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Abundance, Distribution, and Characterization of Microplastics on Two Recreational Beaches in Kota Kinabalu, Sabah, Malaysia

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Abstract: Currently, there is a lack of assessment of the level of microplastics (MPs) pollution on recreational beaches around the world. Therefore, this study was conducted to determine the current state of MP pollution on two popular recreational beaches of Kota Kinabalu, Sabah, namely, (1) Tanjung Aru Beach and (2) UMS ODEC (Outdoor Development Center) beach. MPs from the sediments were extracted using the density separation method and analyzed through a stereoscopic microscope. The overall MPs abundance, weight, size, colors, and polymer types were recorded. Tanjung Aru beach recovered higher numbers of MPs particles for all stations, with 857 MPs/kg dry sediment with a total mass concentration of 57.72 g/kg, while UMS ODEC recorded 160 MPs/kg particles with a total mass concentration of 17.96 g/kg. The maximum MPs abundance was observed in the size of <1 mm with a high proportion of white/transparent coloring. Micro Fourier Transform Infrared Spectroscopy (FTIR) analysis revealed that polypropylene (PP:60%) and polyethylene (PE:43%) were the two most common plastic polymers found on both beaches, followed by polyethylene terephthalate (PET), and the least common was polystyrene (PS). Metals (arsenic, chromium, copper, and nickel) were found within the MPs collected. The present study demonstrated an alarming quantity of MPs on two recreational beaches in Kota Kinabalu, Sabah, Malaysia. However, information concerning the primary sources, local dynamics, and repercussions of MPs in this location is still limited; thus, further research is required.

Keywords: microplastics; recreational beaches; sediment; polymer types; morphology

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1. Introduction

Plastic debris is now recognized globally as a major environmental issue aggravated by excessive production and improper disposal. Plastic has been used widely on a daily basis in the packaging of foods and drinks, and in medicinal, industrial, and construction applications [1]. This persistent solid material has been disposed into the marine environment through channels of water or domestic and industrial outfalls. A previous study by Osman [2] showed that the primary sources of MPs on beaches come from plastic debris fragmentation, plastic litter, synthetic fibers such as polyester, nylon, and tiny fibers shed during washing, and microbeads in personal care products such as face scrubs and toothpaste. Under the influence of wind, waves, and ocean currents, plastic debris floating on the ocean's surface is swiftly transported to the shoreline, where it is repeatedly stranded and accumulated [3]. The chemical and mechanical degradation of plastic debris is promoted by saltation and vulnerable to embrittlement due to ultraviolet light, tidal erosion, and biological activities which can break down into plastic fragment sizes including MPs [4]. Currently, most plastics discovered in the ocean are MPs (<5 mm), and MPS are a dominant component of ocean pollution, threatening marine life through consumption

and/or entanglement [5]. Recent studies suggest that MPs pose a greater threat to marine organisms than larger-sized plastics, as organisms at lower trophic levels, such as plankton, are especially susceptible to MPs ingestion, with subsequent effects on organisms at higher trophic levels due to bioaccumulation [6]. Furthermore, MPs frequently contain dangerous chemical pollutants such as organic pollutants or plasticizers which can enter sea turtle eggs via osmosis, affecting embryonic development, lowering hatching success, and ultimately endangering population sustainability [7]. Due to the unique surface characteristics of MPs, such as tiny size, porosity, large specific surface areas, and high hydrophobicity [8], it is easier for MPs to absorb and accumulate heavy metals in aquatic environments. The absorption of heavy metals by MPs could have potentially toxic effects on aquatic biota, such as changing the photosynthesis of algae [9,10] and the growth and reproduction of certain aquatic organisms [11,12], which would spread up the food chain and put human health at risk. According to Duncan [13], the presence of MPs in sea turtle nesting grounds may alter hatching success and sex ratio. In 1997, the State Government of Sabah, Malaysia issued the legislation of Wildlife Conservation Enactment on the ban on turtle egg consumption and trade [14]. A national ban will ensure full protection of all marine turtle species throughout Malaysia. Therefore, it is vital to examine MP pollution, especially on recreational beaches that are extremely crowded during the tourist season and are particularly vulnerable as they are areas of plastic accumulation. In the present study, we investigate the abundance and distribution of MPs in sediment on two popular recreational beaches in Kota Kinabalu, Sabah, namely, Tanjung Aru Beach and UMS ODEC (Outdoor Development Center) beach. The data obtained provide new information regarding MP pollution and encourage the establishment of national plans to propose effective ways to alleviate this problem, with the goal of reducing the impact of plastic debris on the marine ecosystem.

2. Materials and Methods

2.1. Sampling Area

Kota Kinabalu is the state capital of Sabah, Malaysia, and is located on the northwest coast of Borneo, facing the South China Sea. It is a tropical country with uniform temperatures, high humidity, and copious rainfall [15]. Situated at equatorial doldrums between roughly 4° N and 7° N, under the monsoon and typhoon belt, Sabah is often referred to as "The Land Below the Wind" [16]. Due to its topography, Sabah has varied climate zones, and unevenly distributed seasons, but generally, only two seasons are distinguished, a dry one and a rainy one. The rainy season starts in November, with the onset of the northeast monsoons in Peninsular Malaysia, and ends towards April. The northwest coast of Sabah experiences a rainfall regime in which the primary maximum occurs in October and the secondary occurs in June. Tanjung Aru Beach, located near the west coast of Kota Kinabalu, is one of the most iconic attractions in Sabah [17]. It is approximately 6 km from Kota Kinabalu city. The beach is 3 km in length. The entrance is freely accessible to the public, making it one of the most popular tourist destinations for getaways. Meanwhile, Outdoor Development Centre (ODEC) is among the landmark beaches for the University of Malaysia Sabah [18]. It is a private beach managed by the University of Malaysia Sabah and only accommodates 300 visitors per entry. It is situated 13.5 km from Kota Kinabalu city. It is a location where an outdoor activity, such as a picnic, beach sport, or retreat program, can be held. These workshops and regular leisure activities are not open to the general public. However, both study sites provide pristine beaches with magnificent views and are well known for their diversity of marine life. Figure 1 shows maps of Tanjung Aru and ODEC, UMS beach, in Kota Kinabalu, Sabah Malaysia.

2.2. Sample Design and Data Collection

Sampling was carried out during November and December 2022, which was the peak tourist season in Sabah. Each sampling site was geographically located using GPS (Global Positioning System). A total of 6 stations were selected: 3 stations at Tanjung Aru Beach and 3 stations at UMS ODEC beach. Each station was located 100 m apart from the next chosen

station, with a 30 m transect along the intertidal zone of each site. The sediment sample (2 kg) was taken within a 20 cm × 20 cm square frame [19]. Sampling was conducted in the low tide line (line of deposition from high and low tide). At each sampling site, three samples of sediment (triplicates) were taken using a stainless-steel scoop at a depth of 3 cm below the surface, while visible MPs were collected and placed in a glass jar to be inspected. All equipment and glasses were carefully cleaned with water before use to avoid plastic contamination. To prevent airborne plastic particle contamination, all glassware and stainless-steel containers containing sediment samples in the laboratory were covered with aluminum foil for preservation [19].

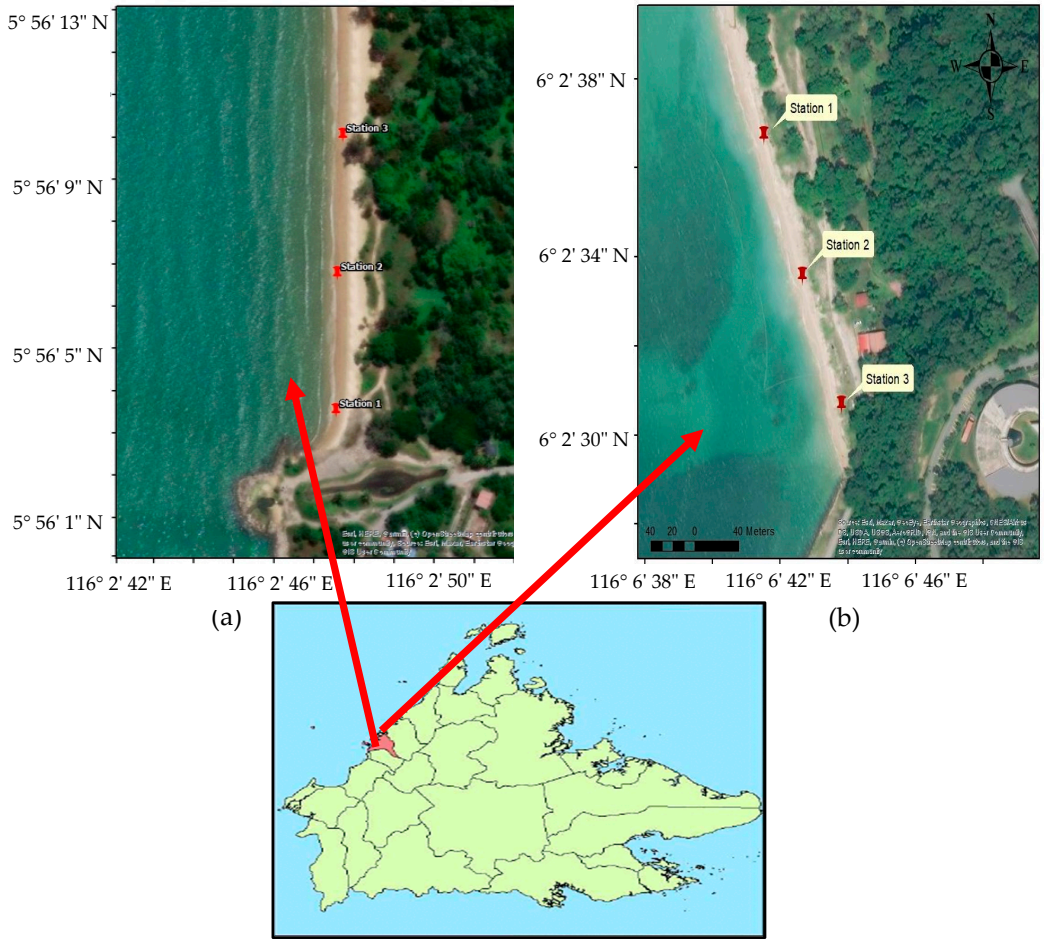

Figure 1. Sampling sites on two different beaches in Kota Kinabalu, Sabah, Malaysia: (**a**) Tanjung Aru Beach and (**b**) UMS ODEC beach.

2.3. Quantification of Microplastics in Sediment

In the laboratory, all sediments were dried at room temperature. A stainless-steel sieve with a 1 mm mesh was used to sieve the dried sediments [20]. Plastics that were collected and sieved from the sediment were then classified as MPs (less than 5 mm) and deposited in separate glass jars for polymer classification. Stainless steel tweezers were used to pick up various sizes of plastics that remained on the sieve, which were then visually sorted and quantitatively measured for size and weight. Plastics with a thickness greater than 5 mm were not accepted for the study [21,22]. All plastic particles were classified according to their morphological characteristics (sizes, shapes, and colors). Material fractions less than 1 mm were submitted for the extraction of MPs using the density separation method [23]. We used saturated sodium chloride (NaCl) with a density of 1.2 gcm^{-3} [19]. A total of 450 mL of NaCl was added to the 100 g dry sediment and stirred for 3 min. Then, up to 0.5 cm from the flask mouth, salt water was added. The buoyant particles were isolated

by pouring 50 mL NaCl into the mixture after it had been left standing overnight. Using a vacuum pump, the supernatant was then passed through a glass microfiber filter with a pore size of 1.2 mm. To remove NaCl solution residues, the filtered products were rinsed numerous times with prefiltered distilled water. The filter paper was dried for 24 h at 27 °C. All filtered particles were examined under a microscope to determine the number of MPs present [24]. To estimate the potential laboratory contamination, we conducted a blank. We used 200 mL of the same filtered, saturated salt solution without sand following the same procedure. This was repeated for each set of replicates.

2.4. Microplastics Detection

The physical characteristics of microplastic particles such as weight, size, shape (foam, fragments, pellet, fiber, and line) [25,26], and color were recorded. For morphological features, the microplastic was observed under a stereomicroscope (LEICA WILD M8, Switzerland) at 50× magnification with a micrometer eyepiece and an accessory UV light. Images were captured and then enhanced for suitable brightness and contrast. The polymer type of all 1017 MPs was identified using a micro-Fourier Transform Infrared (u-FTIR) spectrometer (Model: Brucker). The samples were then scanned in 4000–450 cm^{-1} wave number [19]. The data were present in the form of spectrum peaks output from the scans expressed as%T. The results were identified with online polymer spectra databases from the libraries.

2.5. Heavy Metal Analysis in Microplastics

Heavy metals (As, Cr, Cu, and Ni) were evaluated after MPs were digested. The acid digestion method was carried out with a 95–97% sulfuric acid and a 65% nitric acid mixture [27]. The plastic polymer types were segregated into distinct porcelain crucibles after the MPs were separated according to their polymer types. The samples were weighed to a precision of 50 mg. Then, 2 mL of 95–97% sulfuric acid was added to each sample in the porcelain crucible with a lid. The sample was heated on a hotplate in a fume hood to the maximum temperature setting until an oil-like dark-colored liquid formed. The black carbon was next digested by adding two to three drops of concentrated (65%) nitric acid to the boiling liquid. Digestion was continued by adding nitric acid drop by drop until the solution became a clear liquid and dense white fumes developed, indicating that the digestion was complete. The sample was then chilled to room temperature once the digesting process was completed [19]. The polypropylene centrifuge tube was filled with 5 mL ultrapure water for post-digestion treatment. The tube was filled with the cooled extracts. The contents of the crucible were washed with ultrapure water before being put into the tube and this process was undertaken three times. Screwcaps were used to close the tube tightly [18]. The extract was put into a syringe with a 0.45 um nylon membrane and filtered into a new set of sanitized 15 mL polypropylene centrifuge tubes, which were then topped up with ultrapure water to the final volume (12 mL), making them ready for instrument analysis. Inductively coupled plasma-optical emission spectrometry (ICP-OES; Optima 5300 DV, Perkin Elmer) reading, the volume of dilution factor, and the weight of each sample were used to calculate the heavy metal concentration [19]. The concentrations of heavy metals were determined using Formula (1).

$$\text{Concentration of heavy metal } (\text{mg/kg}) = \frac{\text{ICP-OES reading}}{(\text{Each average concentration metal})} \times \text{Dilution factor} \Big/ (\text{Weight of sample}) \quad (1)$$

3. Results and Discussion

3.1. Microplastics Abundance

The abundance of MPs in the sediment sample for each station was recorded by the number of MPs and total weight found (Table 1). The most abundant MPs were observed in Tanjung Aru Beach (S1), with a total of 408 MPs/kg, followed by S2 (303 MPs/kg)

and S3 (146 MPs/kg), respectively. Meanwhile, for UMS ODEC beach, the distribution of MPs in the sediment followed the descending order of S2 (62 MPs/kg), S3 (50 MPs/kg), and S1 (48 MPs/kg) particles. It should be noted that the total numbers of MPs for both sampling sites were recorded as 857 MPs/kg in Tanjung Aru and 160 MPs/kg in UMS ODEC beach. The results show that the difference in the abundance of MPs between each beach can be attributed to the variety of recreational activities there. Tanjung Aru Beach is known as an open beach that has a high density of visitors and is exposed to stronger South China Sea tides and wave currents. It is possible that plastic trash from the maritime industry has contributed to the increasing number of MPs because the South China Sea is one of the busiest shipping routes in the world [28]. Meanwhile, ODEC beach is located inside the University of Malaysia Sabah which is private and limited to 300 visitors per day. The recreational activities were seen more in Tanjung Aru beach, as compared to UMS ODEC beach.

Table 1. The number of MPs found in the sediment of Tanjung Aru and UMS ODEC beaches, with total mass concentration recorded.

Sampling Sites	Type of Beach	Total Abundance of MPs/kg Dry Sediment								Total Mass Concentration (g/kg)	Total Number of MPs/kg Dry Sediment
		Station 1		Total Mass Concentration (g/kg)	Station 2		Total Mass Concentration (g/kg)	Station 3			
		Nov	Dec		Nov	Dec		Nov	Dec		
Tanjung Aru Beach	Recreational (open beach)	352	56	22.76	188	115	23.65	75	71	11.31	857
UMS ODEC Beach	Recreational (private beach)	22	26	1.70	34	28	8.82	33	17	7.44	160

The variation in the distribution of MPs in each station for both areas may be influenced by waves and currents that might have encouraged the sedimentation of MP particles [29]. Tanjung Aru Beach, which is located more directly exposed to marine current and tidal flow, had a higher number of MPs than locations with less marine influence. There is a possibility that the wind direction from the southeast transports MPs from the area adjacent to Tanjung Aru Beach before being deposited in the surface sediment. Other than that, the major sources of MPs' abundance in Tanjung Aru Beach are household activities and visitors who board boats to travel to other islands. As this area is located near residential houses, a substantial amount of garbage was found embedded and buried in the sediment. The sources of MPs also include recreational activities such as fishing (which uses plastic gear), land-based plastic waste, and the direct dumping of food containers, polystyrene, water bottles, plastics, bags, and many more [30]. Furthermore, environmental factors, including wind, tides, gyres, river runoff, tributary inputs, and anthropogenic factors will contribute to the possibility of transporting MPs in the sediment. The largest difference in the number of MPs in the sediment from Tanjung Aru Beach and UMS ODEC beach may be a consequence of anthropogenic impacts due to increased tourism activity and accumulation of MPs. This can be explained by the lower population density at UMS ODEC beach and therefore the lower anthropogenic influences. At UMS ODEC beach, some activities involving the use of the sea can be requested and are restricted.

This finding is in line with Stolte's suggestion that the frequency and the type of activities in a certain area would affect the number of MPs found [31]. Imhof [32] arrived at the same conclusion, stating that the proximity of urbanization and high population density contributes to the high MPs concentration in surface water and sediment. The study by Pinon [33] found that high MP abundance on beaches of key tourist regions is due to human activities, including plastic products discarded by tourists and fibers released from their clothing. In general, this finding can be used to conclude that the distribution and abundance of MPs on both beaches are primarily influenced by wind, tides, water currents, and industrial and human activities in that area.

3.2. Physical Characteristics of the Microplastics Found

At both beaches, the MPs that could be seen with the naked eye ranged in size from 5 mm to 1 mm. Microplastic sizes of less than 5 mm were less frequently seen by the naked eye, but the sedimentation process of the sample led to a substantial concentration of MPs smaller than 1 mm. Tanjung Aru Beach showed about 227 MPs particles of 5 mm to 1 mm size and the remaining were less than 1 mm, compared to 23 MPs particles the size of 1 mm to 5 mm size found on UMS ODEC beach. The highest number of MPs with less than 1 mm size was recorded in Tanjung Aru (Station 1), whereas the lowest was in ODEC UMS (Station 1). The MPs with a size range from 5 mm to 1 mm were recorded as highest in Station 2, Tanjung Aru, and the lowest was in Station 3, ODEC UMS beach. Figure 2 shows the number of MPs in each station from both beaches according to the sizes found.

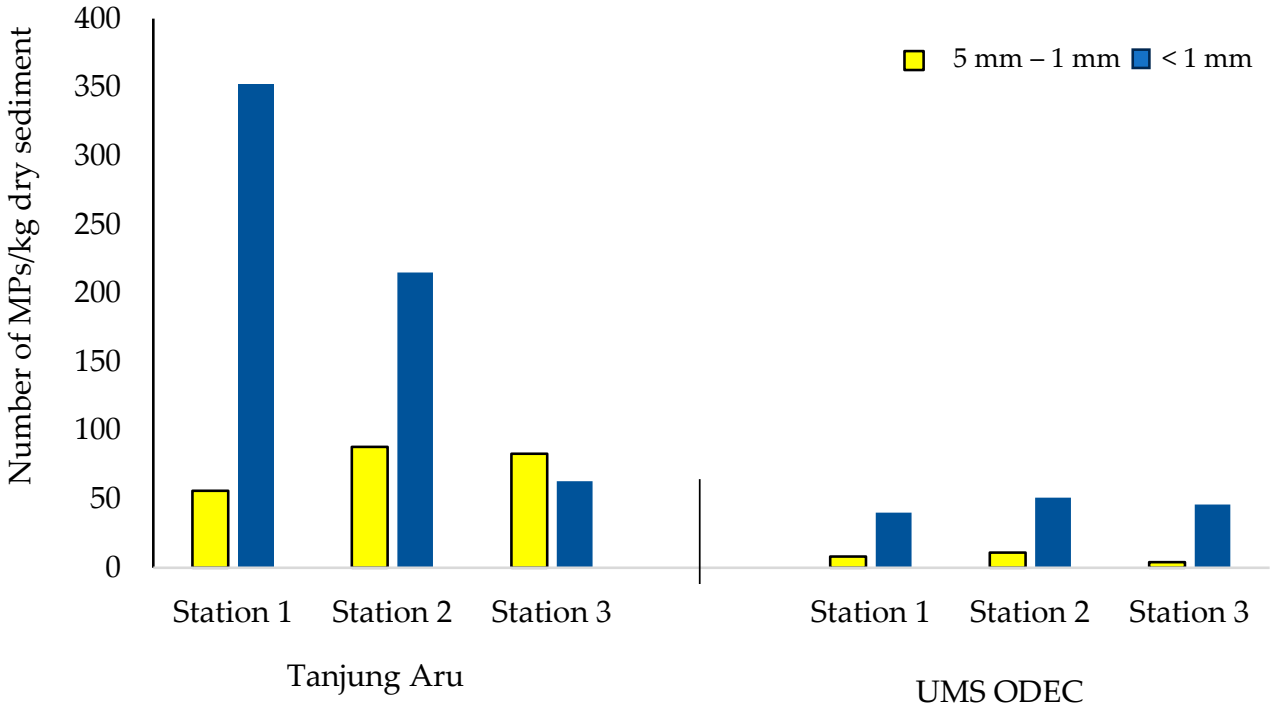

Figure 2. Size classification of MPs recovered from two beaches.

The results show that Tanjung Aru Beach contained substantially more MP particles than UMS ODEC beach. Primary MPs generally undergo the degradation process which breaks the particle down to a size of less than 5 mm. The plastic trash was crushed into smaller pieces until it was reduced to nano plastics and finally to particles that cannot be seen after exposure to dry, light conditions and weathering events [34]. This shows that beaches undergo greater plastic trash degradation due to weathering processes than other types of natural environments. The degrading of plastics results in sizes that may be measured in centimeters, which gives rise to the microscopic forms that are common in the environment worldwide. This is proven by the previous study from Zaida [35] and Fauziah [28], showing that the breakdown of plastics from larger to nano plastic is caused by weathering and the biodegradation process. These MPs might be transported further by abiotic elements such as land and water.

In this study, five different shapes of MPs (fragments, pellet, fiber/line, foam, and film) were found in both studied areas (Figure 3). Fragments are the dominant MPs (approximately 60%) found in Tanjung Aru Beach, followed by film (20%), fiber/line (12%), foam (5%), and pellet (3%), respectively. Similarly, at UMS ODEC beach site, fragments also contribute to the highest MPs abundance, with 53%, while the foam had the lowest abundance, with 3%. In addition, film was found (22%), followed by fiber/line (18%), and pellet (4%). It is important to note that the abundance of fragment-shaped MPs indicates

that particles showed signs of degradation, taking on shapes including flatness, irregularity, cracks, discoloration, fragility, and fragmentation. The bulk of the MPs debris in this study was in a degraded state due to the discovery of diverse shapes and sizes and various colors, which indicated that they were from larger and degraded particles. The variety of colors present in the sample can be categorized into white (including transparent), black, blue, green, red (including pink), and yellow (Figure 4). The most common colors were white with 40.4% and 52% found on the beaches, followed by black and blue in the range of 11–29.7%, yellow with 5.5–10%, and the least common were red and green with (2–3%), respectively. The plastic fragments' colors were dulled by prolonged exposure to weathering on the sand, in contrast to more recent bits that still had brilliant, strong tones [36].

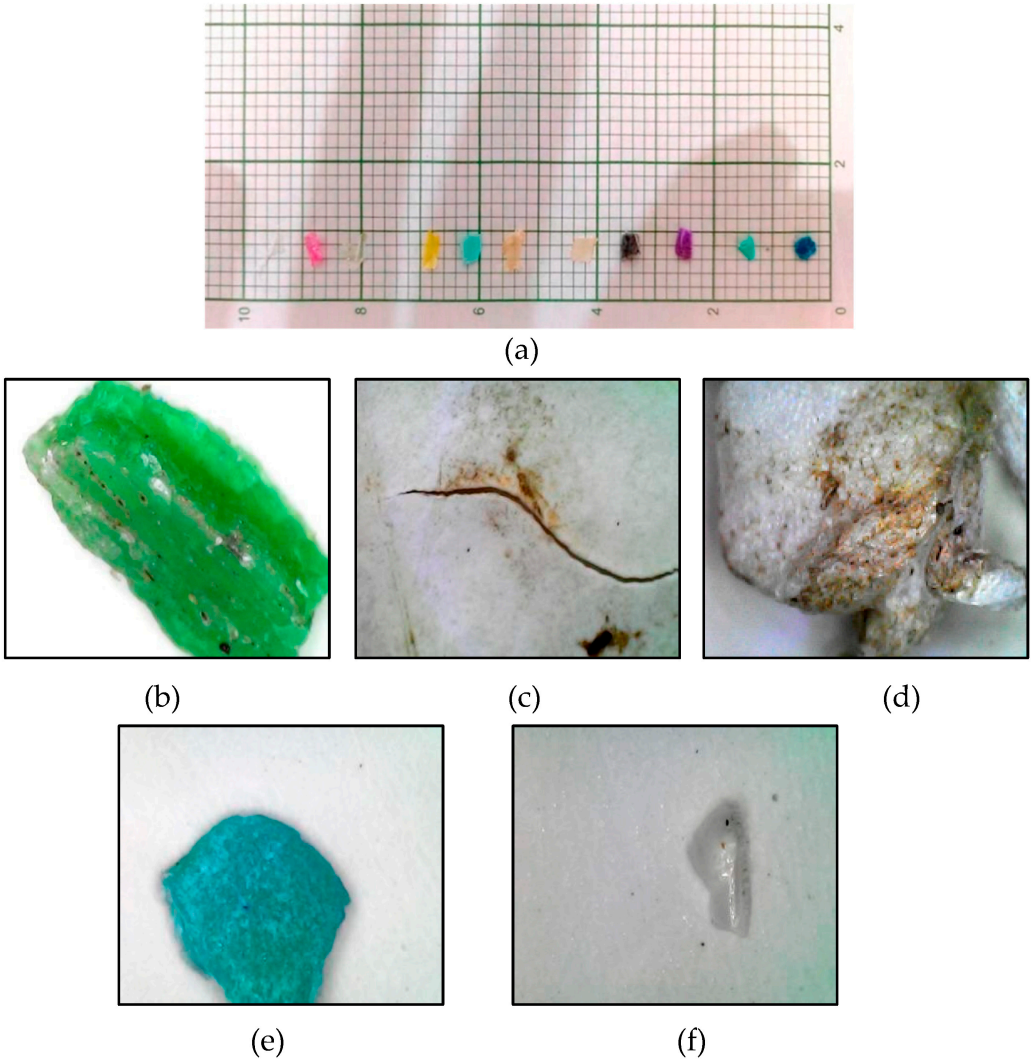

Figure 3. Various MPs colors (1–5 mm) viewed under electronic microscope. (**a**) Microplastics collected with the naked eye and with different colors, (**b**) pellets of polyethylene terephthalate, (**c**) fiber/line of polypropylene, (**d**) degraded polystyrene foam, (**e**) polyethylene, (**f**) polyethylene film.

The large proportion of white/transparent MPs found is in line with Prata [37], who found 62% white MPs on a sandy beach in Aveiro, Portugal. The presence of the colors black, white, blue, brown, yellow, green, red, purple, and pink is primarily attributable to washing ropes, cosmetics, and commercially colored packaging materials [38]. Some of the plastic pieces were dull and faded, indicating that they had been exposed to the elements on the beach for an extended period of time, whereas others were bright and vibrant [39]. Previous studies on MPs' uptake in the food chain have shown that the primary method of

uptake of MPs by marine creatures is by ingestion because the particles are mistaken for food [40]. In some vulnerable creatures, this will have a significant impact on tissues at the cellular level. Long-term exposure to MPs severely reduces the ability of marine species to reproduce by preventing them from fertilizing [19].

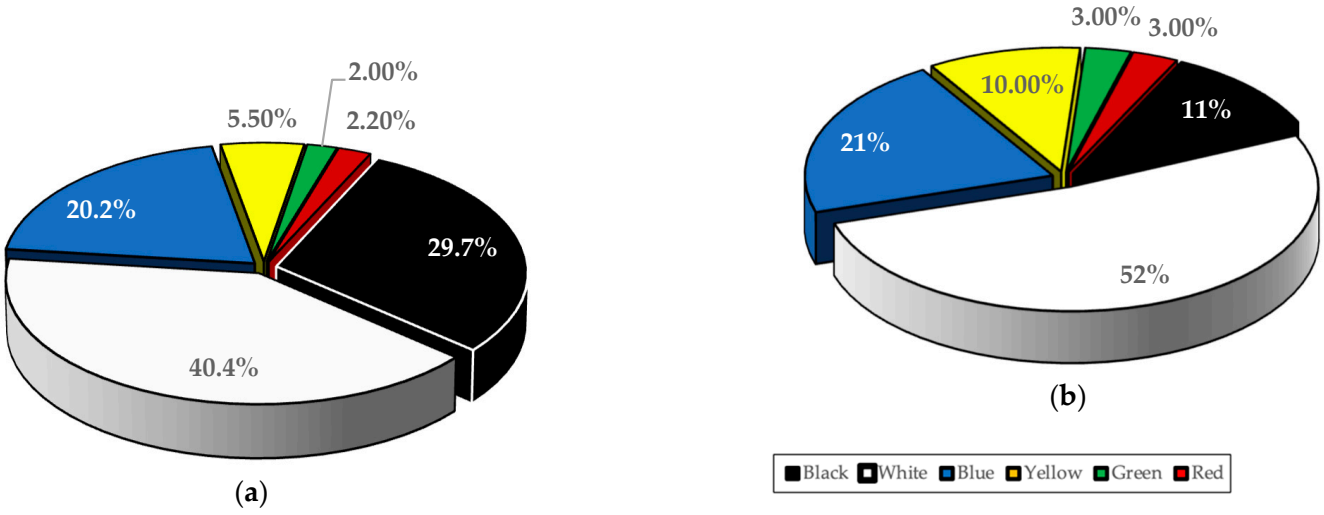

Figure 4. Percentage of microplastics found based on color from two different beaches (**a**) Tanjung Aru Beach and (**b**) UMS ODEC beach.

3.3. Identification of Microplastics' Polymer Composition

There were 160 pieces of plastic debris from UMS ODEC beach (n = 160 MPs/kg) and 857 pieces of plastic debris from Tanjung Aru Beach (n = 857 MPs/kg). All plastic particles from both beaches were analyzed using a Micro Fourier transform infrared spectrometer (Model: Brucker). Polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and polystyrene (PS) were the polymers recognized and present on both beaches studied. Polyethylene and polystyrene represented the highest percentages in UMS ODEC beach, with 60.63% and 14.38%, respectively (Figure 5). Polypropylene and polyethylene had the highest percentage in Tanjung Aru Beach, with 43.06% and 30.11%, respectively. Based on FTIR analysis, polypropylene and polyethylene terephthalate accounted for 13.13% and 11.88% at UMS ODEC station, meanwhile, 14.12% and 12.72% polyethylene terephthalate and polystyrene were found in Tanjung Aru station. It is important to note that PP, PE, PET, and PS can be found in a wide range of commercial and consumer goods.

Despite the fact that the percentage of PP and PS in UMS ODEC only differs by 1.25%, the micro-Fourier-transform infrared (FTIR) spectrometer examination results showed that, overall, PP and PE were the more prominent types of plastics compared to other polymers. Polypropylene and polyethylene made up most of the plastic trash that was recovered from the UMS ODEC and Tanjung Aru beaches. Because PP and PE have a specific gravity of less than one, they tend to be positively buoyant and it is easy for them to be dumped on beaches [41]. The analysis' findings revealed that PE and PP were the two polymers with the greatest abundance, which is not surprising given that PE contributes approximately 80 million tons to annual global production that have been used to manufacture packaging (plastic bags, plastic films, and containers including bottles) [35]. Whereas, PP, with an annual global production of about 55 million tonnes, is primarily used for packaging, reusable containers, stationery, textiles, ropes, etc. This finding is in line with Erni [42], who reported that PE, PP, and PS were among the most abundant polymer types found in aquatic environments. This is supported by William [43], who reported that the highest proportion was found to constitute PE, PP, and PS, which represented, respectively, 54.5%, 16.5%, and 9.7% of the total MPs found in the Western Mediterranean Sea. Meanwhile, the other polymers category included PET, PVC, and nylon were found in lower proportions. The study by Emilia [44] mentioned that PP and PE were the most common polymer types

found in the surface water of a northern European lake. This is not surprising, as these materials accounted for 74% of global plastic production in 2015 and are commonly used in short-life-cycle products [45]. Figure 6a–d shows the spectrum of polymers present in the types of MPs found on both beaches.

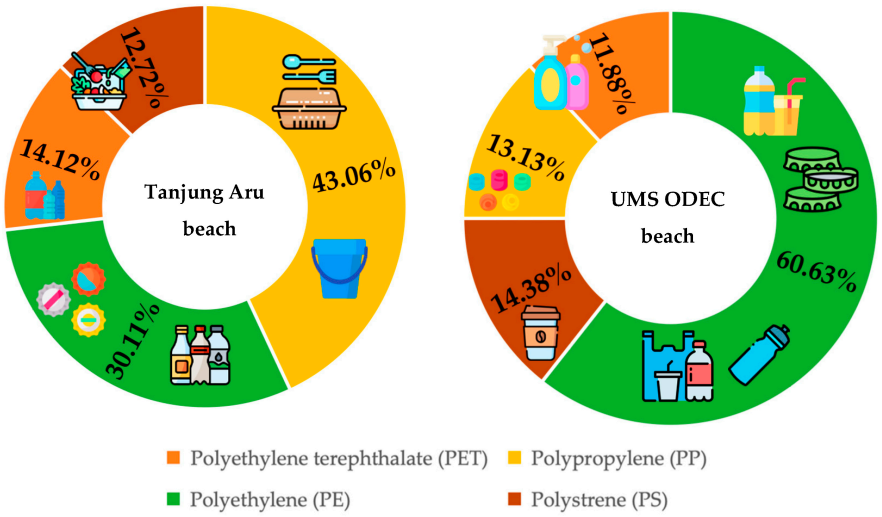

Figure 5. Percentage of polymers discovered at both beaches studied.

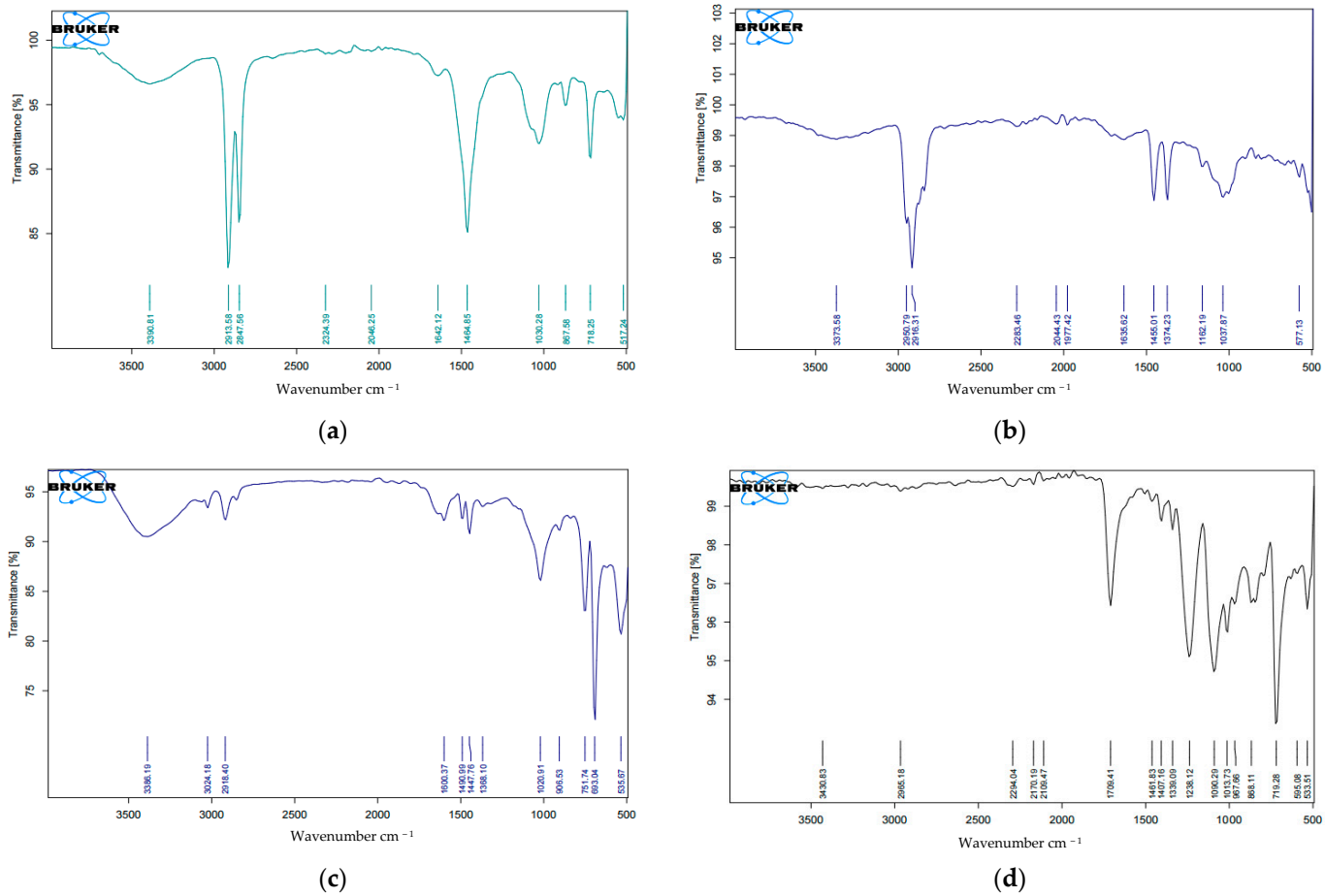

Figure 6. Peak graph of FTIR analysis. (**a**) Polyethylene (PE), (**b**) Polypropylene (PP), (**c**) Polystyrene (PS), (**d**) Polyethylene Terephthalate (PET) found in both beaches.

3.4. Heavy Metals Content in Microplastics

The interaction of heavy metals in MPs in the marine environment may originate from the chemicals absorbed by the surrounding environment or from additives added to the plastics [46]. MPs are known to serve as carriers for attached heavy metals. There is evidence that the interaction between MPs and heavy metals has a stronger effect on organisms than MPs alone. In this study, arsenic, chromium, copper, and nickel were all found in three different types of MP polymers: polypropylene (PP), polyethylene (PE), and polystyrene (PS). In general, both beaches presented the highest concentration of Cr in PP and PS, with 111.48 mg/kg in Tanjung Aru Beach and 97.99 mg/kg in UMS ODEC beach (Figure 7). Meanwhile, PS accumulates less Ni, with only 8.91 mg/kg. Cu and As were found in a range of 15.43–75.40 mg/kg in all polymer types analyzed. This study shows that heavy metal accumulations in different polymers present in MPs may not be so different from one another. This might be explained by the fact that when plastic particles are discarded or released into the water column, their surface characteristics and porosity help the materials absorb heavy metals [47]. As a result, larger levels of surface and reactivity are linked to a higher absorption of heavy metals. As plastic particles age, longer weathering cycles, hydrogenous compound precipitates, and biofilm accumulations may lengthen the reactivity of those particles and cause higher adsorption of heavy metal ions from the water column [48]. This indicates the potential for the accumulation of heavy metals in plastic that might have been layered by a biofilm.

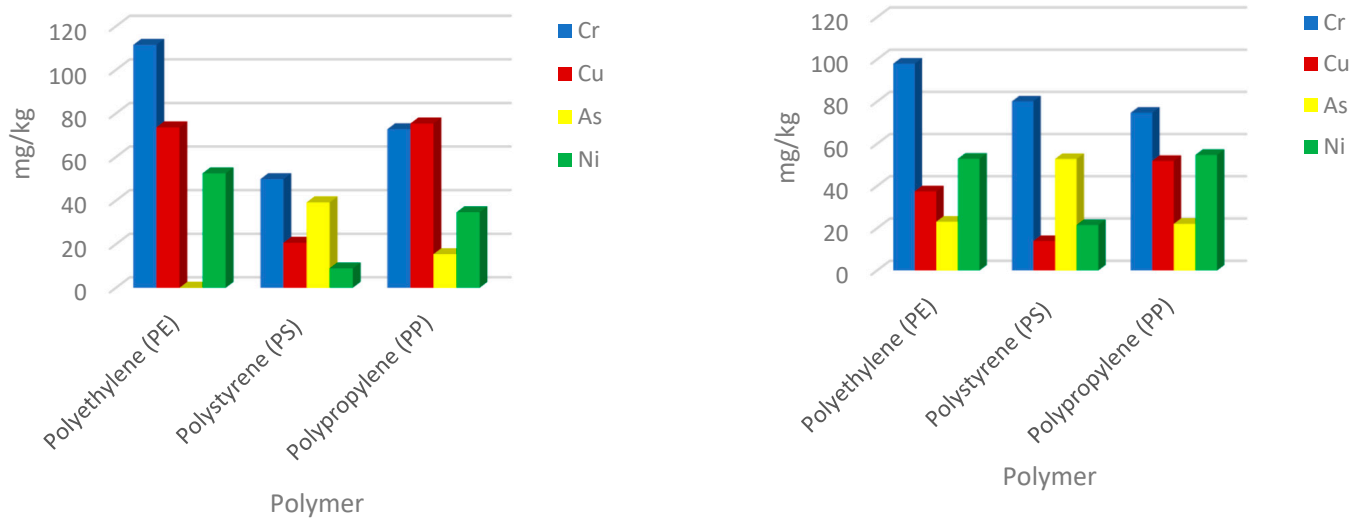

Figure 7. Heavy metals concentration found in a different type of polymers from (**a**) Tanjung Aru Beach and (**b**) UMS ODEC beach.

A previous study by Munier and Bendell [49] compared the trace metals in plastic debris collected from urban intertidal regions and unused plastic. They found that plastic particles accumulated Cu and Pb from the surrounding environment, while Cd and Zn were likely derived from the inherent metal loads, implying that plastic debris can act as both a source and sorbent for heavy metals. Furthermore, Li [50] found a high concentration of metals, including Cu, Fe, Ni, and Mn, in MPs collected from a site with substantial riverine inputs, and these metals were found in significantly higher concentrations in the sediments of that region. It is worth noting that as plastics are weathered or degraded in the environment, metal additions are more prone to diffuse and transfer from the matrix to the surrounding water [51]. Thus, it is vital to ascertain the concentration of metal compounds leached from polymers and evaluate their possible risk. The combined exposure of MPs and heavy metals has significantly negative effects on aquatic organisms such as microalgae, fish, and oysters. This has been proved by Lu [52], who stated that the

combined exposure of Cd and PS has a greater impact on glutathione, metallothionein, and superoxide dismutase in the tissues compared with a single exposure to Cd.

Furthermore, Tunali [53] investigated the combined effects of PS and triple metals (Cu, Mn, and Zn: 0.25 mg L^{-1}) on the microalgae *Chlorella vulgaris*; it was discovered that MP–metal combinations caused greater inhibition rates of *Chlorella vulgaris*, with 70.43% inhibition on growth and 64.09% inhibition on chlorophyll a concentration. In conclusion, the co-exposure of MPs and heavy metals poses a potential threat to aquatic organisms. MPs may be trophically transferred through the food chain and eventually consumed by humans, posing a significant threat to human health [52,54]. Unfortunately, the actual risks of exposure to MPs and metals to human health are largely unknown; it is imperative that further research be conducted on the toxicology and pathology of MPs.

4. Conclusions

This study compares the abundance and distribution of MPs in the sediment of two recreational beaches in Kota Kinabalu, Sabah, Malaysia. The findings show that the highest abundance of MPs was found in Tanjung Aru Beach, which has significant tourist visits per day during which various recreational activities are conducted. The fragment type of MPs was the most abundant in the sediment samples, formed by the degradation and breakdown of larger plastics. MPs with a diameter of 1 mm were the most common size in all samples collected from the beaches. PE and PP are the most common polymers found in MPs, as they are commonly used in bottles, food packaging, and containers. This study shows that the accumulation of MPs in the beach sediments of Tanjung Aru and UMS ODEC is primarily driven by anthropogenic disturbances, such as recreational and fishing activities. This finding can be used to raise public awareness and assist policy makers in planning for sustainable management to reduce plastic pollution on Kota Kinabalu beaches. Therefore, it is recommended that future research concentrate on the effects of MPs in various environmental media (e.g., soil, atmosphere) and especially on human health.

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