Occurrence and Distribution of Microplastics on Coastal Intertidal Zones of Brunei Darussalam

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Abstract

Microplastic pollution has become a major environmental concern due to its ubiquity and potential adverse effects on marine ecosystems. This study investigates the types and distribution of microplastics in the coastal intertidal zones of Brunei Darussalam. Sediment samples were collected from various beaches, and an extraction process was employed to isolate microplastics from the sediments. Fourier Transform Infrared (FT-IR) spectroscopy was then used to identify the microplastics present. The most common polymers detected include polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyamide (PA), and acrylonitrile butadiene styrene (ABS), which constitute a significant portion of global plastic production. Results reveal the widespread presence of microplastics across the selected study sites, with PP being the most commonly detected polymer. The distribution of microplastics is associated with varying degrees of human activities, such as recreational use and fishing. The presence of these plastic polymers in coastal intertidal zones indicates potential threats to marine ecosystems through chemical and biological decomposition, which can lead to bioaccumulation and toxicity in marine organisms. This research provides valuable insights into the prevalence and types of microplastic pollution in Brunei Darussalam's coastal regions and highlights the need for targeted interventions to mitigate the impacts of microplastic pollution on marine ecosystems.

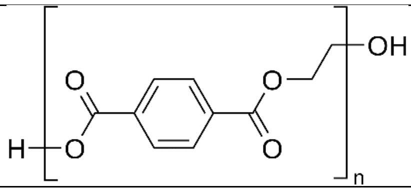
Keywords:
Microplastic pollution, Coastal intertidal zones, Polymer types, Fourier Transform Infrared spectroscopy (FTIR), Marine ecosystem

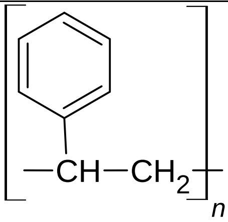
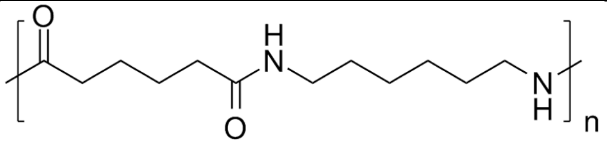
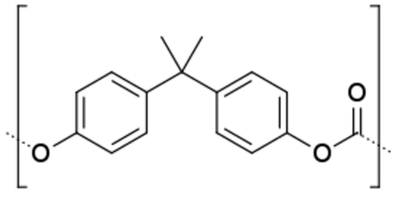
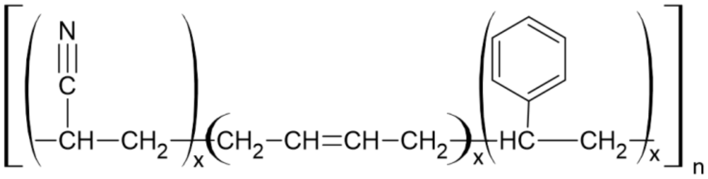
1. Introduction

Plastics have become an indispensable part of modern life and find extensive use in a wide range of daily activities, leading to their exponential production [1]. Studies predict that plastic production will increase by 40% in the next decade[2]. The most commonly produced plastics worldwide are polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS), accounting for approximately 90% of global plastic production [3–5]. ***Table 1*** shows the recycling codes and monomer unit structures of common plastics. The Department of Environment, Parks, and Recreation data show that Brunei Darussalam generated 189,000 and 216,000 tons of Municipal Solid Waste (MSW) in 2015 and 2016, respectively [6]. This corresponds to 1.4 kg of waste per person per day, with projections of 263,000 tons in 2030 and 308,000 tons in 2050. Another study reported that plastics constituted the majority of debris on Brunei's coastline, both in terms of frequency (90.02%) and total mass (39.12%), with most plastic waste originating from the Brunei Muara District [7]. As a result, plastics rank third in solid waste generation in Brunei Darussalam.

Plastics enter the marine environment in various sizes and do not decompose naturally. Instead, they break down into smaller pieces called microplastics under ultraviolet (UV) light and relatively low temperatures. The European Chemical Agency and National Oceanic & Atmospheric Administration (NOAA) define microplastics as plastic polymers with a diameter of less than 5 millimeters [8]. Microplastics can be classified into two categories: primary and secondary microplastics. Primary microplastics are intentionally produced for industrial or domestic use, such as plastic pellets, fibers, powders, and additives in cosmetic and cleaning products [9,10]. Secondary microplastics form when larger plastic products degrade into smaller fragments in marine environments due to photodegradation under weathering or aging processes of poorly managed waste, such as discarded plastic bags or inadvertent losses like fishing nets [8,11]. Both primary and secondary microplastics are found in high quantities in marine environments, with an estimated 245 tons of microplastics produced annually ending up in water bodies, where they are ingested and incorporated into the bodies and tissues of marine organisms [8,9].

Table 1. Types of plastics with their recycling codes and monomer units.

Plastic Type	Recycling Code	Monomer unit structure
PET polyethylene terephthalate	1	
HDPE high-density polyethylene	2	$-[CH_2-CH_2-]_n$
PVC polyvinyl chloride	3	$-[CH(Cl)-CH_2]_n-$
LDPE low-density polyethylene	4	$-[CH_2-CH_2-]_n$
PP polypropylene	5	$-[CH(CH_3)-CH_2]_n-$

PS polystyrene	6	
OTHER	7	 Polyamide (PA)
		 Polycarbonate (PC)
		 Acrylonitrile Butadiene Styrene (ABS)

1.1 *Environmental impacts of microplastics*

Microplastics in marine environments consist of particles with varying sizes, chemical compositions, shapes, and densities, originating from diverse sources [12]. Due to their size and large surface-to-volume ratio, microplastics tend to absorb and accumulate contaminants from surrounding water [13,14], with contaminant concentrations on microplastics varying geographically [15]. Microplastics have emerged as a global concern due to their widespread distribution, particularly in marine systems, and are considered one of the top threats to biota [16].

Since the 1970s, plastic pollution has significantly impacted biodiversity, especially in marine systems [16,17]. The growing risk to biota from marine waste, particularly plastics, raises global concerns and affects ecological and economic aspects [18]. As microplastics enter marine environments from industrial, agricultural, and human activities, some float in the water, while high-density particles settle in sediment [19]. Exposure to plastic particles can cause harmful effects on marine species, including immunological and neurotransmission malfunctions, behavioral abnormalities, poor feeding activity, oxidative damage, hindered growth and development, inflammatory responses, and early mortality [20].

Toxic compounds such as organotin, phthalate, polybrominated biphenyl ether, triclosan, and nonylphenol are used as additives in microplastics [21]. Furthermore, toxic chemicals like bisphenol-A, monomers, flame retardants, oligomers, metal ions, and antibiotics are incorporated with plastics [22]. Bisphenol-A and phthalates in plastics have been shown to significantly affect reproduction, genetic mutations, and organism development in laboratory settings [23]. These hazardous compounds are Persistent Organic Pollutants (POPs) that resist biodegradation and are released into the environment through the chemical or biological decomposition of plastic polymers, threatening marine life, such as fish, which are crucial to the human food chain [18].

Microplastics are easily ingested by marine organisms across different trophic levels and have been shown to biomagnify through the food chain [24]. As microplastic particles are similar in size to feeding matter like plankton and suspended particles, invertebrates can inadvertently ingest these synthetic microplastics [25]. Ingestion of microplastic items may cause intestinal blockage and internal damage to marine organisms, while sharp-edged microplastics can injure gill tissues and digestive systems [26]. Entanglement and ingestion are critical issues associated with microplastic fragments, resulting in the death or severe injury of coastal and marine biotic species. Entanglement cases primarily involve fishing nets or plastic rope in fishing gear, while ingestion is strongly linked to microplastic fragments [27]. Sea turtles, marine mammals, invertebrates, and seabirds are among the species at higher risk due to entanglement and ingestion [18].

A recent study discovered plastic polymers in the blood of 17 out of 22 participants [28] indicating that human blood is a new route for microplastics. The detected polymers ranged in size from 700 to 500,000 nm. Polyethylene terephthalate (PET), the most prevalent plastic polymer commonly used in disposable water bottles, was found in 50% of the participants' blood samples. Polystyrene (PS), the second most common plastic polymer used for food packaging and polystyrene foam, was discovered in approximately 36% of the blood samples. These microplastics in human blood could potentially transport throughout the body, posing threats and becoming a dominant concern.

Numerous studies have investigated the health of workers in PVC polymerization facilities, establishing a causal link between angiosarcoma of the liver and statistically significant excesses of brain cancer and neurological effects among workers exposed to vinyl chloride monomer (VCM). Polyvinyl chloride is considered more harmful due to its loosely bound phthalates leaching out behavior as a result of photodegradation, causing endocrine disruption in marine organisms [7].

The primary aim of this research is to identify the types of microplastics present on the coastline of Brunei Darussalam. To achieve this aim, several objectives have been outlined, including the extraction and collection of microplastic samples from the coastal intertidal zone of Brunei Darussalam, the determination of the quantity of microplastics present in the sediment, and the analysis of the collected microplastics using Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR) for accurate identification.

2. Materials and Methods

2.1 Chemicals and Glassware

The reagents used in this study included 30% Hydrogen Peroxide (Merck, Germany) for wet peroxide oxidation and Sodium Chloride (Merck, Germany) for density separation. The glassware employed consisted of crucibles, measuring cylinders, beakers, volumetric flasks, watch glass, spatulas, glass rods, forceps, and glass vials. All glassware was thoroughly cleaned with double distilled water and subsequently dried in a hot air oven.

2.2 Instrumentation

In this study, an Attenuated Total Reflectance (Shimadzu ATR, QATR-S) was connected to a Fourier Transform Infrared Spectrophotometer (Shimadzu FT-IR, IRSpirit) to identify the chemical structures of each microplastic sample. The sample was placed on the diamond prism used in the ATR accessory, and it was pressed against a high-refractive index prism to generate an IR spectrum. The diamond prism was cleaned with ethanol (Merck, Germany) between each sample analysis. The ATR-FTIR spectra were set at a range of 4000 – 400 cm^{-1}. The ATR-FTIR approach is considered one of the most significant spectrometric techniques for the quantification and identification of microplastics.

***2.3** Collection of samples*

Sediment samples were collected from the intertidal zone during low tide between February and July 2022 along the Brunei Darussalam coastline at six different sites, including three in Brunei-Muara, one in Tutong, and two in the Belait district. The intertidal zone is defined as an area that experiences two distinct states: exposure to air at low tide and submersion in seawater at high tide. Brunei's weather database, which provides updates on tides in the coastal areas, was monitored, as this study required samples to be collected during low tide. The six sampling sites selected are labeled A-F (***Figure 1***), with detailed information on each site shown in ***Table 2***. Sediment samples were randomly collected using a stainless-steel shovel and then placed and labeled in plastic zip bags. The samples were subsequently brought to the physical laboratory of Universiti Brunei Darussalam (UBD) for further analysis.

Figure 1. The selected study sites along the coast of Brunei Darussalam. (A: Muara, B: Berakas, C: Jerudong, D: Seri Kenangan, E: Kuala Belait (Pantai Ku Ceria) and F: Silver Jubilee)

Table 2. Details of study sites at Brunei Darussalam coastline.

Site	Coastline	Coordinates
A	Muara	4.994344752626775, 114.92102431377145 4.9942644996497245, 114.92089898463783 4.994437352000185, 114.92132141224712
B	Berakas	5.038375069836788, 115.0776446212803 5.038494425289769, 115.07867418025793 5.038530146869802, 115.07923059136183
C	Jerudong	4.958875045059838, 114.84035318765744 4.956343359527402, 114.83960357510037 4.957388015500213, 114.84005281184878
D	Seri Kenangan	4.8070612281064475, 114.63690299164409 4.806149625936998, 114.63586192197735 4.806167598865327, 114.63587811873381
E	Kuala Belait (Pantai Ku Ceria)	4.591474943420934, 114.2114706038616 4.591491494438319, 114.21162080124058 4.5914249904609346, 114.21078376009527
F	Silver Jubilee	4.589900157413719, 114.1946865901768 4.589906128118055, 114.19506073101113 4.589914581494421, 114.19515642316274

***2.4** Extraction of microplastics using density and wet peroxide method*

Beach sediment samples were prepared by weighing crucibles containing wet samples. These samples were then placed in a drying oven at 100-120°C for approximately 2 hours or until completely dry. The crucible with the dried sample was weighed to determine the dry sample mass. Next, the dry sample was separated using sieves based on particle size ranges of 1-5 mm, 0.5 ≥ 1 mm, and 0.2 ≥ 0.5 mm. Plastic particles measuring 0.5 mm and larger were collected using forceps, placed in a vial, and weighed. Smaller plastic size fractions were further processed using hydrogen peroxide and density separation.

The dry sample was transferred into a 600 mL beaker, and 200 mL of 5M NaCl was added to the dried sediment sample. The sand mixture was stirred for several minutes to float the microplastics. Then, 40 mL of 30% hydrogen peroxide was added to the beaker containing the dried sample. The mixture was allowed to stand at room temperature for 5 minutes before being heated to 75-90°C on a hotplate. When gas bubbles were observed, the beaker was removed and placed in a fume hood until boiling subsided. The mixture was reheated at 75-90°C on a hotplate until no organic material was visible. Next, 6 g of NaCl was added to the mixture to increase the solution's density, and the mixture was heated until the NaCl dissolved.

The wet peroxide solution was transferred to the density separator, and the wet peroxide oxidation solution was rinsed with distilled water to transfer any remaining solids to the density separator. Settled solids were visually inspected and placed into glass vials, while floating solids were collected using a 0.2 mm sieve, dried, and stored in glass vials. The glass vials were weighed before and after adding microplastics to determine the mass of microplastics for further analysis.

2.5 Preparation of plastic standards

For the preparation of plastic standards, seven different types of plastic materials were used. These are commonly available polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and polyamide (PA) and acrylonitrile butadiene styrene (ABS). Firstly, these plastics were cut into smaller pieces and then blended to create a fine, powdery form. The pulverized plastics were transferred onto sieves with mesh sizes of 0.5 mm and 0.2 mm to ensure the collection of larger plastic fragments on the 0.5 mm sieve and smaller fragments needed for this study on the 0.2 mm sieve. The plastic powder underwent a drying process in a drying oven at 100-120°C until completely dry. Finally, the dried plastic powder was transferred into glass vials for FTIR analysis.

3. Results and discussion

Microplastics are unevenly distributed in sediments due to their characteristics and environmental influences, such as currents and winds. Some regions may contain larger concentrations of microplastics, heavily influencing the results based on the sampling area and depth[29]. Additionally, microplastics in coastal areas are believed to originate from both land-based and sea-based activities [1]. With a population of approximately 437,000, Brunei has a 161 km long coastline along the South China Sea, with 100% of its residents living near the coast or within 100 km of it [7]. Therefore, microplastic contamination in sediments along the coastline of Brunei Darussalam is contributed by human and recreational activities in these coastal areas.

Table 3 shows the microplastic abundance (%) in dry sediment for each selected sampling site in this study. Microplastics were classified by size: 0.2 ≥ 0.5 mm, 0.5 ≥ 1 mm, and 1-5 mm. The highest microplastic abundance for 0.2 ≥ 0.5 mm and larger than 1 mm was found at Berakas Beach, with 0.71 % and 0.80 % by weight, respectively. In contrast, Seri Kenangan Beach had the highest microplastic abundance for the 0.5 ≥ 1 mm size, with 0.98% by weight in dry sediment. The lowest abundance of 0.2 ≥ 0.5 mm and 0.5 ≥ 1 mm microplastics was found at Kuala Belait (PKC) Beach, with 0.09 % and 0.23 % by weight, respectively. Finally, the lowest abundance of microplastics larger than 1 mm was at Silver Jubilee Beach (0.40 % by weight).

Table 3. Percentages of microplastics (classified by size) in dry sediment collected during the study from each beach.

Coastline	weight % microplastics in dry sediment			
	1-5 mm	0.5 ≥ 1 mm	0.2 ≥ 0.5 mm	total
Muara	0.59	0.29	0.27	1.15
Berakas	0.80	0.38	0.71	1.89
Jerudong	0.44	0.52	0.25	1.20
Seri Kenangan	0.44	0.98	0.29	1.70
Kuala Belait (Pantai Ku Ceria)	0.67	0.23	0.09	0.98
Silver Jubilee	0.40	0.55	0.17	1.12

3.1 *Beach description*

Brunei Darussalam has over ten beaches of varying sizes along its coastal area, and six beaches were selected for this study (***Figure 1***). Muara, Berakas, and Seri Kenangan beaches host recreational activities year-round, with visitor numbers peaking on weekends. These beaches are well-equipped with playgrounds, barbecue, and picnic areas. Seri Kenangan Beach is particularly popular among locals and tourists due to its well-developed infrastructure and proximity to Tutong city. Jerudong Beach is also a hotspot for local visitors and foreign tourists, as many establishments surround it, including local flea markets, souvenir shops, restaurants, and a bay boat landing, which serves as a base for small fishing boats operating off the Brunei coastline. Kuala Belait (PKC) Beach is surrounded by residential areas and hotels, making it a frequent destination for locals and tourists. Silver Jubilee Beach, situated next to a playground park and close to residential areas, schools, and restaurants, also attracts visitors. As a result, areas with high human activity exposure contribute to the distribution of microplastics in these coastal regions.

3.2 *Microplastics identification*

The polymer types of microplastics can be directly determined by comparing the resulting spectra with those of known plastic polymers. FT-IR spectroscopy can accurately identify most plastic polymers based on their specific infrared absorption bands. For instance, the C=O band divides eight polymers into two groups: Polyethylene Terephthalate (PET), poly(methyl methacrylate) (PMMA), polyamide (PA), and polyurethane (PU) belong to the carbonyl-containing polymer group. The presence of aromatic signals referring to the phenyl moiety further differentiates PET from other polymers [30]. The N-H signal, which is evident for PA and PU but not for PMMA, can be used to distinguish the remaining polymer types. Similarly, non-carboxylic polymers can be separated using the same approach. PS, PE, PP, and PVC can be distinguished by their aromatic moieties and the presence or absence of C-Cl absorption [30]. In this study, each sample was analyzed multiple times, resulting in several FT-IR analyses of the microplastics collected from each study site along Brunei Darussalam's coastline, as shown in ***Figure 2***.

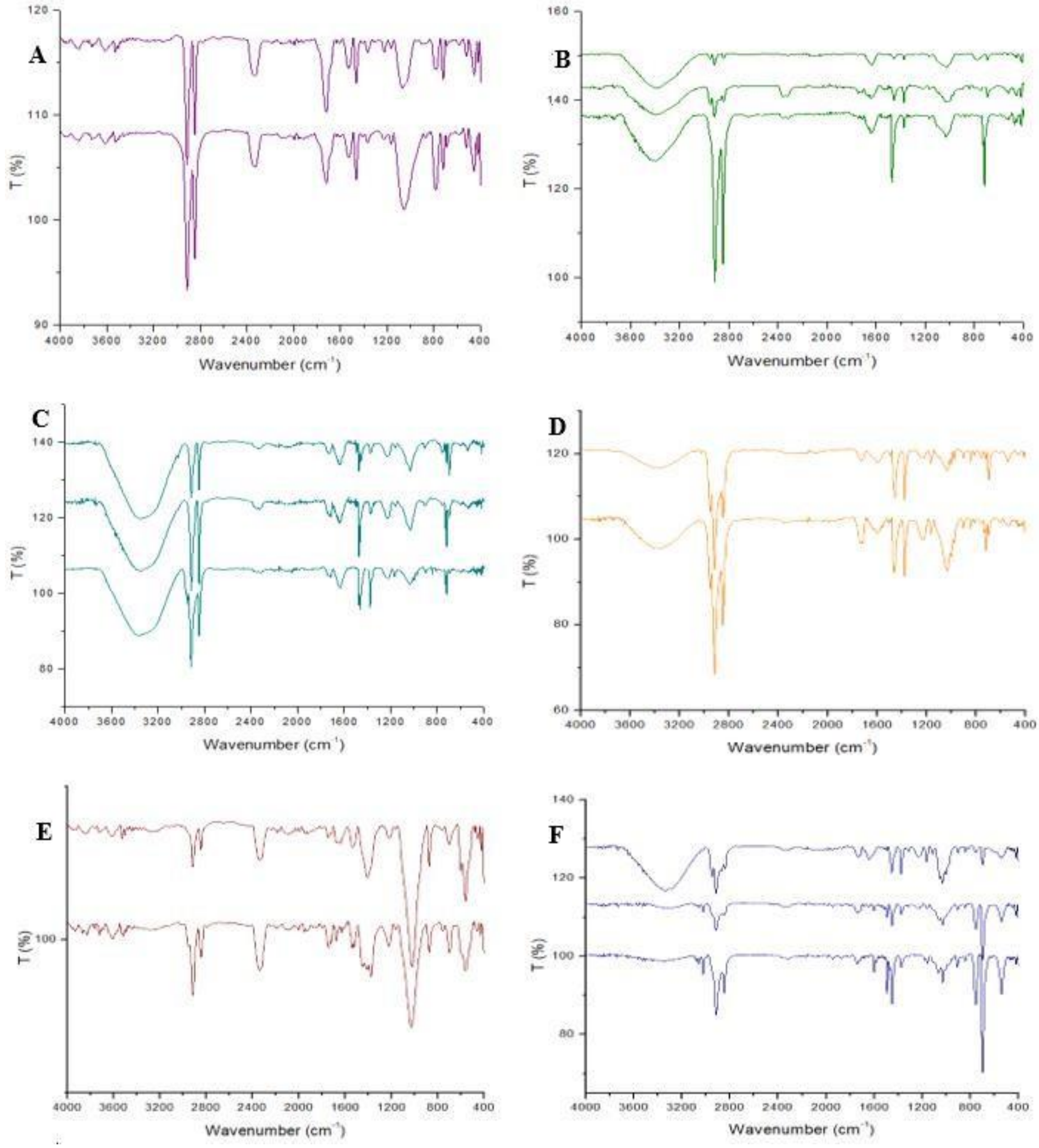


Figure 2. FT-IR spectra of the microplastic samples collected on each study site. (A: Muara, B: Berakas, C: Jerudong, D: Seri Kenangan, E: Kuala Belait (Pantai Ku Ceria) and F: Silver Jubilee)

Table 4 summarizes the types of microplastics found at each study site. The results show that PET was only present at Muara beach, while PVC was only found at Kuala Belait (PKC) beach. HDPE was observed at Muara, Berakas, Jerudong, and Seri Kenangan beaches, while LDPE was found only at Berakas and Seri Kenangan beaches. PP was found to accumulate at all study sites. PS was detected at Berakas, Jerudong, and Silver Jubilee beach. Lastly, the "OTHER" type of plastic, which includes PA, PC, or ABS, was observed at Jerudong and Seri Kenangan beach.

Table 4. Summary of microplastics identified in each sampling site.

Coastline	**PET**	**HDPE**	**PVC**	**LDPE**	**PP**	**PS**	**OTHER**
Muara	✓	✓			✓		
Berakas		✓		✓	✓	✓	
Jerudong		✓			✓	✓	✓
Seri Kenangan		✓		✓	✓		
Kuala Belait (Pantai Ku Ceria)			✓		✓		
Silver Jubilee					✓		✓
Muara					✓	✓	

3.2.1 *Polyethylene Terephthalate (PET)*

Polyethylene terephthalate (PET), also known as PETE, is a linear semicrystalline thermoplastic polymer resin belonging to the polyester (PES) family. It is produced through the polymerization of ethylene glycol and terephthalic acid. Ethylene glycol is an alcohol group with a molecular structure containing two hydroxyl (OH) groups, and terephthalic acid is an aromatic dicarboxylic acid with a molecular structure containing an aromatic ring with two carboxyl groups (COOH). Ester (CO-O) groups are formed when hydroxyl and carboxyl groups react under the action of heat and catalysts [31] acting as a chemical link joining multiple PET units with a chemical formula of $(C_{10}H_8O_4)n$. PET is used in a wide variety of products such as food and drink containers, technological and automotive components, and clothing fibers. Approximately 53.3 million tons of PET are produced annually worldwide.

After analyzing the samples, the resultant spectra displaying the samples' absorption bands were compared to those known for plastic polymers. The spectrum of PET shows similar absorption bands with the sample from Muara beach (***Figure 3***). The peaks at 2914 and 2847 cm^{-1} represent the strong and sharp symmetrical stretching of C-H, and absorption bands at 2344 cm^{-1} were observed for the axial symmetrical deformation of CO_2. The medium peak detected at 1723 cm^{-1} shows the stretching of C=O of the carboxylic acid group. Additionally, the bands of three peaks at 1637, 1605, and 1522 cm^{-1} correspond to the vibrations of an aromatic skeleton with C=C stretching. The vibrational modes of ethylene glycol and stretching of C-O group deformation of the O-H group showed three peaks at 1464, 1411, and 1367 cm^{-1}. Moreover, two weak peaks at 1226 and 1165 cm^{-1} were obtained, showing the presence of the terephthalate group ($OOCC_6H_4$-COO). The vibrations of the ester C-O bonds and methylene group were also observed at 1069 cm^{-1}. Additionally, the medium peak at 790 cm^{-1} and 721 cm^{-1} shows the vibrations of aromatic H bands and the interactions of polar ester groups and benzene rings, respectively.

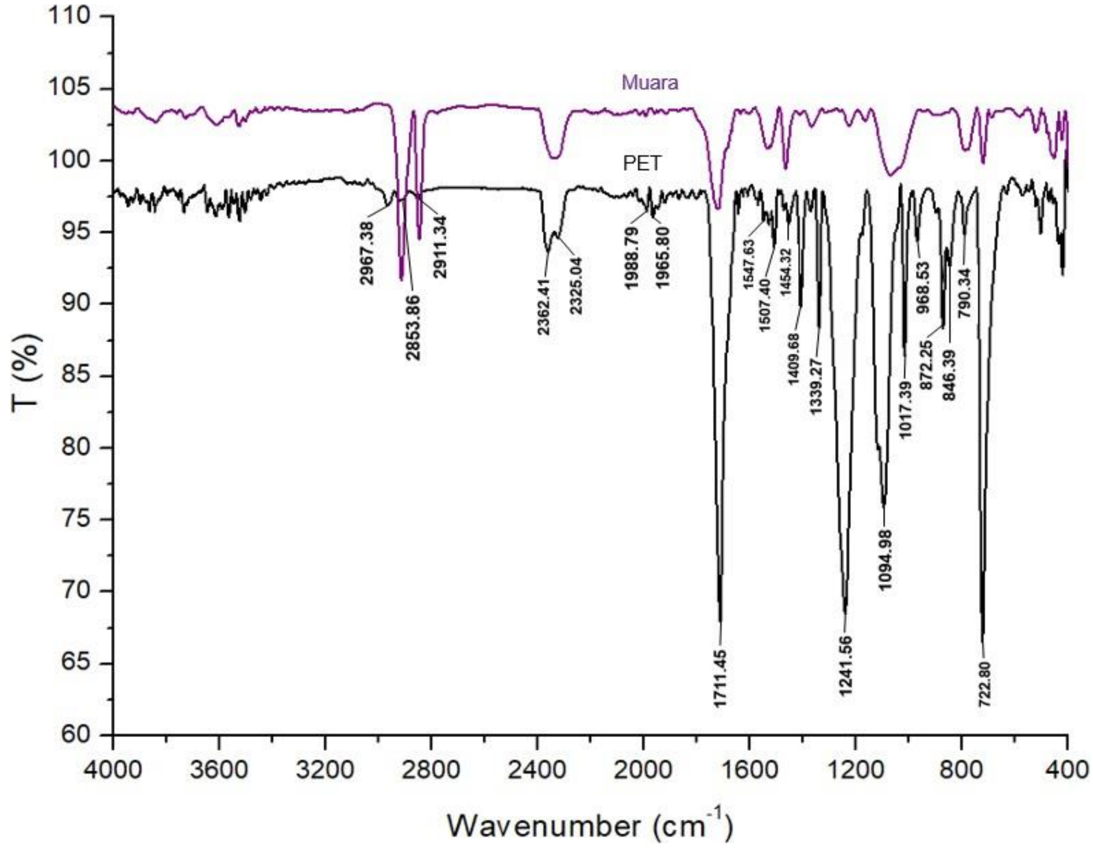


Figure 3. Superimposed FT-IR spectra of PET and microplastic sample collected from Muara beach.

The detection of PET at the sampling site of Muara beach indicates the presence of food packaging, such as plastic beverage bottles and soft drinks. Similarly, recreational activities such as picnics at Muara beach often leave traces of plastic material PET, which results in littering and pollution. For this reason, PET may cause nausea, vomiting, diarrhea, eye, and respiratory problems, as PET is a potential human carcinogen [7].

3.2.2 *High-density Polyethylene (HDPE)*

High-density polyethylene (HDPE) is a lightweight, flexible synthetic resin created through the addition polymerization of ethylene monomer. This type of polyethylene (PE) has a linear structure and a chemical formula of $(C_2H_4)n$. HDPE is manufactured at low temperatures and pressures, utilizing metallocene and Ziegler-Natta catalysts or activated chromium oxide, which is also known as the Phillips catalyst (a catalyst responsible for producing approximately half of the world's polyethylene) [32]. Due to its linear structure, HDPE's polymer chains are tightly packed, resulting in a dense, highly crystalline material with high strength and moderate stiffness [33]. HDPE is commonly used for bottles, buoys, construction films, and other rigid containers [9] due to its high melting point compared to other polymers. The use of HDPE resin in containers has significantly increased, accounting for about 34% of the global market [33].

The FT-IR spectra in ***Figure 4*** show the identified polymers in comparison to the standard spectrum of HDPE, with absorption peaks at approximately 2914 and 2848.11 cm^{-1} for Muara, Berakas, and Jerudong samples. Similarly, absorption peaks at around 2917 and 2847 cm^{-1} can be observed for the Seri Kenangan beach. These peaks are attributed to the asymmetric and symmetric stretching of CH_2 respectively. Additionally, a weak absorption peak at 1465.73 cm^{-1} for Muara and strong absorption peaks at 1470, 1473, and 1453 cm^{-1} for Jerudong, Berakas, and Seri Kenangan, respectively, result from the bending formation of the CH_2 group. Lastly, the split rocking mode of CH_2 peaks appear at 721 and 688 cm^{-1} for Muara, 717 and 697 cm^{-1} for Berakas, 730 and 717 cm^{-1} for Jerudong, and 718 and 695 cm^{-1} for Seri Kenangan beach. These results indicate the presence of HDPE plastic in the samples collected, as shown.

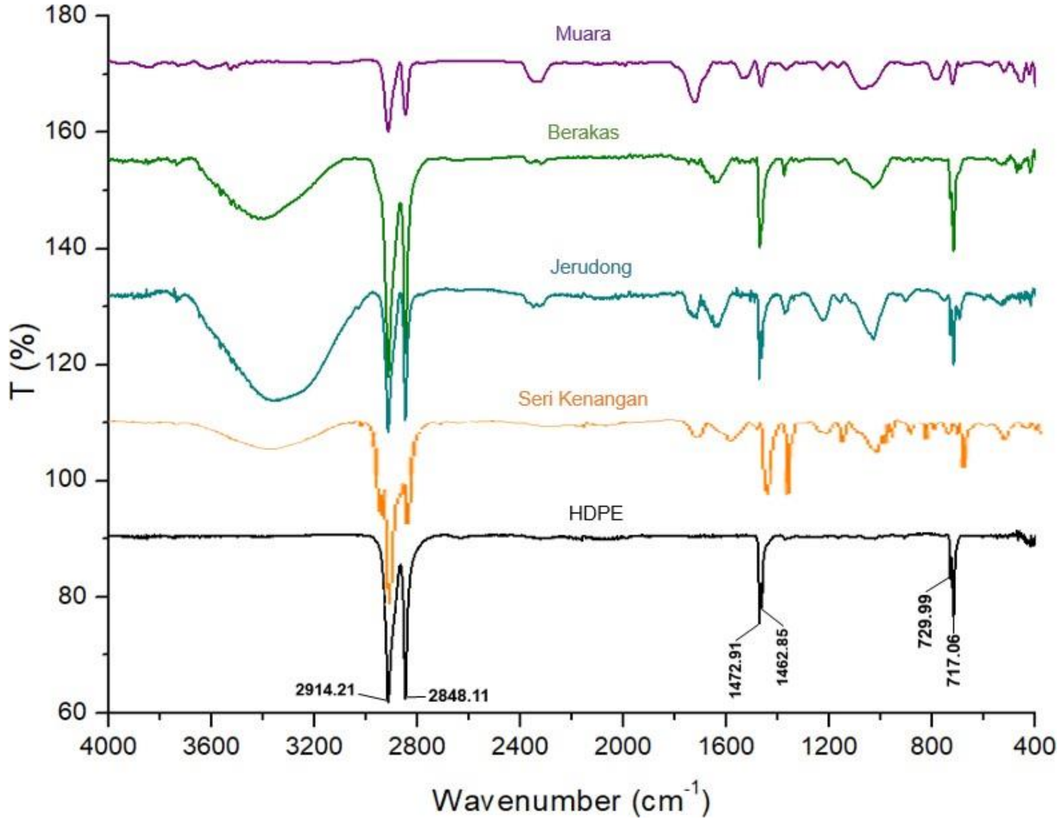


Figure 4. Superimposed FT-IR spectra of HDPE and microplastic samples collected from Muara, Berakas, Jerudong, and Seri Kenangan beach.

HDPE was found primarily at Muara, Berakas, Jerudong, and Seri Kenangan beaches. The detection of HDPE at these sampling sites is due to human recreational activities. Visitors frequently use plastic products containing HDPE and often utilize HDPE plastic packaging for storing food or drinks during picnics. However, the presence of HDPE at Jerudong beach could be a result of industrial fishing, both recreational and commercial, since the beach is located in close proximity to busy local flea markets, souvenir shops, restaurants, and the bay boat landing. Unfortunately, these activities often lead to littering and pollution, which is reflected in the plastic found at the sampling sites. Consequently, HDPE may affect reproductive systems when it undergoes photodegradation at higher temperatures.

3.2.3 *Polyvinyl Chloride (PVC)*

Polyvinyl chloride (PVC) is an economical, flexible thermoplastic polymer widely used in the building and construction industries. Its main applications include floor, wall, and wire coatings, pipes, fibers, films, and toys [34]. PVC is the third-largest thermoplastic polymer in terms of volume, following polyethylene (PE) and polypropylene (PP) [32]. PVC is formed through the addition polymerization of vinyl chloride monomer. Moreover, vinyl chloride monomer (VCM) is produced from the chlorination of ethylene and pyrolysis of ethylene dichloride (a precursor for VCM production) in a cracking unit. Consequently, VCM molecules are linked together to create PVC, with its chemical formula being $(C_2H_3Cl)n$.

In ***Figure 5***, the FT-IR spectrum of PVC and KB (PKC) were compared, and the detected absorption peaks were assigned. The similar peaks of PVC and KB (PKC) at 2917 and 2851 cm^{-1} correspond to the asymmetric and symmetric stretching of the CH_2 group, respectively. Additionally, the weak absorption bands at about 1416 cm^{-1} of KB (PKC) are due to the deformation of CH_2 and C-H aliphatic bending. The presence of peaks in the spectral ranges 1230-220 cm^{-1}, 1190-1020 cm^{-1}, and 980-960 cm^{-1} are attributed to the bending and rocking of C-H close to the Cl group (1243 cm^{-1}), stretching of C-C group (1198 and 1098 cm^{-1}), and trans-CH wagging mode (964 cm^{-1}), respectively. Moreover, the absorption peaks present in the spectral ranges 870-850 cm^{-1} and 610-550 cm^{-1} are due to the skeletal vibrations with stretching of C-Cl (874 cm^{-1}) and cis-CH wagging mode (611 cm^{-1}), respectively.

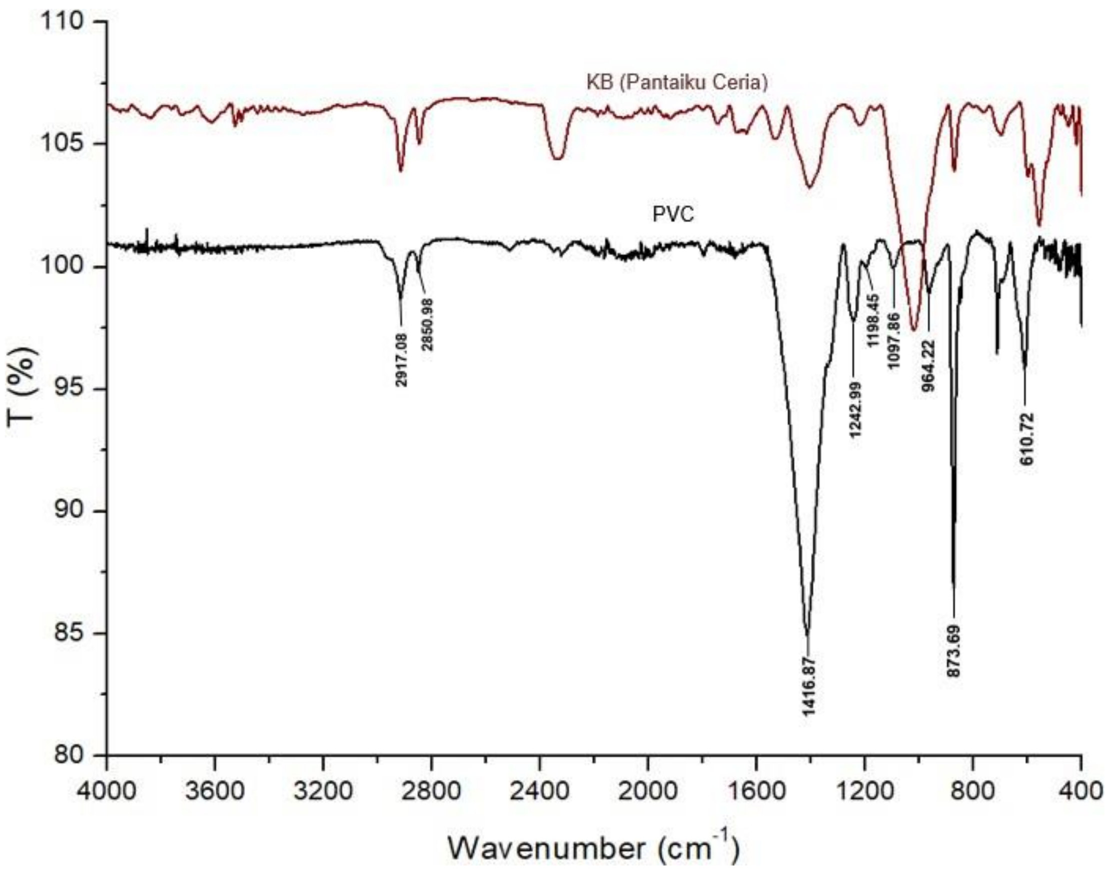


Figure 5. Superimposed FT-IR spectra of PVC and the microplastic sample collected from Kuala Belait (Pantaiku Ceria) beach.

The detection of PVC microplastic at 'Pantaiku Ceria' located in Kuala Belait suggests the presence of common materials, such as toys, wire coatings, pipes, and flooring. The PVC detected on the beach may be due to items used in creative infrastructure and artwork built at the beach. This is plausible since PKC is surrounded by hotels and residential areas. According to a study, photodegradation of PVC may lead to cancer, vision failure, interference with testosterone, deafness, and vision impairment in organisms [25].

3.2.4 Low-density Polyethylene (LDPE)

Low-density polyethylene (LDPE) is a thermoplastic with a chemical formula of $(C_2H_4)n$, produced by free radical polymerization of ethylene monomer under high pressures and temperatures in the presence of oxide initiators [35]. This polymerization process results in a polymer structure with both long and short branches, causing LDPE molecules to be arranged more loosely compared to HDPE [36]. LDPE's major attributes include low-temperature impact toughness, low-temperature impact resistance, good resistance to chemicals, and good creep resistance [37]. Due to these properties, LDPE is commonly used in packaging film, trash and grocery bags, wire and cable insulation, squeeze bottles, housewares, and netting [11].

Figure 6 displays the overlaid FT-IR spectra of LDPE and the microplastic samples collected from Berakas and Seri Kenangan beaches. The absorption bands of the Berakas sample exhibit the highest similarity to LDPE. For example, the strong and sharp absorption peaks at 2914 and 2848 cm^{-1} are attributed to the asymmetric and symmetric stretching of the CH_2 group, respectively. Additionally, the similar peaks observed at 1469 cm^{-1} for LDPE and samples from Berakas and Seri Kenangan beaches represent the bending formation of the CH_2 group. The peaks at 1368 and 718 cm^{-1} are ascribed to the symmetric deformation of CH_3 and rocking deformation of the CH_2 group, respectively.

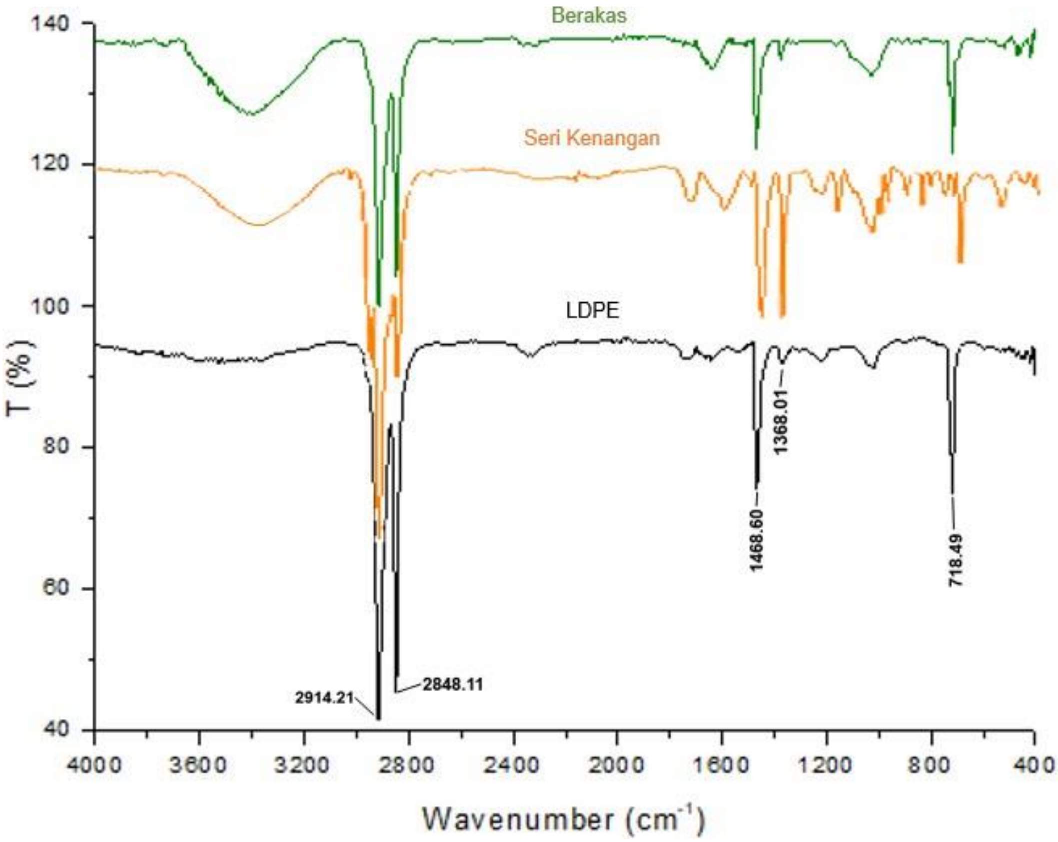


Figure 6. Superimposed FT-IR spectra of LDPE and microplastic samples collected from Berakas and Seri Kenangan beach.

Traces of LDPE were found at sampling sites such as Berakas and Seri Kenangan beaches. LDPE is commonly present in plastic bags, tubing, squeeze bottles, diapers, and netting. Recreational activities and fishing could be some of the factors contributing to the presence of LDPE at these sampling sites.

3.2.5 *Polypropylene (PP)*

Polypropylene (PP) is a widely manufactured thermoplastic polymer, with an annual global production volume of approximately 75.4 million metric tons [38]. PP is a tough, rigid, and crystalline thermoplastic derived from the propylene monomer and has the chemical formula $(C_3H_6)n$. Among common plastics, it has the lowest density, ranging from 0.89 to 0.91 g cm-3 [32]. The production of polypropylene involves two main synthesis methods: Ziegler-Natta polymerization and metallocene catalysis polymerization [39]. As a member of the polyolefin group, PP is utilized in various applications and industries, including straws, bottle caps, nets, ropes, tape, clothing, and camping equipment [34].

The FT-IR spectra obtained from microplastic samples collected at each study site exhibit similar absorption bands to the FT-IR spectrum of PP. The detected peaks are assigned and labeled in the graphs (***Figure 7***). Notably, the typical and main vibrations of PP are evident in all microplastic samples. The absorption peaks at 2953 and 2877 cm^{-1} represent the asymmetric and symmetric stretching of the CH_3 group, respectively. Meanwhile, the two peaks at 2917 and 2839 cm^{-1} signify the CH_2 asymmetric and symmetric stretching. The symmetrical bending and umbrella mode of the methyl group, CH_3, are observed in the 1370-1460 cm^{-1} region. Additionally, the absorption peak at 1164 cm^{-1} indicates the wagging and rocking of the CH and CH_3 groups, respectively. Two absorption peaks at 999 and 973 cm^{-1} are observed for the rocking mode of CH_3 and stretching of the C-C group. Stretching of the C-C group is also observed at 808 cm^{-1}. Furthermore, a peak at 841 cm^{-1} signifies the presence of CH_3 and CH rocking mode.

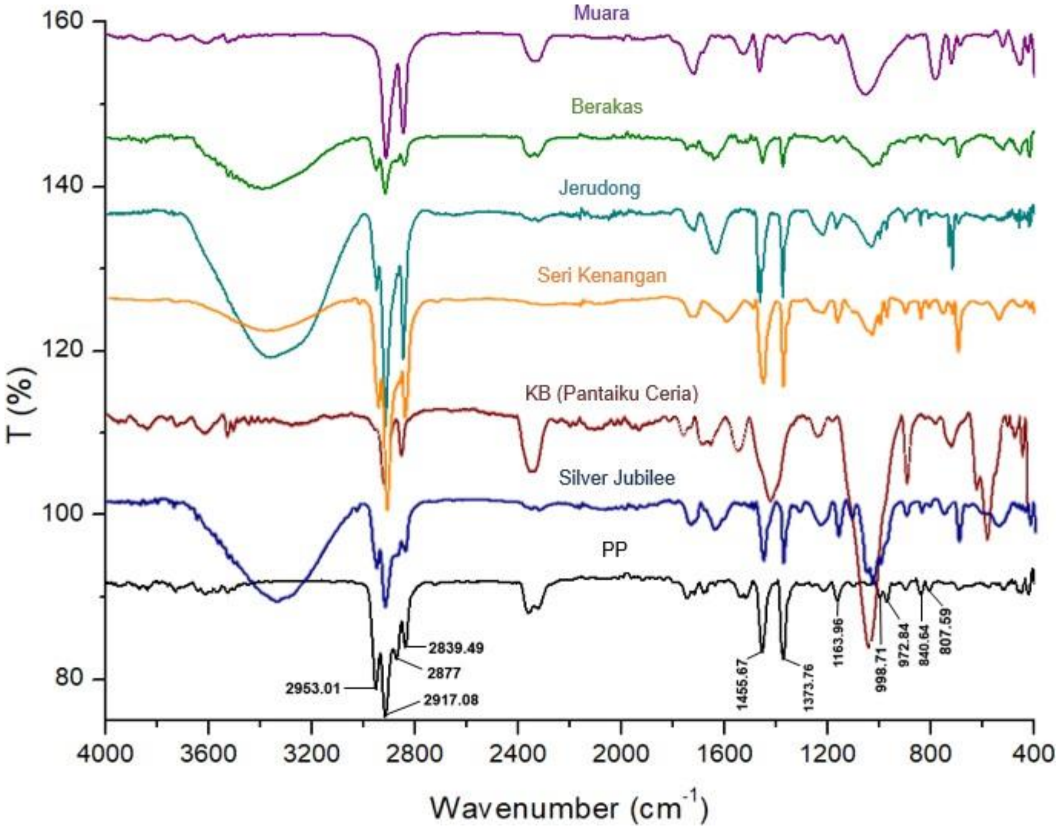


Figure 7. Superimposed FT-IR spectra of PP and microplastic samples collected from Muara, Berakas, Jerudong, Seri Kenangan, Kuala Belait (Pantaiku Ceria), and Silver Jubilee beach.

PP was detected at all sampling sites, suggesting that materials containing PP, such as straws, bottle caps, containers, ropes, and nets, are common at the beach. This finding indicates frequent human activities like fishing in addition to recreational activities, as nets and ropes made of PP are commonly used in fishing gear. However, PP can negatively impact the development and reproductive systems and may interfere with thyroid hormones.

3.2.6 Polystyrene (PS)

Polystyrene (PS) is an aromatic polymer with the chemical formula $(C_8H_8)n$, derived from the polymerization of styrene monomer. Styrene, a liquid hydrocarbon, is commercially manufactured from petroleum. It is obtained by reacting ethylene with benzene in the presence of aluminum chloride to yield ethylbenzene. The benzene group in this compound is then dehydrogenated to produce phenylethylene, or styrene, a clear liquid hydrocarbon with the chemical structure $CH_2=CHC_6H_5$. Styrene is polymerized using free-radical initiators, primarily in bulk and suspension processes, to form the linkage structure of polystyrene.

Polystyrene possesses numerous appealing properties for medical applications, including low cost and density, clarity, dimensional stability, and adaptability to radiation sterilization [40]. Additionally, it is commonly used in toys, food containers, cutlery, and plates.

As shown in ***Figure 8***, the overlaid spectra reveal that the absorption bands of the Silver Jubilee sample have the strongest similarity to the standard PS absorption bands. The absorption bands at 3090-3020 cm^{-1} were observed for the aliphatic and aromatic stretching of the CH_2 group. Additionally, two absorption peaks at 2920 and 2850 cm^{-1} are ascribed to the CH_2 asymmetric and symmetric stretching, respectively. The absorption band at 1600 cm^{-1} has been assigned to C=C, while the absorption bands at 1493-450 cm^{-1} are due to the C=C stretching and vibrations of the benzene rings. Notably, the presence of absorption bands at about 752 cm^{-1} is attributed to the out-of-plane aromatic CH_2, and the absorption peaks at 694 and 537 cm^{-1} are assigned to the bending mode of aromatic C-H.

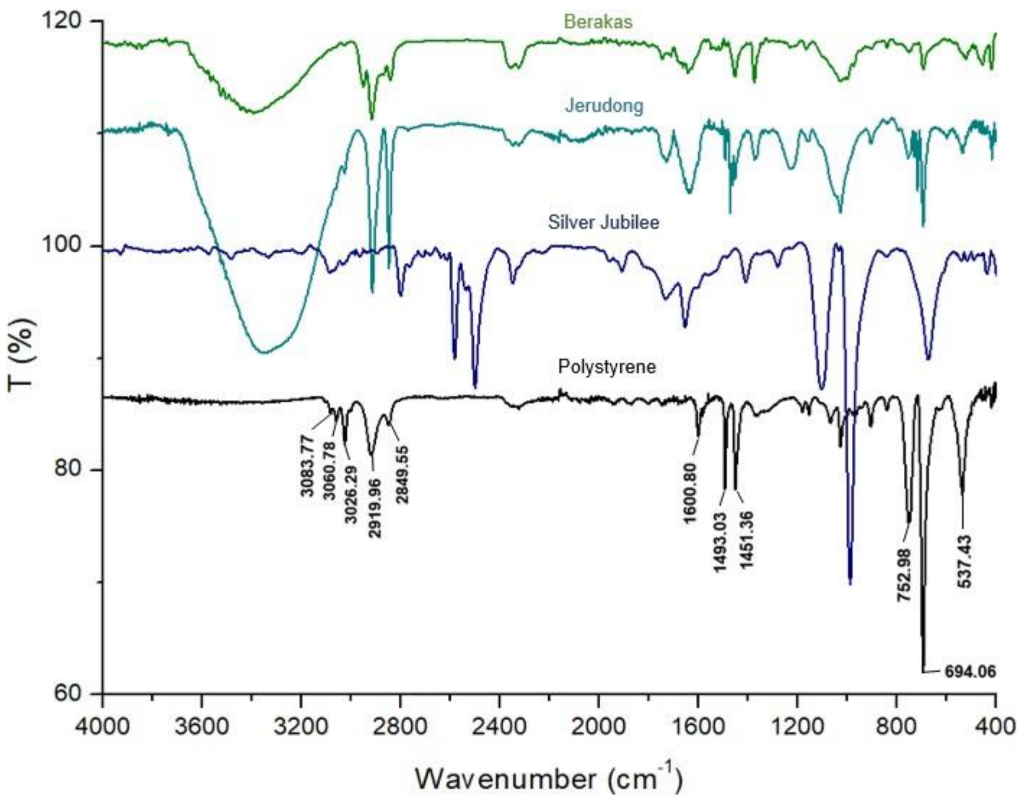


Figure 8. Superimposed FT-IR spectra of PS and microplastic samples collected from Berakas, Jerudong, and Silver Jubilee beach.

Berakas, Jerudong, and Silver Jubilee beaches are popular for human recreational activities, which explains the detection of PS at these locations. Furthermore, Berakas and Silver Jubilee beaches feature well-equipped playgrounds, attracting more human activity. This suggests that the presence of materials containing PS, such as cutlery, plates, food containers, and toys, indicates the frequent activities associated with the detection of PS.

3.2.7 OTHER

Plastic recycling code number 7, labeled 'OTHER,' encompasses recyclable, non-recyclable, and biodegradable plastics that do not belong to categories 1 to 6 (PET, HDPE, PVC, LDPE, PP, and PS). Plastic number 7 includes multilayer or mixed resin types of plastics. Examples of common plastics in this group are polyamide (PA), polycarbonate (PC) or melamine, and Acrylonitrile Butadiene Styrene (ABS). PA consists of polymers with continuous amide (CO-NH) linkages and is a significant group of synthetic polymers used in the industry. Nylon, the most important polymer in this group, is used to create essential fibers and plastics. Polyamide 6 and polyamide 6,6 are the most commonly used polyamides worldwide.

Polycarbonate, on the other hand, is a thermoplastic with high thermal stability and impact resistance, made from polymers containing carbonate groups in their structure. PC is an excellent glass alternative, featuring a natural UV filter, which makes it popular for use in windows and eyewear. Additionally, ABS is an opaque thermoplastic derived from petroleum. Everyday items made from plastic number 7 include CDs, eyeglasses, baby bottles, and car parts.

In ***Figure 9***, the FT-IR spectra of samples from Jerudong and Silver Jubilee beaches were compared, and the detected absorption peaks were assigned. The main vibrations are clearly evident in the microplastic samples collected. Additionally, the absorption bands of Jerudong beach show similarity with those of PA, while Silver Jubilee beach exhibits the strongest similarity with ABS absorption bands. For instance, the absorption peaks at 3025 and 2950 cm^{-1} represent the aromatic and aliphatic C-H group vibrations, respectively. The peaks at 2920 and 2850 cm^{-1} are ascribed to C-H symmetrical stretching.

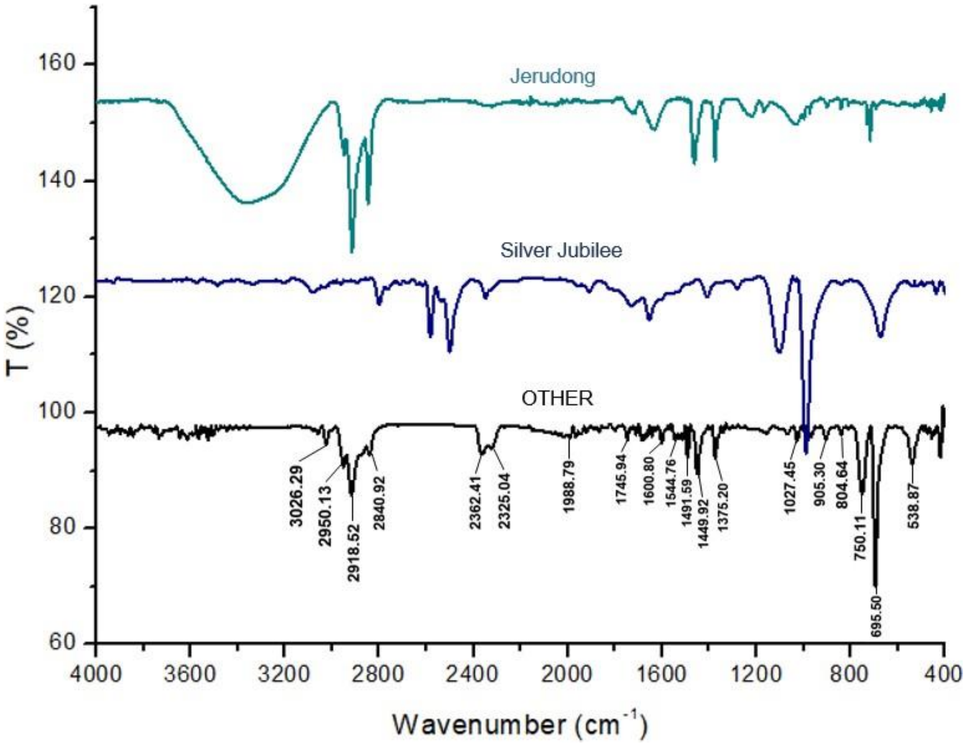


Figure 9. Superimposed FT-IR spectra of 'OTHER' and microplastic samples collected from Jerudong, and Silver Jubilee beach.

Moreover, the absorption band for Silver Jubilee reveals that the peaks at 2362, 2325, and 1450 cm^{-1} have been assigned to the C≡N of ABS, whereas the absorption bands at 1680 cm^{-1} are due to the C=O stretching of Polyamide. The presence of absorption bands at about 1600-1490 cm^{-1} is attributed to C=C stretching and vibration of benzene rings. Furthermore, a peak at 1375 cm^{-1} was obtained from the Jerudong spectrum, indicating the stretching of the C-N group and thus, clearly showing the presence of PA. The absorption bands in the spectral ranges of 980-960 cm^{-1}, 750-700 cm^{-1}, and 695-530 cm^{-1} are attributed to the bending modes of aliphatic C-H, the C-H out-of-plane vibrations, and the bending modes of aromatic C-H, respectively.

Lastly, PA and ABS were also detected at Jerudong and Silver Jubilee beaches, respectively. This suggests that common items made from these plastic materials, such as toothbrushes, nylon, and fishing lines for PA and pipes and electronic equipment for ABS, were used. In addition, the detection of PA at Jerudong beach is presumably due to fishing activities.

4. Conclusion

This study has provided insights into the types of microplastics (PET, HDPE, PVC, LDPE, PP, PS, PA, and ABS) found in selected coastal intertidal zones of Brunei Darussalam. The extraction and quantification of the microplastic samples were also presented in this study. Furthermore, FT-IR analysis revealed that PET and PVC were found in Muara and Kuala Belait (PKC) beaches, respectively. HDPE was observed at Muara, Berakas, Jerudong, and Seri Kenangan beaches, while LDPE was only detected at Berakas and Seri Kenangan beaches. Among the microplastics identified, PP was detected at all selected study sites. The presence of PS was discovered at Berakas, Jerudong, and Silver Jubilee beaches. Subsequently, PA and ABS were found at Jerudong and Seri Kenangan beaches, respectively. The introduction of these plastic polymers into the environment, potentially through chemical and biological decomposition, may pose threats to living organisms.

5. References

(1) Cole, M.; Lindeque, P.; Halsband, C.; Galloway, T. S. Microplastics as Contaminants in the Marine Environment: A Review. *Marine Pollution Bulletin*. 2011. https://doi.org/10.1016/j.marpolbul.2011.09.025.

(2) Smith, O.; Brisman, A. Plastic Waste and the Environmental Crisis Industry. *Crit Criminol* **2021**, *29* (2). https://doi.org/10.1007/s10612-021-09562-4.

(3) de Sá, L. C.; Oliveira, M.; Ribeiro, F.; Rocha, T. L.; Futter, M. N. Studies of the Effects of Microplastics on Aquatic Organisms: What Do We Know and Where Should We Focus Our Efforts in the Future? *Science of the Total Environment*. 2018. https://doi.org/10.1016/j.scitotenv.2018.07.207.

(4) Smith, M.; Love, D. C.; Rochman, C. M.; Neff, R. A. Microplastics in Seafood and the Implications for Human Health. *Current environmental health reports*. 2018. https://doi.org/10.1007/s40572-018-0206-z.

(5) Zhou, P.; Huang, C.; Fang, H.; Cai, W.; Li, D.; Li, X.; Yu, H. The Abundance, Composition and Sources of Marine Debris in Coastal Seawaters or Beaches around the Northern South China Sea (China). *Mar Pollut Bull* **2011**, *62* (9). https://doi.org/10.1016/j.marpolbul.2011.06.018.

(6) Lyons, Y.; Neo, M.; Lim, A.; Tay, Y.; Vu Hai, D. RESEARCH ON MARINE PLASTICS IN ASEAN+3: PART 1 SECTION 2 – RESEARCH IN ASEAN+3 A SCIENCE-LAW-POLICY GAP ANALYSIS. **2020**, 40–45.

(7) Qaisrani, Z. N.; Shams, S.; Guo, Z. R.; Mamun, A. A. Qualitative Analysis of Plastic Debris on Beaches of Brunei Darussalam. *Pollution* **2020**, *6* (3). https://doi.org/10.22059/POLL.2020.297713.751.

(8) Boucher, J.; Friot, D. *Primary Microplastics in the Oceans*; 2017; Vol. 111.

(9) Auta, H. S.; Emenike, C. U.; Fauziah, S. H. Distribution and Importance of Microplastics in the Marine EnvironmentA Review of the Sources, Fate, Effects, and Potential Solutions. *Environment International*. 2017. https://doi.org/10.1016/j.envint.2017.02.013.

(10) Guo, X.; Wang, J. The Chemical Behaviors of Microplastics in Marine Environment: A Review. *Marine Pollution Bulletin*. 2019. https://doi.org/10.1016/j.marpolbul.2019.03.019.

(11) Andrady, A. L. Microplastics in the Marine EnvironmentAndrady, A. L. (2011). Microplastics in the Marine Environment. Marine Pollution Bulletin, 62(8), 1596–1605. Https://Doi.Org/10.1016/J.MARPOLBUL.2011.05.030. *Mar Pollut Bull* **2011**, *62* (8).

(12) Duis, K.; Coors, A. Microplastics in the Aquatic and Terrestrial Environment: Sources (with a Specific Focus on Personal Care Products), Fate and Effects. *Environmental Sciences Europe*. 2016. https://doi.org/10.1186/s12302-015-0069-y.

(13) Bakir, A.; Rowland, S. J.; Thompson, R. C. Transport of Persistent Organic Pollutants by Microplastics in Estuarine Conditions. *Estuar Coast Shelf Sci* **2014**, *140*. https://doi.org/10.1016/j.ecss.2014.01.004.

(14) Fries, E.; Zarfl, C. Sorption of Polycyclic Aromatic Hydrocarbons (PAHs) to Low and High Density Polyethylene (PE). *Environmental Science and Pollution Research* **2012**, *19* (4). https://doi.org/10.1007/s11356-011-0655-5.

(15) Holmes, L. A.; Turner, A.; Thompson, R. C. Adsorption of Trace Metals to Plastic Resin Pellets in the Marine Environment. *Environmental Pollution* **2012**, *160* (1). https://doi.org/10.1016/j.envpol.2011.08.052.

(16) Gray, J. S. Marine Biodiversity: Patterns, Threats and Conservation Needs. *Biodivers Conserv* **1997**, *6* (1). https://doi.org/10.1023/A:1018335901847.
(17) Wagner, M.; Lambert, S. The Handbook of Environmental Chemistry Freshwater Microplastics Emerging Environmental Contaminants? *Springer Open*. 2018.
(18) Thushari, G. G. N.; Senevirathna, J. D. M. Plastic Pollution in the Marine Environment. *Heliyon*. 2020. https://doi.org/10.1016/j.heliyon.2020.e04709.
(19) Ma, P.; Wei Wang, M.; Liu, H.; Feng Chen, yu; Xia, J. Research on Ecotoxicology of Microplastics on Freshwater Aquatic Organisms. *Environmental Pollutants and Bioavailability* **2019**, *31* (1). https://doi.org/10.1080/26395940.2019.1580151.
(20) Rochman, C. M.; Parnis, J. M.; Browne, M. A.; Serrato, S.; Reiner, E. J.; Robson, M.; Young, T.; Diamond, M. L.; Teh, S. J. Direct and Indirect Effects of Different Types of Microplastics on Freshwater Prey (Corbicula Fluminea) and Their Predator (Acipenser Transmontanus). *PLoS One* **2017**, *12* (11). https://doi.org/10.1371/journal.pone.0187664.
(21) Aragaw, T. A. Surgical Face Masks as a Potential Source for Microplastic Pollution in the COVID-19 Scenario. *Mar Pollut Bull* **2020**, *159*. https://doi.org/10.1016/j.marpolbul.2020.111517.
(22) Lithner, D.; Larsson, A.; Dave, G. Environmental and Health Hazard Ranking and Assessment of Plastic Polymers Based on Chemical Composition. *Science of the Total Environment* **2011**, *409* (18). https://doi.org/10.1016/j.scitotenv.2011.04.038.
(23) Jagnytsch, O.; Kloas, W.; Kusk, K. O.; Lutz, I.; Oehlmann, J.; Paull, G. C.; Santos, E. M.; Schulte-Oehlmann, U.; Tyler, C. R.; van Look, K. J. W. A Critical Analysis of the Biological Impacts of Plasticizers on Wildlife. *Phil. Trans. R. Soc. B* **2009**, *364*, 2047–2062.
(24) Hüffer, T.; Praetorius, A.; Wagner, S.; Von Der Kammer, F.; Hofmann, T. Microplastic Exposure Assessment in Aquatic Environments: Learning from Similarities and Differences to Engineered Nanoparticles. *Environ Sci Technol* **2017**, *51* (5). https://doi.org/10.1021/acs.est.6b04054.
(25) Wright, S. L.; Thompson, R. C.; Galloway, T. S. The Physical Impacts of Microplastics on Marine Organisms: A Review. *Environmental pollution (Barking, Essex : 1987)*. 2013. https://doi.org/10.1016/j.envpol.2013.02.031.
(26) Gillespie, A. *Look inside Conservation, Biodiversity and International Law*; 2011. https://doi.org/10.4337/9780857935168.
(27) Gall, S. C.; Thompson, R. C. The Impact of Debris on Marine Life. *Mar Pollut Bull* **2015**, *92* (1–2). https://doi.org/10.1016/j.marpolbul.2014.12.041.
(28) Leslie, H. A.; van Velzen, M. J. M.; Brandsma, S. H.; Vethaak, A. D.; Garcia-Vallejo, J. J.; Lamoree, M. H. Discovery and Quantification of Plastic Particle Pollution in Human Blood. *Environ Int* **2022**, *163*. https://doi.org/10.1016/j.envint.2022.107199.
(29) Hanvey, J. S.; Lewis, P. J.; Lavers, J. L.; Crosbie, N. D.; Pozo, K.; Clarke, B. O. A Review of Analytical Techniques for Quantifying Microplastics in Sediments. *Analytical Methods*. 2017. https://doi.org/10.1039/c6ay02707e.
(30) Konechnaya, O.; Lüchtrath, S.; Dsikowitzky, L.; Schwarzbauer, J. Optimized Microplastic Analysis Based on Size Fractionation, Density Separation and μ-FTIR. *Water Science and Technology* **2020**, *81* (4). https://doi.org/10.2166/wst.2020.173.
(31) Schmidt, P. G. Polyethylene Terephthalate Structural Studies. *J Polym Sci A* **1963**, *1* (4). https://doi.org/10.1002/pol.1963.100010417.
(32) Goswami, T. K.; Mangaraj, S. Advances in Polymeric Materials for Modified Atmosphere Packaging (MAP). In *Multifunctional and Nanoreinforced Polymers for Food Packaging*; 2011. https://doi.org/10.1533/9780857092786.2.163.
(33) Selke, S. E.; Hernandez, R. J. Packaging: Polymers for Containers. In *Encyclopedia of Materials: Science and Technology*; 2001; pp 646–652. https://doi.org/10.1016/b0-08-043152-6/01175-x.
(34) Hidalgo-Ruz, V.; Gutow, L.; Thompson, R. C.; Thiel, M. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environ Sci Technol* **2012**, *46* (6). https://doi.org/10.1021/es2031505.
(35) Pham, N. T. H. Characterization of Low-Density Polyethylene and Ldpe-Based/Ethylene-Vinyl Acetate with Medium Content of Vinyl Acetate. *Polymers (Basel)* **2021**, *13* (14). https://doi.org/10.3390/polym13142352.
(36) Jordan, J. L.; Casem, D. T.; Bradley, J. M.; Dwivedi, A. K.; Brown, E. N.; Jordan, C. W. Mechanical Properties of Low Density Polyethylene. *Journal of Dynamic Behavior of Materials* **2016**, *2* (4). https://doi.org/10.1007/s40870-016-0076-0.

(37) Salehi, S. M. A.; Mirjajili, G.; Amrollahi, J. Effects of High-Energy Electron Beam on Low-Density Polyethylene Materials Containing EVA. *J Appl Polym Sci* **2004**, *92* (2). https://doi.org/10.1002/app.20079.
(38) Tiseo, I. Production Forecast of Thermoplastics Worldwide from 2020 to 2050, by Type. *statista*. 2020.
(39) Wang, W. Introductory Chapter: Polypropylene - Synthesis and Functionalization. In *Polypropylene - Polymerization and Characterization of Mechanical and Thermal Properties*; 2020. https://doi.org/10.5772/intechopen.92067.
(40) Sarsby, R. W. *Geosynthetics in Civil Engineering*; 2006. https://doi.org/10.1533/9781845692490.