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Spatial Distribution of Microplastics Abundance Along Selected Beaches in Kelantan, Malaysia

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ABSTRACT

The issue of microplastics is far from being in its infancy. This study investigates the spatial distribution of microplastics along selected beaches in Kelantan, Malaysia, addressing a critical environmental issue. It highlights the environmental and health threats posed by microplastics, especially in the coastal regions of Kelantan, and identifies the significant challenge of microplastic pollution exacerbated by natural coastal phenomena and human activities. The objective is to quantify the abundance and distribution of microplastics using advanced analytical and geospatial techniques. Methodologically, samples were collected from ten locations, each comprising 30 subsampling areas. Fourier Transform Infrared (FTIR) Spectroscopy was employed to identify predominant contaminants, including Polyvinyl Chloride (PVC), Acrylonitrile Butadiene Styrene (ABS), Polypropylene (PP), and Polystyrene (PS). Spatial distribution was analyzed using ArcGIS 10.8.0 with Inverse Distance Weighting (IDW) Interpolation to model the microplastics' distribution patterns. A total of 1,607 microplastics were found, with an average of 5.3567 pieces per gram. Fragment-type microplastics dominated, with black and blue being the most common colours identified. The findings also revealed that the intertidal zones were the most heavily impacted areas along the coast. In *conclusion, this research provides crucial insights into the prevalence and spatial distribution of microplastic pollution in the coastal environments of Kelantan, underscoring the need for continuous monitoring and the development of targeted mitigation strategies to address this growing environmental concern.*

Keywords: Microplastics; Spatial Distribution; Fourier Transform Infrared Spectroscopy; Geospatial Modelling; Coastal Environments

INTRODUCTION

Microplastic pollution is a burgeoning environmental issue, posing significant threats to marine ecosystems and human health [1-2]. These minuscule plastic particles, often less than 5 millimetres in size, originate from various sources including the breakdown of larger plastic debris, microbeads in personal care products, and synthetic fibers from textiles [1,3]. Due to their small size and persistence, microplastics can easily be ingested by marine organisms, leading to bioaccumulation and potential biomagnification through the food chain [2, 4], ultimately affecting human health. The coastal regions of Malaysia, particularly the state of Kelantan, are not immune to this global environmental challenge. Kelantan's extensive coastline, which stretches nearly 80 kilometres, is characterized by its vulnerability to the North-East Monsoon, bringing heavy rainfall, high tides, and waves from the South China Sea. These natural phenomena exacerbate coastal erosion and sedimentation, potentially contributing to the redistribution and accumulation of microplastics along the beaches [5]. Despite growing global attention to microplastic pollution, research focused specifically on its spatial distribution along Malaysia’s east coast is limited. This study aims to address this gap by quantifying the abundance and distribution of microplastics along selected beaches in Kelantan, Malaysia. Through sediment sampling, Fourier Transform Infrared (FTIR) Spectroscopy, and geospatial modelling with ArcGIS, this research identifies the primary contaminants and examines the spatial variation in microplastic composition along the coastline. The identification of predominant contaminants and the variation of its polymer provides critical insights into the types and sources of microplastics prevalent in these coastal areas.

Study Area

Kelantan is a state on the East Coast of Peninsular Malaysia, characterized by its predominantly Malay population and a diverse cultural heritage that includes Thai, Chinese, and Indian communities [6, 7]. Known for its scenic villages, small towns, and traditional stilt houses, Kelantan's rich cultural landscape sits alongside a dynamic and ecologically significant coastal region [8-9].

During the North-East Monsoon season from November to March, Kelantan faces severe coastal impacts due to high rainfall, elevated tides, and strong waves from the South China Sea [7-8]. These seasonal conditions accelerate coastal erosion, sedimentation, and flooding, which not only threaten infrastructure but also contribute to the redistribution and accumulation of microplastics along the shorelines. This combination of natural forces amplifies the microplastic pollution problem, as sediments and pollutants are washed up along the coastline or swept inland, potentially affecting both terrestrial and marine ecosystems.

The government has undertaken several measures to mitigate these impacts, including building seawalls and breakwaters, improving drainage systems, and replanting mangrove forests to stabilize the coastline [10]. However, despite these efforts, Kelantan remains vulnerable to ongoing erosion and sedimentation, which exacerbate the challenges of managing and monitoring microplastic pollution in the region. Additionally, Kelantan faces other environmental challenges, such as deforestation and water pollution, which further strain its ecosystems and complicate conservation efforts [8, 10].

Given the coastal dynamics and high human activity along the shoreline, Kelantan's coastline is a critical area for studying microplastic pollution. Insights gained here are essential to developing effective, location-specific mitigation strategies that address not only the microplastics issue [11], but also the broader environmental sustainability of Malaysia's eastern coastal regions.

METHODOLOGY

Data Sources and Analytical Tools

This study utilized SPOT satellite imagery from the Malaysia Space Agency (MYSA) as a foundational data source to develop a comprehensive digital map of the study area, capturing spatial variations in sedimentation and coastline changes over time.

For spatial analysis, ArcGIS 10.8.0 was employed to process and generate geospatial maps, while Microsoft Excel was used for data entry, modification, and preliminary data handling. This combination of high-resolution satellite data and advanced geospatial tools supports accurate mapping and an in-depth analysis of microplastic dispersion along Kelantan's coastline

Sediment and Surface Sand Sampling

Sediment samples were collected along a 70-kilometre stretch of Kelantan's coastal area. Sampling stations were selected based on distinct sedimentation patterns and variations in coastal geomorphology, identified using SPOT satellite imagery. These images, dated 07 October 2013, 15 October 2018, and 24 February 2022, provided insights into changes over time in the coastal area, allowing the identification of significant sedimentation sites. This approach allows for the analysis of microplastic distribution across different tidal zones to capture potential influences of tidal dynamics as highlighted in Figure 1.

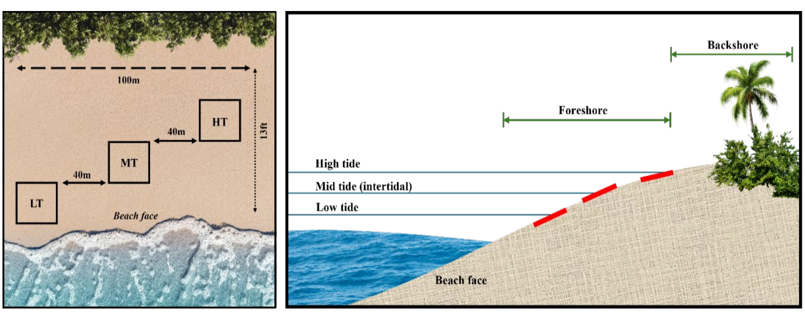

Figure 1: Illustration of sampling zones and distances.

Sampling was carried out at the 10 established points along Kelantan's beaches, focusing on both sedimentation and microplastic pollution. Each location was divided into zones based on tidal variation: low tide (LT), mid tide (MT), and high tide (HT), with samples taken approximately 13 feet apart within each zone [12].

Sampling was conducted over two days during the dry season, from 11:00 am to 4:00 pm, under clear conditions. Surface sand samples were taken using a 1-foot PVC frame placed within each zone, following a method adapted and improved from Hien *et al.* [1], with samples collected to a depth of 1.5 inches. This resulted in a total of 30 sediment samples from the study area. Samples were carefully inspected and stored in sanitized containers to prevent contamination from other material other than the sample taken before being transferred to the laboratory for analysis. The sampling processes and site determination is depicted in Figure 1 and following site selection, sampling was conducted across the locations listed in Figure 2.

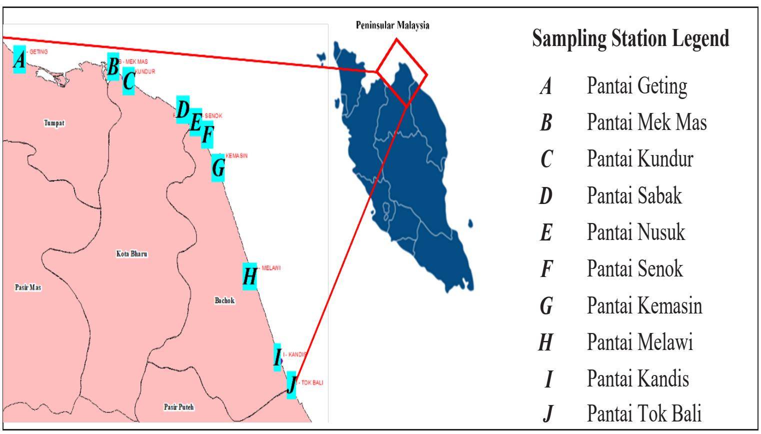

Figure 2: Map of the sampling station across Kelantan selected beaches.

Figure 3 illustrates the sampling process, which is repeated three times across the sampling stations, as outlined in Figure 1. The sampling process was done at Pantai Kandis and Mek Mas as shown in Figure 3

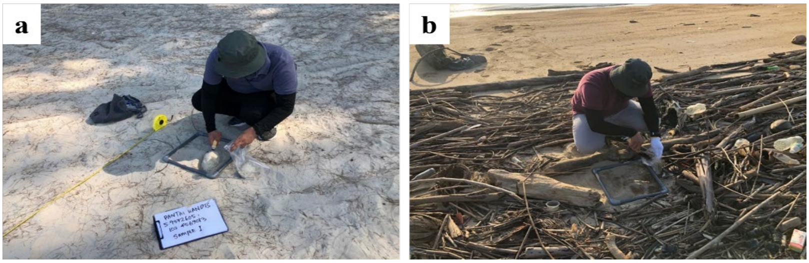

Figure 3: Sampling process taken place in (a) Pantai Kandis and (b) Pantai Mek Mas

Sediment Separation Analysis

Microplastics were extracted using a density separation method involving a zinc chloride ($ZnCl_2$) solution. To prepare for this analysis, sediment samples were first dried in an oven for 24 hours. A $ZnCl_2$ solution with a density of approximately 1.6–1.7 g/cm^3 which is sufficient to separate microplastics from denser sediment particles was prepared simultaneously [13]. The dried sediment was then mixed with the $ZnCl_2$ solution, stirred thoroughly, and left undisturbed for 24 hours to allow for density-based separation.

After this period, floating materials, including microplastics, were carefully collected for further analysis. To eliminate organic matter from the collected floating materials, a hydrogen peroxide (H_2O_2) solution was applied, resulting in samples composed primarily of microplastics for subsequent examination.

Microscopic Imaging and Polymer Variations Analysis

Microscopic observation was conducted as a preliminary step to identify and document microplastics in the collected samples [8-9]. The AmScope B120 Series LED Binocular Compound Microscope, with a magnification range of 40X-2500X and equipped with a 5MP digital camera, was employed to examine particles visually. This allowed for the classification of microplastics based on physical characteristics and its diversity such as shape (e.g., fragments, fibers, beads), size, and colour [10]. High-resolution images were captured using the digital camera, providing detailed visual records for documentation and further analysis. This step was essential for distinguishing microplastics from other materials, such as sediment and organic debris, ensuring that only relevant particles were selected for subsequent chemical analysis via FTIR spectroscopy [14], using THERMOFISHER FTIR-6700. The microscope's capabilities significantly enhanced the accuracy of the identification process, contributing to a comprehensive understanding of the microplastics' physical diversity.

The remaining materials, mainly microplastics, are analyzed using Fourier Transform Infrared (FTIR) analysis to identify and characterize their types using SpectraGryph software. The fingerprint identification of polymer variations is determined using a database curated by Primpke and Birch [14]. FTIR identifies specific plastics like polyethylene (PE), polypropylene (PP), and polystyrene (PS) by examining their unique infrared spectra. This analysis also provides information on the physical forms (granules, fragments, fibers), sizes (microscopic to larger fragments), and colours (translucent to opaque) of the microplastics [14-15]. By understanding these characteristics, researchers can better assess the environmental impact, sources, and extent of microplastic pollution in aquatic ecosystems.

Spatial Statistical Modelling

After Fourier Transform Infrared (FTIR) analysis, the microplastics data is compiled into a quantitative dataset including plastic type, form, size, and colour. These datasets are organized into CSV files and integrated into an attribute table within ArcGIS 10.8.0 for spatial statistical analysis. The Inverse Distance Weighting (IDW) method is used to analyze the geographic patterns and distributions of microplastics. IDW interpolates values for unmeasured locations based on the similarity of nearby measured values, with closer measurements having a greater influence. This method uses an inverse square distance calculation, encapsulated by Equation (1), Here, z_p represents the elevation at individual points, while d_p denotes the respective distance at each of these points.

$$z_p = \sum \frac{\sum_{i=1}^{n} \left(\frac{z_i}{d_i^{\,p}}\right)}{\sum_{i=1}^{n} \left(\frac{1}{d_i^{\,p}}\right)} \tag{1}$$

The results are visualized using the Classified symbology version in ArcGIS, creating maps that display the spatial distribution and patterns of microplastics [16]. These maps enhance the understanding and communication of microplastic pollution research findings. IDW is well-suited for this application due to its adaptability to datasets with irregular sampling points, which is common in field-based environmental research [4, 17]. Microplastic samples often come from spatially dispersed locations, and IDW allows these irregularly spaced points to be interpolated effectively, providing a continuous surface of estimated microplastic concentrations across the study area.

Moreover, IDW's flexibility in adjusting the power parameter allows the interpolation to reflect localized concentration gradients, capturing subtle spatial variations in microplastic density across different coastal zones. This adaptability is especially useful for microplastic research, as it can reflect the natural distribution patterns influenced by both environmental factors (like tides and currents) and human activity. By visualizing the results using classified symbology in ArcGIS, IDW creates intuitive, accessible maps that clearly communicate spatial trends in microplastic pollution. These maps thus enhance the understanding and communication of microplastic pollution research findings, facilitating more targeted environmental monitoring and management strategies.

RESULTS & DISCUSSION

Microplastics Shapes and Sizes

The study categorized microplastics into three main shapes: beads/granules, fragments, and fibers. Fragments were the most common, making up 88% (1415 pieces) of the total microplastics. This indicates persistent plastic pollution from the breakdown of larger plastic items [2-3]. Beads and granules each accounted for 6% (93 pieces each) and are typically from personal care products, industrial processes, and plastic manufacturing. Fibers, also making up 6% (99 pieces), likely originate from textiles and clothing. This distribution underscores the need for stringent controls on microplastic sources to prevent environmental accumulation. The microscopic images of the microplastic found were grouped as shown in Figure 4.

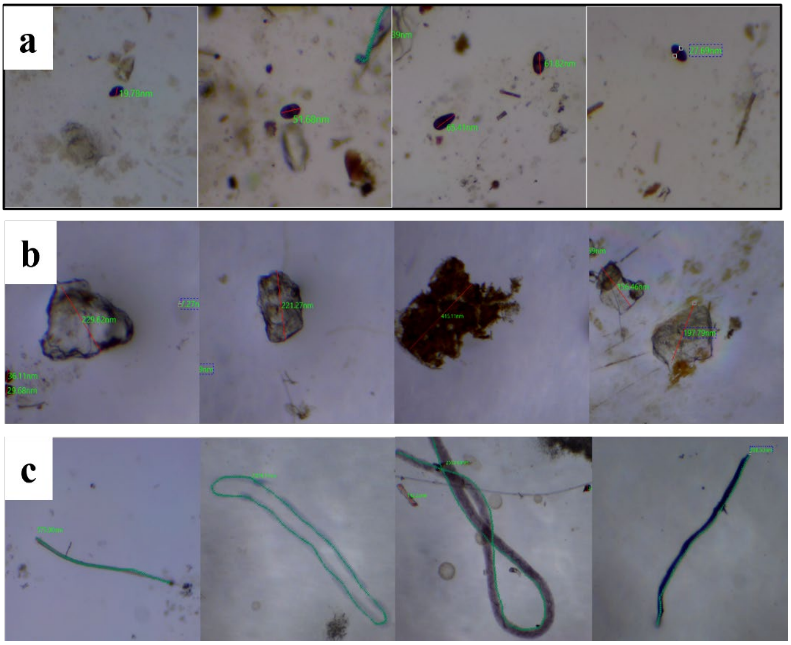

Figure 4: The microplastics found from sampling based on shape; (a) beads and granules;(b) fragments; (c) fibres.

The images in Figure 4(a) show microscopic imaging of bead and granule-shaped microplastics (MPs) found on Kelantan's beaches. Most granules ranged from 7.0 nm to 50 nm, with an average size of 28.5 nm. Figure 4(b) displays fragmented MPs, which ranged from 20 nm to 1200 nm, with a notable size of 1180 nm. Figure 4(c) illustrates fiber-like MPs, ranging from 30 nm to 1300 nm, with a range of 1270 nm. These findings highlight the diverse shapes and sizes of microplastics in the coastal environment. The variety of bead, granule, fragmented, and fiber-like MPs emphasizes the complexity of microplastic pollution on these beaches. Additionally, the study revealed the presence of potentially living organisms, such as calcified organisms, hardened algae, and diatoms, likely brought ashore by waves and currents. These biological samples, shown in Figure 5, ranged from 10 nm to 180 nm, aligning with typical diatom sizes of 1 nm to 200 nm. The coexistence of these biological entities alongside microplastics highlights the complex interactions within the marine ecosystem.

Figure 5: The biological entities found within the coastal ecosystem.

To isolate microplastics, a hydrogen peroxide (H_2O_2) solution was applied at the beginning of the research to remove organic matter from the collected samples. H_2O_2 treatment effectively breaks down most soft organic materials without significantly altering the microplastics themselves, enabling more accurate identification and analysis. However, some organic structures, such as calcified organisms and diatoms with silica-based structures, are highly resistant to H_2O_2 oxidation and may persist even after treatment. Incomplete oxidation or handling steps after H_2O_2 treatment could also contribute to residual organic material. These resilient entities and potential post-processing contamination primarily resulted in the preservation of certain inorganic and calcified structures within the samples.

The discovery of these biological entities within microplastic samples underscores the need for further investigation into their transport and deposition mechanisms, as well as the ecological implications of their interactions with microplastics. Understanding these interactions could provide valuable insights into the impacts of microplastic pollution on coastal biodiversity.

Microplastic Colour

Table 1 analyses microplastic distribution across ten sample locations, revealing trends in microplastic colours. Black microplastics are predominant in several locations (Pantai Geting, Pantai Mek Mas, Pantai Sabak, Pantai Nusuk, and Pantai Senok), while blue, red, and green microplastics are less prevalent but consistently present in some areas (Pantai Nusuk, Pantai

Senok, and Pantai Tok Bali). Translucent microplastics, often from food packaging, are notably found in Pantai Nusuk and Pantai Senok. Translucent microplastics, mainly linked to polypropylene from food packaging, were most prevalent in estuary and beach areas, ranging from 15% to 38% [4].

Table 1: Amount of microplastic found by colour.

Sampling Station	MPs found based on colours (%)								
	BK	*BE*	*RD*	*GN*	*YW*	*GY*	*BN*	*WE*	*TT*
A - Pantai Geting	70	10	5	5	0	5	5	0	0
B - Pantai Mek Mas	60	10	5	5	5	10	5	0	0
C - Pantai Kundur	70	15	5	0	0	0	5	0	5
D - Pantai Sabak	40	5	5	5	0	30	15	5	0
E - Pantai Nusuk	50	10	10	5	0	20	15	5	0
F - Pantai Senok	55	10	5	10	5	10	10	5	0
G - Pantai Kemasin	55	10	5	5	0	10	10	5	0
H - Pantai Melawi	50	10	10	5	5	10	5	5	0
I - Pantai Kandis	60	10	5	5	0	5	10	5	0
J - Pantai Tok Bali	50	10	5	5	0	10	10	5	5

Notes: BK: Black, BE: Blue, RD: Red, GN: Green, YW: Yellow, GY: Grey, BN: Brown, WE: White, TT: Translucent

Brown, white, and grey microplastics appear consistently across locations, suggesting common sources. Yellow microplastics are unique to Pantai Nusuk, indicating localized sources. Green microplastics are notable in Pantai Nusuk and Pantai Senok, potentially linked to specific environmental factors. This analysis highlights the complexity of plastic pollution, suggesting variations in sources and environmental conditions, and sets the stage for further research on microplastic pollution and its ecological impacts [5]. Figure 6 categorises the spectrum of colours into nine distinct hues: (1) black, (2) blue, (3) red, (4) green, (5) yellow, (6) translucent, (7) brown, (8) white, and (9) grey.

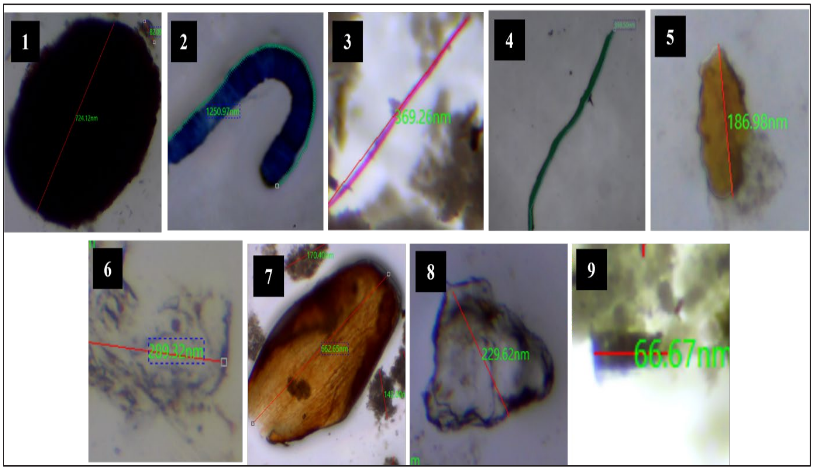

Figure 6: The colours of microplastics found.

Microplastics may not always have strong colours, often showing subtle variations in hues such as black, blue, green, yellow, red, brown, white, translucent, and grey. This reduced coloration can result from factors like movement, degradation by sunlight, natural processes, and chemical reactions, including photooxidation and weathering [4, 6]. Studies indicate that plastic colours affect aging, microplastic formation, and environmental impact, with darker colours absorbing more light [7]. Different colours can also influence microbial colonization [11], contaminant sorption/release [18], shading effects, and biological uptake [19].

Tidal Influences of Microplastic Transportation

This study extensively examines microplastic distribution patterns in a specific research area. Sampling was conducted at ten different geographical points, with the mid-tide interval showing the highest number of instances (641), followed by low tide (510) and high tide (456). This dataset in Figure 7 provides a comprehensive view of microplastic prevalence across different sampling stations and serves as a strong basis for further research into potential links between tidal dynamics and microplastic presence. The A – Pantai Geting microplastic counts varied across tide levels [20], with 61 microplastics observed during low tide, 43 during mid tide, and 43 during high tide. Sample Location B – Pantai Mek Mas exhibited fluctuations as well, recording 42 microplastics during low tide, 63 during mid tide, and 56 during high tide. Meanwhile, at C – Pantai Kundur, the microplastic counts showed a gradual increase from 20 during low tide to 28 during mid tide, and a further rise to 52 during high tide. Moving on to D – Pantai Sabak, the microplastic count surged from 28 during low tide to 107 during mid tide, before dropping to 19 during high tide.

Similarly, sample location E – Pantai Nusuk saw a significant rise, reaching 19 microplastics during low tide, 124 during mid tide, and 72 during high tide. This spike may indicate that certain local features, such as the beach slope, coastal morphology, or the influence of nearby river inflows, could be enhancing microplastic deposition at this tide level [14, 21-22]. Similar trends of mid-tide accumulation were noted at other locations, such as location D – Pantai Sabak and location B – Pantai Mek Mas, which also recorded their highest microplastic counts at mid-tide. F – Pantai Senok, the counts remained relatively steady, measuring 97 microplastics during low tide, 98 during mid tide, and 60 during high tide. Sampling location G – Pantai Kemasin displayed notable disparities, with 51 microplastics during low tide, a significant drop to 7 during mid tide, and a subsequent increase to 67 during high tide. Meanwhile, the area of H – Pantai Melawi showed less variability, recording 95 microplastics during low tide, 60 during mid tide, and 53 during high tide; the percentage of the abundance is shown in Figure 7.

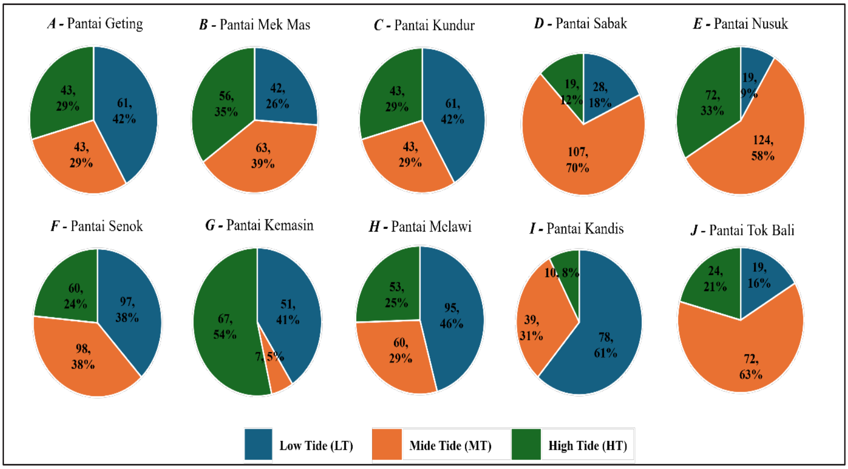

Figure 7: Microplastics found in different tidal conditions at 10 sampling stations.

Sample location I – Pantai Kandis, demonstrated a decrease in counts from 78 microplastics during low tide to 39 during mid tide, and a further decline to 10 during high tide. Lastly, around J – Pantai Tok Bali, the microplastic counts were 19 during low tide, 72 during mid tide, and 24 during high tide, indicating some fluctuations in the presence of microplastics across the tide levels. The data reveals notable variations in microplastic quantities across different sample locations and tidal phases [21]. This means that each MPS found is carried by tidal processes. For instance, sample location E – Pantai Nusuk demonstrates a substantial increase in microplastic count during mid tide, while G – Pantai Kemasin experiences a significant reduction in microplastics during mid tide compared to the other tidal phases.

Amount of Microplastics

The detailed look at microplastic levels in various coastal areas, each with its unique geographic features. This data underscores how widespread microplastics are in these regions, revealing potential patterns and changes over time. F – Pantai Senok, exhibited the highest concentration of microplastics, with a recorded count of 255 particles equivalent to 15.87% of the MPs found. This observation suggests a notable accumulation of microplastics in this coastal region, which could be influenced by local factors such as coastal currents, anthropogenic activities, or specific geomorphological features [23-24]. In close succession, E – Pantai Nusuk and H – Pantai Melawi also displayed relatively elevated counts of microplastics, with recorded quantities of 215 (13.38%) and 208 particles (12.94%), respectively. These findings imply that these areas may also be susceptible to heightened microplastic pollution, possibly due to factors like proximity to pollution sources or prevailing wind and wave patterns. Conversely, C – Pantai Kundur, J – Pantai Tok Bali, and G – Pantai Kemasin recorded comparatively lower quantities of microplastics, with counts of 100 (6.22%), 115 (7.16%), and 125 particles (7.78%), respectively and all the MPs found were sorted accordingly based on its parameters. These regions could either experience lower levels of microplastic pollution or be influenced by factors that mitigate their accumulation, such as effective waste management practices or limited anthropogenic activities [5, 7].

Number of MPs found in a sample

The analysis encompassed 30 sampling stations, each providing a 500-gram sample, summing up to 15 kilograms (15,000 grams) of samples analyzed. For analysis, each area's 500-gram sample was downsized to 10 grams, resulting in a collective sample weight of 300 grams across all areas. The examination uncovered a total count of 1,607 microplastic pieces across these 30 sampling stations. This implies an average of roughly 5.3567 microplastic pieces per gram of the 10-gram sample size.

Based on this average, to forecast the total number of microplastics in a 15-kilogram sample (15,000 grams), we can multiply the average microplastics per gram (5.3567 pieces/gram) by the total sampled weight (15,000 grams), yielding an estimated total of around 80,350 microplastic pieces in the 15-kilogram sample.

Variations of Polymer in the Microplastics

After collecting microplastic samples, an extensive FTIR Spectroscopy Analysis was conducted to examine the polymer composition of the microplastics. This analysis compared and identified polymers using reference databases curated by Primpke and Birch [14], which include predetermined wavelengths for various synthetic materials. The analysis was considered convincing if the spectral match exceeded a threshold of 60%, ranging from 60.00% to 100.00% [24]. Results below this threshold were not classified as identifiable plastic, as they could be influenced by contamination or external particulate matter.

The findings revealed significant variation in the polymer types present in the samples. Among the 30 sampling sites, 22 showed matches exceeding the 60% threshold, indicating high confidence in polymer identification. These included 17 sites correlating with Polyvinyl Chloride (PVC), 2 with Acrylonitrile Butadiene Styrene (ABS), and 2 with Polystyrene (PS) and Polypropylene (PP) within a single area. PVC was the dominant polymer detected, aligning with its widespread use in construction, packaging, and other industries [5, 15]. This prevalence highlights the potential role of anthropogenic activities, such as improper disposal of construction materials or consumer plastics, in contributing to microplastic pollution [25]. For the remaining 8 samples that did not meet the 60% threshold, the spectral analysis confirmed that it exhibited synthetic plastic characteristics. These samples likely contained weathered or degraded polymers, which may explain the weaker spectral matches [15, 26]. Weathering processes such as UV degradation and chemical exposure can alter the molecular structure of plastics, leading to less distinct infrared spectra [26].

The variation in polymer composition also provides insights into the potential sources and environmental pathways of microplastics. The high occurrence of PVC suggests localized sources related to coastal urbanization or industrial activities [24, 27], while the presence of ABS and PS could be linked to consumer goods or marine-based litter, such as fishing equipment or packaging materials [25, 28]. These findings underscore the need for targeted mitigation measures addressing specific polymer types predominant in the region.

These variations reflect the interplay of human activity, material durability, and environmental factors influencing microplastic prevalence in coastal environments [24, 29-30]. Further investigation into the sources and degradation pathways of these polymers will enhance understanding of their environmental impacts and inform strategies for reducing microplastic pollution.

GIS Interpolation on MPs Empirical Data

The collected data, detailing the features and variety of microplastics (MPs), was organised into a structured attribute table in CSV format. This table was combined with a geospatial shapefile in ArcGIS, which included geographical coordinates for the sampling sites. After merging the attribute table and shapefile, spatial analysis was conducted using the IDW method for spatial interpolation to estimate the distribution of microplastics.

MPs Found in Different Tidal Conditions Parameters

Figure 8 and Table 2 data highlights a distinct concentration of microplastics (MPs) in sampling stations D, E, and F, located between the Sungai Peng Datu and Sungai Raja Gali rivers in Kelantan (illustrated in blue line on Figure 8). It aligns with previous research suggesting that microplastics tend to accumulate in river estuaries and coastal beaches, likely transported from rivers to beaches and subsequently deposited by waves and sea currents [24, 27-28].

This pattern is consistent across tidal conditions. During low tide, MPs disperse over approximately 15 kilometres between areas H and I; the area displayed relatively consistent microplastic counts across tidal phases, suggesting that tidal forces may have a less pronounced effect on microplastic distribution in these areas [25, 28]. This stability could be due to factors such as beach morphology or human activities that influence microplastic presence consistently across tides [3]. At high tide, MPs spread from area B to H, covering about 40 kilometres. Sampling area J consistently shows a low presence of MPs regardless of tidal variations. The analysis underscores the clustering of MPs in areas D, E, and F, with a broader dispersal observed from H to I at low tide and from B to H at high tide. Sampling area J consistently registers minimal MPs. It is aligned based on past research which stated that microplastics uniformly distributed across tidal levels [24, 30].

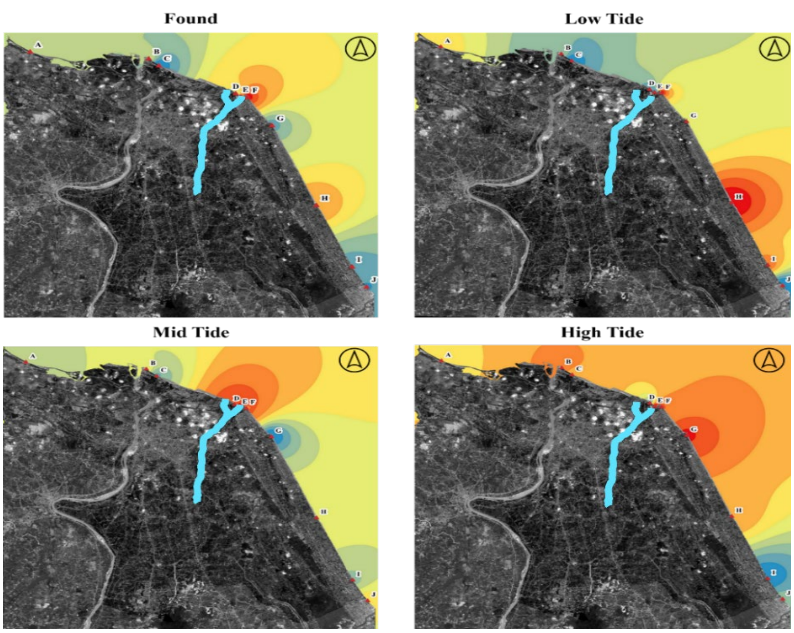

Figure 8: Microplastics found according to the subsampling area.

Table 2: MPs found (pcs) in low, middle, and high tide.

Legend	Found	Low Tide	Mid Tide	High Tide
	100 – 115	19 – 26	7 – 18	9 – 15
	116 – 131	27 – 34	19 – 30	16 – 22
	132 – 147	35 – 42	31 – 42	23 – 29
	148 – 163	43 – 50	43 – 54	30 – 36
	164 – 179	51 – 58	55 – 66	37 – 43
	180 – 195	59 – 66	67 – 78	44 – 50
	296 – 211	67 – 74	79 – 90	51 – 57
	212 – 227	75 – 82	91 – 102	58 – 64
	228 – 243	83 – 90	103 – 114	65 – 71
	244 – 259	91 – 98	115 – 126	72 – 78

MPs Found in Different Shape Parameters

The collected microplastics (MPs) were classified into three major shapes: beads/granules, fragments, and fibers. Beads/granules are small, spherical objects; fragments are pieces broken off from larger materials; and fibers are tiny, thread-like structures [14, 28]. These shapes provide critical insights into the potential sources, degradation processes, and environmental pathways of microplastics. The IDW has projected an extensive of predictive model which depicted on Figure 8 below.

Based on Figure 9 and Table 3, beads/granules were notably widespread in sampling stations A and B, with a maximum of 7 pieces per 10 grams of sample, but had lower counts in areas C to J. This distribution may indicate proximity to localized sources of primary microplastics, such as industrial processes or the use of personal care products containing microbeads [9, 28]. The sharp decline in bead/granule counts beyond areas A and B suggests limited transport mechanisms for these denser particles or a lack of significant sources further along the coastline.

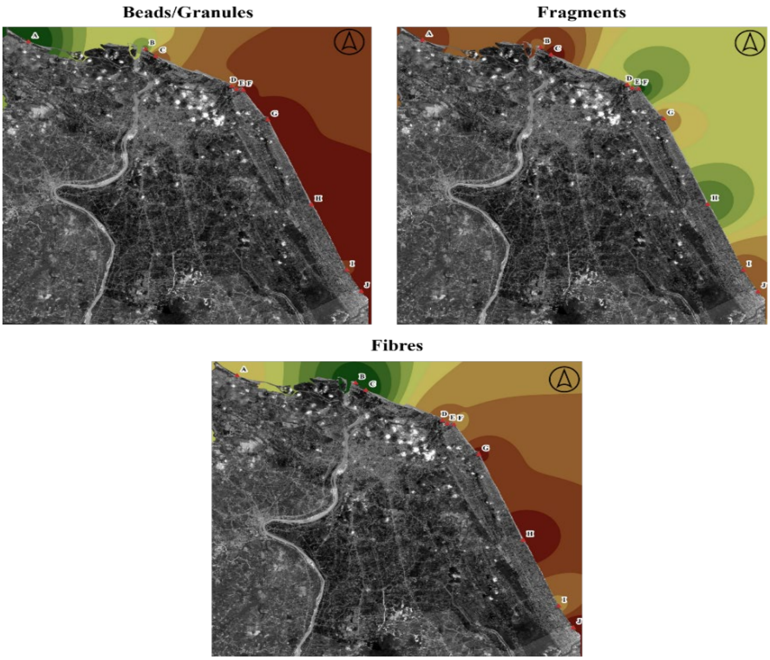

Figure 9: Microplastics abundance according to its shape.

Table 3: MPs abundance according to its shape.

Legend	Beads/Granules	Fragments	Fibres
	0 – 3	67 – 84	0 – 2
	4 – 7	85 – 102	3 – 5
	8 – 11	103 – 120	6 – 8
	12 – 15	121 – 138	9 – 11
	16 – 19	139 – 156	12 – 14
	20 – 23	157 – 174	15 – 17
	24 – 27	175 – 192	18 – 20
	28 – 31	193 – 210	21 – 23
	32 – 35	211 – 228	24 – 26
	36 – 39	229 – 246	27 – 29

Fragments, which are often the result of the breakdown of larger plastic items such as bottles, packaging, or fishing gear, were the most prevalent shape across the study area. Sampling stations D, E, and H exhibited the highest concentrations of fragmented MPs, indicating significant secondary microplastic pollution in these regions. Coastal activities, including tourism, fishing, and improper waste management, may contribute to the abundance of fragments [21, 30]. The lower quantities of fragments observed in areas I and J could reflect either reduced human activity or effective waste management practices in these locations. Fibers, which were most prominent in sampling stations B and C with counts ranging from 21 to 29 pieces per 10 grams, are often associated with textile fibers from clothing and fishing nets. Their prevalence near these locations may be influenced by proximity to urban runoff, river discharges, or coastal industries [21, 29, 31]. The lower fiber counts in areas D, E, F, G, H, I, and J suggest that these regions may have fewer sources of textile-derived pollution or that fibers are less likely to be transported and deposited in these areas due to their lighter weight and tendency to remain suspended in water.

Schröder *et al.* [25] also noted that fragmented shapes are the most common form of microplastic and plastic debris. In these regions shown in Figure 10, 6 to 11 pieces per 10 grams were detected. Microplastics come in various shapes, but fibers are particularly prominent [22, 31]. Sampling stations D, E, F, G, H, I, and J have a lower diversity of microplastic shapes, dominated by fragment-shaped microplastics. The quantity of fragments ranges from 157 to 246 pieces per 10 grams of tidal sample, highlighting their prevalence in these areas. Fragments' high prevalence underscores the significance of secondary microplastic pollution, arising from the degradation of larger plastics through environmental weathering processes like UV radiation, wave action, and physical abrasion [25, 30, 31].

MPs found in Colours Parameters

The distribution of MPs shows distinct patterns across sampling stations, categorized by colour: black, blue, brown, green, translucent, grey, red, yellow, and white in Figure 10. Black MPs are notably concentrated in areas A to F, over a 35-kilometer stretch, with 80 to 120 pieces per 10 grams of sample. Blue MPs are confined to areas E and F. The results of the microplastics found were commonly in blue/black colour in all sample, which this statement can be seen to correspond to the results of the analysis [32-33]. Not only that, also found that black and blue were the predominant colours (>80%) of the total microplastics particles sampled [9]. The distribution varies by colour across different sampling stations. This high concentration of black and blue microplastics highlights their dominance across the study area, suggesting they may be linked to specific sources that are either prevalent or more persistent in the region. Figure 10 shows the distribution of microplastics (MPs) in IDW modelling, with the legend color-coded as follows: (1) Black, (2) Blue, (3) Brown, (4) Green, (5) Translucent, (6) Grey, (7) Red, (8) Yellow, (9) White. Black MPs are concentrated in areas A to F, with 80 to 120 pieces per 10 grams over a 35-kilometre stretch. Blue MPs are confined to areas E and F which may reflect a specific local source or environmental condition favouring the deposition of these particles in these locations [9, 25]. Brown MPs are predominantly found in areas D to J, with counts ranging from 24 to 60 pieces per 10 grams. This spread of brown microplastics could indicate their origins from a variety of sources such as packaging materials or agricultural runoff, which are typically associated with urban and rural activities in these regions [14, 27].

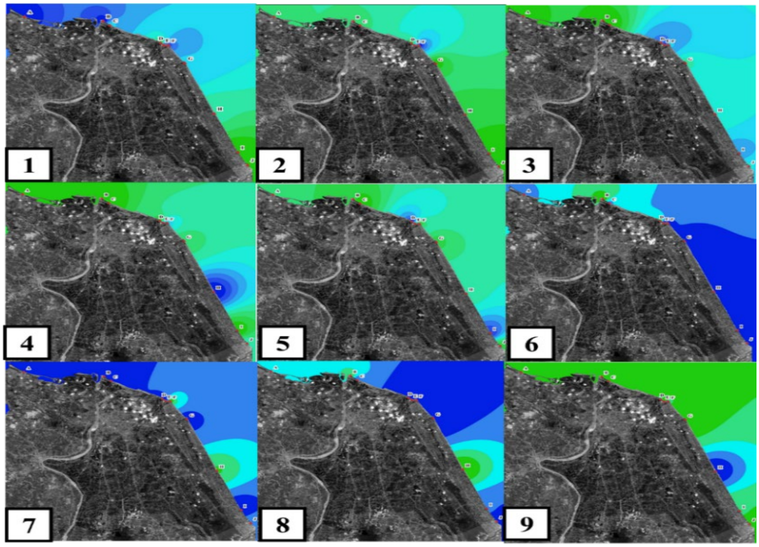

Figure 10: Microplastics estimated distribution according to its shape.

Green MPs exhibit a distinct concentration along the shores of area H, with 28 to 39 pieces which the presence of green microplastics may reflect localized environmental conditions or be associated with specific types of consumer goods, like food packaging or toys [17, 29]. Translucent MPs are clustered primarily in areas D, E, and I, with quantities ranging from 31 to 50 pieces per 10 grams which it can happen because translucent particles are often linked to polypropylene and other lightweight plastics, which are common in consumer goods and food packaging [25, 32]. Grey MPs show a more extensive distribution, spanning areas A to E, G, I, and J, with counts between 28 and 70 pieces per 10 grams.

Red and yellow MPs are relatively rare, with only 1 to 4 pieces found across areas D, E, F, G, and J for red MPs, and area H for yellow MPs. White MPs are found along the shores extending from area C to J, over a distance exceeding 50 kilometres, with a moderate presence of 18 to 30 pieces per 10 grams which the spread of white microplastics, often associated with common packaging materials like polystyrene, suggests a more widespread environmental impact across the region [14, 25, 27].These colour-coded distributions reveal the complex dynamics influencing the dispersion and concentration of microplastics across the studied regions [24, 33].

The diverse colours of microplastics found in the research also include red as predominant colours [9], white or translucent particles were second and followed by few others like green and yellow. This research confirms the widespread distribution of microplastics (MPs) along the Kelantan coastline. Studies emphasize the high concentration of MPs in estuarine and beach areas, particularly in regions with intensive human activities and urban development [16-17]. MPs are also prevalent in Tumpat, Kelantan, an area known for resorts, dining venues, jetties, and tourist attractions [8, 22].

CONCLUSION

This research provides a comprehensive analysis of microplastic pollution along the beaches of Kelantan, highlighting the significant environmental challenges posed by the North-East Monsoon, coastal erosion, and sedimentation. By utilizing satellite imagery, systematic sediment sampling, and advanced analytical techniques such as FTIR Spectroscopy, the study identified a wide range of microplastics in terms of polymer types, shapes, sizes, and colours. The study found that fragments were the most prevalent form of microplastics, indicating ongoing degradation of larger plastic debris, while beads/granules and fibers also contributed to the microplastic load, with distribution varying across sampling stations.

The analysis revealed distinct patterns in the abundance and distribution of microplastics across the selected beaches of Kelantan, showing that some areas, particularly Pantai Nusuk and Pantai Sabak, exhibited significantly higher concentrations, especially during mid-tide. This highlights the influence of tidal dynamics in the dispersion and deposition of microplastics, which may be further influenced by localized coastal erosion and sedimentation processes. Coastal erosion, exacerbated by the North-East Monsoon, likely contributes to the release of microplastics trapped in sediments, while accretion in certain areas may facilitate the accumulation of these pollutants on the shoreline.

Spatial statistical modelling using IDW in ArcGIS revealed significant geographic variations in microplastic distribution, with concentrations varying based on tidal phases and proximity to human activity. Areas with high urban and tourism development, such as near resorts and jetties, exhibited greater concentrations of microplastics, reinforcing the link between human activity and plastic pollution.

While the study provides valuable insights into the types, abundance, and distribution of microplastics along Kelantan's coastline, it also underscores the urgent need for continued monitoring and targeted mitigation strategies. Future research should focus on understanding the specific impacts of erosion and accretion on the accumulation and redistribution of microplastics, as well as the long-term ecological and health impacts. This study calls for collaborative efforts among stakeholders, including government bodies, local communities, and environmental organizations, to develop comprehensive strategies for managing and mitigating microplastic pollution, ensuring the protection and preservation of Kelantan's coastal ecosystems for future generations.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

While preparing this work, the author(s) utilized ChatGPT to enhance the readability and language of the text. Following the use of this tool, the author(s) thoroughly reviewed and edited the content as necessary and assume full responsibility for the publication's content.

REFERENCES

[1] T. Hien, N. T. T. Nhon, V. T. M. Thu, D. T. T. Quyen & N. T. Nguyen, 2020. The distribution of microplastics in beach sand in Tien Giang province and Vung Tau City, Vietnam, *Journal of Engineering and Technological Sciences,* 52(2), 208 – 221.

[2] C. M. Free, O.P. Jensen, S.A. Mason, M. Eriksen, N.J. Williamson & B. Boldgiv, 2014. High levels of microplastic pollution in a large remote mountain lake, *Marine Pollution Bulletin,* 85(1), 156 – 163.

[3] C. Akarsu, F. Deniz & R. Kahveci, 2020. Evaluation of microplastic pollution in sediments from riverine systems: A case study from the Tiber River, *Environmental Science and Pollution Research*, 27(3), 3281 – 3291

[4] E. A. Wicaksono, S. Werorilangi, T. S. Galloway & A. Tahir, 2021. Distribution and seasonal variation of microplastics in Tallo River, Makassar, eastern Indonesia, *Toxics*, 9(6), 129

[5] C. Campanale, C. Massarelli, I. Savino, V. Locaputo & V. F. Uricchio, 2020. A detailed review study on potential effects of microplastics and additives of Concern on human health, *International Journal of Environmental Research and Public Health,* 17(4), 1212.

[6] A. L. Andrady, 2017. The plastic in microplastics: A review, *Marine Pollution Bulletin,* 119(1), 12 – 22.

[7] X. Zhao, J. Wang, K. M. Y. Leung & F. Wu, 2022. Color: an important but overlooked factor for plastic photoaging and microplastic formation, *Environmental Science and Technology*, 56(13), 9161 – 9163.

[8] M. Nasir & I. Salleh, (2014). Kota Bharu Islamic City – the concept of a new cultural tourism product, *SHS Web of Conferences*, 12, 01021.

[9] T. Montoto-Martinez, G. Anfuso, A.T. Williams & E. Pranzini, 2020. Microplastics in coastal environments: A review on distribution, transport, and impacts, *Marine Pollution Bulletin*, 150, 110751.

[10] Unit Perancang Ekonomi Negeri Kelantan. (2019). Kelantan State Sustainable Development Master Plan 2019-2023, In Kelantan Utilities. Kelantan Utilities Mubaarakan Holdings Sdn. Bhd. https://www.dropbox.com/s/qbzmd6pcd4misya/Pelan%20Induk%20Pembangunan%20Mampan%20Kelantan%202019-2023.pdf?dl=1

[11] X. Zhai, X. Zhang & M. Yu, 2023. Microbial colonization and degradation of marine microplastics in the plastisphere: A review, *Frontiers in Microbiology,* 14.

[12] V. H. Da Silva, F. Murphy, J. M. Amigo, C. A. Stedmon & J. Strand, 2020. Classification and Quantification of Microplastics (<100 μm) Using a Focal Plane Array–Fourier Transform Infrared Imaging System and Machine Learning, *Analytical Chemistry,* 92(20), 13724–13733.

[13] A. M. Lagos, M. V. Leon, A. Colorado, D. Giraldo, L. Fragozo, A. M. Lagos & A. Martínez, 2023. Effects of microplastics pollution on the abundance and composition of interstitial meiofauna, *Revista De Biologia Tropical,* 71(1), e50031.

[14] S. Primpke, M. Wirth, C. Lorenz & G. Gerdts, 2018. Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy, *Analytical and Bioanalytical Chemistry,* 410(21), 5131 – 5141.

[15] C. Rathore, M. Saha, P. Gupta, M. Kumar, A. Naik & J. De Boer, 2023. Standardization of micro-FTIR methods and applicability for the detection and identification of microplastics in environmental matrices, *Science of the Total Environment*, 888, 164157.

[16] M. Bitlus, E. Tunca, E. Yildirim & S. Gormus, 2020. Presence and implications of microplastics in marine environments: Insights from the Marmara Sea, *Science of the Total Environment,* 720, 137601.

[17] S.T. Anuar, M.F. Yusof & S. Ismail, 2023. Microplastic pollution in tropical estuarine systems: Assessment and future directions, *Environmental Pollution*, 268, 115659.

[18] S. H. Joo, Y. Liang, M. Kim, J. Byun & H. Choi, 2021. Microplastics with adsorbed contaminants: Mechanisms and Treatment, *Environmental Challenges,* 3.

[19] İ. Koraltan, S. Mavruk & O. Güven, 2022. Effect of biological and environmental factors on microplastic ingestion of commercial fish species, *Chemosphere,* 303, 135101.

[20] Q. Feng, Z. Chen, C. An, X. Yang & Z. Wang, 2023. Tide-induced infiltration and resuspension of microplastics in shorelines: Insights from tidal tank experiments, *Water Research,* 236, 119970.

[21] R. Talbot & H Chang, 2022. Microplastics in freshwater: A global review of factors affecting spatial and temporal variations,

Environmental Pollution, 292, 118393.

[22] C. L. Cheam, N. A., Othman & F. N. S. B. a. K. Johari, 2018. Tourists perceptions of Kota Bharu Islamic city, *Malaysian Journal of Social Sciences and Humanities (MJSSH)*, 3(4), 60 – 72.

[23] A. Z. Zakaria, I. H., Salleh & M. S. A. Rashid, 2018. Malay Garden as tourism product in Malaysia, *Asian Journal of Environment-Behaviour Studies,* 3(10), 89 – 98.

[24] G. Z. Dodson, A. K. Shotorban, P. G. Hatcher, D. C. Waggoner, S. Ghosal & N. Noffke, 2020. Microplastic fragment and fiber contamination of beach sediments from selected sites in Virginia and North Carolina, USA, *Marine Pollution Bulletin*, 151, 110869

[25] K. Schröder, E. Kossel & M Lenz, 2021. Microplastic abundance in beach sediments of the Kiel Fjord, Western Baltic Sea, *Environmental Science and Pollution Research, 2*8(21), 26515–26528.

[26] V. Morgado, L. Gomes, R. J. B. Da Silva & C. Palma, 2022. Microplastics contamination in sediments from Portuguese inland waters: Physical-chemical characterisation and distribution, *Science of the Total Environment,* 832, 155053.

[27] I. Kim, D. Chae, S. Kim, S. B. Choi & S. Woo, 2015. Factors influencing the spatial variation of microplastics on High-Tidal coastal Beaches in Korea, *Archives of Environmental Contamination and Toxicology,* 69(3), 299 – 309.

[28] R. Bissen & S. Chawchai, 2020. Microplastics on beaches along the eastern Gulf of Thailand – A preliminary study, *Marine Pollution Bulletin,* 157, 111345.

[29] J. P. Da Costa & T. Rocha-Santos, 2017. Microplastics – occurrence, fate and behaviour in the environment, *In Comprehensive Analytical Chemistry.* 1 – 24.

[30] M. Claessens, S. D. Meester, L. V. Landuyt, K. De Clerck & C. R. Janssen, 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast, *Marine Pollution Bulletin*, 62(10), 2199 – 2204.

[31] Q. Zhou, H. Zhang, C. Fu, Y. Zhou, Z. Dai, Y. Li, C. T & Y. Luo, 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea, *Geoderma*, 322, 201 – 208.

[32] F.A. Lots, P. Behrens, M.G. Vijver, A.A. Horton & T. Bosker, 2017. A large-scale investigation of microplastic contamination: Abundance and characteristics of microplastics in European beach sediment. *Marine Pollution Bulletin,* 123(1-2), 219 – 226.

[33] Y. Zheng, J. Li, W. Cao, X. Liu, F. Jiang, J. Ding, X. Yin & C. Sun, 2019. Distribution characteristics of microplastics in the seawater and sediment: A case study in Jiaozhou Bay, China, *Science of the Total Environment,* 674, 27 – 35.