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Sampling and Analysis of Microplastics in the Coastal Environments of Sri Lanka: Estuaries of Kelani River to Mahaoya

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Article

Sampling and Analysis of Microplastics in the Coastal Environments of Sri Lanka: Estuaries of Kelani River to Mahaoya

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Abstract: Microplastic pollution (MP) in marine environments around the globe is severe and enough precautions have not been taken so far for its prevention. The focus of this study is to quantify MPs from beach sediment and seawater samples and to identify their distribution and types along the western coast of Sri Lanka from the Kelani River estuary to the Mahaoya estuary. Nine sites along this 42 km stretch were selected and random sampling was employed to collect a minimum of 8 sediment samples from each site between October and December 2021. Water samples were also collected, parallel to the sediments, from the ocean surface. FTIR analysis revealed that most of the MPs found were polyethylene(PE), polypropylene(PP), polystyrene(PS), polyethylene terephthalate(PET), and phenol formaldehyde resin. The mean abundance of MPs varied from 2.0 ± 0.6 items/L to 161.0 ± 15.7 items/L in water samples and, from 3.0 ± 0.3 items/m^2 to 656.0 ± 34.5 items/m^2 in sediment samples. The MPs found were identified in different shapes as fragments (80.2%), pellets (14.9%), fibers (2.7%) and foams (2.5%). Analysis revealed that the beach sediments were contaminated with PS, phenol formaldehyde resin, PET, PP and PE, while surface seawater is dominated by phenol formaldehyde resin, PS, PP and PE.

Keywords: microplastics; coastal pollution; FTIR; Negombo; Sri Lankan beaches

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1. Introduction

Plastics are synthetic organic polymers with features, such as durability and low price that make them perfect for many applications. Unfortunately, the same characteristics that make plastic a perfect material caused it to become a serious pollution [1]. Plastic waste in the maritime environment is a major concern worldwidely [2]. Plastics are the most common waste material found in the marine environment, accounting for 70% of marine debris [3]. This plastic litter can severely impact marine health, with macroplastics causing entanglement and meso and MPs being ingested by marine creatures [4]. MPs are synthetic materials with a high polymer content which are insoluble in water and non-degradable or slowly decomposed in nature [5]. MPs have emerged as a threat to the global environment due to mismanagement [6]. MPs were defined as plastics ≤5 mm in size [7]. According to the size, the plastic particles can be classified into nanoplastics (1 nm-1 mm) [8], microplastic (≤5 mm) [7], mesoplastic (5–20mm), macroplastic (> 20 mm), and megaplastic (>100 mm) [9,10]. MP particles are usually sorted into different forms depending on the observed morphology [11]. Based on the source of origin MPs are divided into primary and secondary MPs [12]. Primary MPs are manufactured intentionally by industries for cosmetics and personal care products like cleansers, scrub(as skin exfoliators) shower gels or toiletries agents [6] whereas secondary MPs occur due to weathering/degradation of plastic residues in the environment by ocean waves, growth of bio-film, sun's radiation, mechanical shear, and thermal oxidation [13]. Examples of secondary MPs are eroded tire particles, abrasion of synthetic textiles during laundry, road markings, marine coatings(protective coating used mainly in the marine environment to protect ships, vessels, tankers, and other materials from saline water), such as anti-fouling and anti-corrosion paints, and city dust [14]

Presently, only 9% of the total quantity of plastic waste generated is recycled or reused; the other 22% is disposed of as garbage, which is classified as ill-managed plastic waste; 50% is disposed of in landfills; and 19% is burned in incinerators [15]. The latter is typically discharged into aquatic or terrestrial habitats. Estimates indicate that 22% of the total created plastic waste indicated above, or around 10% of the plastic trash that is illegally disposed of, ends up in the marine habitat where it will eventually accumulate [16]. Scientists have already issued an alert that by 2050, there will be a greater amount of plastic than fish in aquatic bodies if the current rate of rapid growth in the disposal of plastic waste continues [17]. MPs are so microscopic that they are found in many different habitats [18]. Moreover, they infiltrate organisms via a variety of routes, endangering a range of species and having a substantial impact on the general well-being of ecosystems [18]. Plankton and other aquatic animals are among the many species that can consume microplastics when they find their way into aquatic environments [19]. MPs can enter the environment from a variety of sources, including road runoff, industrial and agricultural wastewater, litter, sewage treatment facilities, and atmospheric breakdown [20]. Since MPs can now be found in all environments including soil, natural waterways, the air, biota, and human bodies, they are a serious problem. Even in places that are protected or regarded as pristine, plastic contamination is evident in almost all aquatic and marine habitats [20–24]. This needs to act as a warning regarding these pollutants' potential hazards and impacts on aquatic life, as well as their dispersion and transport capability, particularly for smaller-sized contaminants [25,26]. Microplastics are abundant in the ocean and can be found from the top to the seafloor. Indeed, some estimates place the number of plastic particles in our oceans at five trillion or higher, with microplastics making up a large component of this total [19,27]. Hydrodynamics, however, also has an impact on the pattern of microplastic dispersion and accumulation in riverine and/or marine environments. When surface longshore currents are present, floating plastics exhibit enhanced transportation ability [28]. Bottom currents may carry less buoyant plastic at lower water depths. Therefore, it is evident from all the variables that have been exposed that the process of MP particle migration and deposition in the ocean environment follows a highly specific and variable pattern, making it challenging to predict its decanting pattern and accumulation dynamics [29].

MP particles have been found widespread in numerous sites: from coastal regions to remote offshore areas. MPs can originate from plastic waste disposed on land or in the ocean, leakage from the transport of goods and preproduction pellets, wastewater treatment plants and fishing activity [30]. One factor is the buoyancy of the plastics; for instance, PE and PP floating on water surfaces due to their lower density [31]. In contrast, PVC and PET have higher densities than water, hence they tend to sink. MPs are widely distributed in the world's oceans [32]. Most plastics are light materials with low density and hence they will float in seawater (density: 1.02-1.03 g cm^{-3}) [33]. In seawater, during its degradation, plastics can have their density modified by processes such as UV rays' action, the leaching of additives, biofouling, and incorporation within marine aggregates. These processes stimulate MPs to sink onto the aquatic environment floor, even if their original characteristics kept them buoyant [34,35]. Floating plastics present higher transportation competence under surface currents. In deeper water depths bottom currents potentially carry less buoyant plastic [7]. Reported concentrations of MPs in water samples have ranged from <1 to several hundred particles per cubic meter [32], but measurements can be inconsistent in terms of sampling methods (device, mesh size, and depth layers), extraction protocols and units of measurements, highlighting the need for scientific conventions and standardizations with respect to sampling and quantification of MPs [32]. Typically, the most abundantly found MP types are fibers, granules, and films [33]. The macroplastics loads in beaches can affect the presence of MPs [32]. MPs are transported from the water column to sediments. So that the significant amounts of plastic litter in beaches and the sea floor are similar to the litter found in the water column, and a large proportion of the debris on the seabed is often plastic [15]. Open oceans favor the density-based segregation of different microplastic polymer types [37]. Only

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denser polymers, like polyesters and acrylics, were higher with depth, while lower density polymers, like polypropylene and polyethylene, predominated in sea surface samples but became less abundant as one entered the water column. Furthermore, some of the most prevalent and resistant man-made plastics are more enduring at the sea surface [37].

Since Sri Lanka is a tropical island, its shoreline is home to a wide variety of ecosystems. In addition, the island is surrounded by offshore coastal areas in the eastern, southern, western, and northwestern regions. Studies have shown that excessive concentrations of MP have been found in coastal sediments, water in marine protected areas [38], marine beaches [39], and marine biota [40] all along the coastline in Sri Lanka. Studies performed to evaluate the amount of microplastics in Sri Lankan waters indicate that the West Coast waters are more MP polluted than the East Coast [41]. Additionally, recent studies were carried out to evaluate the potential toxic elements (PTEs) associated with the concentrations of plastic nurdles, pyrolytic debris, and coastal pollution, as well as the mitigation measures taken in response to the worst maritime accident ever involving a chemical and plastic-boarded container vessel, the MV X-Press Pearl [42,43]. However, most of the data in the local context is insufficiently analyzed and reported. Furthermore, the effects of plastic pollution on Sri Lanka's western coastline region have not received adequate attention.

There is an urgent need for baseline data on MPs in Sri Lanka, particularly in the aftermath of the X-Press Pearl environmental emergency. A fire onboard resulted in the vessel capsizing and losing all cargo off the west coast of Sri Lanka [44]. Nitric acid Leakage was suspected for the onset of fire on 21st May 2021 followed by explosions and the shipwreck sank on the sea bottom after 10 days. This accident is considered as the utmost chemical and plastic based marine disaster from a single vessel ever happened in the maritime history of Sri Lanka [45]. A significant impact was created on Sri Lanka's sensitive coastal environment, local communities and economy through spilled of more than 1,750 tons of plastic pellets which is the largest on record that were stored in the X-Press Pearl vessel with various hazardous substances. Establishing baseline data is crucial for understanding the extent of MP pollution, assessing potential risks to both marine life and human health, and developing effective policies for mitigation. Furthermore, without baseline data it is not possible to determine the full impact of environmental disasters, as no knowledge of existing nurdle contamination is available, or to quantify the success of mitigation strategies. To address the data gap, as part of ongoing research, this work adopts suitable methods to collect and separate MPs from beach sediment and surface seawater samples and to identify their distribution, types, and abundance along the western coast of Sri Lanka from the estuary of the Kelani River to the estuary of Mahaoya. The main estuary points, Kelaniya and Mahaoya located in the west of Sri Lanka, which has an important ecosystem complex. Therein, the distribution, types and abundance of MPs along the western coast from the estuary of the Kelani River to the estuary of Mahaoya in Sri Lanka were investigated while selecting nine sites along a stretch of 42 km (Hendala, Wattala, Uswetakeiyawa, Sarakkuwa, Bopitya, Dungalpitiya, Morawala, Browns beach and estuary of Mahaoya). The coastal area contains a variety of biological and physical resources. Estuaries serve as a nursery ground for ecologically and commercially. As of right now, no research has looked into the presence of MPs in the coastal area along the estuary of Kelani River to the estuary of Mahaoya.

2. Materials and Methods

2.1. Study Area and Sample Collection

Nine sampling sites (A-I, Figure 1) were randomly selected for the study along a stretch of 42 km of the western coast from the estuary of the Kelani River to the estuary of Mahaoya in Sri Lanka with approximately 6 km between each sampling site. Hendala and Wattala sites located near potential MP inputs near Estuary of the Kelani River. Sampling sites were expanded from Colombo to Negombo beach area. Colombo is the capital of Sri Lanka while its densely populated. Ten samples (10) each of surface sea water (1 L) and sediments (1 kg) were collected concurrently from each site (A-I) within 100 m stretch in the intertidal zone (line between high tide and low tide) along the beach during October (Sites A–E) and December (Sites F-I). When collecting sediment samples, a quadrat

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(0.2 m × 0.2 m) was placed on the surface and the sand under the quadrat at a depth of 3 cm was collected. While a stainless bucket was used to collect surface water. Collected surface water and sediments were placed in sample collection glass bottles. The samples collected were labelled with a sample ID, GPS location and date of collection.

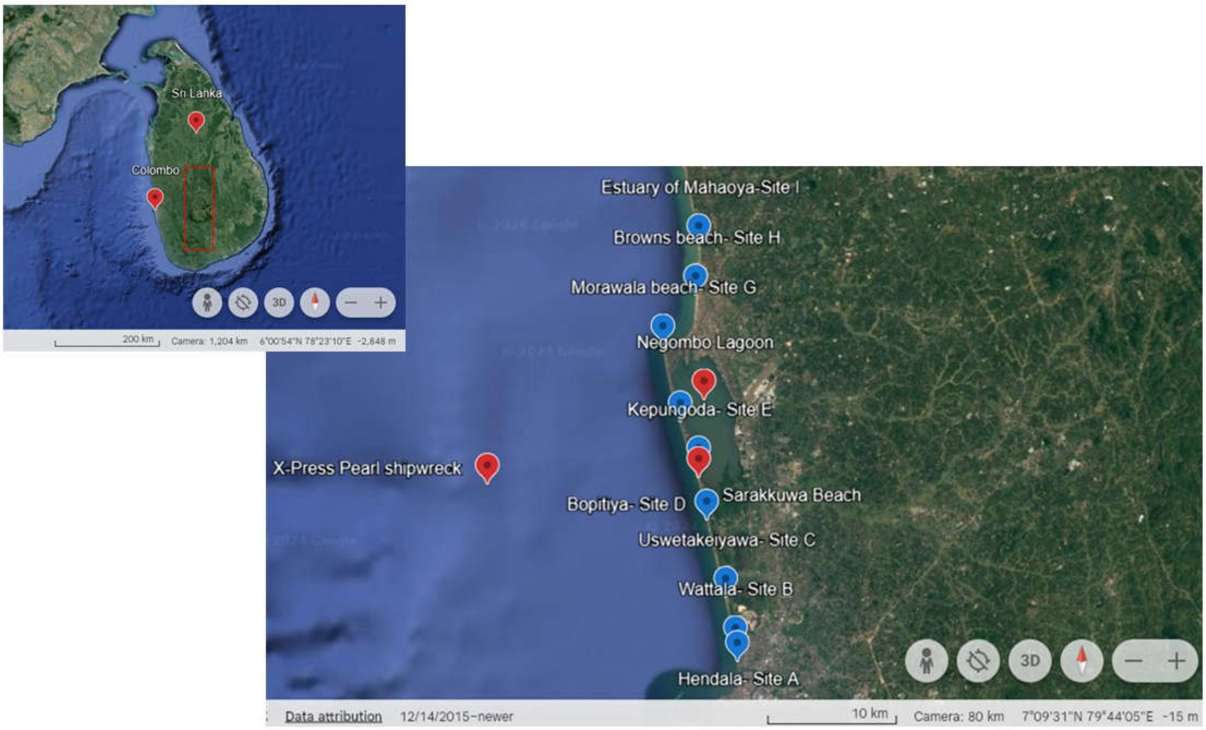

Figure 1. Sampling sites from Colombo to Negombo coastal areas: (A) Hendala; (B) Wattala; (C) Uswetakeiyawa; (D) Sarakkuwa; (E) Bopitya; (F) Dungalpitiya; (G) Morawala beach; (H) Browns beach; (I) Estuary of Mahaoya. Google, Inc. 3D View of western coastal area, Sri Lanka. Generated by Data SIO, NOAA, U.S. Navy, NGA, GEBCO Landsat/Copernicus Maxar Technologies [generated January 16, 2024], using Google Earth [version 10.43.0.2].

2.2. Microplastic Analysis: An improved NOAA Method

The MP analysis was performed using modified NOAA laboratory methods [46] and consisted of five main steps for water and sediment samples separately: filtration and sieving, wet peroxide oxidation, density separation, and MP detection.

2.2.1. Extraction of MPs

Each water sample was poured through a stacked mesh sieve of 5.6 mm (No. 3.5, top) followed by 0.3 mm (No. 50, bottom) [18]. A 0.05 mol L^{-1} Fe (II) solution was added dropwise to the solids obtained from the 0.3 mm sieve fraction. Afterward, 5 mL of 30% H_2O_2 was added to each mixture and left at room temperature for 5 minutes. The mixtures were then heated to 50 °C on a hotplate while stirring for 5 minutes. Next, a 20 mL portion of 5.00 mol L^{-1} NaCl (specific density =1.20 g mL^{-1}) was added. The resulting solids were left to settle overnight in a density separating funnel. Floating solids were collected on a clean filter paper (Whatman No: 42, pore size 11 μm) using a vacuum filtration apparatus (Glass Filter Holder Assembly with stainless steel screen) and subsequently dried in a desiccator.

Each of the wet sediment samples were air dried and 400 g of each sample were taken. A modified NOAA method (section 3.5) [46] was applied. To each sample 250 ml of aqueous NaBr solution (specific density= 1.40 g mL^{-1}) was added. After leaving 20 min for settling, all floating solids were poured on to a 0.3 mm sieve. Any visible material > 5 mm (Organic matter and polymers) were

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removed. Collected solids on 0.3 mm sieve were transferred on to a filter paper (Whatman No: 42, pore size 11 µm) using the vacuum filtering apparatus. In the wet peroxide oxidation step, an aqueous 0.05 mol L^{-1} Fe (II) solution was added drop wise to the solids collected from 0.3 mm sized fraction followed by the addition of 20 mL of 30% H_2O_2. Mixture was allowed to stand at room temperature for 5 minutes and allowed to heat up to 50 °C on a hotplate for 30 min with stirring. Solids which were collected on the filter paper were transferred to a separating funnel followed by the addition of 20 mL of saturated NaBr solution (specific density 1.40 g mL^{-1}). Solids were allowed to settle overnight in the separating funnel. The MPs that were visually inspected in the settled solids, were extracted using forceps. Floating solids were collected on a filter paper (Whatman No: 42, 11 µm).

2.2.2. Identification and Characterization of MPs

Microplastic particles were detected under a stereomicroscope (Euromex StereoBlue SB.1902-P, Euromex Microscopen bv, Arnhem, The Netherlands) with magnification from 10× to 20× directly on the entire filter surface [36]. The extracted MPs were classified into five groups: fragments, fibers, pellets, foams, and films. The Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) spectroscopy (ALPHA Bruker, Billerica, MA, USA) was used for the identification of MPs in the range of 500 - 4000 cm^{-1} with 32 scans and resolutions of 4 cm^{-1}. The percentage of the matching score of the spectra obtained was matched against the polymer databases and was used to confirm the identity of the compound (ATR-FTIR-library complete, vol. 1–4; Bruker Optics ATR-Polymer Library; IR-Spectra of Polymers, Diamond-ATR, Geranium-AT and IR-Spectra of additives, Diamond-ATR). Matches greater than 60% probability were chosen for the MP conformation and polymer identification.

2.3. Method Validation and Contamination Sources

To assess the recovery rates of the proposed method, PVC fragments were added as an internal standard to a known mass of natural sediment sample before the first extraction step. The method validation was done by density separation of sediment samples with NaBr followed by H_2O_2 treatment with PVC fragments as the spiked MPs. In the method validation for KOH & methanol treatment, as an alternative digestion method, sediment samples were spiked with PVC fragments. Then the KOH & methanol treatment Vs H_2O_2 treatment with sediment sample from Site A was done.

Standard Operating Procedures (SOPs) for the collection of sediment samples were developed to ensure reproducibility of sampling [47] to minimize the field contamination during sampling for the time-period. Empty pre-rinsed glass jars were used as field blanks and were open for the time required to transfer a sediment sample. The environmental contamination in the field was assessed with glass jars left near the collection point. This is used as a control sample. Blanks were conducted in each stage during the process. Furthermore, there was no MP identified in atmospheric blanks. Precautions were taken during the field sampling to minimize sample contamination by only opening jars for the minimum amount of time during sample transfer. Throughout the process, cotton lab coats were worn. To check for potential contamination, environmental blanks were also utilized at each stage of the procedure.

2.4. Determination of Pellet Pollution Index (PPI)

Pellets were extracted from sand by density separation procedure. When counting the number of plastic pellets extracted from sand samples, PPI (pellet pollution index) for each sampling point were calculated using the equation 1[45]. This ratio was then multiplied by a correction coefficient p (p = 0.02), arbitrarily determined to conveniently classify the result within a range of 0.0 to 3.0 according to the degree of pollution as follows: very low (0.0 < PPI ≤ 0.5); low (0.5 < PPI ≤ 1.0); moderate (1.0 < PPI ≤ 2.0); high (2.0 < PPI ≤ 3.0); and very high (PPI > 3.0) [48].

$$\mathrm{PPI} = \frac{n}{a} \times p \qquad (1)$$

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where (n) is the number of sampled pellets, (a) is the area (m^2) of sampled sediment and ($p = 0.02$) is the correlation coefficient [48].

2.5. Data Analysis

Percentages of the detected MPs in the samples by the shape, polymer type, and color; the MPs abundance in (items L^{-1}) and (items m^{-2}) were calculated. Since the data from this study were not normally distributed, a Kruskal-Wallis Test was used to evaluate significant differences in MP abundance in sediments and surface sea waters among different sampling sites. Spearman correlation was carried out to determine the correlation between MP abundance in surface sea waters and beach sediments. Furthermore, the association between the category, polymer type, and color of MPs in surface sea waters and beach sediments. All statistical tests and chart designs were generated using IBM-SPSS (IBM Corp. Released 2023. IBM SPSS Statistics for Windows, Version 29.0. Armonk, NY: IBM Corp), MS Excel, and Originpro 8.0. Map diagrams were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

3. Results

3.1. Abundance and Spatial Distribution of MPs in sampling sites

In the hypothesis testing of the independent samples Kruskal-Wallis test, an asymptotic significance (df = 8; $p < 0.05$; test statistic = 8.000) is shown, suggesting that the distributions of MP abundance in sediments and surface sea waters are not significantly different across the sites. In contrast, the hypothesis testing of the independent samples Kruskal-Wallis test displays a significance (df = 8; $p < 0.05$; test statistic = 8.000) that suggests at least two sites differ significantly in terms of MPs abundance in beach sediments. The polymer type and different colors in surface sea waters showed a positive correlation, according to the Spearman correlations ($r_s = 0.344$, $p < 0.01$). However, there was a significant negative correlation ($r_s = - 0.775$, $p < 0.01$) between the polymer type and MP morphology in surface sea waters. While, a positive correlation was displayed between the polymer type and different colors in sediments ($r_s = 0.371$, $p < 0.01$), there was a significant negative correlation observed between the morphology of MPs and between the polymer type in sediments. ($r_s = - 0.100$, $p < 0.01$). Furthermore, a positive correlation was observed between MP abundance in surface sea waters and beach sediments ($r_s = 0.385$, $p < 0.01$).m Figure 2 illustrates the map of spatial distribution of MPs with sizes 1 - 5 mm in the coastal area. The color index indicates the level of distribution of MPs in each sampling site along the estuary of Kelani River to the estuary of Mahaoya. Abundance of MPs varied widely and ranged from 2.5 ± 0.3 to 656.3 ± 34.5 items m^{-2} in coastal areas. The highest MPs abundance occurred in site I (656.3 ± 34.5 items m^{-2}) in estuary of Mahaoya (Figure 3a). Besides, the lowest MPs abundance was detected at site F (2.5 ± 0.3 items m^{-2}) in Dungalpitiya. The MP abundance at all the other sampling sites, (A, B, C, D, E, G, and H) exceeded 10.0 items m^{-2}.

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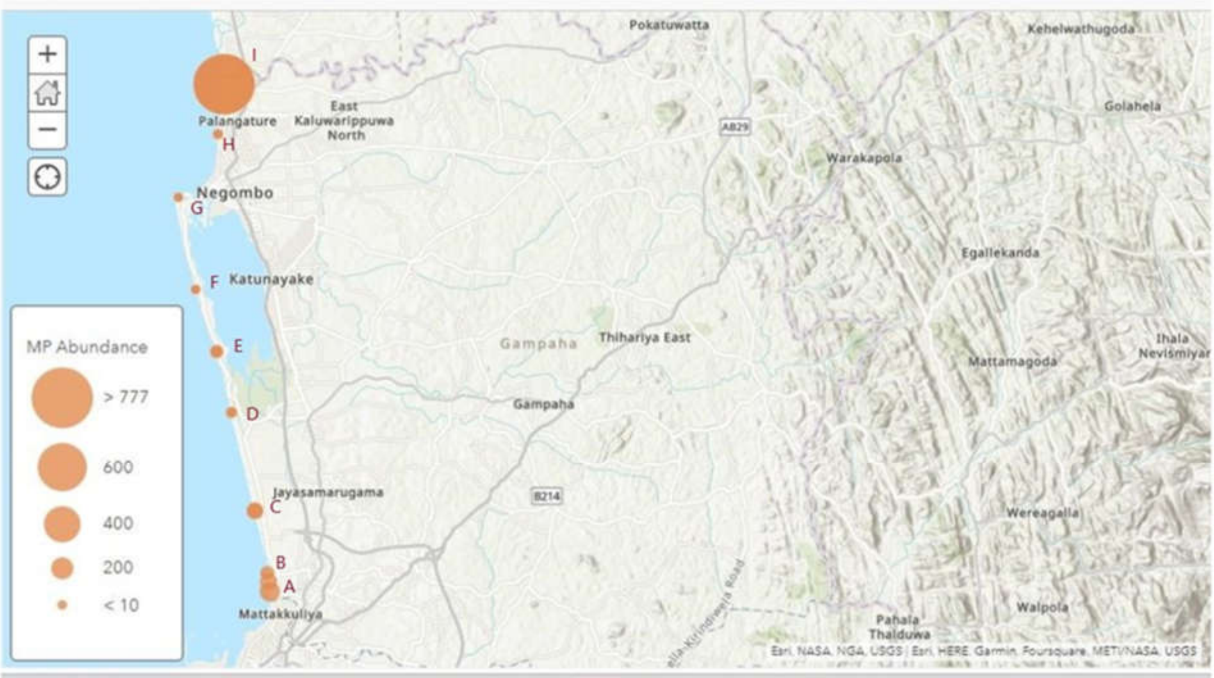

Figure 2. Spatial distribution of MPs along the coastal area investigated. ArcGIS online basemap copyright©Esri. .

Abundance of MPs varied widely and ranged from 2.0 ± 0.6 to 161.0 ± 15.7 items L^{-1} in surface water. The highest MPs abundance occurred in site A (161.0 ± 15.7 items L^{-1}) in Hendala (Figure 3b). Sampling points I, B, and C consisted of a notable higher abundance of microplastics, 121.0 ± 21.7, 63.0 ± 8.3, and 23.0 ± 1.9 items L^{-1} respectively than other sampling points. However, the sampling point D and F showed MP abundances of 12.0 ± 1.2, and 7.0 ± 0.8 items L^{-1} respectively. Among those nine sampling sites, site E and H exhibited an overall lowest abundance in water (2.0 ± 0.6 items L^{-1}). Site G was recorded as having zero abundance of MPs.

(a) (b)

Figure 3. (a) Sampling point at Site I **(b)** Sampling point at Site A.

3.2. Morphology of MPs

In this study, identified MPs were categorized into five groups based on their shape. From the total of 85 sediment samples, 403 MPs and, 391 MPs were detected across 81 water samples. In this study, five irregular shapes of MPs were observed (Figure 4), and identified as fibers, fragments, pellets, foam, and films.

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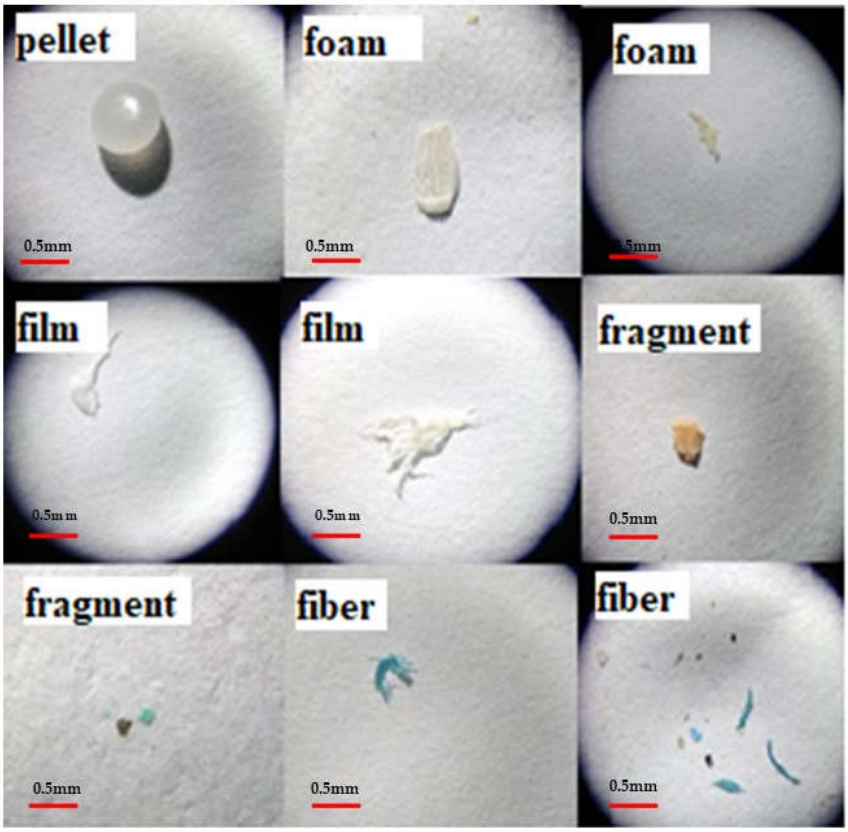

Figure 4. Microplastics recovered from sediments and water samples.

In this investigation out of the identified MPs, 4.2% (fibers), 69.9% (fragments), 72.7% (foam), 50.0% (films), and 100.0% (pellet) in sediments as shown in Figure 5. MPs were observed consisted of 95.7% (fibers), 30.1% (fragments), 27.3% (foam), and 50.0% (films) in surface waters. No MPs with the shape of the pellet were identified in water samples.

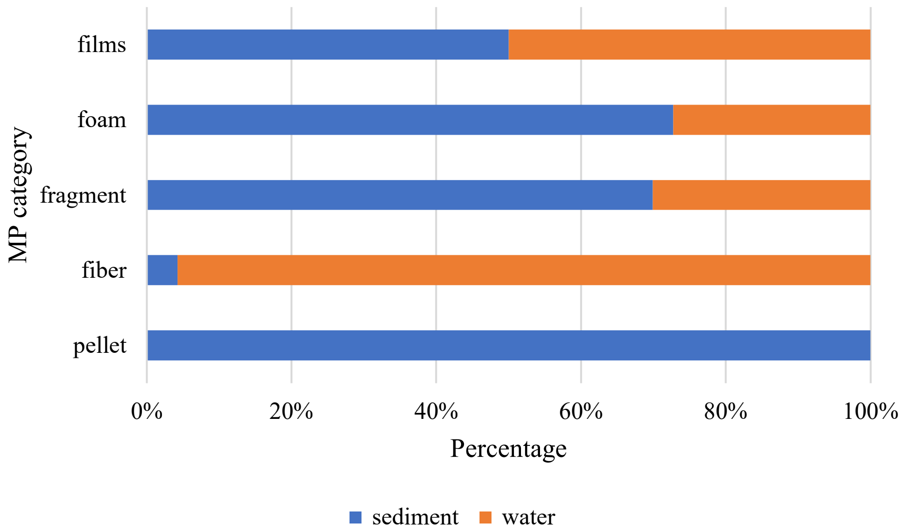

Figure 5. Percentage variation of different shapes of MPs identified from the sediment and water samples.

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More than 50.0% of MPs observed were fragments in sediments, indicating that MPs in the form of fragments dominated at sampling sites. MP pellet distribution ranged from 80.0% (site D) to 17.0% (site H). There were three sites with more than 30.0% of MP identified were fibers (sites B, E, and F) (Figure 6). Although the fraction of foam ranged from 50.0% (site G) to 4.5% (site D) and films were only 2.8%, the total distribution was around 33.0%. More than 50.0% of MPs are fibers in water samples at several sampling sites. There were five sites with more than 30.0% of MP fragments, (sites D, E, F, H, and I). MP foams distribution was 1.0% - 8.0%, (8.3% at site D, 0.8% at site I)(Figure 6). While no MPs were identified at site G.

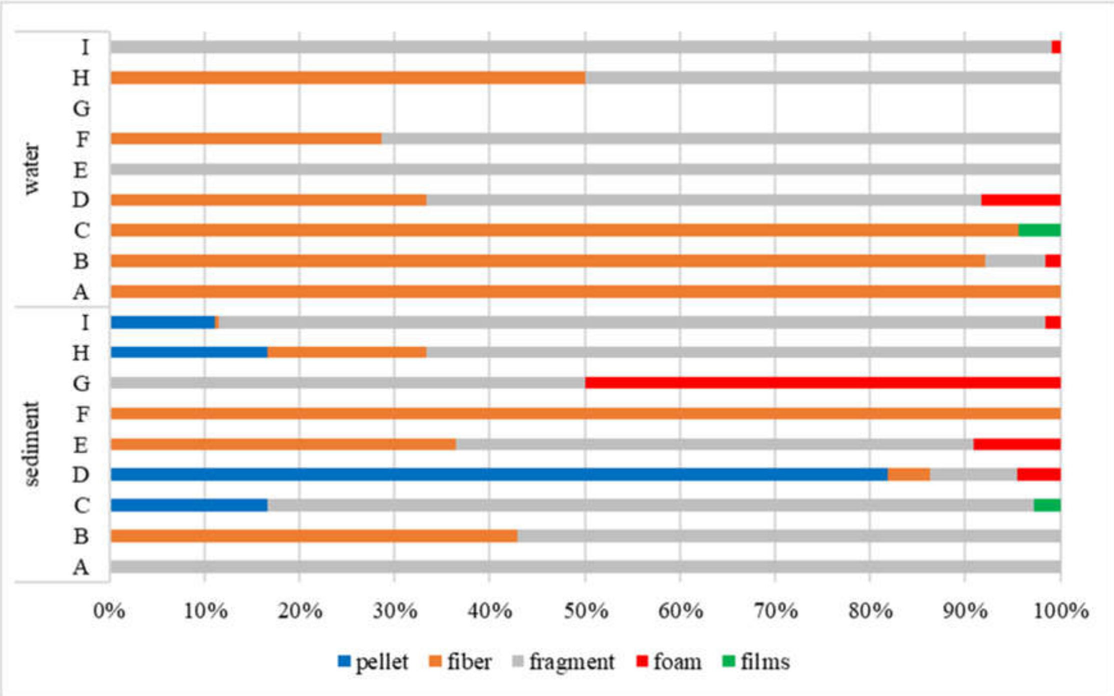

Figure 6. Percentage variation of category of MPs identified in sediment and water samples.

3.3. Color of MPs

Microplastics extracted from sediment samples appeared in different colors (Figure 7); blue (75.9%), followed by white (19.8%), red (1.6%), yellow (1.3%), green (1.1%), and black (0.3%). The distribution of the colors of MP fibers and fragments were present in blue and white colors. The dominant color of MPs fibers was blue (94.5%), followed by white (2.4%), green (1.3%), red (0.8%), and yellow (0.5%) in surface waters. Fragmented MPs, foams and films were the next most abundant categories. The prominent colors of MPs fragments were blue, green, red, and white. 100.0% of MP foams were white in appearance. Films were the least abundant type of MPs and consisted of both white and light pieces.

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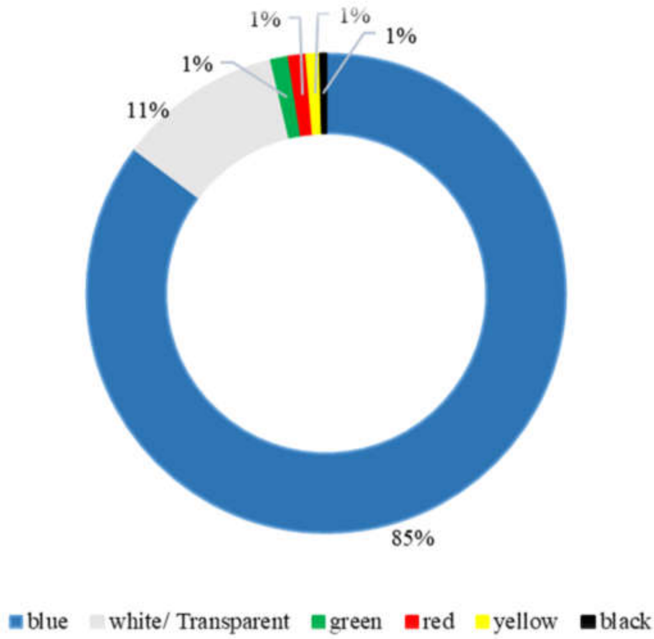

Figure 7. Chart showing color variation of MPs identified in sediment and water samples.

3.4. Polymer Characterization of MPs

PE showed the highest (65.3%) than other common polymer types found, such as PP (15.3%), and phenol formaldehyde resin (4.2%). Also, PET and PS could be found in considerable amounts in sediment samples (2.8%) (Figure 8a). Additionally, other less common plastic materials (9.7%) include HPS (High impact polystyrene), SEBS (styrene ethylene butylene styrene block copolymer), NR (natural rubber), SAN (styrene acrylonitrile) and FEPM (tetrafluoroethylene propylene rubber) were copolymers (Figure 8b). Some pellets were identified as PP beads. Fibers were predominantly PE. Fragments were common plastics of PE, PP, phenol formaldehyde resin and PET. PE showed a higher abundance (60.9%) than other commonly present polymer types such as PP, PS and phenol formaldehyde resin (4.2%) (Figure 8b) in water samples. Additionally, other less common plastic materials (26.1%) include HPS, SEBS, NR, SAN and FEPM.

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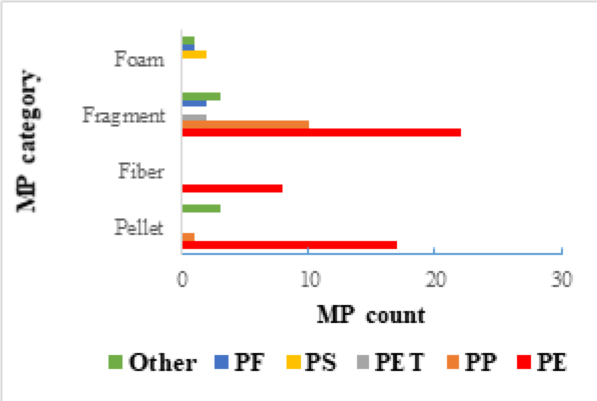
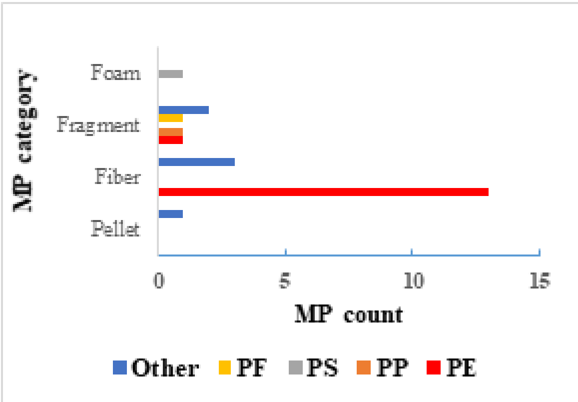


(a)



(b)

Figure 8. Chemical composition of MPs extracted from **(a)** sediment samples **(b)** water samples.

Figure 9 reports the FTIR spectrum of the identified MPs from sediment samples. MPs were identified as PE, PP, PS, and PET.

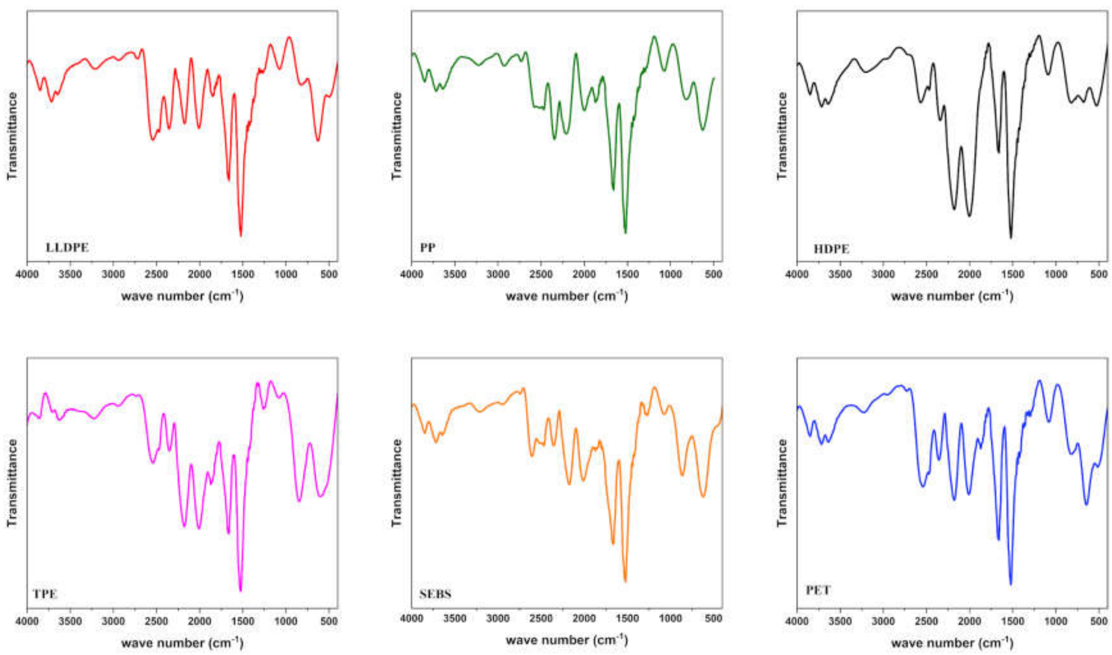


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Figure 9. FTIR spectra of some MPs obtained from sediment samples.

Figure 10 reports the FTIR spectrum of the identified MPs from surface water samples. MPs were identified as PE, PP, and PS, and some were of less common copolymers, such as SEBS (styrene ethylene butylene styrene block copolymer), and SAN (styrene acrylonitrile).

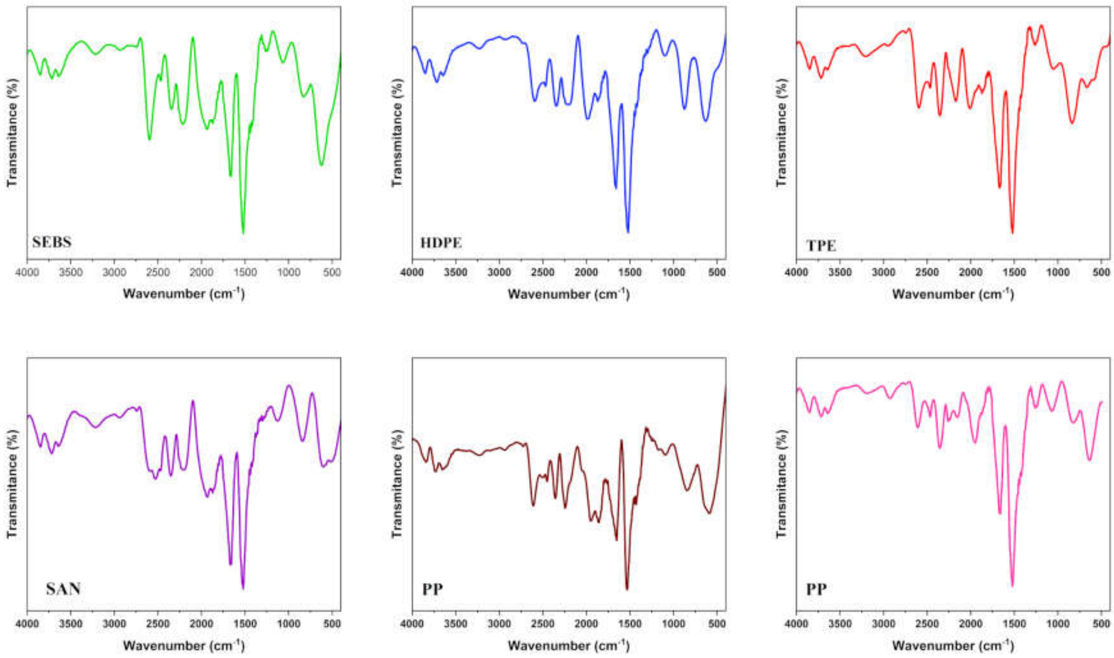

Figure 10. FTIR spectra of some MPs obtained from surface seawater samples.

3.5. Pellet Distribution

Sediment samples from site C (Figure 11a) consisted of pellets in various colors in addition to different secondary plastic debris. Plastic pellets were primarily found in off-white, while a few were found in different colors; brown, and black (Figure 11a). They were identified as medium-density polyethylene (MDPE), styrene ethylene butylene styrene (SEBS), and PP by the FTIR-ATR analysis (Figure 11b) [49]. The FTIR-ATR spectrum of white pellet confirmed the type as MDPE with the characteristic peaks of asymmetric, symmetric C–H stretching, C–H_2 bending deformation, and C–H_2 rocking deformation at 2927, 2852, 1463, and 720 cm^{-1} respectively (Figure 11b). The characteristic peak at 699 cm^{-1} assigned to monosubstituted aromatic band gives the most important indicator to distinguish SEBS copolymer. This confirmed the brown colored plastic pellet isolated as SEBS. Moreover, with the characteristic peaks of CH_2 deformation, symmetric CH_3 deformation, and isotactic polypropylene band (methylene - (CH_2) - rocking band vibration) at 1456, 1376, 1166, and 970 cm^{-1} (Figure 11b) [22,50], confirmed the black colored pellets as PP [23,51]. The chemical changes that occurred on the MPs via radiation, water, oxygen, temperature, and organisms may mislead the identification and may not reveal the exact type they originated from. Hence, the environmental condition to which the samples exposed may affect the analysis [24,52].

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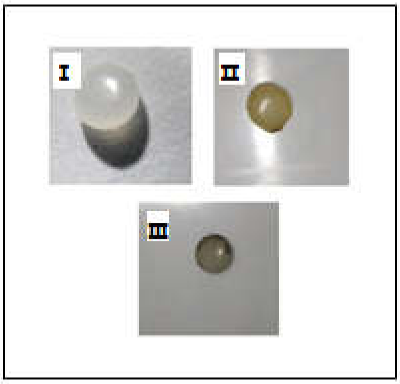
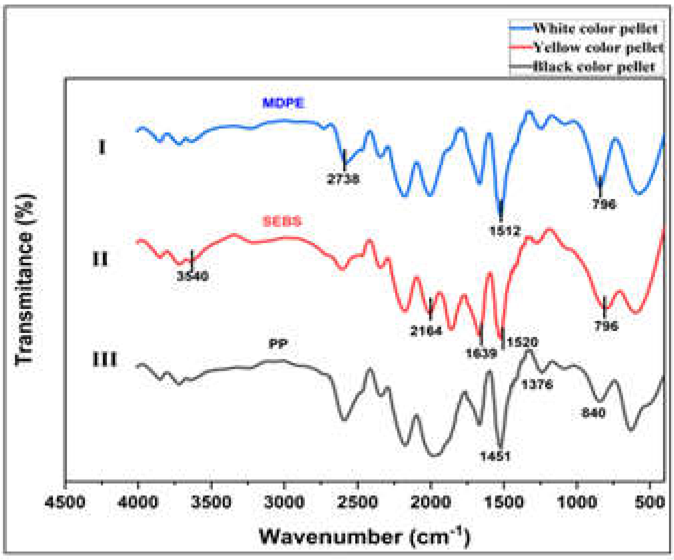


(a)



(b)

Figure 11. (a) Differently colored pellets from beach sediments **(b)**FTIR spectrum of differently colored pellets from Site C.

3.6. Plastic Pellet Pollution Index

Along the coastal beaches from the nine sampling sites, 60 pellets were found within the quadrat (0.20 × 0.20 m^2). The resultant PPI at Site I (estuary of Mahaoya), Site D (Bopitiya), and Site C (Uswetakeiyawa beach) showed a range of very high degree of pollution of 18 pellets per m^2, 9 pellets per m^2, and 3 pellets per m^2 respectively according to the scale developed by [48]. Site G (Morawala beach) shows the lowest abundance with 1 pellet per m^2 and hence, very low degree of pollution. According to this classification, 33.3% of the total of sampled sites show very high MP contamination while 11.1% of the sites fall under the very low PPI category.

4. Discussion

The current research outlined the occurrence of MP debris on the west coast of Sri Lanka. Findings from this project showed notable contamination with MPs in coastal areas along the estuary Point of Kelani River to the estuary point of Mahaoya. More than 50.0% of MPs revealed in surface waters are fibers at several sampling sites having the dominant color of blue (94.5%). Their chemical composition showed a notable abundance (65.3%) of PE than other common polymer types. Their numerous applications in the fishing industry and other fields are responsible for their high abundance. In a similar study of MPs in surface water samples from along the Bay of Bengal coastal stretch of Tamil Nadu, South India evidenced the granular, filamentous, filmy, and tubular fragments in marine samples including those in the marine water column, those found in wet sediment and those found in dry sand. Furthermore, revealed MPs, of which micro-filaments and micro-tubular particles in eight different colors were found, are also used in the production of fishing nets and enter the ocean from fishing vessels [53]. Another study of MP pollution along the Bay of Bengal coastal stretch of Tamil Nadu, South India showed micro-filaments and micro-tubular particles contained polyesters and fluoro-polymers [53]. Fishing materials usually result in micro-filaments. Treated or untreated domestic wastewater, polypropylene materials, fishing materials, and airborne fibers are possible sources of releasing micro-filaments [53].

Local and foreign tourists have a higher attraction towards the segment of the coastline from the Kelani River estuary to Negombo, which is a straight coastline. The accumulation of MP debris in the site of the Kelani River estuary is relatively higher due to a densely populated area and mainly due to recreational activities. Uswetakeiyawa and Browns Beach sites cover over 2 km of the coastal area, and these coastal sites act as popular family-friendly destinations with swimming, diving, and water sports activities. As per the results, overall MP abundance was highest in the Mahaoya estuary site, near Kochchikade has the highest overall MP abundance and thus serves as the next important landmark.

A recent study that was carried out in Marine Protected Areas of Southern Sri Lanka indicated that the fragments were identified as the most common shape of MPs that led to MP pollution in those areas [54]. Furthermore, another study on coastal beaches and waters in southern Sri Lanka revealed that the MP fragments derived from larger debris dominated most sites [39]. Another study focused on the spatial distribution of plastics in coastal surface water from 12 coastal regions in the southern part of Sri Lanka showed that filaments were identified as the majority of MPs followed by films [55]. A recent study of MP pollution of Coral Reef Ecosystems on the Eastern coast of Sri Lanka reported the average abundances of MP in surface water and surface sediments were 11.9±2.0 items/m^3 and 42.2±5.9 items/kg (dry weight) respectively [56]. A study on the occurrence of MPs particles in seafloor sediments along the Arabian Sea and the Andaman Sea recorded fiber had the highest distribution over fragments and pellets [57].

Our reported concentrations are higher than other reported concentrations in neighboring areas in the Indian Ocean. According to our study, MPs are accumulating in sediment instead of water, this will impact longer-term retention of plastics as well as bioavailability. Movement of MPs into the water column from the beach sediments mainly due to tidal waves near the shore. This transports low-density MPs in the offshore mixed with the surface coastal waters. This lateral transportation can be elevated by the direction of the wind, climatic conditions, and anthropogenic activities.

The increment in human population correlates with the plastic pollution in the sampling sites in the Gampaha district in Western Province. Accordingly, improper housing, fisheries, commercial, and recreational activities could lead to plastic pollution through anthropogenic sources along the western coastal belt in Sri Lanka. Morawala Beach is one of the leading fish harbor sites in the western coastal area. Whereas Browns Beach is a famous tourist attraction site in the Negombo coastal zone. Recreational activities like commercial fishing and tourism play a major role in plastic pollution along these sites. Especially, in the Negambo region the vast development in infrastructure facilities in tourism has led to the MPs accumulation along the western coastal belt. Since the western coastal zone is commercially valuable, to have a sustainable coastline area, we need to implement mitigation measures for plastic pollution.

The resulting MP abundance level of the current study was higher compared to previous studies in other coastal regions. A recent study survey on the abundance of marine debris on 22 beaches along the coast of Sri Lanka, revealed there was an average of 4.1 large (> 25 mm) and 158 small (5–25 mm) pieces of debris m^{-2} of the beach [40]. A study on microplastic pollution in coastal beaches and waters in southern Sri Lanka showed MP contamination in sand and 70% in surface waters off the coast [58]. Furthermore, a study on plastics in surface water of the southern coastal belt of Sri Lanka reported that the total MPs density (overall mean MPs density: 17.5 ± 3.4 items/m^3) and where > 45% of the total number of MPs are MP debris of less than 1 mm size [59].

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When comparing our results with previous studies, a study conducted on MPs in beach sediments along the Tanzanian coastline in East Africa revealed the significantly highest abundance of MPs (2972 ±238 particles/kg dry sediment) [60]. Fragments and fibers were found at all sites and polymers were identified as mainly Polypropylene and polyethylene. Studies conducted in the surface waters of the Northwest Pacific, the Bering Sea, and the Chukchi Sea (MPs abundances varied from 0.018 items/m^3 to 0.31 items/m^3, with a mean abundance of 0.13 ± 0.11 items/m^3) [61], the mid-west Pacific Ocean (MP concentration range of 6028- 95,335 pieces/km^2 and a mean concentration of 34,039 ± 25,101 pieces/km^2)(Wang et al., 2020), Northwestern Pacific Ocean (abundance from 6.4 × 102 items km^{-2} to 4.2 × 104 items km^{-2} and an average abundance of 1.0 × 104 items km^{-2}) [64], and South China Sea and East Indian Ocean (4.2 ± 2.5 items/100 m^3 and (0.4 ± 0.6 items/100 m^3) [65] reported MPs contamination with high levels than our current study. When compared to other regions across the world, the MP accumulation along the western coastal area of Sri Lanka is at a low level.

Our current study found that PE was identified as the dominant polymer type following PP and PS. PE is commonly found in water bottles, food containers, bags, pipes, flexible films, ropes, and fishing nets. while PP is a versatile thermoplastic polymer used in various applications mainly in flexible packaging, disposable cups, piping, clothing, ropes, and carpets. Moreover, PS is a synthetic polymer found in protective packaging, food containers, bottles, insulators, styrofoam, and, fishing-related applications. Similarly, PP, PE, and PS polymers are often used as packaging materials (plastic bags, bottles, beverage container caps and drinking straws) and discarded after a short lifetime. Further, Fishing ropes can be made from various polymers including natural fibers and synthetic fibers (such as nylon, PP, or polyester). The composition of fibers was reported as a synthetic polymer made of PP. Recently, the Sri lanka Environment Ministry has banned single-use polythene and plastics products from March 31, 2021, in order to take strategies to mitigate the use of polythene and plastics. The production, and distribution of disposable lunch sheets made of polythene were also banned from August 1, this year.

Similar to the current study, the majority of MPs were identified as PE and PP with some PS foam in coastal beaches and waters in southern Sri Lanka [58]. According to this study, PS was found as a major component in fishery applications and recreational sites. Another study conducted in Marine Protected Areas of Southern Sri Lanka confirmed that PE is the most abundant polymer in plastics [38]. Another study conducted in the Eastern Indian Ocean during the monsoon transition period revealed that the majority of MPs consisted of PP (51.11%) and PE(20.07%). Another study conducted in the Eastern Indian Ocean during the monsoon transition period revealed that the majority of MPs consisted of PP (51.11%) and PE (20.07%) [63]

The current study highlighted color of MPs extracted from sediment samples appeared in different colors (blue, white, red, yellow, green, white, black, and, transparent. Among these blue color dominates following rest of the colors. Blue-colored MPs were highly abundant in this coastal line due to Fisheries, and tourism [59]. The presence of colored MP debris in seawater correlates with the colored plastic materials(textiles, and packaging items). Fishing applications used in fishing activities are one of the major sources of blue colored MPs along the western coastal region. Also, the color categorization of plastics was identified, where colored plastics represent (47%), followed by white, transparent, and black in the surface waters along the west coast, off Colombo Sri Lanka [54]. These previous findings agree with the present study results.

Fibers, films, pellets, and foams can be defined as plastic Pollutants. Monofilament ropes used in fishing activities could be made into films. Synthetic MPs also originated from fishing-related operations, such as restoring broken nets and discarding old nets [68]. Moreover, it is very possible that the fragments originated from activities that happened both on land and in the ocean.

Fiber abundance was higher in densely populated areas due to fishing and recreational activities like microfibers released from fishing nets. Synthetic fiber ropes such as those made from polyester, nylon, or PP, can release fibers into the environment. However, the presence of PP fibers emphasizes the significance of exploring other inputs, such as construction materials, medical applications, thermal wear, and sanitary goods [69]. Fragments can originate from a variety of sources and can

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make their way into coastal areas via household and industrial effluent. PE and PP are the most identified plastics predominant in surface sea waters of areas investigated. Their high abundance is attributed to their extensive uses in the fishing industry and others. The blue PP fiber was like those in seawater suggesting a potential association with the fishing nets in pollution created by MPs. The copolymers, resulting from the combination of two or more types of monomers were also found to be in sediments and seawater suggesting a potential trend of growing environmental prevalence for these compounds. This observation can be a sign of new practices being used in the production of different kinds of plastic items. In light of changing plastic consumption patterns, it is important to recognize and address the existence of these copolymers for responsible use and environmental protection [70]. Findings showed that most of the raw materials for fishing nets, ropes, and trawls used in fisheries in the ocean may be the main origin of the identified MPs in coastal regions. Synthetic fabrics are the primary source of MPs in the ocean, accounting for 35 % of the entire volume. 60 % of the fabric content of our clothing is made mostly in the form of plastic, such as polyester, nylon, acrylic, and other synthetic fibers.

Monsoonal conditions and anthropogenic sources affect the distribution of MP in both ways, indirectly and directly. The area up to the mouth of the Kelani River is thickly populated with a dense network of roads and buildings that play a major role in MP debris accumulation in these coastal regions. As was previously mentioned, climatic factors influence the spatial distribution of MPs. The level of abundance of MPs is significantly high in December followed by October due to climatic factors. Southwestern parts of Sri Lanka experienced the best weather conditions from October to December. The period between mid-October and December generally offers the most favorable, pleasant, and perfect weather conditions. Moreover, December is considered the peak season, attracting visitors to the western coast of Sri Lanka. Therefore during December, a significant rise in the tourism and other fisheries activities led to a rising accumulation of plastic debris in these areas.

Similar to the current study, MPs were recorded with a significantly higher abundance (± SE) of total plastics (0.30–100 mm) found at Wellawatta (229.40 ± 46.39 items/m^3) in surface seawaters, along the Uswetakeiyawa, Kerawalapitiya, Dikowita, Modera, Kollupitiya, Bambalapitiya, and Wellawatta along the west coast, off Colombo, in August, October, and November 2017[54]. Furthermore, a recent study on the abundance of Pelagic MPs in surface water of the Eastern Indian Ocean during the monsoon transition period conducted in 2020 revealed that the MP density varied from 0.01 items/ m^2 to 4.53 items/ m^2, with an average concentration of 0.34 ± 0.80 item/ m^2[55].

These studies outlined MPs as a major threat to plastic pollution along the west coastal belt. However, it is worth to implement reduction strategies to overcome this issue in the western coastal belt of Sri Lanka.

The existence of several types of MPs indicated that the beach and surface seawater were contaminated with waste based on diverse plastics, disposed of by anthropogenic activities mainly from fishing, and human recreational activities. Most of the identified MPs were commonly used as packaging materials (food containers) and fishing nets which were used by humans in their day-to-day activities. Hence the extracted MPs from the beach sediment and surface sea water would be secondary MPs originating from anthropogenic plastic sources. Plastic pollution is a serious worldwide threat to marine and coastal environments, with a range of negative social and economic effects. The impact includes higher costs for maintaining and replacing damaged fishing equipment and boats, costs associated with environmental cleanup efforts, a reduction in the scenic value of the coast that affects tourism, and a decrease in the fish harvest. In addition to being crucial for the environment, addressing plastic pollution is also essential to maintain the economic well-being of maritime communities and protect aquatic ecosystems [71].

One important sustainable technique for reaching the zero waste target is to promote sustainable goods and containers together with customer responsibility. Recognizing the amount of plastic that enters the world's oceans, seas, and coastal zones seas mainly relies on scientific investigation. A world free of plastic can be achieved by implementing effective site-specific management strategies, which are made possible by extensive research on various aspects of plastic production, waste management, and the effects of plastic pollution. We think that by employing site-specific control

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techniques, plastic accumulation along the western coastal region of Sri Lanka could be sustainably performed, creating cleaner, plastic-zero ecosystems. The findings of this research could be used as baseline or reference information for upcoming investigations and development of coastal and marine plastics subsiding programs. Significant amounts of plastic were detected across various marine environments in Sri Lanka, highlighting the urgent problem of severe MP contamination along the country's coastline and beaches. Prompt response and careful investigation are required in this case. Moreover, the X-press pearl ship accident which occurred on the 21 st of May 2021 marked the worst maritime disaster in Sri Lanka's history. Despite all of these concerns, the current work reveals valuable information about the distribution and composition of MPs across a key coastal area, providing insights into the severity of plastic pollution. The results highlight the critical need for efficient strategies to mitigate and control plastic pollution to protect the marine ecosystems and coastal areas of Sri Lanka. This research provides essential data for making decisions and taking actions targeted at addressing the challenges posed by MP contamination in the region.

5. Conclusions

This research was executed to measure the abundance of MPs in sediment and water samples collected along the western coast from the estuary of the Kelani River to the estuary of Mahaoya selecting nine sites along a stretch of 42 km during October 2021 and December 2021. The visual sorting of suspected MPs were identified in different shapes as fragments, pellets, fibers, foams, and films. Most of MPs were identified as synthetic polymers of PE, PP, PS, PET, and some fewer common types of copolymers of SEBS (styrene ethylene butylene styrene block copolymer), and SAN (styrene acrylonitrile). Non-plastic materials were also found in samples such as cellulose (cotton), sulfur, PA (polyamide) and Ambicat LE 4472, crosslinking catalyst. The FTIR analysis revealed that the beach sediments are mainly contaminated with PE (65.3%) and PP (15.3%) while surface seawater contamination is dominated by PE (60.9%) and PP (4. 3%). An unusual abundance of pellets found in coastal areas could be due to the X-Press Pearl disaster that happened in May 2021. Sarakkuwa beach showed this unusual abundance which was found to be a victim beach area after the spill.

The wet peroxide oxidation (WPO) which was applied in this study, is an efficient method according to the NOAA guidelines [18], however some samples were found to be deteriorated by H_2O_2. Therefore, an alternative digestion method was validated by using KOH and methanol. But it was not as efficient as WPO. As there was no other efficient method available for digestion, it is recommended to follow the WPO method in future studies. Overall, the highest MPs abundance occurred in site I (in the estuary of Mahaoya). Besides, the lowest MPs abundance was detected at site F, and G (in Dungalpitiya and Morawala beach). The MP abundance at all the other sampling sites, (A, B, C, D, E, and H) showed notable abundance.

As was previously discussed, the spatial distribution of plastic waste is caused by anthropogenic sources and climatic factors, mainly monsoonal actions. Therefore, it is crucial to have a systematic, long-term monitoring methodology of plastic pollution to figure out changes in the patterns of plastic debris distribution. The accumulation of plastic waste along the western coastal area is primarily caused by human sources in addition to environmental and climatic factors. Specific rules and regulations have been put in place to protect this environment. The results from this study supported the argument that beach sediments and surface seawater represent suitable matrices for the monitoring of microlitter (including MPs). This allows for future assessments at a national remediation measure and at a regional level to allow for some regional action plans. Further research is needed to investigate the impacts of MPs on marine organisms and to determine the ecological impact on the ecosystems. It is important to determine the underlying processes and pathways e.g., the effect of monsoon currents on the distribution of MPs, because it supplies important information to define measures.

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Silva and, A.A Deeptha Amarathunga, A. Bakir, D. B. Sivyer and C. Reeve; Data curation, P.G.Y.W.Weerasekara and A. Bakir; writing—original draft preparation, P.G.Y.W.Weerasekara; writing—review and editing, D. S. M. De Silva, R.C.L. De Silva and, A.A Deeptha Amarathunga, A. Bakir, A. McGoran, D. B. Sivyer and C. Reeve; visualization, P.G.Y.W.Weerasekara; supervision, D. S. M. De Silva, R.C.L. De Silva and, A.A Deeptha Amarathunga; project administration, D. S. M. De Silva, R.C.L. De Silva, A.A Deeptha Amarathunga, D. B. Sivyer and C. Reeve; funding acquisition, D. S. M. De Silva. All authors have read and agreed to the published version of the manuscript.".

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