 mm size fraction.

4.5. Colour Class

The colour of shoreline MPs in the marine environment is of great concern because aquatic organisms have been found to ingest MPs with colorings similar to that of their prey [53] [54]. Microplastics can sometimes show a single colour or an aggregate of colours [55]. Our results (**Figure 5(a)**) show that white, followed by transparent colour had the highest microplastic abundance, 50 particles/number (22.28 g) and 42 particles/number but 13.22 g and in terms of weight, it is the third in rank. Previous studies have reported similar findings [56] [57]. [58] stated that among the 68 studies they reviewed, the most dominant colors were white (or colors related to white) and transparent. The ratio of white and transparent microplastics in this study supports this information. White and transparent colored MP possibly indicates prolonged plastic degradation. Natural weathering, aided by photo-oxidation due to high temperatures, can result in discoloration. As plastics degrade spontaneously, contaminants (additives + dyes) can be leached out from the polymer surface since they are not usually bonded covalently to the polymer matrix [59]. Green colour microplastic had the least particles/number as 9 (2.16 g) mean concentration of 1.8 ± 1.3 particles/m². The array of colors present that is blue, brown, red, yellow and black points to a strong anthropogenic influence on the sources of MP. In addition, color also determines the residence time and extent of degradation in the environment. Different degrees of fading represent

the exposure time of the sample in the environment [60]. Even though the color of microplastics can somewhat indicate the microplastic source (such as white pellets are polypropylene, transparent pellets are polyethylene, etc.), determining the exact sources may require advanced analytic methods. In addition, colour leaching may occur due to the use of oxidative reagents in certain digestive methods. Both factors may contribute to the high level of transparent MPs observed in this and other studies.

4.6. Microplastic Polymer Type Identified

Common polymers detected on marine beach shorelines in other studies worldwide were also identified in our samples (Figure 5(b)). Five different polymer compositions were identified within the study area in all the < 2 mm size fractions of MPs using FTIR-ATR. Generally, the abundance of identified polymer types followed this order: PP > PE > PS > PVC > PET. The total abundance of PP and PE in all sampled beaches were 90 particles/m² (33.42 g) and 76 particles/m² (24.19 g) with a mean concentration of 18.0 ± 7.5 particles/m² and 15.2 ± 10.9 particles/m² respectively. The dominance of PP and PE has been reported in previous studies ([61] [62]). In our study, unlike the previous cases, PP was more dominant than PE. [63], in a review of MP contamination in African waters, identified the relative frequency of abundance as PP > PE > PS. Polypropylene (PP), with low UV and oxidation resistances [11], is used in the fabrication of plastic tools (sports-wear), furnishings (carpets, floor covering and rugs) fishing nets and pipes due to its unique mechanical and chemical properties [64]. Consequently, PP is likely more dominant in the waste stream than PE, which originates from the breakdown of rigid plastics commonly used as the primary material in the production of plastic bottles, bags and films. [64], reported that PP and PE are in high demand annually and are most frequently found around marine environments. The lowest polymer concentration was found in all polymer compositions identified to be polyethylene terephthalate, (PET) and polyvinyl chloride, (PVC) with 18 particles/number each but differed in terms of weight, 7.20 g and 8.13 g respectively. This may be linked to the fact that these denser polymers (PET; 1.37 - 1.45 g/cm⁻³ and PVC; 1.16 - 1.58 g/cm⁻³) [61], tend to settle on the seafloor [65]. The dominance of these polymers in SEM and IDN beaches can be attributed to differences in factors affecting sinking (*i.e.*, sea surface tension, size or particle shape) [65], of these polymers in these zones. In terms of polymer composition and type, PP, PE, and PS polymer were dominant in terms of particle/number in the shape class as follows: irregular (39 > 33 > 11), broken edges (20 > 11 > 3), and in rough (11 > 12 > 2) microplastic particles accounting for 79%. Furthermore, the degraded shaped microplastic particles had PS (19), PP (17), and PE (15) plastic polymer types with an average of 61% dominance in particle abundance on average (Figure 5(a)).

In the individual polymer weight class analysis, 0.01 g weight class had the highest abundance in number (98 particles/number with mean concentration of

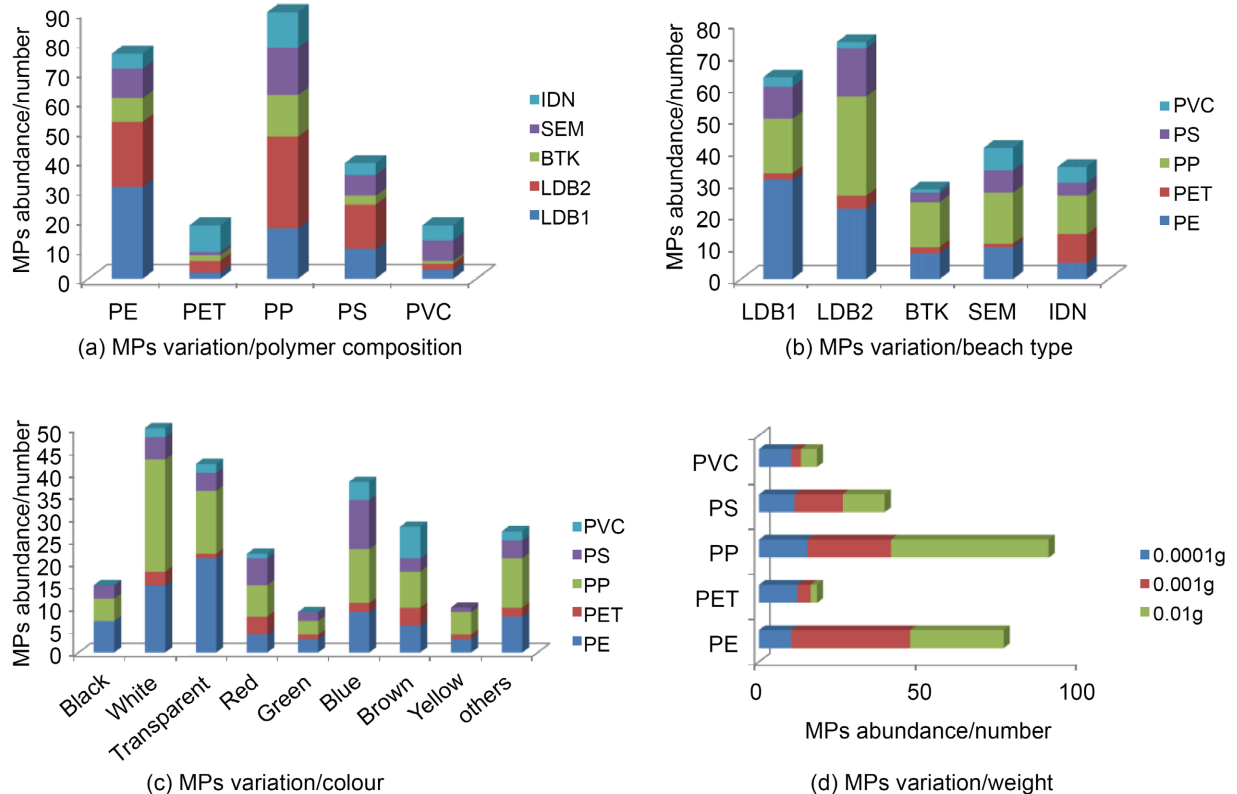


Figure 5. Along the Limbe-Idenau Coastline. (a) beach polymer in colour; (b) polymer type; (c) weight; (d) beach type.

19.6 ± 19.4 particles) and the Limbe Down Beach (1 and 2) sites remain the most affected zone. The 0.0001 g weight class recorded the least abundance in a number of 58 particles/number with a mean concentration of 11.6 ± 2.1 particles. In general, PP, PE and PS polymer types were predominant in the 0.01 g and 0.001 g weighted particles with mean concentrations of 83.3%, 86.8% and 71.8% respectively (**Figure 5(c)**). The constant turbulence of the wind force and storm wave towards the seashore on a daily basis (and this increases during the rainy), gives such weightless floating plastics the tendency to be horizontally transported easily to the beach shoreline and sink due to bio-fouling mechanism; this is a vertical phenomenon.

This has been observed in previous studies (*i.e.*, [58] [66]) and has been attributed to the fact that floating microplastics are weightless particles that might be transported to shore in a shorter time than is necessary for biofouling to cause it to sink into smaller systems like coastal seas (e.g., the Baltic Sea). Uniquely, no black, green and yellow microplastics particles/number were recorded in PVC polymer composition whereas the dominant polymers in blue colour microplastic particles were PP and PS with particle/numbers 12 and 11 respectively. [67], reported the blue alongside white and transparent color MP.

Lastly, in **Figure 5(d)** the irregularly and elongated shaped MPs particles were equally dominant representing 73 particles/number (74.5%) and 11 particles/number (61.1%) in both FWPP (73), OWPP (17), and FWPP (11), IWPP (4)

in decreasing order meanwhile rough, broken edges and degraded shaped MPs particles were also dominant in both OWPP (14), IWPP (9), OWPP (20), FWPP (11) and OWPP (37), IWPP (13) respectively. This might be due to long aging collision processes of larger plastic debris from surface run-off as they meander along channel and canal to surf zones of the beaches most especially in LDB 2 > LDB 1 > IDN [39] [68].

4.7. Ecological Risk Model Assessment

In terms of beach risk factors along the Limbe-Idenau Coastline, LDB 2 (13, 508) is highly contaminated due to the presence of high PE (15) followed by PE (22). LDB 1 (9218) is the second most contaminated as a result of high PS (10) followed by PE (31) whereas BTK had the least contaminated beach (2805) due to the high number of PS (03) and PE (08) when multiplied with their hazard scores as indicated above.

Additionally, the potential ecological risk assessment of the different types of microplastic polymer identified on the coastline revealed that during both dry (587.95) and rainy (504.66) seasons, the risk potential of PET was classified as high (Level III). Across polymers, the contamination factor (CF) during the dry season ranges from category II (3) to category V (12), whereas, during the rainy season, it ranges from category II (2.25) to category V (6). Overall, the CF_{ZONE} shows a category V (5.07), indicating that the contamination threats along the coastline are extremely dangerous to the ecosystem services in this area [57]. The pollution load index (PLI) in the dry season ranges from category II (1.73) to category IV (3.46) while in the rainy season, it ranges from category II (1.50) to category III (2.45) thus PLI_{ZONE} shows a category III indicating medium pollution [69]. Likewise, polymer hazard index (PHI) per month (4.57), in August (7), in July (7), in the dry (2.29) and rainy (2.01) seasons (see Table 4), each shows a category II

Table 4. Risk assessment of microplastics on the beach-shore along the Limbe Coastline.

Polymer	PP		PE		PS		PET		PVC	
S_n	1		11		871		30		30	
Season	D	R	D	R	D	R	D	R	D	R
Dry/Rainy										
P_n (%)	35.10	29.90	6.80	7.80	40.50	35.90	13.50	17.40	4.10	9.00
H-value	3.86	3.29	2.04	2.34	0.41	0.36	117.59	151.55	1.23	2.70
CF	12	4.75	5	6	4.33	2.25	5	3.33	3	5
PLI	3.46	2.17	2.24	2.45	2.08	1.50	2.24	1.82	1.73	2.24
$PHI_{(Season)}$	$PHI_{August} = 7, PHI_{July} = 7, PHI_{Month} = 4.57, PHI_{Dry} = 2.29, PHI_{Rainy} = 2.01$									
PLI_{zone}	2.14									
$PERI_{(Single)}$	46.32	15.63	10.20	14.04	1.76	0.81	587.95	504.66	3.69	13.50
$RI_{(Combined)}$	1198.56									

NB: S_n = Hazard score; P_n = MPs abundance/%; CF = Contamination factor; H-value = Probability for chemical risk.

thus PHI_{ZONE} shows a category II risk factor indicating medium pollution potential but the potential ecological risk index indicates a higher risk factor which ranges from minor (0.81) to extremely dangerous (587.95) category within the coastline [70]. Furthermore, the combined risk index of the coastline shows an extremely dangerous (1,198.56) risk potential to both marine life and humans.

Comparison in the PLI and RI with Other Beaches around the World

Per pollution load index (PLI), Cape Town of South Africa, West Coast of India, and Touristic Beaches of Spain have a higher average PLI value of (10.56), (9.27) and (6.14) which is higher than the Limbe coastline (2.30) but the PLI value of the present study is similar to the east coast of India (3.57), Moheshkhali channel of Bangladesh (2.51) [71], Western Cape of South Africa (2.42) [72], Raquette River of New York, USA (1.78) [73] and Shiwuli River (2.13) [74]. Likewise, the PLI of Limbe coastline (2.30) is higher than the Manas River Basin (0.98). Per risk index (RI), the risk potential of Limbe coastline and Cape Town of South Africa are extremely higher (Level V) than that of the study areas such as the Western Cape coastline of South Africa (Level I), Chagan Lake and Xianghai lake (Level III), Manas River Basin (Level III), Shiwuli River (Level III), and Raquette River of New York, USA [69] [73] [75]-[77] as highlighted in **Table 5**.

Table 5. Comparing the results of this study with other studies in the world.

Research zone	Country	Abundance	Assessment model	Results of assessment	References
Coast of India	India	12.22 - 439 items/kg in sediment	Pollution load index (PLI)	PLI of west coast of India: 3.03 - 15.5 (heavy pollution) PLI of east coast of India: 1 - 6.14 (moderate to heavy pollution)	[78]
Chagan lake and Xianghai lake	China	Chagan Lake: 3.61 ± 2.23 particles/L; Xianghai lake: 0.29 ± 0.11 particles/L	Risk index (RI)	Levels-III (heavy pollution) in Chagan Lake and Xianghai Lake	[79]
Manas River Basin	China	17 ± 4 items/L (April) 14 ± 2 items/L (July)	Risk index (RI) Pollution load index (PLI)	Most of the study areas: Level-III (heavy pollution) All the sampling sites: slightly polluted	[14]
Moheshkhali channel of Bangladesh	Bangladesh	Sediment: 138.33 items/m ² Water: ~0.1 items/m ³	Pollution load index	PLI _{sediments} : 2.51 (heavy pollution) PLI _{surface water} : 1.67 (moderate pollution)	[71]
Shiwuli River	China	Water: Flood season (f.): 8.4 ± 2.5 particles/L Non-flood season (n.f.): 5.8 ± 1.7 particles/L; Sediment: Flood season (f.): 78.9 ± 8.3 particles/kg Non-flood season (n.f.): 63.9 ± 7.1 particles/kg.	Risk index (RI) Pollution load index (PLI)	PS: Level-III in water and Level-II in sediments; Other polymers: Level-I Water: PLI _{zone(f.)} : 2.24 (heavy pollution); PLI _{zone(n.-f.)} : 1.66 (moderate pollution) Sediments: PLI _{zone(f.)} : 2.34 (heavy pollution); PLI _{zone(n.-fl.)} : 1.91 (heavy pollution)	[74]

Continued

Limbe coastline (This study)	Cameroon	Sediment: Dry season: 0.93 ± 0.77 particle/m ² Rainy season: 2.09 ± 1.30 particles/m ²	Risk index (RI) Pollution load index (PLI)	Most of the study site: Level III (High/heavy pollution) Risk index: Extremely danger (Level V) PLI _{Dry} = 2.29 (High) PLI _{Rainy} = 2.01 (High) PHI _{Zone} = 2.14 (Medium)	
Touristic beaches	Spain	Sediment: Summer: 0.34 ± 0.19 particle/g Winter: 0.14 ± 0.09 particle/g	Risk index (RI) Pollution load index (PLI)	All beaches in the study area: Level I (Low pollution) Risk index: Level I (Minor pollution) PLI _{summer} = 2.19 (Moderate) PLI _{winter} = 10.09 (Very high) HI _{zone} = 69.83 Level III (Very high) Most beaches had Level II (Both in sediment and in water) Risk index: IV (Danger)	[77]
Western cape coastline	South Africa	Sediment: 0.36 ± 0.04 particles/g Water: 4.97 ± 0.18 particle/L	Risk index (RI) Pollution load index (PLI)	PLI _{sediment} = 3.85 (Level III) PLI _{water} = 0.99 (Level I) HI _{zone} = 114 (Level IV) Most of the study sites: Level II (Medium pollution) Risk index: Level I (minor)	[72]
Raquette river	New York USA	Sediment: 0.20 ± 0.07 particle/g Water: (20.2 ± 7.86) particles/L	Risk index (RI) Pollution load index (PLI)	PLI _{sediment} = 1.68 (Medium) PLI _{water} = 1.87 (Medium) HI _{zone} = 70.65 (High) Both studied sites: Level II Risk index: Level V (Extremely danger)	[73]
Cape town ocean	South Africa	Sediment: 0.07 ± 0.007 particle/g Water: 2.62 ± 0.41 particles/L	Risk index (RI) Pollution load index (PLI)	PLI _{sediment} = 6.56 (Level V) PLI _{water} = 8 (Level V) HI _{zone} = 905.64 (Level V)	[76]

5. Conclusions

This study's forensic assessment along the Limbe Coast led us to the conclusion that microplastics were found in the five sites studied at varying abundances and concentrations. The concentration of microplastics along the Limbe-Idenau Coastline can be described by coastal morphologies, tidal height, wind action, wave force, and a few features of coastal anthropogenic activity. Overall, 98% of the beaches' MPs were located mostly in the surface layer of shore sand, with the majority of the microplastics identified between the upper and lower strandlines. The accumulation of beach shoreline MPs increased as size decreased, with film, fiber, and microbeads found only in the <1 mm size fractions. In LDB 2, LDB 1, and IDN beaches, around 75% of the average number of beach MPs contamination particles were found. PP, PE, and PS were the most prevalent polymer types across all mor-

phological traits analyzed. The most prevalent particle/number characteristics, as determined by forensic polymer MPs analysis, were white, irregularly shaped, and fragmented, with a size range of 1.5 - 1.99 mm and a weight of 0.01 g, respectively. 65.5% of those were old, weathered plastic particles (OWPP). The ecological risk assessment states that the shoreline presents a major risk to beachgoers, marine life, and the marine ecosystem as a whole because CF, PLI, PHI, and PERI show category III (Level III) risk potential. The majority of the beach microplastic comes from the site or neighboring region, according to the forensic analysis of the contamination pathway. Given that 69% of the MPs particles detected were 15% enveloped with organic materials and that their color could be readily identified visually, the analysis may yield valuable information about the paths of pollution. The PP and PE fragmented MPs are substantial components in the sample and were determined to be sourced from recreational activities and partially from fishing boat installations and repair activities carried out near the beach. Given that the most polluted size ranging class was 1.5 to 1.99 mm, research on how marine dynamics affect microplastic migration should also be done to shed more light on the fate of microplastics in the environment. As baseline material, further study is required to better link sources and MPs pollution.

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Author Contributions

The first and second authors have equally contributed to preparing the study design, material preparation, data collection, and analysis. The whole discussion section of the manuscript is written by the second author. The third author has edited the draft. All authors have reviewed the manuscript.

Ethics Approval and Consent to Participate

The authors have read, understood, and complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors. This study contains no studies with human participants or animal experiments

conducted by the author.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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