MICROPLASTICS MONITORING AND ASSESSMENT IN SUNGAI PERAI

2025

FINAL PROJECT REPORT

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A final report documenting microplastic pollution levels in Sungai Perai, the influence of land use and hydrology, and strategies for monitoring and management, under the Think City Grant

Project Summary Table

Item	Description
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I. Introduction

➢ Background

Microplastic pollution has emerged as a significant environmental issue worldwide due to its persistence, ubiquity, and potential to impact ecosystems and human health (Hassan & Haq, 2019). These particles, with diameters of less than 5 mm, originate from various sources, including degraded plastic waste, industrial effluents, domestic wastewater, and urban runoff. Once released into the environment, they are deposited in aquatic ecosystems, where they are ingested by aquatic organisms and could potentially enter the food chain.

In Malaysia, rapid urbanization and industrialization have provoked severe concerns regarding plastic pollution in freshwater systems. Rivers, as conduits linking terrestrial sources and marine systems, are extremely vulnerable to microplastic pollution (Windsor et al., 2019). The level of microplastic pollution in rivers is therefore relevant to effective environmental governance.

➢ Study context

The Perai River Basin in Penang is an industrialized and urbanized area. There are a few industrial parks, residential areas, and agricultural lands along the river course. The river ultimately discharges into the ecologically sensitive Strait of Malacca, thus serving as a significant pathway for land-based plastic litter to the sea. Nevertheless, extremely limited scientific research has been conducted to establish microplastic levels in the Perai River and assess environmental variables influencing their distribution. Notably, the influence of land-use changes and hydrological indicators (e.g., water quality, sediment quality, and land use) on microplastic densities is inadequately explained.

➢ Importance of the Perai River (Sungai Perai)

Sungai Perai is ever more strategically important to Penang's future water security, especially with Sungai Muda ecologically strained by upstream logging. The river also offers critical ecosystem services like paddy crop irrigation, fish nursery for local fisheries livelihoods, and mangrove shoreline buffers to prevent coastal erosion. With unique biodiversity like peat swamps and migratory birds, Sungai Perai is rich with potential for eco-tourism and community-based river rehabilitation, and urban renewal of Seberang Perai.

➢ Objectives

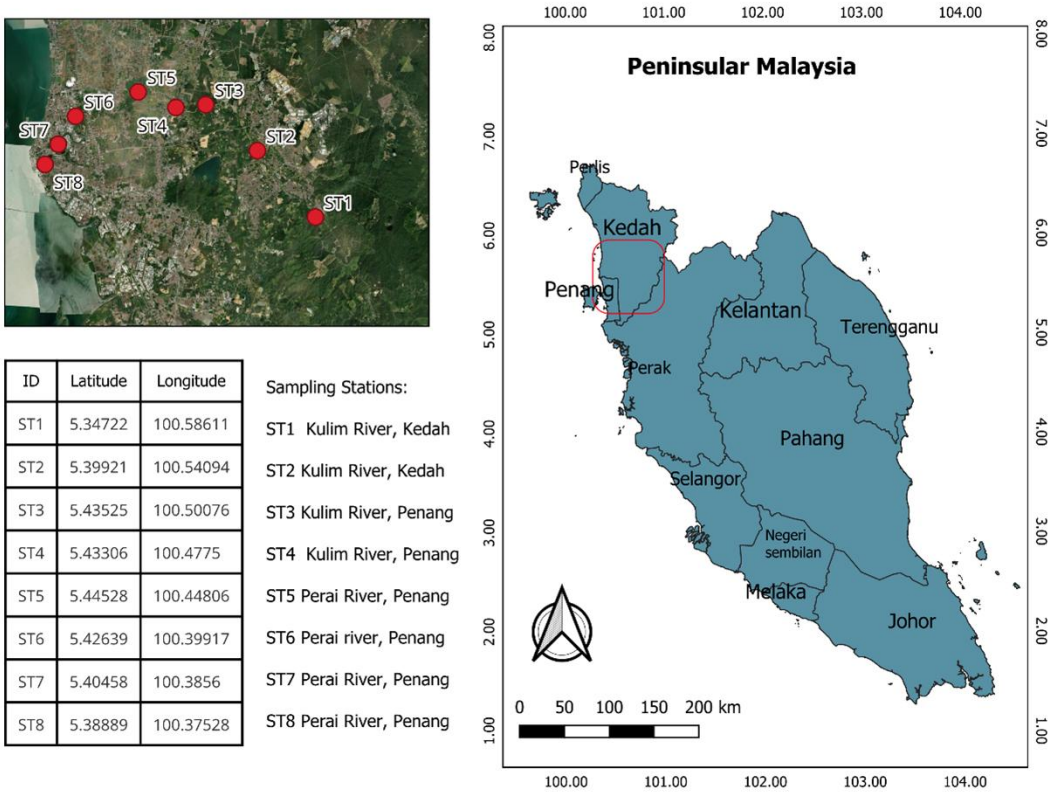
This study was undertaken with the support of Think City under the Seberang Perai Small Town Grants Programme. The main objectives are:

1. To determine the abundance, morphology, and polymer types of microplastics in water and sediment samples collected from the Perai River.
2. To analyse the spatial and temporal variations in microplastic distribution across selected sampling stations.
3. To investigate the influence of hydrogeological parameters (e.g. water quality and sediment quality).
4. To evaluate the relationship between land use/land cover (LULC) patterns and microplastic pollution using remote sensing and GIS-based analysis.
5. To establish a standardized protocol for microplastic sampling, processing, and identification applicable to Malaysian river systems.

II. Methodology

➢ Study Area

The study was conducted along the main channel of Sungai Perai, located in Seberang Perai, Penang. Sampling covered eight stations distributed from the upstream area near Kulim, Kedah, to the downstream near the estuary and jetty area in Perai, before the river discharges into the Strait of Malacca, as shown in (**Figure 1**). The sampling stations (ST) are located in areas characterised by different land-use types: ST1 is surrounded by forest, ST2 by urban development, ST3 by agricultural land, and ST4-ST8 by urban areas. This river is ecologically significant and socioeconomically important, supporting paddy irrigation, fisheries, and mangrove ecosystems, while also being subject to pressures from human development. Sampling focused on the main river stream only, excluding tributaries.



ID	Latitude	Longitude
ST1	5.34722	100.58611
ST2	5.39921	100.54094
ST3	5.43525	100.50076
ST4	5.43306	100.4775
ST5	5.44528	100.44806
ST6	5.42639	100.39917
ST7	5.40458	100.3856
ST8	5.38889	100.37528

Sampling Stations:
ST1 Kulim River, Kedah
ST2 Kulim River, Kedah
ST3 Kulim River, Penang
ST4 Kulim River, Penang
ST5 Perai River, Penang
ST6 Perai river, Penang
ST7 Perai River, Penang
ST8 Perai River, Penang

Figure 1. Study area and sampling stations in the Perai River Basin

- **Field Sampling and Sample Handling**

Surface water and sediment samples were collected at eight stations along the Perai River during the dry season and wet season of 2024. Surface water samples were collected by manually scooping into clean containers and then poured through a series of stacked sieves set at each station. Three replicates were taken at each sampling point to ensure representative samples. Further, the physicochemical parameters of water, including pH, temperature, and dissolved oxygen were measured using a HACH multiparameter probe (HQ4300**)**. Turbidity was measured with a Lovibond turbidity meter (Tintometer Group). Water depth was estimated using a Secchi disk. Furthermore, sediment samples were collected using a stainless-steel Ekman grab sampler to target the top 3–5 cm of the riverbed sediment. The sediment was immediately transferred into prewashed glass jars, which were labelled with the station number and the sampling date. All samples were stored in a chest cooler box and transported to our laboratory at the Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia (USM) for further laboratory analysis.

- **Sediment Quality analysis (texture)**

To evaluate the quality of sediment and its role in retaining microplastics. Soil texture was measured using a jar settling test: sieved soil was mixed with water, shaken well, and left to settle. Sand (for 1 min), silt (2 h), and clay (48 h) layers were marked and measured. The percentage of each fraction was calculated using the following equation (Gee & Bauder, 1986)

$$\%component = \left(\frac{layer\ height}{total\ height}\right) \times 100$$

The particle size analysis was conducted to determine the distribution of sand, silt, and clay fractions based on particle diameter. A representative sediment sample was oven-dried to remove moisture, ground to break up aggregates, and sieved to ensure uniform particle size (<2 mm). The prepared sample was then analysed using a particle size analyser, which measured particle size distribution based on particle light interaction or settling behaviour. The resulting percentages were used to determine the soil texture class using the USDA (United States Department of Agriculture) Soil Texture Triangle. This classification provided insights into sediment properties that influence the retention and accumulation of microplastics across stations.

- **Microplastics Determination in Water and Sediment Samples**

The laboratory analysis of microplastics in water and sediment samples was conducted using a combination of established protocols, including the National Oceanic and Atmospheric Administration (NOAA) and other peer-reviewed methods, such as the method used by Tan & Mohd Zanuri (2023), with several modifications adapted to local conditions, sample volume, and available laboratory equipment.

- **Water Sample Processing**

Water samples were shaken thoroughly to ensure homogeneity before sieving. A series of stainless-steel sieves arranged from largest to smallest mesh size was used to filter the samples.

Retained particles on the sieve surfaces were transferred into clean beakers using a portion of the original water sample. An additional 250–300 mL of water was used to rinse the sieve mesh and recover all visible particles. Organic matter in the sample was digested using a 10% potassium hydroxide (KOH) solution. The solution was mixed thoroughly and added to each sample beaker containing the filtered material. A magnetic stir bar was placed in each beaker, and the samples were stirred on a hot plate until bubbling indicated an active reaction. Beakers were partially covered with aluminium foil and left to digest for 24 hours at room temperature. After digestion, the clear supernatant was filtered using a vacuum filtration system with GF/C Whatman glass microfiber filter paper. The bottom settled residue was not poured to prevent loss of target particles. Filter papers were carefully removed using clean forceps and transferred to labelled glass Petri dishes. These were dried in an oven and stored for microscopic examination.

- **Sediment Sample Processing**

Sediment samples were homogenized and dried in an oven before processing. A representative 200 g of each sample was weighed and placed into a glass beaker. A 10% KOH solution was added and stirred over a hot plate. Once bubbling indicated digestion activity, the beaker was removed from heat, labelled, and left to digest for 24 hours at ambient conditions. Additional digestion cycles were performed if visible organic matter remained. To separate MPs from heavier mineral particles, density separation was performed using zinc chloride ($ZnCl_2$) solution prepared at a density of 1.8 g/mL. The solution's density was verified using a micropipette method. The $ZnCl_2$ solution was added to the digested sediment sample and stirred thoroughly. The mixture was poured into a density separator and rinsed to ensure complete transfer. After settling, the supernatant containing potential MPs was collected and filtered using GF/C filter paper. Filter papers were dried and stored in clean Petri dishes.

- **Land Use Data Collection**

Land use and land cover (LULC) classification was conducted using Sentinel-2 satellite imagery, analyzed in QGIS version 3.40.4**.** A supervised classification was applied to delineate major land cover types, including urban/built-up areas, industrial zones, agriculture, forest, and water bodies. A 500-meter buffer was created around each sampling station to quantify localized land use percentages. This classification followed the 2024 Sentinel Land Cover Explorer classes to ensure consistency with recognized global datasets. The LULC percentages

were then statistically correlated with microplastic abundance in both water and sediment samples, aiming to identify potential land-based drivers of microplastic input into the river system.

Spatial Analysis using Inverse Distance Weighting and Area-Weighted Mean

To assess the influence of land use on MP distribution, Inverse Distance Weighting (IDW) interpolation was applied to MP abundance data for both surface water and sediment samples. IDW interpolation was used for estimating values at unsampled locations based on the assumption that sampling points closer to each other exhibit more similar values than those farther apart (Ogbozige et al., 2018).

Zonal statistics were applied to extract the mean MP concentration for each land use polygon. An Area-Weighted Mean (AWM) was then calculated for each land use category using Equation (3). This weighted approach was essential to account for the varying sizes of land use patches, preventing smaller land use patches from having too much influence on the overall average pollution values (Huang et al., 2007).

$$AWM = \frac{\sum(MP\ mean \times Area)}{\sum(Area)}$$

- **Microplastic Characterization and Composition**

To further characterize the microplastics (MPs) identified under the stereomicroscope, selected particles were subjected to advanced analytical techniques to determine their morphology and polymer composition.

- **Microscopic Identification using a stereomicroscope**

Dried filters were examined under a stereomicroscope (Nikon ECLIPSE E200) equipped with an *i*-solution camera and imaging software. Suspected particles were identified based on visual

features such as shape, size, and colour, in accordance with the modified National Oceanic and Atmospheric Administration (NOAA) protocol. Photographic documentation was conducted for all confirmed particles to support further classification and analysis. To further characterise the microplastics identified under the microscope, selected particles were subjected to advanced analytical techniques to determine their morphology and polymer composition.

- **Micro Fourier-Transform Infrared Spectroscopy (µFTIR)**

Selected filter papers containing suspected microplastic particles were brought to the Advanced Analytical Laboratory (AAL) at the School of Health Sciences, Universiti Sains Malaysia, in Kelantan, Malaysia. The suspected particles were sorted using forceps and a light microscope, then placed on a double-sided tape affixed to a glass slide. The slide was then placed on the micro FTIR stage, and the particles were analysed using the LUMOS FTIR instrument from BRUKER, which was connected to OPUS software, where the results were displayed.

- **Scanning Electron Microscopy and Elemental Analysis (SEM-EDX)**

In addition, samples were analysed using Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDX) at the Earth Material Characterisation Laboratory, Universiti Sains Malaysia (Main Campus). SEM provided high-resolution imaging of particle surface morphology. At the same time, EDX was used to determine the elemental composition of individual particles, confirming the presence of plastic-related elements and any potential contamination from heavy metals or additives.

- **Microplastics Ecological Risk Assessment**

Microplastics contamination Factor (MPCf) and Microplastics Pollution Load Index (MPPLI) was employed to assess the pollution status that can be posed by microplastics in the Perai River Basin. The models were originally developed by Fostner and Calmano (1993) and Thomilson et. al., (1980), and later modified by Enyoh et al. (2021) to calculate for microplastics contamination. By using the following equations (1) & (2):

$$MPCf_i = \frac{MP\ i}{MP_b} \quad (1)$$

Where MP_i is the microplastics concentration in each station

MP_b is the background value (the lowest microplastic concentration in perai river)

For the background value, we considered the lowest value recorded in the Perai River from our study. The first reason is the methodological consistency; we used the same mesh sizes, filter size, and laboratory analysis. The second reason is that the background value is within the same river, which has special characteristics when compared to other rivers. PLI levels were classified as follows: low (PLI < 10), moderate (10 ≤ PLI < 20), high (20 ≤ PLI < 30), and dangerous (PLI ≥ 30) according to Zhao et al. (2024); Mithu et al. (2026).

$$MPPLI = \sqrt[n]{MPCf_1\ x\ MPCf_2\ x\ MPCf_2\ \cdots x\ MPCf_n} \quad (2)$$

- **Data Processing and Statistical Analysis**

All quantitative data, including MP abundance, morphology, polymer type, and environmental parameters, were processed using Microsoft Excel. Statistical analyses, including descriptive statistics and correlation, were carried out using RStudio (R 4.3.1) to explore relationships between microplastic levels and environmental variables such as land use, water quality, and sediment characteristics.

- **Quality Assurance and Quality Control (QA/QC)**

To ensure the accuracy and reliability of the findings, several QA/QC measures were implemented throughout the field sampling, laboratory analysis, and data processing stages. During fieldwork, blanks were used at selected stations to monitor for airborne or procedural contamination, and replicates were taken at each sampling point to ensure the consistency and representativeness of both water and sediment samples. The blank consisted of around 2L of double-filtered deionized water and was subjected to identical processing protocols as environmental samples. All sampling containers and tools were thoroughly cleaned and rinsed with double-filtered water before and after use. In the laboratory, procedural blanks were processed alongside environmental samples to detect possible contamination during digestion and filtration. To monitor potential airborne contamination, GF/C membrane filters (n = 3) were placed in open Petri dishes within the laboratory during sample processing procedures.

Analysis of these control samples confirmed the absence of microplastics. Only glass and stainless-steel equipment were used, and filter papers were visually inspected under the microscope prior to use. Calibration of analytical instruments, including HACH multiparameter, microFTIR, and SEM-EDX systems, was conducted by trained personnel in accordance with standard operating procedures. Data were double-checked during entry, and analysis was performed using validated tools (Excel and RStudio) to maintain data integrity.

III. Results and discussion

- **Spatial distribution of microplastics in water and sediment samples**

Microplastics were detected in water at all stations in both seasons. During the dry season, microplastic abundance ranged from 4 to 52 items/L, with the highest concentration at (ST1), which was undergoing a bridge construction project during the time of our sampling, and the lowest at (ST8), which is close to the river mouth, near the mangrove area, and the jetty called Wak Ali (**Error! Reference source not found.**, **Error! Reference source not found.**). In the wet season, abundance ranged from 8 to 208 items/L with peak values at (ST8). Mean abundance increased from 15.33 ± 11.46 items/L in the dry season to 58.5 ± 19.9 items/L in the wet season (**Error! Reference source not found.**), indicating a clear seasonal contrast. The higher wet-season microplastic abundance likely reflects rainfall-driven runoff and resuspension that mobilise plastics from other sources.

Table 1. Descriptive statistics of microplastic abundance in river water and sediment during the dry and wet seasons

Matrix	Season	n (stations)	Mean abundance ± la	Min	Max	Unit
Water	Dry	8	15.33 ± 11.46	4	52	items/L
Water	Wet	8	58.5 ± 19.9	8	208	items/L
Sediment	Dry	8	15.41 ± 8.8	5	60	items/kg
Sediment	Wet	8	107.8 ± 39.63	20	255	items/kg

Microplastics were detected in sediment at all stations in both seasons. During the dry season, sediment microplastic abundance ranged from 5 to 60 items/kg, with the highest values at (ST1) and the lowest at (ST6). In the wet season, abundance ranged from 20 to 255 items/kg, with peak concentration at (ST6) (**Error! Reference source not found.**). Mean abundance was 15.41 ± 8.8 items/kg in the dry season, and Mean abundance was 107.8 ± 39.63 items/kg in the wet season (**Error! Reference source not found.**). Sediment acts as a significant sink for microplastics, so station-level hotspots likely reflect areas of enhanced particle trapping and deposition, e.g., low flow energy. Seasonal differences may be driven by changes in flow and rainfall: higher flows can increase sediment resuspension and redistribution, while calmer periods can promote settling and accumulation. Compared with other studies, our findings are similar to those from a study on surface sediment in the Pearl River estuary, where microplastic abundance ranged from 4 to 220 n/kg. While for surface water, our findings revealed a lower microplastics level of the Langat River, Malaysia, 181 to 4,157 items/L, and that in the Melaka River, 569 particles/L (Ali et al., 2025; Abdul Halim et al., 2024). These increases in microplastic values could be explained by the urban/industrial pressures received by different riverine systems. Besides recording less microplastic levels than a larger river such as Langat River, Perai River is still holding a concerning microplastic concentration which require a strategic mitigation plans to reduce this contamination.

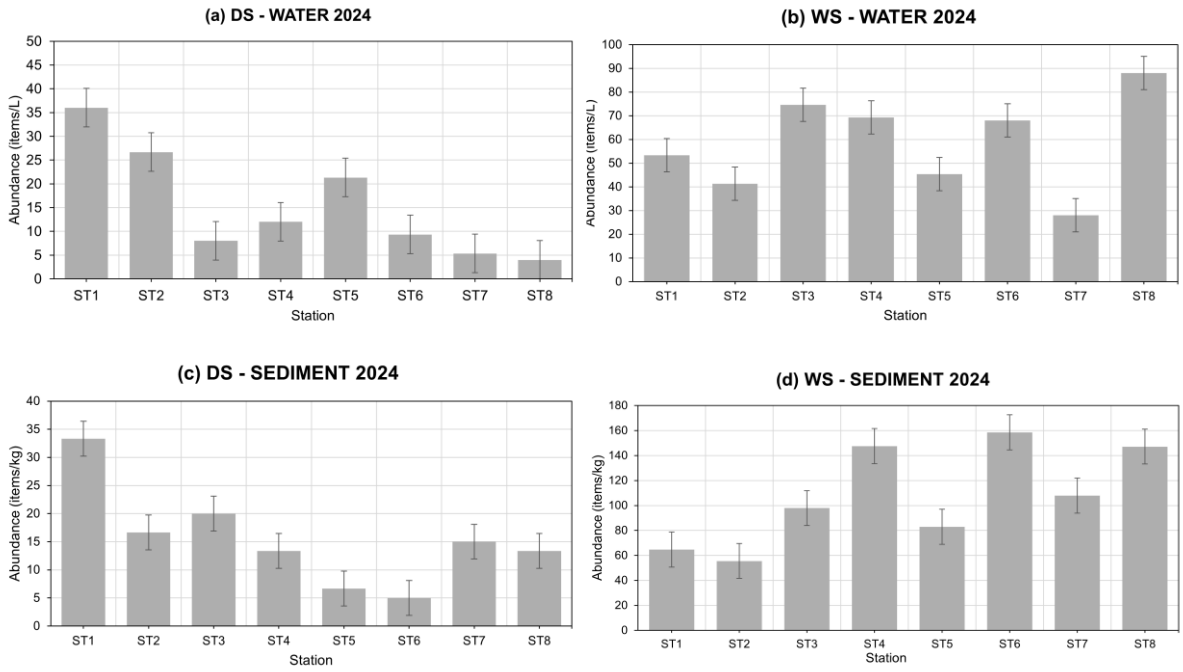


Figure 2. Spatial distribution of microplastic abundance across the Perai River sampling stations in river water (items/L) and river sediment (items/L) during the dry and wet seasons. Bars represent mean abundance, and error bars indicate standard deviation. (a) microplastic abundance in water during the dry season. (b) microplastic abundance in water during the wet season. (c) microplastic abundance in sediment during the dry season. (d) microplastic abundance in sediment during the wet season.

- **Seasonal variation of microplastic abundance in water and sediment (dry vs wet season)**

Across the Perai River Basin, microplastic abundance was consistently higher during the wet season than the dry season. This wet season increase was observed at all stations (**Figure 3**). It was evident in both matrices (water and sediment), indicating a basin-wide seasonal signal rather than a station-specific anomaly. Water samples collected during the wet season contain more microplastics, especially in (ST8) and (ST3). In contrast, microplastic abundance is lower in the dry season at the downstream stations. In sediment, microplastic abundance in the wet season was also higher than that in the dry season across all the sampling stations, with a significant increase in (ST6) and most of the downstream stations.

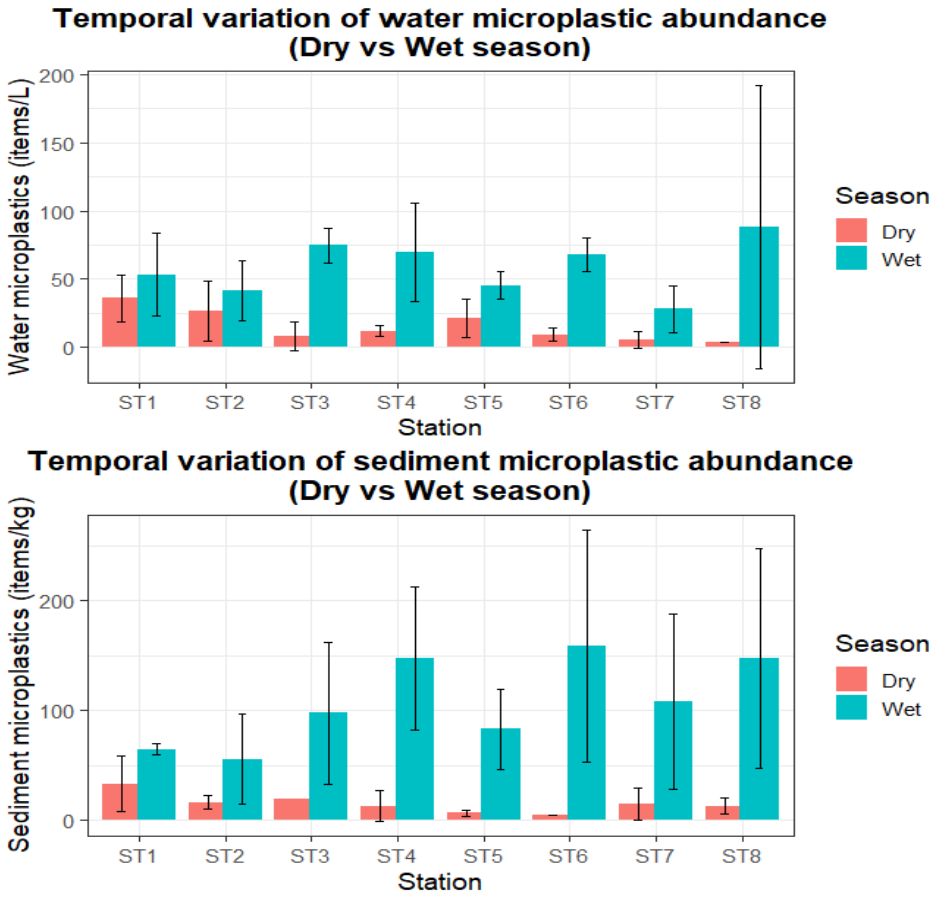


Figure 3. Temporal variation in microplastic abundance in river water (items/L) and sediment (items/kg) between the dry and wet seasons across the sampling stations.

This pattern is consistent with the role of the wet season in enhancing the mobilisation and delivery of microplastics to the river system. Higher rainfall and runoff can increase surface wash-off from roads, urban/ industrial zones, and riverbanks, transporting plastics and secondary microplastics into the river (Ross et al., 2023). In addition, wet-season increases can be reinforced by high-flow turbulence and resuspension, whereby microplastics stored in bed sediments are re-entrained into the water and subsequently redistributed and redeposited downstream, producing coupled seasonal signals in water and sediment (Xia et al., 2021). While some other river systems show the opposite pattern (dry > wet) due to dilution or rapid-flushing storms (Jin et al., 2025). The wet season increase in the Perai River Basin suggests that monsoon runoff and hydrodynamic remobilisation are the dominant seasonal controls in this catchment.

- **Morphology and microplastic composition in water samples**

In the dry season water samples, microplastics were dominated by fibers (>60%), with the <300 µm size class being the most abundant (>60%). In terms of appearance and composition, black particles were the most frequently observed colour category (>20%), and EPDM (EPCAR Ethylene Propylene Diene Monomer) was the dominant polymer type

Figure 4

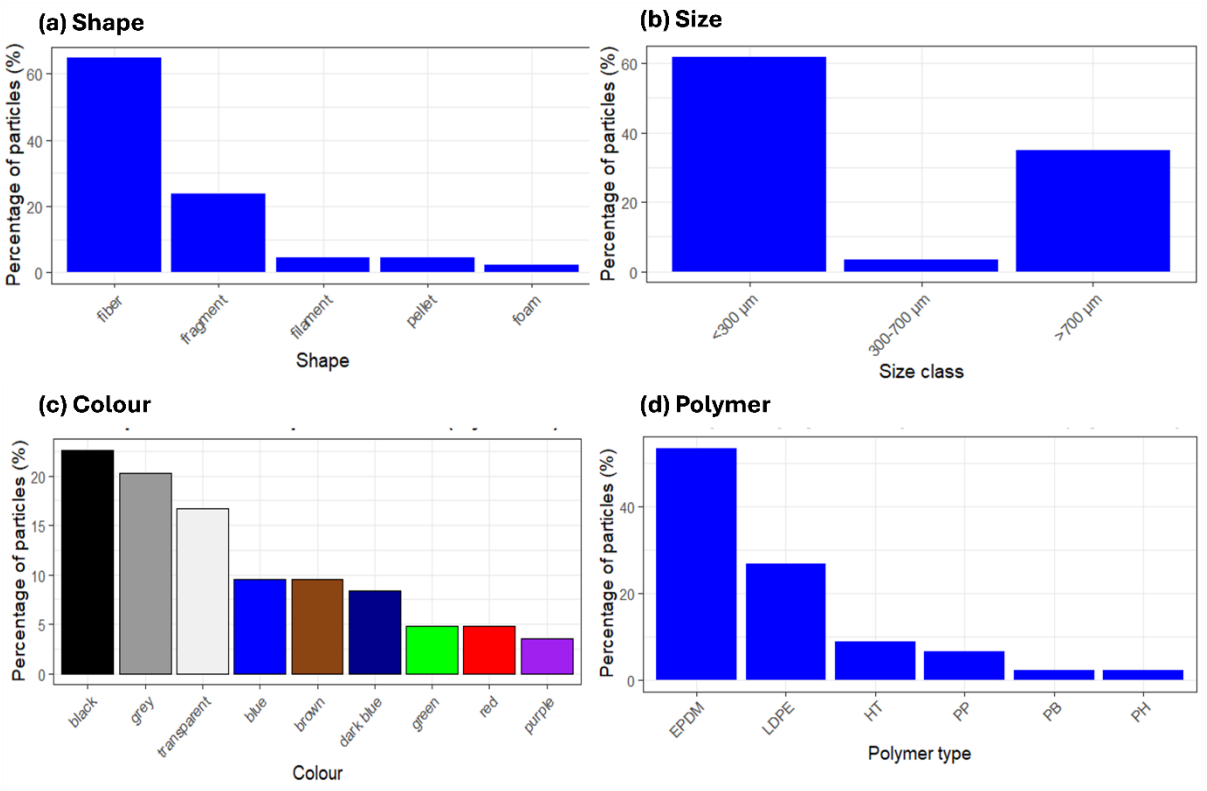


Figure 4. Characterization of microplastics in the water samples during the dry season

In contrast, the wet-season water samples showed a shift in character, with fragments (>60%) becoming the dominant shape class and the >1000 µm size class (>50%) the most abundant. Black remained the dominant colour in the wet season (>50%), while PP (Polypropylene) was the dominant polymer (>60%) as shown in (**Figure 5**)**Error! Reference source not found.**.

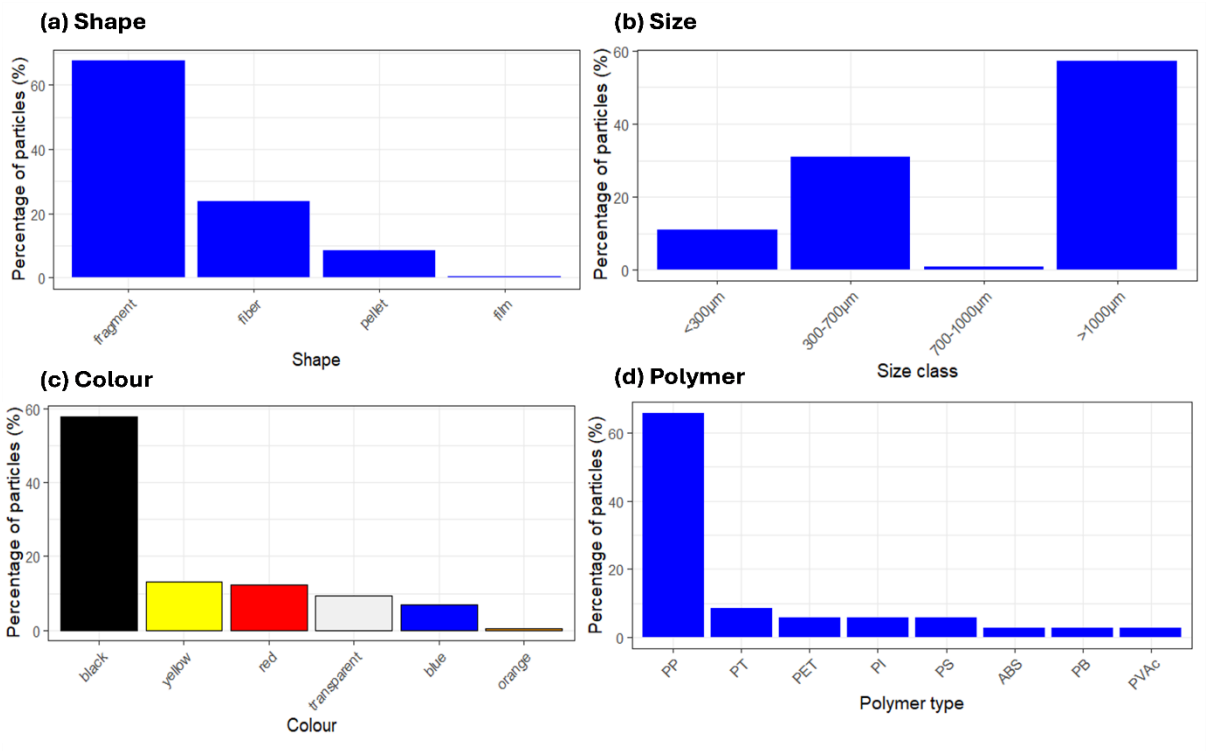


Figure 5. Characterisation of microplastics in the water samples during the wet season

The dry-season dominance of fibers and fine particles (<300 µm) was consistent with findings from Izlal et al.'s (2024) study and suggests a more substantial influence of chronic, continuous inputs and prolonged river processing. Fibers are commonly associated with everyday sources such as domestic wastewater, textile shedding, and urban activities, and their small size may also reflect fragmentation and long residence times under lower-flow conditions. A seasonal study at a tropical river estuary in Kenya (Kamau et al., 2024) reported that fibers dominated in the dry season, while fragments increased in the wet season, and that larger particles were more common in the wet season. These results are similar to the findings of the current study. The dominance of EPDM in the dry season may indicate contributions from rubber-based materials, e.g., industrial applications or traffic-related sources, which can enter the river through diffuse runoff or bankside deposition and subsequently remain detectable during low-flow conditions. During the wet season, the shift toward fragments, consistent with findings from Kamau et al. (2024), and toward coarser particles (>1000 µm), consistent with increased

rainfall-driven runoff and higher river energy, is observed. High-flow events can mobilise larger plastic debris from roads, riverbanks, and surrounding land uses and transport it into the river before extensive fragmentation occurs (van Emmerik et al., 2023). The dominance of PP in the wet season supports enhanced wash-off of standard packaging-related plastics and broader contributions to surface runoff (Vibhatabandhu & Srithongouthai, 2022). Across both seasons, the persistent dominance of black particles may reflect input from dark-coloured consumer plastics and/or rubber-like materials (Reynolds et al., 2024). However, it can also be influenced by visual classification bias (dark particles are easier to recognise in filters), so interpretation should be made alongside polymer identification results.

Taken together, the seasonal contrast in characteristics supports the abundance pattern (wet > dry): the wet season appears to introduce higher external loading and mobilise larger particles, whereas the dry season shows signatures of finer material and steadier fiber inputs. These findings indicate that seasonal hydrology influences not only microplastic abundance but also the dominant particle types present in the river water.

- **Morphology and microplastic composition in sediment samples**

In the dry season, sediment microplastics were dominated by fibers. The particle size distribution was strongly skewed toward small particles, with the <300 μm size class accounting for (>75%) of detected microplastics. In terms of appearance, black particles were the most frequent colour category (>30%), and PP was the dominant polymer type, representing (>40%) of the identified polymers, as shown in (**Figure 6**).

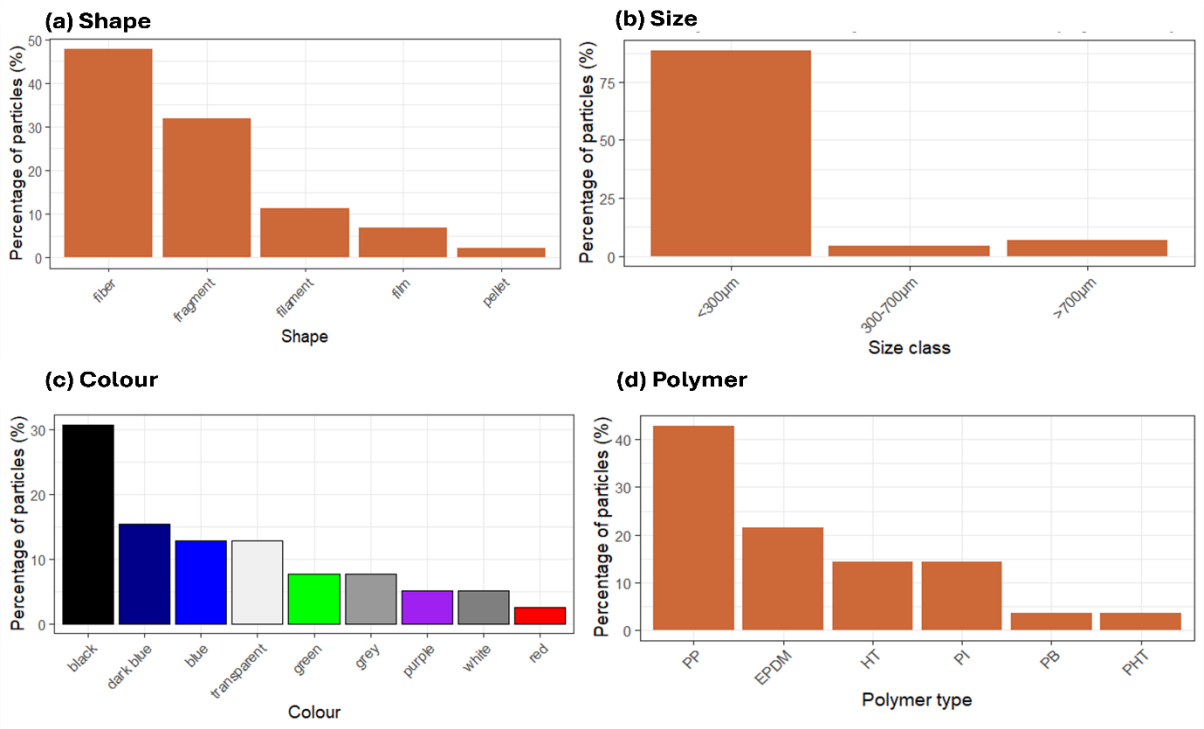


Figure 6. Characterisation of microplastics in the sediment samples during the dry season

In wet-season sediment, the dominant shape shifted to fragments (>45%). Fine particles remained prevalent, with the <300 µm size class representing >60% of detected microplastics. Black particles were markedly dominant in the wet season (>60%), and PP also remained the

dominant polymer (>45%), as shown in ***Figure 7***

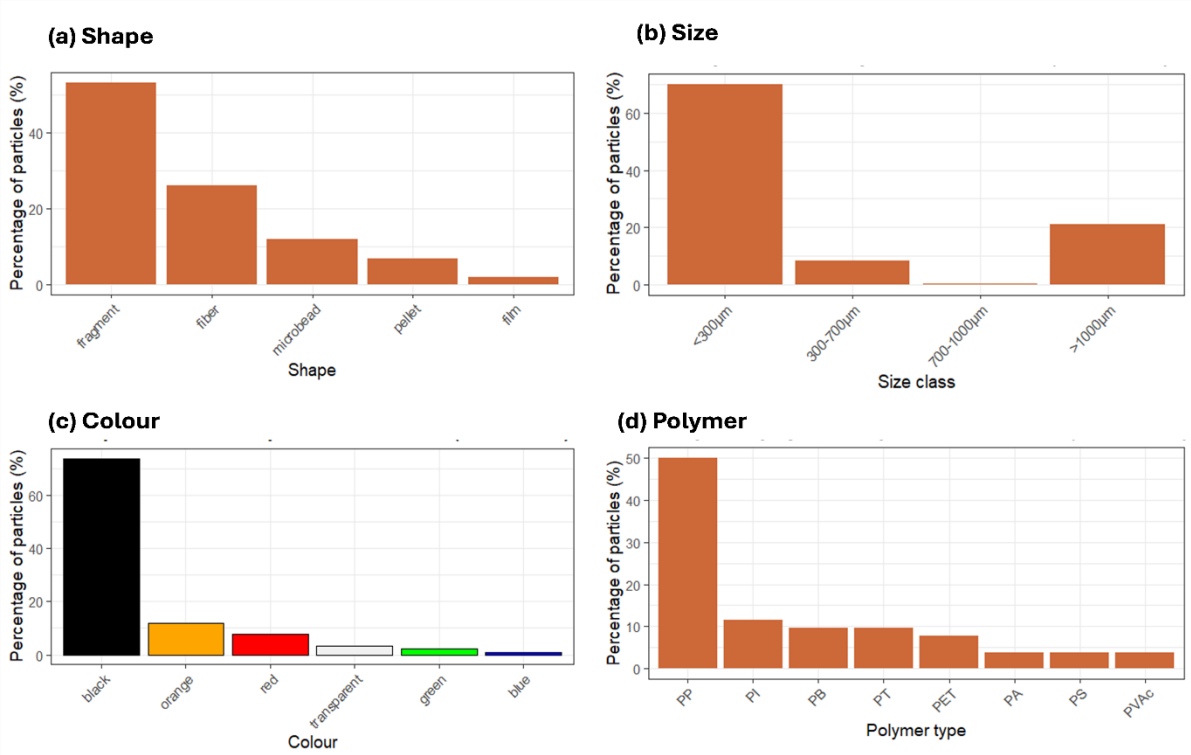


Figure 7. Characterization of microplastics in the sediment samples during the wet season

The shift from fibre-dominated sediments in the dry season to fragment-dominated sediments in the wet season suggests that seasonal hydrology influences the dominant input pathways and depositional processes, as stated in study done on the Mekong River Delta, Vietnam (Gugliotta et al., 2018) where the seasonal hydrology influenced sediment distribution and depositional processes in the river, with significant changes between wet and dry seasons in both upstream and downstream tracts. During the wet season, intensified rainfall, runoff, and higher-flow events can mobilise larger plastic debris from roads, banks, and surrounding land uses, producing a greater contribution of fragments that are transported and deposited during high-flow pulses and subsequent settling. Multiple studies provide strong evidence for this phenomenon. (van Emmerik et al., 2023), demonstrated that during floods, plastic transport can multiply by over 100 compared to non-flood conditions, with one third of annual plastic item transport occurring within just 6 days of extreme discharge. (Belioka & Achilias, 2024), Further confirmed that typhoons, monsoons, and floods contribute substantially more

microplastics to surface sediments through surface runoff, wind transport, and particle redistribution. In contrast, under lower-flow dry-season conditions, fibres often associated with continuous inputs, e.g., domestic and urban sources, may be preferentially retained within the sediment due to entanglement with organic matter and fine particles.

Despite the shape shift, the persistence of fine size classes (<300 μm) in both seasons (dry >75%, wet >60%) indicates intense fragmentation and or preferential retention of small particles within sediments. Finer microplastics are more likely to be trapped in interstitial spaces and cohesive fractions, promoting accumulation. The dominance of PP in both seasons suggests persistent input from everyday consumers and packaging-related plastics throughout the year, with wet-season hydrology primarily altering the relative contribution of particle shapes and colours rather than changing the overall polymer signal.

- **Instrumental analysis results**

Representative SEM images and EDX spectra support the morphology shown in (**Figure 8**). They show the surfaces of microplastics and the inorganic elements present on their surfaces. SEM observations revealed irregular, rough surfaces with fractures and pits. These features provide physical evidence of environmental weathering. From the EDX spectra, elements like carbon and oxygen confirm the plastic origin and chemical aging. The oxygen indicates that the material has been broken down by sunlight overtime which makes the particles more likely to interact with other chemicals in the water. lk

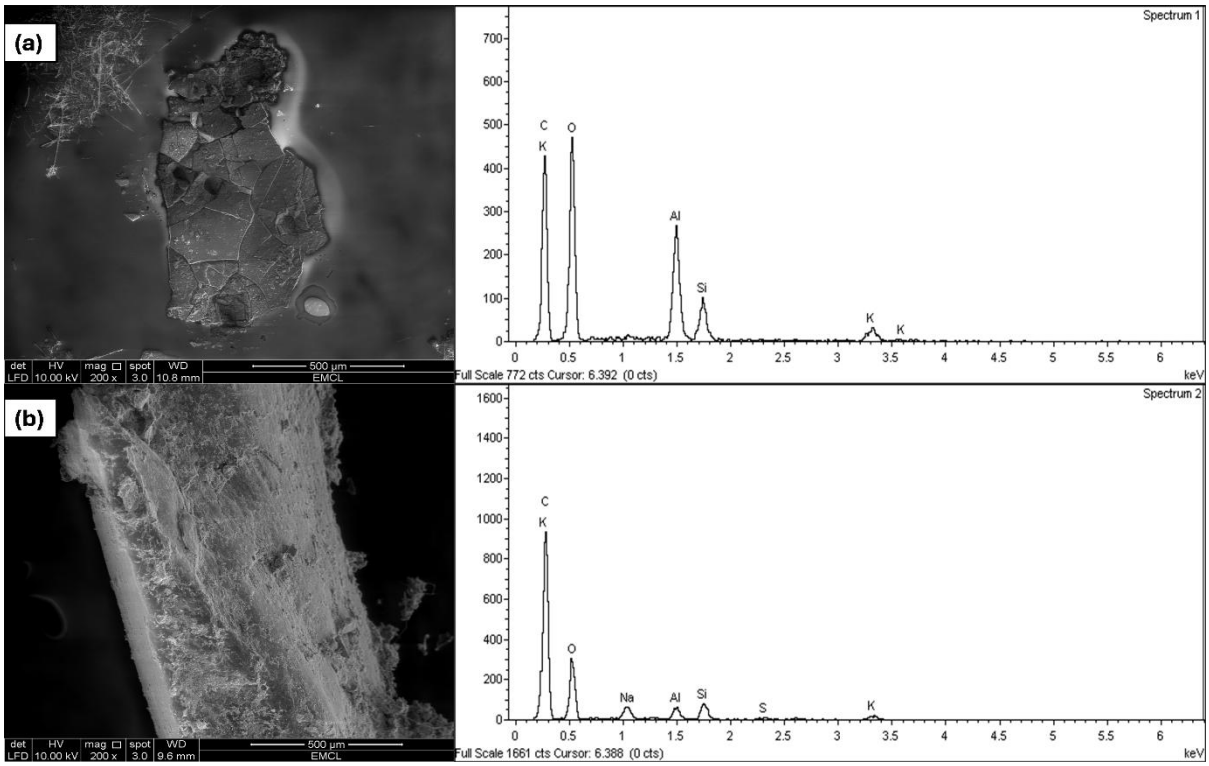
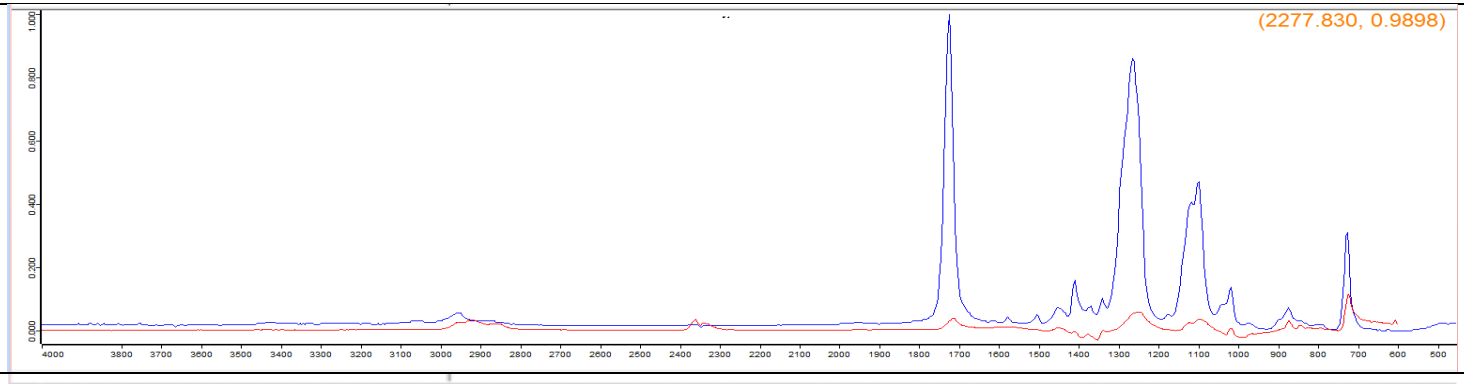
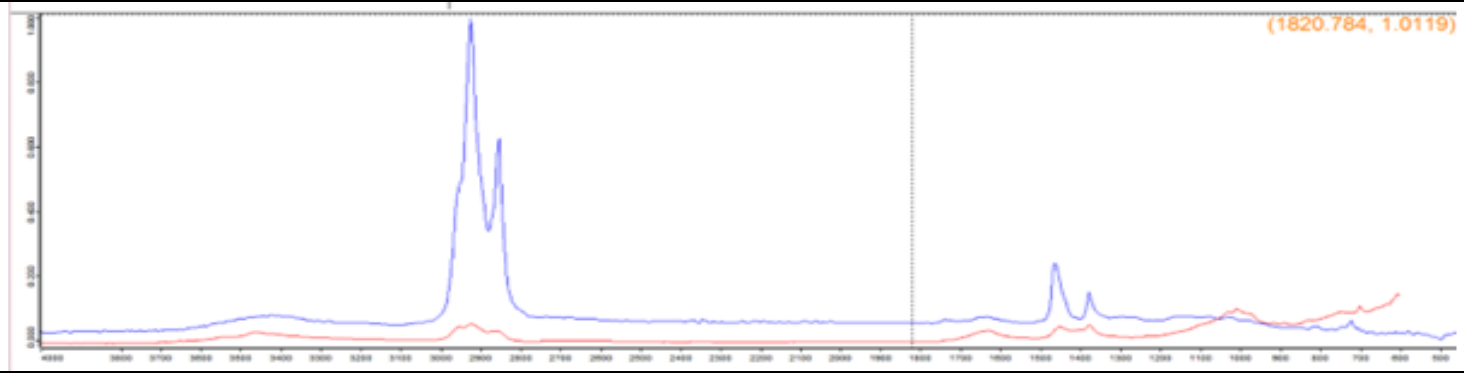
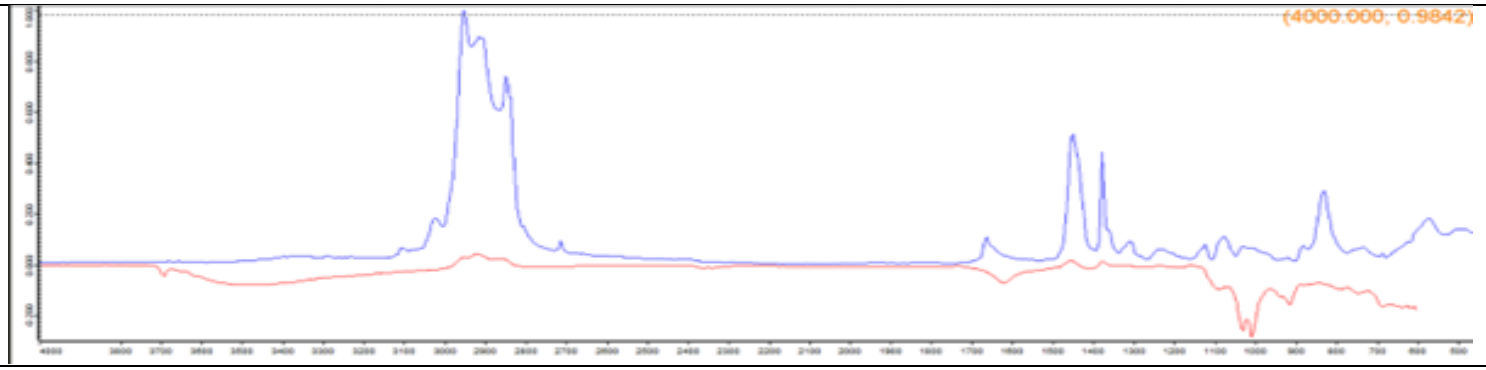
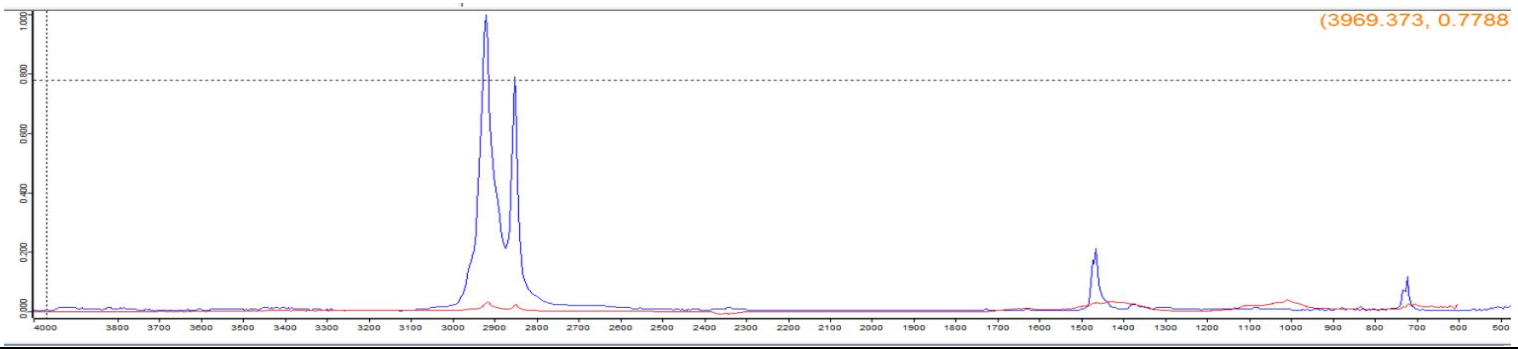
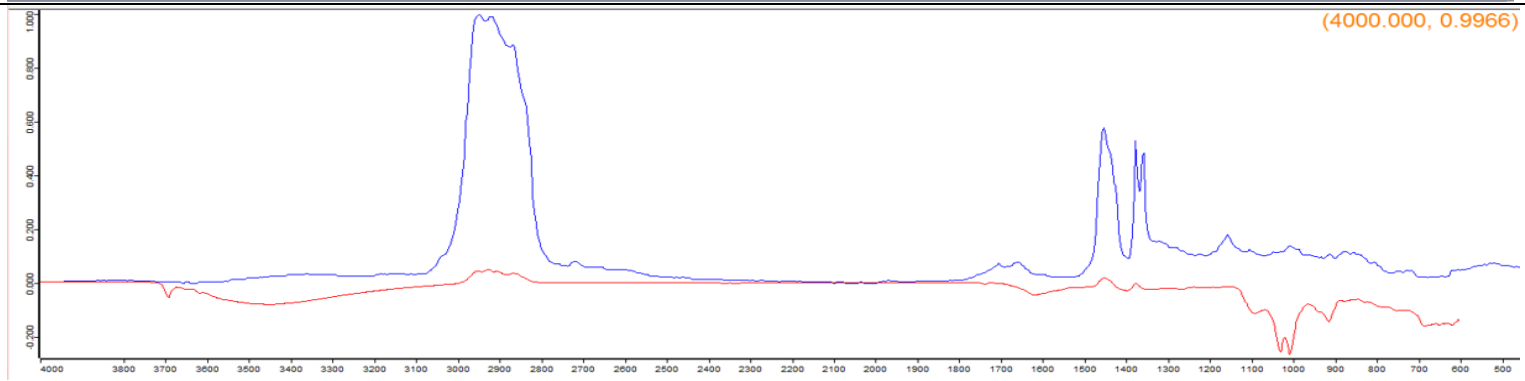


Figure 8. SEM micrographs of representative microplastic particles collected from water and sediment samples, (a) water and (b) sediment.

The chemical composition of the identified microplastics was confirmed using μFTIR (**Table 2**). Across all the sampling stations, a diverse range of polymers was detected reflecting the varied anthropogenic sources along the river with a dominance by Polypropylene. Polypropylene sources include food containers, packaging of single use plastics while polyethylene detected include bottles. Consistently, these sources were also among the most highly collected plastics when we did our river cleanup and plastic waste audit within the Perai River Basin. This findings highlight that the plastics are definitely degrading into microplastics in Perai River.

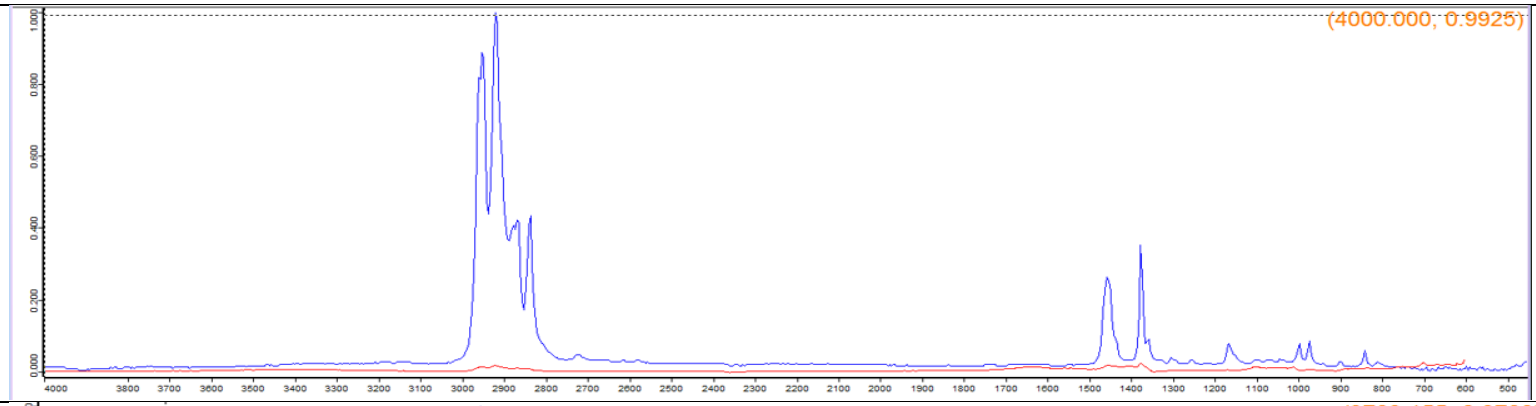
Table 2. microFTIR results from dry and wet seasons

No	Name of compound	Compound Spectra
1	MELINEX POLYESTER Compound information Compound Name: MELINEX TYPE S/92 GAUGE*POLYESTER FILM Technique FILM Classification Polymers= POLYESTERS Source Of Sample ICI AMERICA INC. Entry No. 197 Library name SR.IDX Library description Demo Database Copyright Copr. © 1980, 1981-1999 Sadtler. All Rights Reserved.	
2	ETHYLENE/PROPYLENE/DIENE Compound information Compound Name: EPCAR 5875*ETHYLENE/PROPYLE... Technique FILM Classification Polymers= POLYPROPYLENES Source Of Sample GOODRICH, B.F., CHEMICAL COMPA... Entry No. 171 Library name SR.IDX Library description Demo Database Copyright Copr. © 1980, 1981-1999 Sadtler. All ...	

3	NATSYN 200 CIS-1,4- POLYISOPRENE Compound Name: NATSYN 200*CIS-1,4-POLYISOPRENE Technique FILM Classification Polymers= SYNTHETIC POLYISOPRE... Source Of Sample GOODYEAR TIRE AND RUBBER CO.... Entry No. 178 Library name SR.IDX Library description Demo Database Copyright Copr. © 1980, 1981-1999 Sadtler. All ...	
4	RUMITEN 250 CQ LDPE Compound information Compound Name: RUMITEN 250 CQ*LOW DENSITY P... Technique FILM Classification Polymers= POLYETHYLENES Source Of Sample RUMIANCA S.P.A., ITALY Entry No. 168 Library name SR.IDX Library description Demo Database Copyright Copr. © 1980, 1981-1999 Sadtler. All ...	
5	PICCOLYTES-125 HYDROCARBON THERMO Compound information Compound Name: PICCOLYTE S-125*HYDROCARBON ... Technique FILM Classification Polymers= POLYTEREPENE AND NA... Source Of Sample PENNSYLVANIA INDUSTRIAL CHEM... Entry No. 180 Library name SR.IDX Library description Demo Database Copyright Copr. © 1980, 1981-1999 Sadtler. All ...	

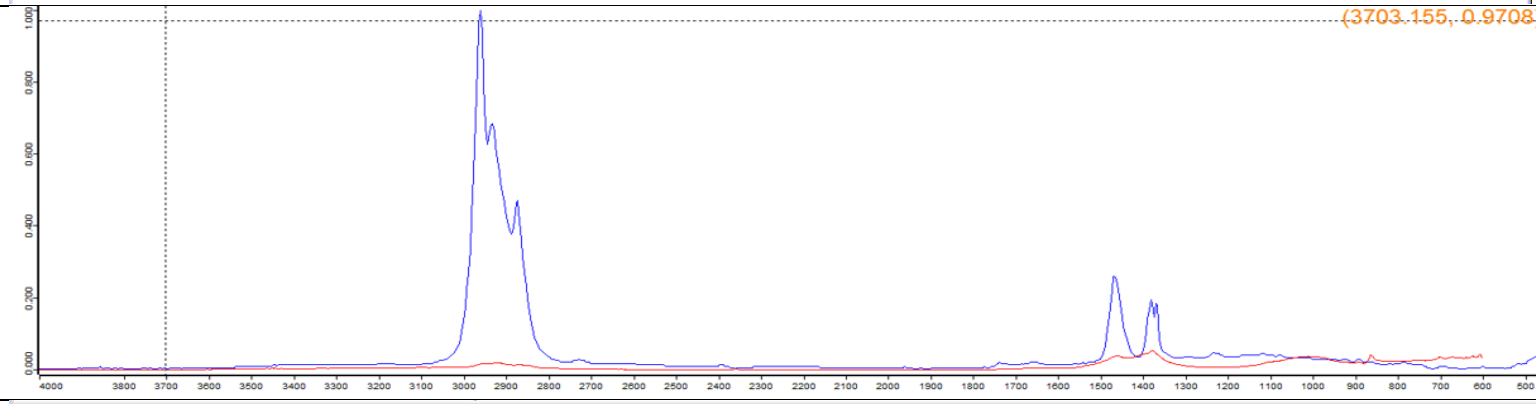
6 ELTEC P HP 603 POLYPROPYLENE

Compound information	
Compound Name:	ELTEC P HP-603*POLYPROPYLENE
Technique	FILM (CAST FROM o-DICHLOROBEN...
Classification	Polymers= POLYPROPYLENES
Source Of Sample	SOLTEX POLYMER CORPORATION
Entry No.	170
Library name	SR.IDX
Library description	Demo Database
Copyright	Copr. ® 1980, 1981-1999 Sadtler. All ...



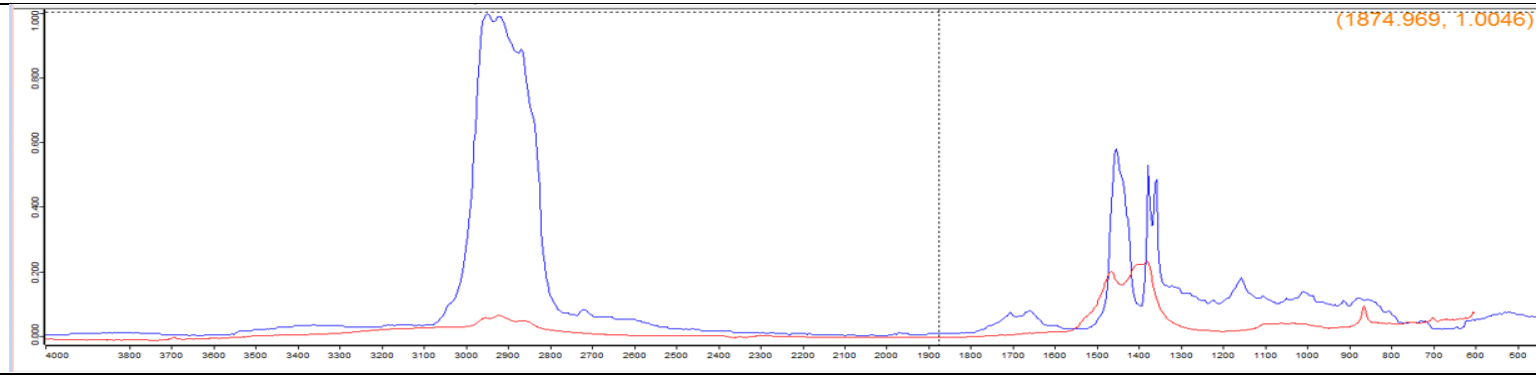
7 INDOPOL 1,4 POLYBUTENE

Compound information	
Compound Name:	INDOPOL L-14*POLYBUTENE
Technique	BETWEEN SALTS
Classification	Polymers= POLYBUTENES AND BUT...
Source Of Sample	AMOCO CHEMICALS CORPORATION
Entry No.	172
Library name	SR.IDX
Library description	Demo Database
Copyright	Copr. ® 1980, 1981-1999 Sadtler. All ...



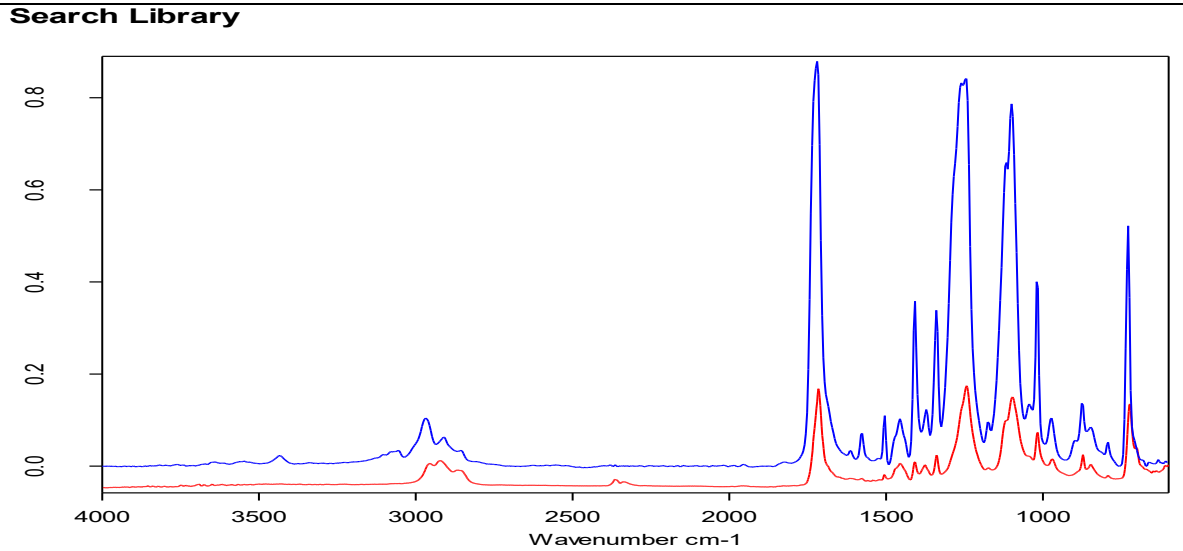
8 piccolyte hydrocarbon thermo

Compound information	
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Technique	FILM
Classification	Polymers= POLYTEREPENE AND NA...
Source Of Sample	PENNSYLVANIA INDUSTRIAL CHEM...
Entry No.	180
Library name	SR.IDX
Library description	Demo Database
Copyright	Copr. ® 1980, 1981-1999 Sadtler. All ...



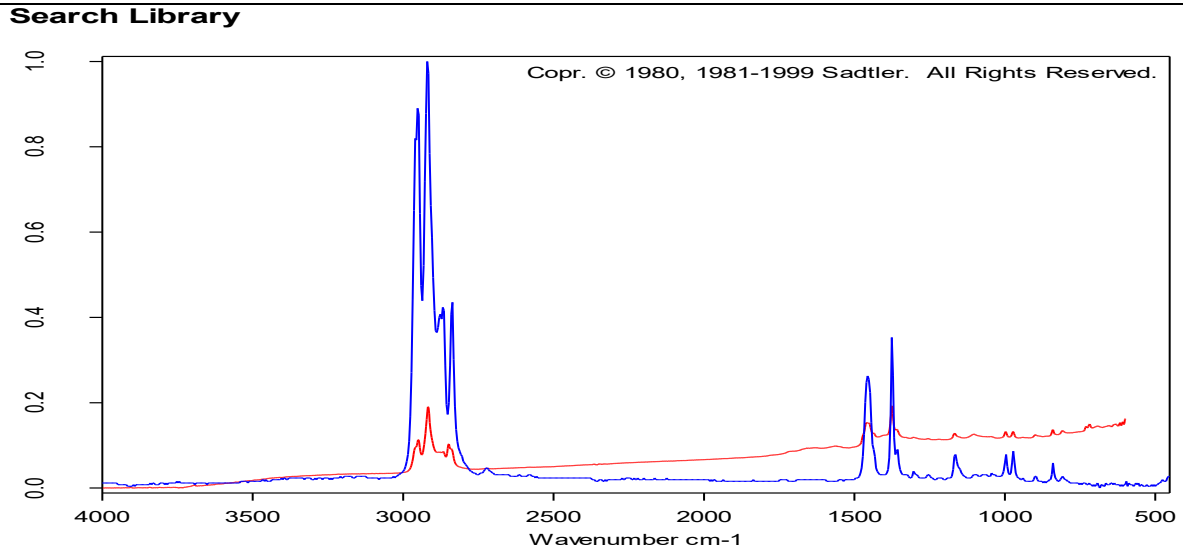
9 Poly(Ethylene Terephthalate)

Compound Name	POLY(ETHYLENE TEREPHTHALATE)
Molecular Formula	C10H8O4
Molecular Weight	
CAS Registry Number	
Sample Preparation	KBR PELLET
Comment	molecular formula means constitutional re
Entry No.	350
Library name	DEMOLIB.S01
Library description	General Library IR
Copyright	User Library



10 Polypropylene

Compound Name:	ELTEC P HP-603*POLYPROPYLENE
Technique	FILM (CAST FROM o-DICHLOROBENZENE)
Classification	Polymers= POLYPROPYLENES
Source Of Sample	SOLTEX POLYMER CORPORATION
Entry No.	170
Library name	SR.IDX
Library description	Demo Database
Copyright	Copr. © 1980, 1981-1999 Sadtler. All Rights



- **Environmental factors and their relationship to microplastics in water and sediment**

Summary statistics for water quality parameters are presented in (**Table 3**). Overall, the measured parameters (pH, temperature, dissolved oxygen, turbidity, conductivity, and depth) showed spatial variability among stations and seasonal differences between the dry and wet periods. This seasonal contrast reflects changes in hydrological conditions and catchment inputs, with wet-season conditions generally associated with greater runoff influence and higher river mixing.

Table 3. In-situ Water Quality Parameters from the Perai River Basin

Station	Season	pH	Temp (°C)	DO	Turbidity (NTU)	Cond (µS/cm)	Depth (m)
ST1	Dry	6.53	26.34	7.60	223	84.17	0.47
ST1	Wet	6.22	25.72	7.84	60.09	NA	0.46
ST2	Dry	6.59	27.54	5.46	281.31	60.07	0.55
ST2	Wet	6.15	27.14	6.24	82.23	NA	0.34
ST3	Dry	7.03	29.80	6.00	343	73.15	0.50
ST3	Wet	6.69	28.03	6.71	247.36	NA	0.79
ST4	Dry	6.95	30.43	4.91	294.59	144.87	1.00
ST4	Wet	6.28	29.69	2.50	117.74	1.60	0.78
ST5	Dry	7.11	30.21	4.60	141.11	253.08	1.19
ST5	Wet	6.81	30.09	1.77	93.72	74.80	0.90
ST6	Dry	7.18	30.27	2.04	230.43	72.38	0.67
ST6	Wet	6.97	30.73	0.97	96.23	4.83	1.02
ST7	Dry	6.96	30.54	3.21	28.17	NA	0.77
ST7	Wet	6.98	30.91	1.6	69.25	31.38	0.42
ST8	Dry	6.79	32.29	3.16	129.50	196.80	0.51
ST8	Wet	7.03	33.57	1.82	35.3	76.58	0.35

Moreover, sediment characteristics across stations are summarised in (**Table 4**). The sediment dataset indicates station-to-station variability in grain size composition and textural properties, suggesting differences in depositional environments and sediment sorting along the Perai River continuum. These sediment properties are relevant because they can influence the retention and accumulation of microplastics in the benthic matrix.

Table 4. Sediment quality parameters from the Perai River Basin

station	season	% Sand	% Silt	%Clay	D50	Span
ST1	dry	96.3	3.7	0	620.424	1.13
ST1	wet	77	23	0	620.424	1.13
ST2	dry	96.3	3.7	0	733.798	0.91
ST2	wet	77	23	0	733.798	0.91
ST3	dry	63	33.3	0.3	85.658	9.12
ST3	wet	82	15	3	85.658	9.12
ST4	dry	64.5	32.3	0.3	397.54	2.39
ST4	wet	74	11	15	397.54	2.39
ST5	dry	60	33.3	6.7	215.096	3.99
ST5	wet	66	17	17	215.096	3.99
ST6	dry	46.8	40.6	12.5	387.898	2.36
ST6	wet	76	15	9	387.898	2.36
ST7	dry	29.4	50	20.6	442.14	1.98
ST7	wet	66	21	13	442.14	1.98
ST8	dry	26.5	52.9	20.6	66.568	1.74
ST8	wet	70	24	6	66.568	1.74

- **Spearman correlation between microplastics and hydrogeological parameters**

During the dry season, microplastic abundance in water showed the strongest association with temperature (ρ = -0.83), indicating a strong negative relationship. A similar inverse-temperature–microplastic pattern has been reported elsewhere. For example, Castro et al. (2024) observed higher microplastic concentrations during cooler months. Microplastic abundance was positively correlated with dissolved oxygen (DO) (ρ = 0.62), while the relationship with pH (ρ = - 0.36) and turbidity (ρ = 0.31) was weaker to moderate. In contrast, microplastic abundance showed negligible correlations with conductivity (ρ = 0.07) and depth (ρ = -0.05), as shown in (**Figure 9**). The dry season pattern suggests that microplastic abundance in the surface water covaries most strongly with the thermal-oxygen regime. The strong negative microplastics – temperature (ρ = -0.83) relationship, together with the positive microplastics – DO relationship (ρ = 0.62), may reflect a linked gradient in which stations with cooler conditions also tended to have higher oxygen and higher microplastic abundance. This is consistent with the strong inverse relationship between temperature and DO (ρ= -0.79), which is commonly observed in natural waters.

During the wet season, microplastic abundance showed weak positive correlations with pH (ρ = 0.24), DO (ρ = 0.21), and turbidity (ρ = 0.19), and depth (ρ =0.19), and a negligible relationship with temperature (ρ=0.17). Microplastic abundance was essentially uncorrelated with conductivity (ρ=-0.09). Overall, the correlations between microplastics and water quality were weak during the wet season. These results from the wet season indicate that microplastic abundance was not strongly coupled with the measured water quality parameters, suggesting that wet season microplastic variability may be driven more by episodic inputs and hydrological transport than by stable physicochemical gradients.

Compared with the dry season, where microplastic abundance showed stronger associations with temperature (ρ = -0.83) and DO (ρ = 0.62), wet-season microplastic abundance exhibited only weak relationships with all measured water-quality parameters ($|\rho| \leq 0.24$). This seasonal contrast suggests that microplastic patterns during the dry season are more closely aligned with spatial physicochemical gradients. In contrast, wet-season microplastic abundance is likely influenced by short-term hydrological inputs and redistribution, which weaken consistent station-level covariation with water-quality conditions.

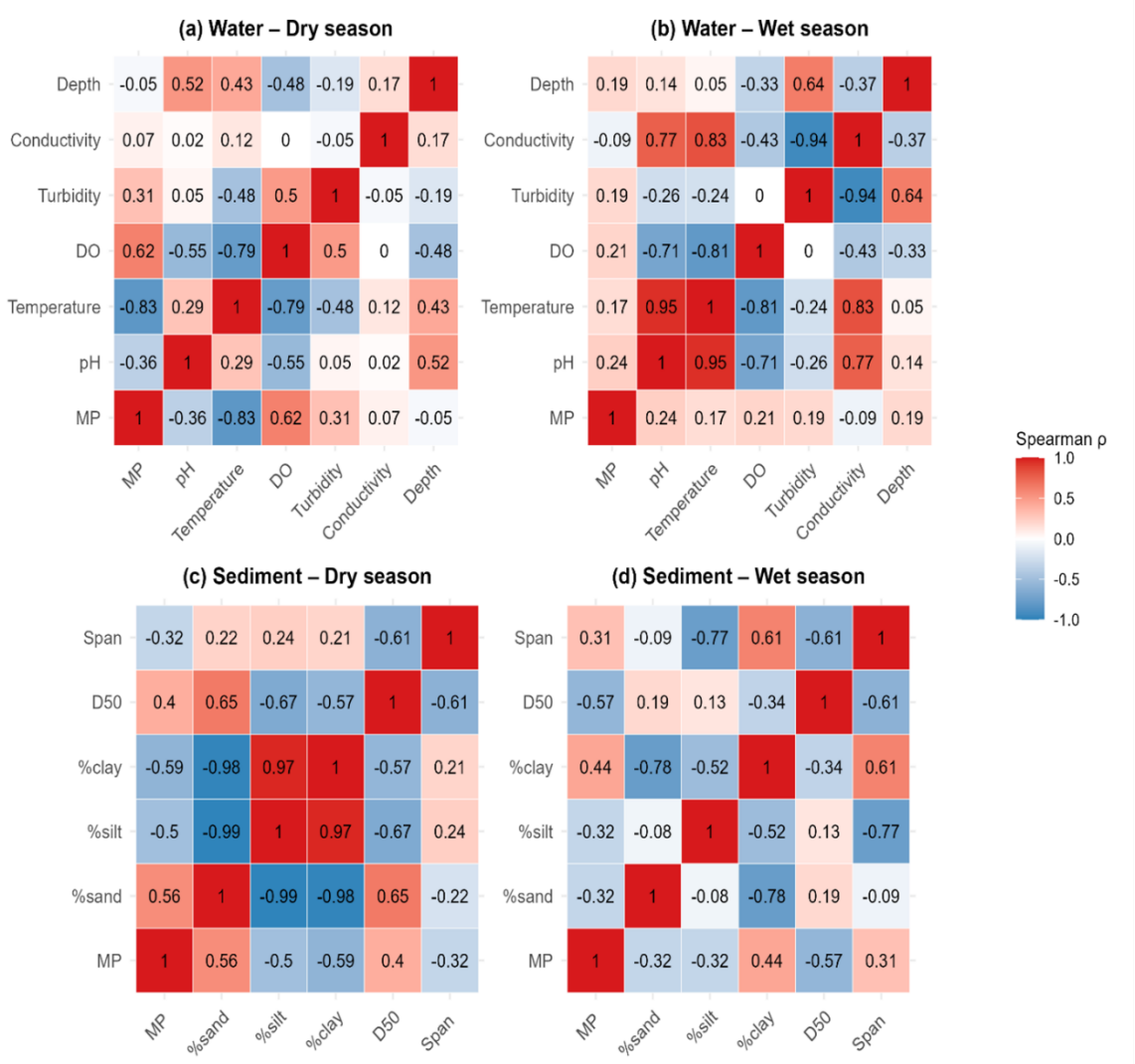


Figure 9. Spearman correlation heatmaps demonstrating relationships between microplastic abundance and environmental parameters in water and sediment during dry and wet seasons

During the dry season, the abundance of sediment microplastics showed a moderate positive correlation with sand content ($\rho = 0.56$) and median grain size (D50, $\rho = 0.40$), indicating higher microplastic accumulation in coarser sediments. In contrast, microplastic abundance showed moderate negative correlations with silt ($\rho = -0.50$), clay ($\rho = -0.59$), and sediment span ($\rho = -0.32$), suggesting reduced microplastic retention in finer, poorly sorted sediments. Microplastic correlations suggest that microplastic abundance increased with coarser sediment characteristics (higher sand percentage and higher D50) and decreased with finer sediment characteristics (lower clay percentage). This pattern may reflect hydrodynamic sorting and depositional setting: stations like (ST1), (ST2), and (ST3) with sandier beds may retain higher

microplastic loads through physical trapping with bedforms and local accumulation which is confirmed by Beaumont et al. (2024) who experimentally demonstrated that sand bed rivers can store up to 40% of their microplastic load within sediment beds. Clay-rich sediments may reflect different settling dynamics and compaction, potentially reducing the detectable fraction of microplastics. The negative association with % clay ($\rho = -0.59$) indicates that fine, cohesive sediments were not associated with higher microplastic abundance in the dry season in this dataset.

In the wet season, sediment microplastic abundance showed a moderate positive correlation with clay ($\rho = 0.44$), indicating a greater association of microplastics with finer sediments under higher hydrodynamic conditions. In contrast, microplastic abundance was moderately negatively correlated with sand content ($\rho = -0.32$), silt content ($\rho = -0.32$), and median grain size (D50; $\rho = -0.57$), suggesting reduced microplastic retention in coarser sediments during the wet season. A weak positive relationship was observed between microplastic abundance and sediment span ($\rho = 0.31$). The wet season pattern indicates that higher sediment microplastic abundance was associated with finer and more poorly sorted sediments, as reflected by the positive association with %clay ($\rho = 0.44$) and span ($\rho = 0.31$) and the negative association with D50 ($\rho = -0.57$) which suggests that stations with coarser median grain size tended to have lower microplastic abundance during the wet season. This is consistent with wet-season hydrodynamics: high-flow events can mobilise particles across the channel and, during flow relaxation, promote deposition of fine fractions in lower-energy zones, where smaller microplastics may accumulate.

Spearman correlation analysis revealed apparent seasonal differences in the relationships between sediment microplastic abundance and sediment texture. In the dry season, microplastic abundance increased with coarser sediment characteristics and decreased with finer sediments. In contrast, in the wet season, microplastic abundance increased with %clay and decreased

with %sand, %silt, and D50. These contrasting patterns indicate a seasonal shift in the association between microplastics and sediments, from coarser sediments during the dry season to finer sediments during the wet season.

- **Land use impact assessment and its relationship to microplastics in the Perai River Basin**

The land use and land cover (LULC) classification is presented in (**Figure 10**). In general, the upstream stretches of the Perai River Basin (ST1–ST3) are dominated by forests, progressing through agricultural landscapes in the midstream (ST4–ST5), to highly urbanized and industrialized landscapes in the downstream stretch (ST6–ST8) with more than 80% urban cover. This spatial gradient provided a perspective on the potential influence of land use intensity on microplastic pollution.

Agricultural land occupies a large proportion of the upstream and midstream catchment, and is closely associated with plantation activities and irrigation networks. Oil palm plantations are found at several upstream sampling stations, including ST1 (Kulim), ST3 (Lunas) and ST4 (Tasek Gelugor). In addition, large areas of paddy cultivation are found across midstream, particularly in Tasek Gelugor, Kepala Batas and Kubang Semang (Figure 2). Paddy fields are also concentrated near sampling stations S5 (Jeti Kampung Terus).

Water bodies constitute the core hydrological structure of the catchment, including the main Perai River, including the major tributaries in Kulim River (Think City & Perunding Pinang, 2018). This tributary flow through varied land use settings such as forested, agriculture and urban land use.

Built-up areas can be found throughout the catchment. In the upstream region, they are mainly linked to settlements and town growth in places like Kubang Semang, Tasek Gelugor, and Kulim Town in Kedah. Midstream built-up areas are concentrated around Permatang Pauh, where residential and mixed-use developments are common. In contrast, the lower catchment

is characterised by dense urban centers such as (ST6) Butterworth, Perai and (ST7) Seberang Jaya, reflecting high urbanisation and human activities.

Industrial land use is concentrated in designated zones. In the upstream section, key developments include the Kulim Hi-Tech Park and Kulim Industrial Park, which serve as major industrial hubs within the Kedah part of the catchment. Further downstream, industrial activities are located in the Mak Mandin Industrial Area and the Perai Industrial Area, situated in Butterworth and Perai (ST8), respectively. These industrial zones are spatially clustered and form important components of the downstream land use pattern.The land use and land cover (LULC) classification is presented in (**Figure 10**). In general, the upstream stretches of the Perai River Basin (ST1–ST3) are dominated by forests, progressing through agricultural landscapes in the midstream (ST4–ST5), to highly urbanized and industrialized landscapes in the downstream stretch (ST6–ST8) with more than 80% urban cover. This spatial gradient provided a perspective on the potential influence of land use intensity on microplastic pollution.

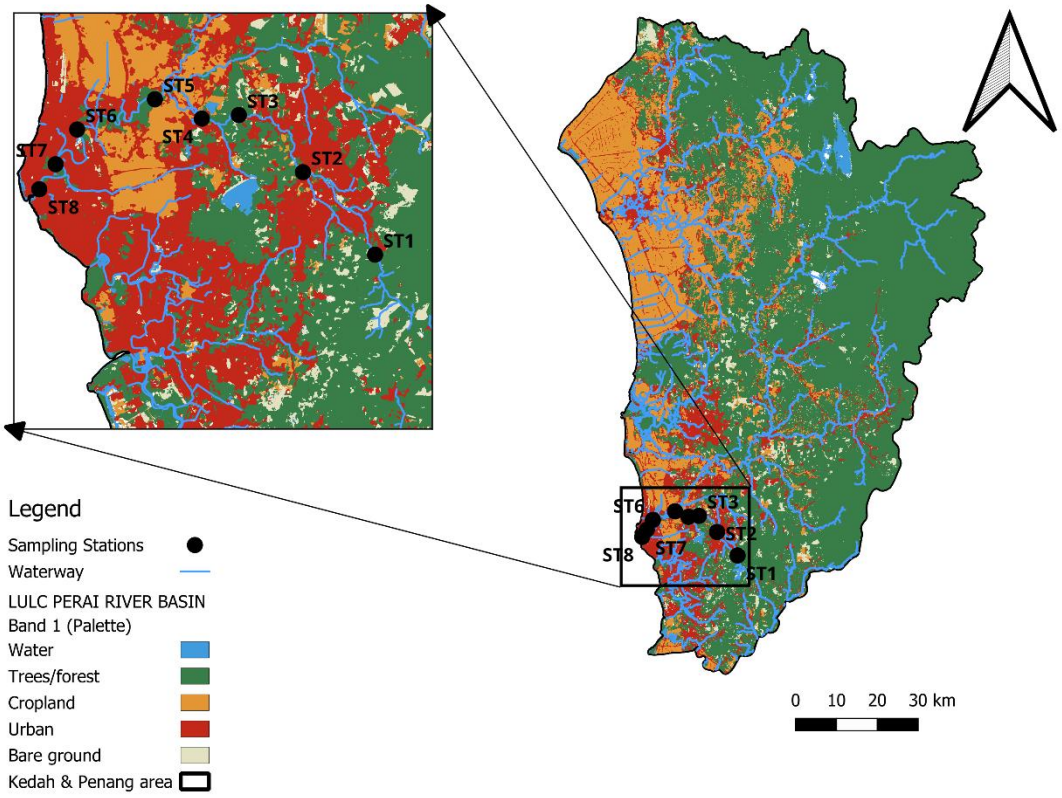


Figure 10. Land use changes surrounding the Perai River Basin

The statistical analysis shows a clear link between land use and microplastic distribution that changes significantly with the seasons. In urban areas, there is a distinct seasonal switch in microplastic pollution. During the dry season, urban land use shows a weak negative correlation with microplastic abundance in both water (ρ =-0.29) and sediment (ρ= -0.28), suggesting these areas are not major contributors during low flow periods. However, during the wet season, this relationship becomes strongly positive for both water (ρ =0.67) and sediment (ρ= 0.77), which is confirmed by Ye and Pei. (2023). This indicates that rainfall acts as a primary transport mechanism, washing accumulated plastics from city surfaces into the river system. The particularly high correlation in the wet season sediment suggests that many of these urban particles are dense enough to settle quickly once they enter the water.

Forests exhibit a more consistent influence on microplastic levels regardless of the season. In the surface water, forested land use maintains a steady moderate positive correlation (ρ= 0.4) in both the dry and wet seasons. This suggests that forests may not be acting as a traditional buffer. While the correlation in sediment remains moderate during the dry season (ρ=0.4), it

weakens during the wet season (ρ=0.2). This change likely occurs because heavy rains flush these particles to the water, allowing them to accumulate in the local riverbed (Allen et al., 2019).

Agricultural land use shows a unique pattern where it only contributes to water contamination during rainy periods. During the dry season, agriculture has a negative correlation with microplastic abundance in water (ρ= -0.3), but this shifts to a positive correlation (ρ= 0.4) in the wet season. This shift suggests that plastics used in farming, such as mulch films or fertilizers, remain trapped in the soil when it is dry and are only mobilized by rain-induced erosion. Interestingly, agriculture shows a consistent negative correlation with sediment abundance (ρ = -0.4) in both seasons. This indicates that agricultural microplastics are likely buoyant and remain suspended in the water flow as wash load rather than settling into the sediment near their source.

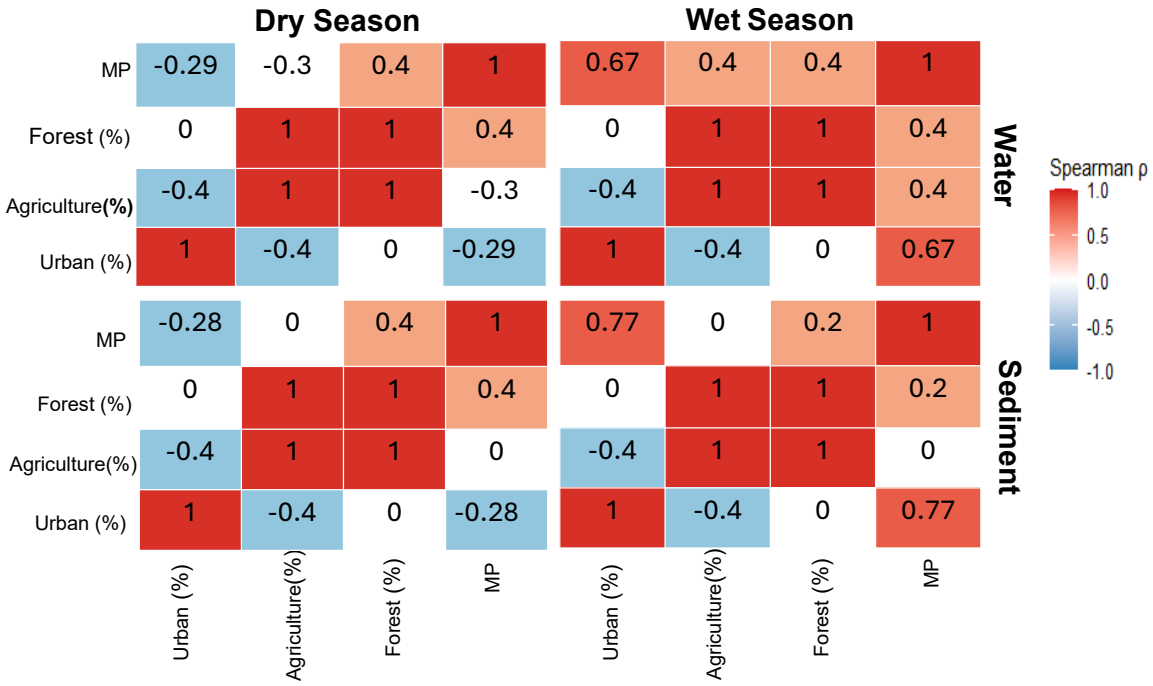


Figure 11. Spearman correlation heatmap between microplastic abundance in water/sediment and land use percentage in the Perai River Basin.

Table 5 summarises the AWM MP concentrations by land use category for surface water and sediment during the dry and wet seasons. The AWM approach enables consistent comparison across land uses by integrating concentration data with spatial coverage, using mean values derived from zonal statistics, and has been widely applied in catchment-scale MP

studies (Windsor et al., 2019; Chen et al., 2021). These AWM values form the basis for subsequent interpretation of MP distribution in relation to land use categories.

Table 5 Area-Weighted Mean Microplastic Concentration by Land Use Type

Land Use	Area (m^2)	Surface Water (particles/L)		Sediment (particles/kg d.w.)	
		Dry Season	Wet Season	Dry Season	Wet Season
Agriculture	233929063.23	169.57	182.27	80.85	123.17
Built-Up Area	155783688.19	130.97	160.00	83.20	130.33
Forest	24295551.52	239.04	218.48	79.55	103.29
Industry	18656156.71	141.23	168.52	93.56	138.09
Water Body	15057521.01	113.49	146.35	75.87	128.33

Overall, the AWM results indicate observable variation in MP concentrations across different land use categories and environmental compartments. For surface water, differences in AWM values among land use types are relatively moderate, with broadly consistent ranking patterns observed between the dry and wet seasons. Such limited seasonal variability in relative spatial patterns has been reported in other tropical river systems, where seasonal hydrological changes affect transport magnitude rather than spatial hierarchy (Chen et al., 2021).

In contrast, sediment AWM values show clearer differentiation across land use categories and increase consistently during the wet season. This seasonal increase reflects enhanced mobilisation and redistribution of MPs during periods of higher runoff and flow energy, followed by deposition and retention within the benthic environment. Similar wet-

season enrichment of sediment-associated MPs has been documented in tropical and monsoon-influenced river systems, highlighting the role of sediments as longer-term sinks for MP accumulation (Horton et al., 2017; Chen et al., 2021).

The AWM values represent spatial associations between land use categories and MP accumulation patterns, rather than direct source attribution. High AWM values signify locations where MPs are more likely to accumulate or coincide with particular land use categories, but they do not confirm specific emission sources. Although previous studies have reported correlations between MP abundance and watershed characteristics such as land cover, urbanisation intensity, and hydrological conditions, the purpose of AWM-based analysis is to facilitate spatial interpretation rather than to establish definitive source identification (Windsor et al., 2019; Van Emmerik et al., 2022).

- **Microplastics Ecological Risk Assessment (Pollution Load Index)**

The calculation of (MP*Cf)* across all sampling stations and seasons is summarized in (**Table** 6). During the dry season, microplastics contamination factor (MP*Cf*) values showed a high level in water compared to sediment, as demonstrated in (**Figure 12**). Whereas, during the wet season, the microplastics contamination factor (MP*Cf)* in sediment increased more than in water. This seasonal shift could be explained by low water flow in the dry season, which keeps microplastics suspended or floating in the water rather than settling, while in the wet season, heavy rains and turbulence could wash and accumulate plastics from the riverbanks and settle them in the sediments, which act as a sink for the increased pollution load.

Table 6. Calculated Microplastics contamination factors

Station ID	MP concentration	MP background	*Cf*
WATER - DRY SEASON			
ST1	36	4	9
ST2	26.33	4	6.58
ST3	8	4	2
ST4	12	4	3
ST5	21.33	4	5.33
ST6	9.33	4	2.33
ST7	5.33	4	1.33
ST8	4	4	1
WATER - WET SEASON			
ST1	53.33	4	13.33
ST2	41.33	4	10.33
ST3	74.66	4	18.66
ST4	69.33	4	17.33
ST5	45.33	4	11.33
ST6	68	4	17
ST7	28	4	7
ST8	88	4	22
SEDIMENT - DRY SEASON			
ST1	33.33	5	6.66
ST2	16.66	5	3.33
ST3	20	5	4
ST4	13.33	5	2.66
ST5	6.66	5	1.33
ST6	5	5	1
ST7	15	5	3
ST8	13.33	5	2.66
SEDIMENT - WET SEASON			
ST1	64.73	5	12.94
ST2	55.55	5	11.11
ST3	97.89	5	19.57
ST4	147.5	5	29.5
ST5	82.94	5	16.58
ST6	158.52	5	31.7
ST7	107.94	5	21.58
ST8	147.14	5	29.42

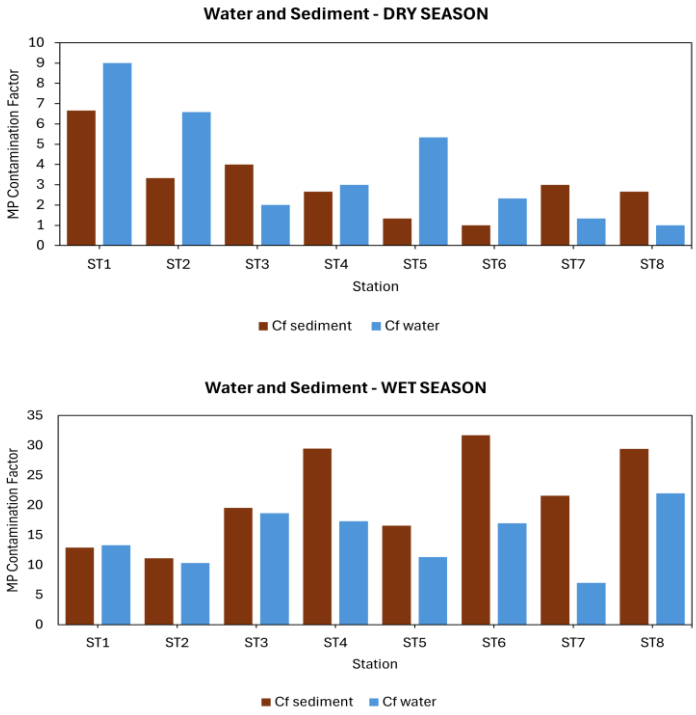


Figure 12. Microplastics Contamination Factor Across the sampling stations during the dry and wet seasons

The Pollution Load Index (PLI) results reveal a significant seasonal shift in the river's contamination profile. During the dry season, PLI values in water (2.95) and sediment (2.65) indicated low pollution, suggesting minimal plastic input during low-flow periods. In contrast, the wet season triggered a drastic surge in risk, with water PLI rising to 13.80 (moderate) and sediment PLI reaching 20.19, categorized as high pollution. This increase confirms that rainfall-induced runoff is the primary driver of land-based plastic waste mobilization into the aquatic environment. The sediment's higher PLI during the wet season compared to water indicates that the riverbed is a major pollution sink, capturing particles as flow dynamics change. These levels are substantially higher than those found in the Old Brahmaputra River, Bangladesh PLI (5.14, 5.5) (Mithu et al., 2026), and the Sharavathi River, India, where scores remained below 5 (Amrutha et al., 2022). The fact that wet-season values in this study are

nearly four times higher than regional levels highlights a severe ecological risk requiring immediate mitigation.

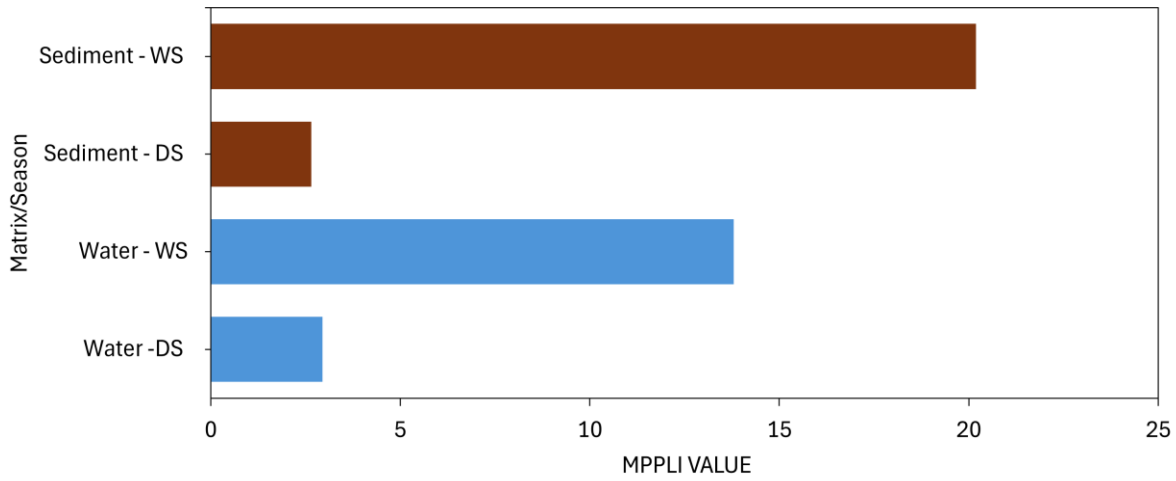


Figure 13. Microplastics Pollution Load in water and sediment during Dry and Wet seasons

IV. Policy Implications, Recommendations and Corrective Action Plan

From our field observations during cleanup activities, we identified specific physical traps where large plastic debris consistently accumulates, particularly within the curved areas of the river. These natural retention zones, often characterised by dense overhanging vegetation, holdup macro plastics and store them for extended durations. This prolonged residence time is a critical concern, under constant exposure to UV radiation and mechanical stress from fluctuating water levels, these trapped plastics undergo accelerated photo degradation and fragmentation. This process transforms localized macro-plastics eyesores into a long-term, continuous source of secondary microplastics that are eventually flushed downstream during high-flow events. To prevent these scenarios, we suggest establishing the following mitigation strategies to tackle the plastic pollution issue in the Perai River Basin:

Establishment of riparian buffer strips, typically 5-50 meters wide, which are mandatory vegetative barriers, should be prioritized along urban industrial stretches and at identified hotspots. These strips serve as a first-stage filter, capturing land-based runoff and preventing debris from immediately entering the aquatic system during heavy rainfall. This can be done through collaborations among agencies and stakeholders. For instance, the Majlis Bandaraya

Seberang Perai (MBSP) can partner with communities such as Koperasi Nelayan Labuh Banting to establish riparian buffer strips along the upstream part of the river. These buffers, typically 5-50 meters wide, can trap MPs from agricultural and forested lands in Kulim and Seberang Perai Utara, acting as a retention trap for temporary collection of the plastics. From here, routine river cleanup targeting this riparian buffer strip can be conducted by locals and Department of Irrigation and Drainage (DID). The establishment of riparian buffer strips support the biodiversity and aligns with MBSP's Landscape Master Plan 2025-2035, which emphasizes green infrastructure in Seberang Perai.

Strategic installation of barrier nets; engineered interventions, such as nets with <5mm mesh size, should be placed at key hydrological blocks, including Jetty Pengkalan Machang, Jetty Kg Terus, and beneath major bridges. These nets will intercept plastics already in the water column before they reach downstream sinks. the Department of Irrigation and Drainage (DID) can collaborate with local groups including Koperasi Nelayan Pengkalan Machang and Jawatankuasa Kerja Kampung Terus to deploy garbage traps with mesh sizes less than 5 mm at strategic points, such as Jetty Pengkalan Machang and Jetty Kg Terus which traps floating plastics after heavy rain and high-water level. This approach draws on DID's river basin management frameworks and initiatives like the Perai River Basin Partnership, which promotes integrated pollution control to prevent plastic breakdown into MPs (Resilient Cities Network, 2025).

- Empowering Community River Rangers: to ensure these nets do not become obstructions or eyesores, the Korperasi Nelayan Pengkalan Machang should replicate the Global Environment Centre (GEC) River Ranger model. This unit would be responsible for routine collection, sorting, and transporting waste to the Majlis Bandaraya Seberang Seberang Perai (MBSP) for recycling. These collaborative initiatives promote ownership and sustained effectiveness in managing floating plastics before its degradation into MP dynamics.

- Urban Stormwater Management: we suggest establishing Bioretention systems near roadsides, car parks, and industrial zones, such as raingardens or bioswales to capture and filter microplastics at the source. In collaboration with the Department of Irrigation and Drainage (DID), existing stormwater infrastructure in flood-prone areas must be upgraded to comply with Urban Stormwater Management Manual for Malaysia (MSMA) guidelines, ensuring both flood mitigation and water quality treatment.
- Hydrogeological and Land-use Integration: future urban development plans must incorporate plastic leakage reduction as a core planning metric. Further investigation into the Perai River's flow dynamics is essential to move from reactive cleanups to a proactive, science-based management network.

➢ **Strategies for reducing microplastics pollution in Perai River**

To minimize microplastic pollution of the Perai River, synergy of action-oriented, scientific, and policy-oriented responses is suggested:

- Routine cleaning activities using boats equipped with nets can be launched to remove plastic garbage in larger sizes before it degrades into microplastics. This should be focused especially in downstream and urban-industrial sections of the river where plastic accumulation is more significant. Community involvement in riverbank and surface cleanups will also enhance the effectiveness and durability of such efforts.
- Further investigation of the Perai River hydrogeology is needed. Flow dynamics, sediment retention, and seasonal variation will enable tracing transport and accumulation patterns of microplastics. This must be followed by investigations of land use impacts on plastic inputs and the determination of important sources and hotspots of contamination.
- Inclusion of microplastic reduction in land use planning is also needed. Plans for urban development should incorporate plastic leakage reduction measures, for instance, the creation of buffer zones and vegetative barriers along the river. These attributes will be capable of capturing plastics before they reach aquatic systems.
- Finally, frequent public campaigns and the development of regional policies are needed to prevent pollution at the source. Improving waste management systems and promoting the adoption of standardized microplastic monitoring protocols can support long-term efforts towards cleaner and healthier river systems.

- **Protocols and manuals**

This section records the developed and employed protocols and guidelines in the process of conducting Sungai Perai microplastics monitoring and assessment. These protocols act as a future monitoring guide and are meant to be operational and replicable.

Water and Sediment Sampling Protocol

Water Sampling:

- When river depth allows use a neuston net (300 µm mesh) to collect surface water microplastics over a set distance or volume.
- When depth is too shallow: manually scoop surface water using pre-cleaned containers.
- Pour water slowly through a series of sieves (from 5 mm to 300 µm).
- Take triplicates per station for consistency.
- Use field blanks (filtered water) to monitor contamination.
- Label containers with station ID and date.
- Store samples in clean glass bottles and place in icebox.

Sediment Sampling:

- Use a stainless steel grab sampler to collect surface sediment (top 3–5 cm).
- Avoid contact with plastic.
- Place sediment into pre-cleaned glass jars.
- Label with station ID and date.
- Store in a cooler and transport to the lab within 24 hours.

Laboratory Processing Protocol

Water Sample Digestion:

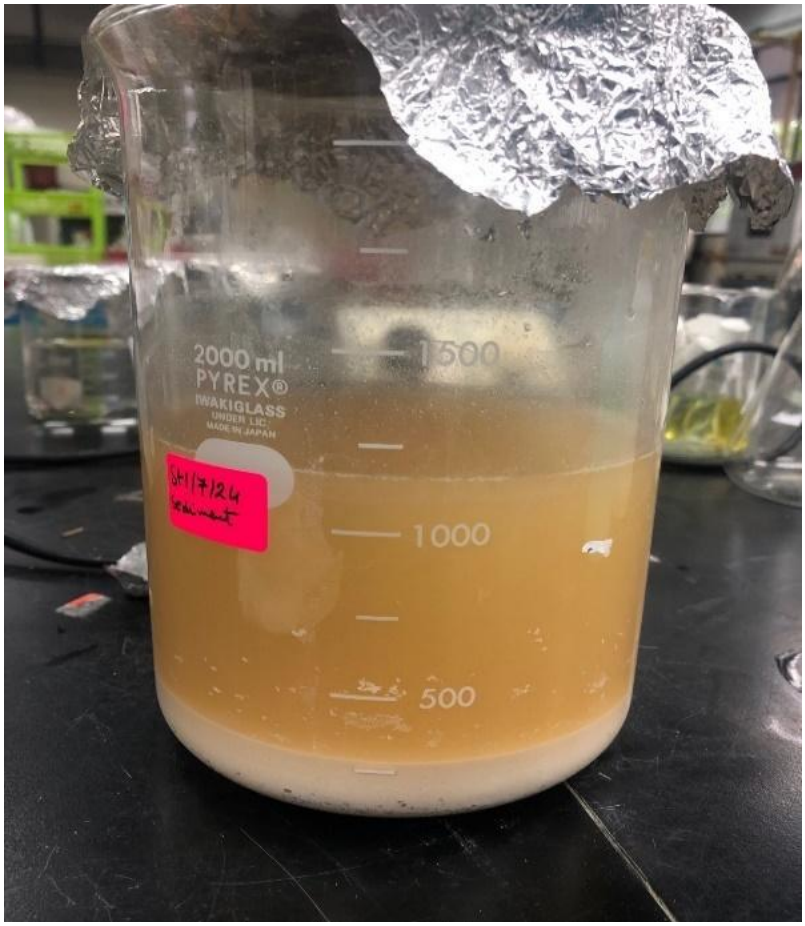
- Shake sample and sieve to isolate particles.
- Transfer sieved material into a glass beaker.
- Add 10% KOH solution (enough to submerge material).
- Cover partially with aluminium foil.
- Stir on hotplate until bubbles form, then let cool.
- Leave to digest for 24 hours.

Sediment Digestion and Density Separation:

- Dry sediment sample in oven.
- Weigh 200 g of dry sediment.
- Add 10% KOH solution and stir on hotplate



- Digest for 24 hours.
- Add $ZnCl_2$ (1.8 g/mL) to separate microplastics by density.



- Let stand for 1 hour.
- Collect supernatant and filter through GF/C filter paper.



- **Dry filter papers in labelled petri dishes.**

Filtration:

- **Use glass microfiber (GF/C) filter paper.**
- **Filter digested solution using vacuum pump.**
- **Transfer filter to labelled petri dish and dry.**

Identification and Characterization Protocol

Stereomicroscope Observation:

- **Place dried filter on microscope stage.**
- **Start with 4X magnification.**

- **Count and classify MPs by shape, color, size.**
- **Document with microscope camera**

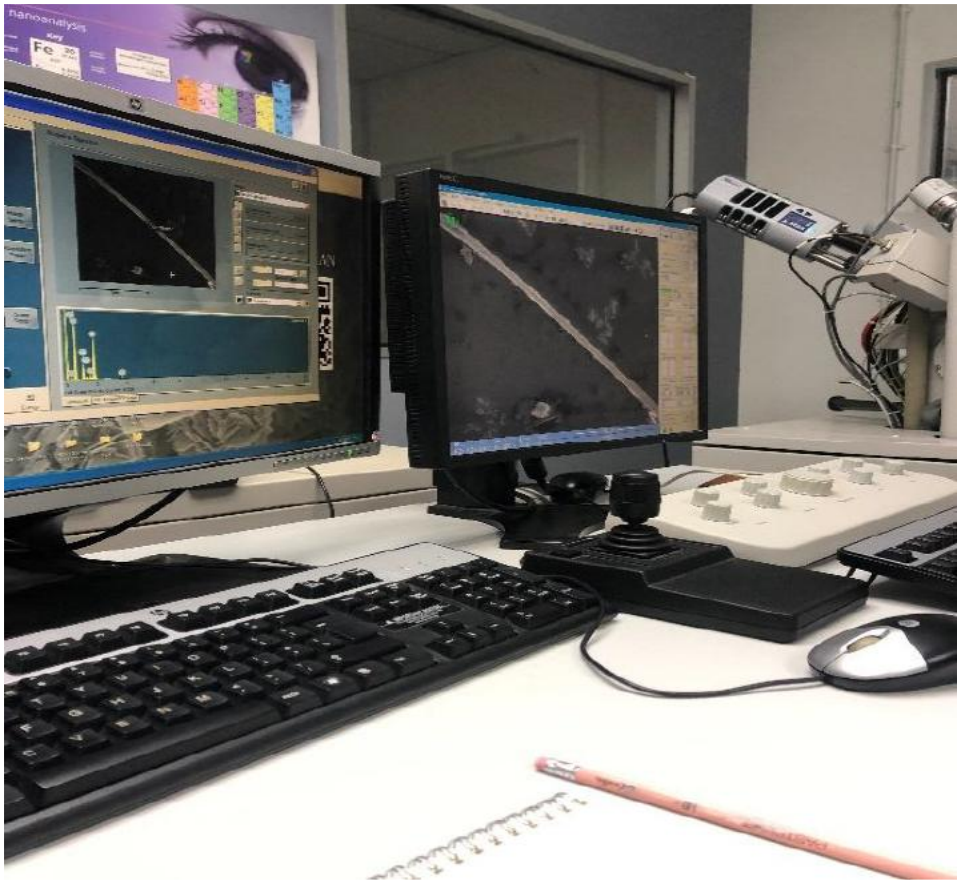


µFTIR Analysis

- **Select representative MPs.**
- **Analyze using micro-FTIR spectroscopy.**
- **Compare spectra with reference polymer library.**

SEM-EDX Analysis

- **Mount dried MPs on SEM stubs.**
- **Analyze morphology with SEM.**
- **Conduct EDX to determine elemental composition.**



QA/QC Checklist

- **Use cotton wears and lab coats to reduce contamination.**
- **Use blanks in field and lab for contamination monitoring.**
- **Collect replicates for each sampling point.**
- **Use only glass and stainless-steel tools.**
- **Calibrate instruments before use.**
- **Double-check all data entries.**

Monitoring and Management Recommendations

Suggested Frequency:

- **Dry and wet season sampling (minimum 2x per year).**

Minimum Equipment List:

- **Neuston net and sieves**
- **Grab sampler**
- **Glass jars, bottles, petri dishes**

- **GF/C filter paper, vacuum pump**
- **KOH and $ZnCl_2$ reagents**
- **Microscope, FTIR, SEM (lab access)**

Suitable Users:

- **NGOs, universities, DOE, school eco-clubs**

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