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RESEARCH ARTICLE

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Spatial and Temporal Distribution of Microplastics in Water and Surface Sediments Along the Jawi River–Kakap Estuary, West Kalimantan, Indonesia

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ABSTRACT

Microplastics (MPs) are ubiquitous contaminants in river-estuary systems but their distribution in the water column vs surface sediments in tropical regions is still poorly understood. The present study aims to investigate the spatial and temporal distribution of MPs abundance and properties in water and surface sediments at the Jawi River–Kakap Estuary, West Kalimantan, Indonesia. Sampling was carried out at 17 sites including upstream residential areas, middle sections and the estuarine zone during June to August in 2025. MPs levels in surface sediments were generally higher than those in the water column during the study. Fibres were the most abundant particle type in the water with a maximum concentration of 161 particles, while fragments were the dominant particle type in the surface sediments with a maximum concentration of 1,250 particles, indicating that these depositional areas are sites of significant accumulation. The Kruskal-Wallis test revealed significant differences in MPs types between water and sediments for all the months of sampling ($p < 0.001$). However, significant spatial differences between the upstream (PT), middle-reach (KR), and estuarine (SK) station groups were detected only in the water column during June ($H = 10.90$, $p = 0.004$) and July ($H = 7.05$, $p = 0.030$), but not in sediments. Transparent particles dominated both water and sediments, but sediment samples contained a greater variety of colours. These results indicate that the water column responded more promptly to the spatial heterogeneity of MPs input and transport, while surface sediments presented more extended periods of accumulation.

Introduction

Currently, microplastics (MPs) are considered a major contaminant in rivers, primarily due to human activities. These MPs originate from wastewater discharges, land runoff, urban dust deposition, and the fragmentation of larger plastic debris. This fragmentation results from domestic activities such as irrigation, household use, or industrial processes [1,2]. Rivers serve as the primary conduits linking terrestrial sources of pollution to downstream aquatic environments. Once pollution enters the rivers, it is carried away by the flow of water. Lighter particles tend to remain suspended and are transported downstream.

In contrast, heavier particles or those that are taken up by organisms tend to settle. These particles can then interact with sediments, riverbanks, and the riverbed [1,2]. Some MPs can be temporarily retained in river sediments and floodplains. Rivers with changing flow conditions and periodic high-discharge events can remobilize MPs that have previously accumulated in the river, resulting in uneven spatial and temporal distributions. Thus, rivers serve not only as pathways for MP transport but also as dynamic systems in which these particles can be temporarily stored, redistributed, and transformed before eventually reaching estuarine and coastal waters [3].

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The share of MPs in river waters varies strongly between locations. Variability is largely driven by the types of MPs and the human activities around them, which determine the patterns of MPs occurrence in the water column and the sediment. In addition, different MPs may have different properties such as density, shape and surface characteristics, which affect their transport, retention and redistribution within the river system. Long, low-density particles such as fibres are more likely to remain suspended in the water column and therefore can be transported further downstream. In contrast, denser fragments and films settle more easily and accumulate in the sediment, particularly in areas of the river where the flow energy [4–6]. This distribution pattern is also affected by changes in human activity along the river and in the estuary. Areas close to densely populated settlements and ports typically receive higher volumes and a greater variety of MPs. These MPs originate from domestic waste, urban runoff, and industrial activities related to plastic use [7,8]. Large changes in the numbers and types of MPs are often recorded in estuaries and port areas. These changes reflect the strength of local pollution sources and the flow conditions that allow for the retention and redistribution of these particles [3,9]. This indicates that rivers serve as transportation routes for MPs and as structured environments in which the amount and composition of MPs change dynamically in response to the intensity of downstream land use and economic activities.

The rapid development along coastlines has increased the need to understand where and when MPs accumulate in river-estuary systems. These transitional environments are becoming critical hotspots for plastic pollution. The river-estuary continuums are highly variable in time and space, with the interaction of factors such as changes in water flow, tides and land use influencing the transport, retention and remobilization of MPs surveys that are carried out only once or in limited areas are often unable to capture episodic inputs related to rainfall, discharge fluctuations or localised human activities, resulting in an incomplete identification of pollution hotspots [10,11]. Intensive and uneven loads of MPs are introduced into fast-developing coastal areas through dense settlements, wastewater discharges, and port-related activities. Estuarine hydrodynamics facilitate temporary accumulation within sediments and turbidity zones before downstream export [6,12,13]. Therefore, thorough investigations carried out over several months and across the entire river–estuary gradient are crucial for addressing short-term variability, distinguishing between persistent and transient hotspots, and providing strong evidence to support targeted, management-focused responses to MPs pollution [8,14].

The study was carried out in the Jawi River–Kakap River estuary system in West Kalimantan, Indonesia, a tropical river-estuary system affected by human activities. Human activities in the area include the discharge of domestic wastewater and urban surface runoff, while port operations, shipping, and coastal processes increasingly impact the estuary itself. These factors create dynamic environmental conditions with changes in salinity, hydrodynamics and sediment characteristics. The waters are also influenced by tidal variation and seasonal rainfall, affecting water movement, sediment transport and the redistribution of suspended particles. The characteristics make the Jawi River–Kakap River estuary a suitable place to study the distribution and spatial and temporal behaviour of these MPs components.

Materials and Methods

Sampling and Survey

The study was conducted along the continuum of the Jawi River-Kakap River Estuary in West Kalimantan, Indonesia. This area represents a river-estuary system that exhibits clear gradients of human influence and hydrodynamic conditions. Sampling was conducted using a field survey design at 17 fixed stations distributed along a longitudinal transect. Such stations were in the upstream section with dense residential areas, *Pontinak Kota* (PT), in intermediate zones with less settlement intensity *Kubu Raya* (KR) and in the estuarine area influenced by the activities of a fish-landing port *Sungai Kakap* (SK)—this sampling design was intended to capture the spatial variability related to the different human pressures along the river-estuary gradient. Moreover, the region is subject to tidal dynamics and seasonal rainfall impacting water flow, sediment transport and particle redistribution. The field surveys were conducted for three consecutive months of June, July and August 2025 as shown in Figure 1.

Laboratory Analysis

MPs are sampled in water using a plankton net and in sediment using an Ekman grab. In 20 L of water, two samples are filtered through a pre-cleaned plankton net membrane filter (30–40 µm), and the volume of water filtered at each sampling station is recorded and used to calculate MPs abundance (particles/m^3) [15–17]. Sediment samples were collected using an Ekman grab sampler from the surface sediment. Sediment

samples were oven-dried at 60 °C to a constant weight to remove moisture without altering the integrity of Microplastic (MP). The dried samples were then homogenized and sieved (e.g., < 5 mm) to remove large debris. Approximately 50 to 100 g of dry sediment was subjected to density separation using a saturated sodium chloride (NaCl) solution (density ~1.2 g/cm³). The mixture was vigorously stirred and left undisturbed for 24 h to allow for separation of low-density particles. Finally, suspected MPs were visually identified and classified under a stereomicroscope based on their morphological characteristics (e.g. fibres and fragments) [18,19].

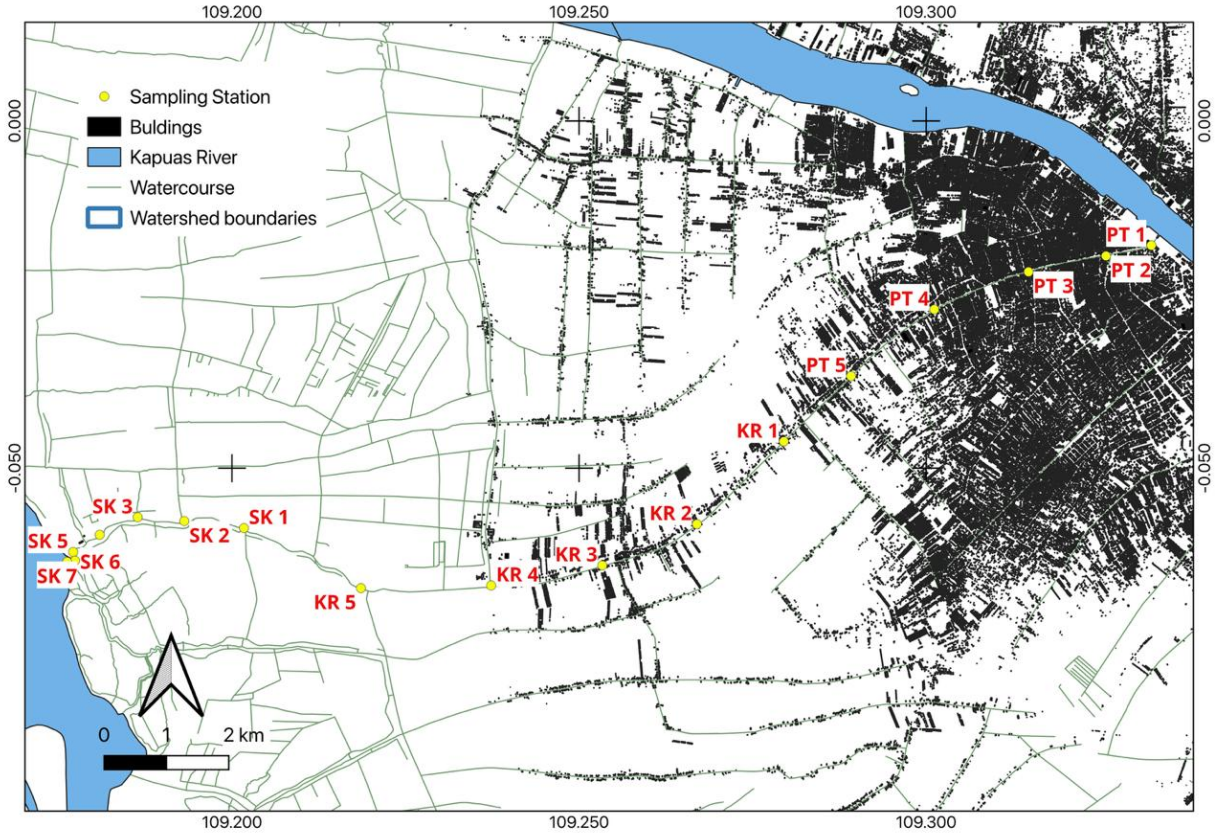


Figure 1. Study area and spatial distribution of sampling stations along the continuum from the Jawi River to the Kakap River estuary, West Kalimantan, Indonesia. This figure presents the research location and 17 sampling points.

All water and sediment samples were analyzed using MPs quantification protocols, with direct observation and abundance calculations based on sample volume or mass. The water sample is filtered through a pre-cleaned plankton net membrane filter, and the appropriate volume of filtrate is recorded for abundance calculation. The sediment samples are dried in the oven to a constant weight and subjected to density separation using a saline solution to isolate the plastic particles from the mineral matrix, followed by oxidative materials to remove residual organic matter [18–21]. Floating fractions of the sediment and water samples are collected into petri dishes and examined under a microscope. MPs particles are visually identified and counted by particle type (fiber, fragments, films, foam, and granules), for abundance-focused analysis [22,23]. Identification was conducted through microscopic observation by assessing morphological characteristics, including shape, color, size, and surface texture, following established visual identification criteria [24,25]. MPs abundance in water samples was calculated as particles per unit volume. At the same time, sediment abundance was expressed as particles per unit dry mass ($A_s = N_s/W$) following widely adopted reporting conventions [15,17,18]. This analysis examined statistically significant differences in the types of MPs observed in the water and sediment, including the dominance of consistently suspended particle types in both environmental matrices [26–28].

Based on their physical characteristics under a stereomicroscope, MPs were classified into five morphological types: fragments, fibers (or filaments), films, foams, and granules. The fragments were described as rigid, irregularly shaped particles with angular or uneven edges, generally resulting from the breakdown of larger

plastic items. Fibers (or filaments) are generally long and threadlike with a high length-to-width ratio. They are usually associated with synthetic textiles, ropes, and fishing gear. Films were defined as thin, flexible particles in sheet form, typically derived from the breakdown of plastic bags, packaging, and other plastic films. The foams were lightweight, porous, and irregularly structured, similar to expanded polystyrene (EPS) or polystyrene. Granules were characterized as relatively rounded or spherical particles with smooth surfaces that could be primary MPs or highly weathered secondary plastic particles. Visual morphological characteristics were used for classification, using previously published identification criteria [29–31].

Data Analysis

The abundance of MPs in the water and sediment samples was examined for spatial and temporal trends among particle types. Particle counts were normalized to the sample volume (particles/m^3) for water and to the sample mass (particles/kg) for sediments. Mean abundance values were determined from duplicate samples at each station and pooled monthly to evaluate temporal variation. All statistical analyses were performed using R software. Descriptive statistics were used to assess distributions of data and variability among the different types of MP. The data did not meet the assumptions of normality and therefore the Kruskal-Wallis test was used to compare MP abundance among particle types in water and sediments, with post hoc pairwise comparisons as appropriate. Boxplots and distribution plots were used to visualise variation patterns.

Principal components analysis (PCA) was performed to investigate the relationships among MPs abundance, water quality parameters and sediment characteristics among sampling stations. For this analysis, the abundance of MP in water and sediment, environmental variables (temperature, pH, dissolved oxygen, salinity, depth), and sediment fractions (coarse sand, fine sand, silt) were incorporated. Prior to the analysis, data for each variable were averaged over the three sampling periods (June, July, and August) to obtain representative values for each station. The dataset was then normalized using Z-score normalization to remove the effect of different measurement units across variables and to make them comparable. The R software's prompt function was used to conduct PCA. The main components obtained from the analysis were used to identify key environmental gradients and their associations with MPs distribution. The first two principal components (PC1 and PC2) were retained for interpretation because they explained the greatest proportion of variance. The biplot was created to visualize the relationship between the variables and the sampling stations. Sampling stations were grouped into three spatial clusters (PT, KR, and SK), and 95% confidence ellipses were overlaid to show their distribution patterns. The variable loadings were analyzed to understand the contribution and direction of each parameter in influencing the distribution of MPs.

Results and Discussion

Results

Distribution

This section presents the abundance of MPs in surface water and sediment samples collected from the Jawi River–Kakap Estuary. The morphological features of the recovered MPs, including particle types, colors, and sizes based on microscopic observations Figure 2. The following figures show the spatial and temporal distribution of MP abundance, highlighting differences among sampling stations along the river-estuary gradient and across sampling months.

These distribution patterns give a detailed overview of MP occurrence in both environmental compartments. In addition, the corresponding tables summarise the statistical differences between stations, sampling periods, and particle types. The figures and tables together provide a complete picture of the spatio-temporal variability in MPs' abundance in the study area. Throughout the study period, the abundance of MP was consistently higher in surface sediments (491–2,807 particles kg−1 dry weight) than in the water column (371–738 particles m^3). Figure 3 presents the spatial and temporal distribution of MPs in both water and surface sediments at the 17 sampling stations along the Jawi River–Kakap Estuary. Sampling stations and months differed in MP abundance and particle composition. Fibers were the most abundant particle type in the water column, with a maximum abundance of 161 particles m^3.

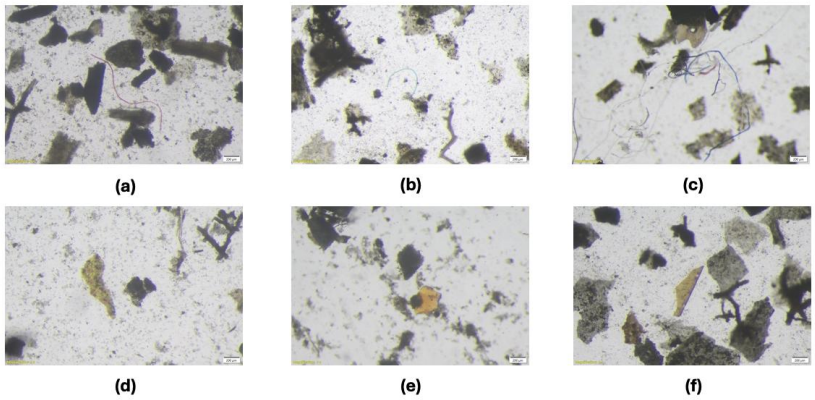


Figure 2. Representative images of MPs morphotype observed in the study: (a–c) fibres and (d–f) fragments collected from water and sediment samples along the Jawi River–Kakap Estuary continuum. The images show the different morphological features used to classify MPs particles, with fibres being long, thread-like structures and fragments being irregular, angular or broken shapes.

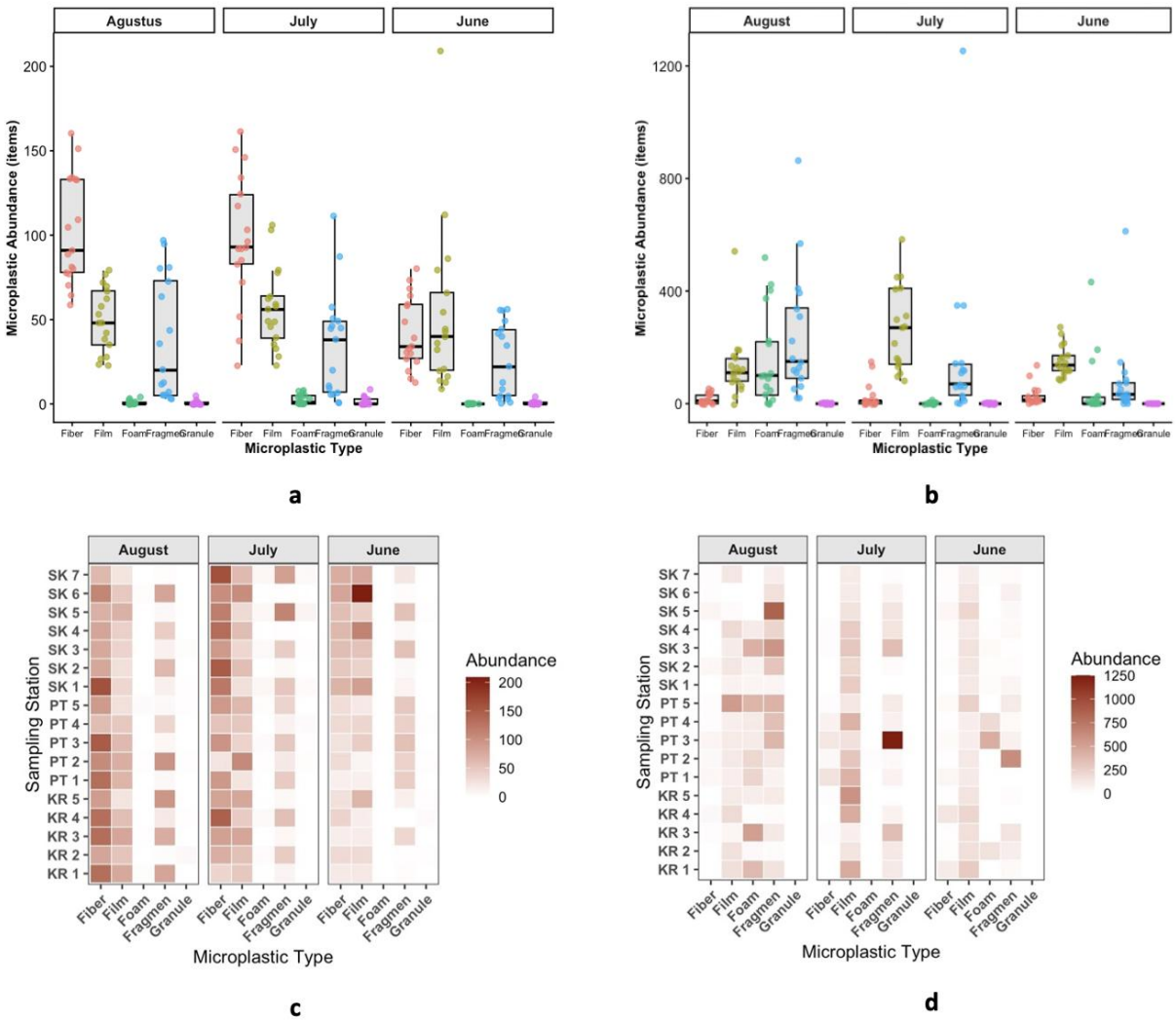


Figure 3. MPs abundance in water (a, c) and sediment (b, d) samples according to MP type across the sampling period in West Kalimantan, Indonesia. Boxplots (a, b) show the distribution of MPs abundance among particle types across sampling months, while heatmaps (c, d) illustrate the spatial distribution of MP abundance across sampling stations and months.

The maximum abundance of fragments (1,250 particles/kg dry weight) in surface sediments indicates higher accumulation in the depositional environment. Fibres dominated the water column and were present during the entire sampling period. The next most abundant particle type was films, and this type showed moderate variability across the stations. Conversely, fragments were recorded in the water column in relatively low abundances. Foam and granule particles were only sporadically detected and had a low contribution to the total MP abundance. The composition of the surface sediments was clearly different. The most abundant particle type was fragments, which exhibited much larger spatial variation than other particle types. Most notably, abundance was concentrated across multiple stations, especially during July and August, indicating localized accumulation in depositional settings. Film particles were widely distributed in the sediments and often in higher amounts than fibers, which were more limited in the sediments than in the water column. Foam particles exhibited sporadic peaks at certain stations in certain months, but varied in magnitude, while granules were present in small quantities throughout the study period.

Figure 3 shows the temporal patterns and compositions of MPs abundance over the sampling period and among particle types. It is seen that the fibres are most abundant and dominate the water column. Films are moderately abundant with high variability among stations, especially in the middle and later parts of the sampling period. This means that the sources of these particles are not uniform everywhere. Interestingly, foam particles are still present at low levels every month, so no large numbers of foam particles are generally present. The distribution and the mean number of MPs of fragment type increase significantly in the course of months with the maximum in July.

Granules, in contrast, were less frequently observed and had different structural characteristics than other particle types. The observed differences among these MP types were statistically validated using the Kruskal-Wallis test, indicating significant differences in abundance across particle categories. The test results showed large differences in MP abundance among particle types during the sampling months (Table 1). In June ($H = 51.3$; $df = 4$; $p < 0.001$), July ($H = 63.1$; $df = 4$; $p < 0.001$) and August ($H = 50.8$; $df = 4$; $p < 0.001$) significant differences were observed. These results indicate that the types of MP were not uniformly distributed over the study period, with some types present in much greater quantities than others.

Table 1. Kruskal–Wallis test results for differences in MPs abundance among particle types during the sampling period. H = Kruskal–Wallis test statistic; df = degrees of freedom; p-value < 0.05 indicates a statistically significant difference in MP abundance among particle types.

Medium	Sampling month	H Statistic (χ^2)	df	p-value	Interpretation
Sediment	June	51.3	4	< 0.001	Significant
	July	63.1	4	< 0.001	Significant
	August	50.8	4	< 0.001	Significant
Water	June	62.5	4	< 0.001	Significant
	July	64.4	4	< 0.001	Significant
	August	69.5	4	< 0.001	Significant

The spatial patterns of total MP abundance differed between the sediment and water samples (Table 2). No significant differences were found between the PT, KR, and SK station groups in sediment samples in June ($H = 5.07$, $p = 0.079$), July ($H = 3.47$, $p = 0.176$), or August ($H = 1.00$, $p = 0.605$). For water samples, however, there was significant spatial variation in June ($H = 10.90$, $p = 0.004$) and July ($H = 7.05$, $p = 0.030$), but not in August ($H = 2.49$, $p = 0.288$). Our results suggest that the spatial variability of total MP abundance was more pronounced in the water column than in surface sediments during the study period.

Table 2. Results of the Kruskal–Wallis test comparing total MPs abundance among station groups (PT, KR, and SK) in water and sediment samples. H = Kruskal–Wallis test statistic; df = degrees of freedom; p-value < 0.05 indicates a statistically significant difference in MP abundance among particle types.

Medium	Sampling month	H Statistic (χ^2)	df	p-value	Interpretation
Sediment	June	5.07	2	0.079	Not significant
	July	3.47	2	0.176	Not significant
	August	1	2	0.605	Not significant
Water	June	10.9	2	0.004	Significant
	July	7.05	2	0.03	Significant
	August	2.49	2	0.288	Not significant

The abundance of sediment MPs significantly differed among particle types and sampling months. The distribution of fibers and films showed a high degree of spatial heterogeneity within the sediment matrix. The distribution was consistently high, but highly variable among stations. The distribution of fragment-type particles was much wider and increased clearly in the following months, indicating a trend of accumulation over time. Importantly, the foam particles were not evenly distributed in the sediment, especially during the mid-sampling period, with episodic peaks, extreme values, and high variability. Conversely, granule-type particles were tightly clustered, with small monthly abundances, indicating consistently low abundances and little spatial variation. Differences in abundance were observed between the two sample types: fibers were more abundant in water and dominated each month, whereas fragment abundance was high in sediment throughout the observation period. Differences in MP types and environmental characteristics were reflected in corresponding differences in abundance. This is a good point to discuss further, as we have seen a difference in MP abundance between the two samples.

The observed spatial patterns have to be considered in relation to the longitudinal river-estuary gradient represented by the three station groups. The PT stations are located in the upstream part of the river, where there is a high density of settlements; the KR stations are located in the intermediate reaches, where the intensity of settlements is lower; the SK stations are located in the estuarine zone, where the activities of fish-landing ports are present. During the sampling period, the abundance of sediment MPs did not differ significantly among these station groups. Significant spatial differences of water samples were observed in June and July, indicating that the distribution of MPs in the water column was different along the river-estuary continuum in these two months.

Color Composition

The spatial-temporal distribution of MPs' colours in the water and sediment samples collected during the study period is presented in Figure 4. Overall, transparent MPs were the most abundant in both environmental matrices in all the sampling months. Their prevalence was notably higher in the water column, whereas sediment samples showed a wider color range. This suggests that sediments had a wider diversity of colored MPs, whereas transparent particles were the most common in the water. The variation in color composition between water and sediment highlights the distinct distribution patterns of MPs in each environment. It provides a foundation for further exploration of transport, weathering, and deposition processes.

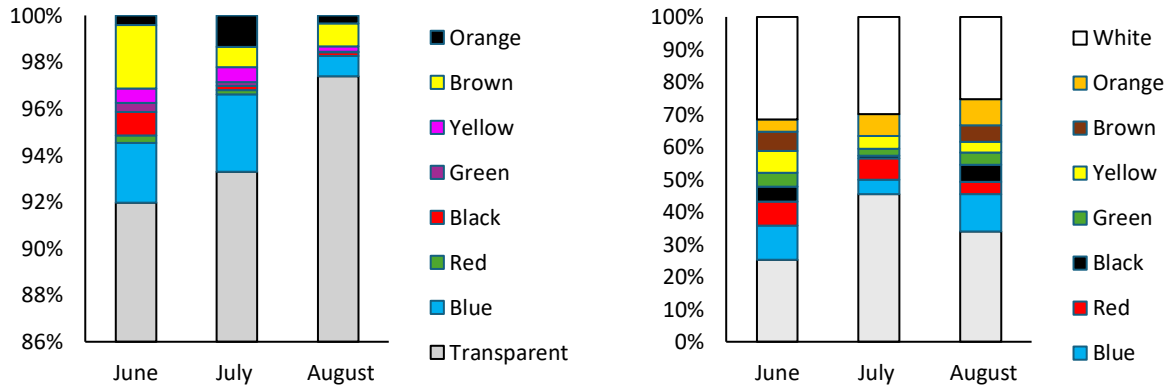


Figure 4. Color composition of MPs in water (a) and sediment (b) samples according to particle type across the sampling period. The figure illustrates the distribution of MP colors across particle types, highlighting differences in color composition between water and sediment samples. Transparent, black, blue, and other colors represent the observed visual characteristics of the MP particles.

Spatial Distribution

This abundance of MPs in surface water can be seen in Figures 5 and 6 and is evident at all sampled stations. In particular, PT station has a fairly uniform pattern. However, the spatial heterogeneity of the KR station is marked by a sharp decline at the first site and an increase at the following sites. Another very notable pattern is observed at the SK station, which has a dramatic spike compared to the other locations. This large increase indicates a clear spatial gradient in the data, with higher MP abundances being detected at stations closer to the estuary.

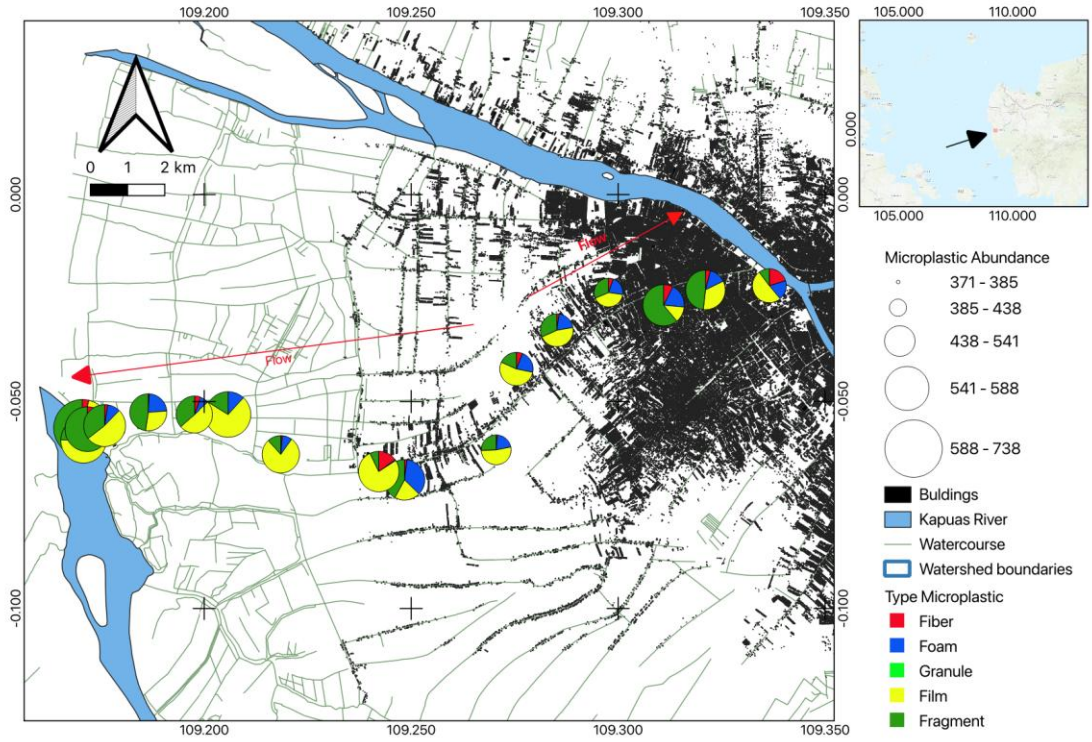


Figure 5. Spatial distribution of micro-abundance in the water across sampling locations, sampling stations along the Jawi River–Kakap Estuary, West Kalimantan, Indonesia, during June–August 2025. The figure also shows the differences in MPs composition and abundance at each station.

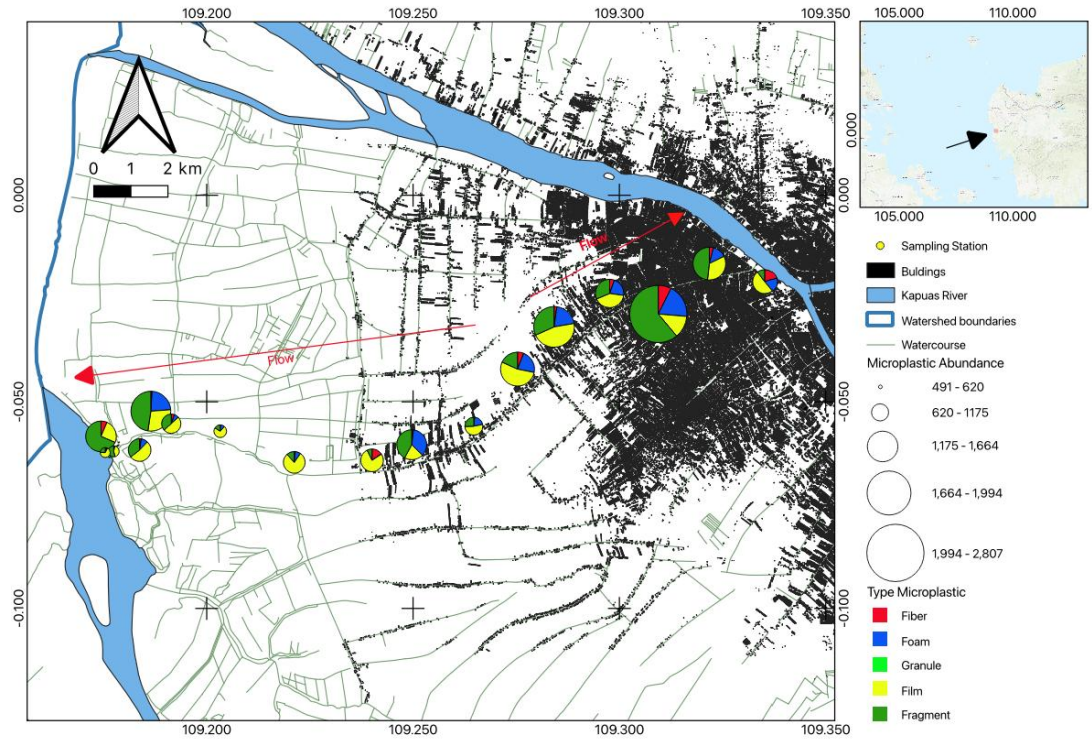
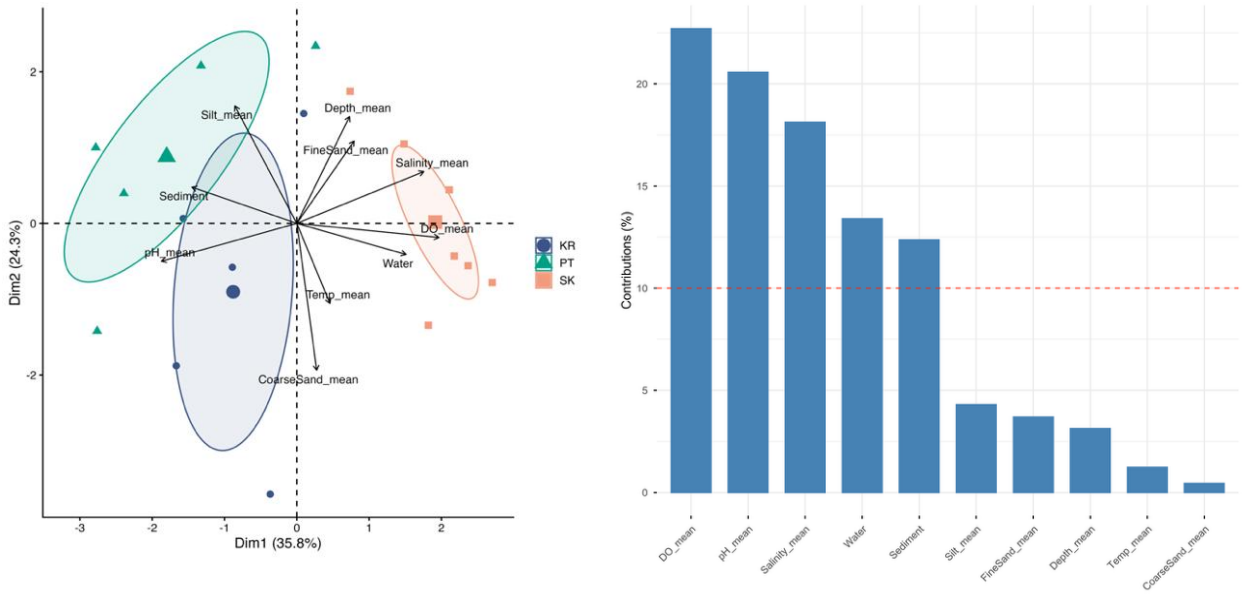


Figure 6. Spatial distribution of micro-abundance in the sediment across sampling locations, sampling stations along the Jawi River–Kakap Estuary, West Kalimantan, Indonesia, during June–August 2025. The figure also shows the differences in MPs composition and abundance at each station.

Principal Component Analysis (PCA)

The PCA results showed that the first principal component (PC1) explained 35.8% of the total variance and the second component (PC2) explained 24.3%, together accounting for 60.1% of the total variance. Thus, the two major axes accounted for the major environmental gradients associated with the distribution of MPs (Figure 7). The ordination plot showed a clear spatial separation of the three station groups (PT, KR, and SK). Stations in the SK group were on the positive side of PC1 and were associated with MPs in the water, dissolved oxygen (DO), salinity, and depth. The pattern indicates a close relationship between the distribution of MPs in the water and water quality and hydrodynamic conditions.

Conversely, PT stations were positioned on the negative side of PC1. They showed good correlations with sediment MPs and the silt fraction, indicating the potential of fine-grained sediments to favor the retention and accumulation of MPs. This pattern demonstrates that depositional environments may be sinks for MPs. The KR stations were intermediate and mostly associated with coarse sand and temperature, which represent relatively high-energy conditions and may limit MP accumulation in sediments via resuspension and transport. The vectors' directions and lengths suggested a positive relationship between the silt fraction and the sediment MPs, whereas the coarse sand showed a negative relationship. These patterns have further consolidated the role of sediment texture as an important factor controlling MP distribution. MPs in water were also related to DO and salinity, suggesting that mixing processes and environmental gradients are also involved in their distribution.



(a) (b)

Figure 7. PCA of microplastic abundance, water quality, and sediment (a) characteristics across sampling stations in the Jawi River–Kakap Estuary, West Kalimantan, Indonesia. The biplot shows the relationships between sampling groups (KR, PT, and SK) and environmental variables, while the bar plot presents the percentage contribution of variables to Dim1 (b). The first two principal components explained 60.1% of the total variance (Dim1 = 35.8%; Dim2 = 24.3%).

Discussion

This study reveals the difference in the distribution of MPs between water and sediment in the Jawi River-Kakap Estuary system. Sediments always had higher MP concentrations than surface water, suggesting that they could act as an accumulation compartment in this river–estuary system. The composition of MPs also differed between the two environments: fibers were more abundant in the water column, while the fragments dominated in the sediment. Further analysis indicated that MPs in the water column were associated with DO and salinity while MPs in sediment were associated with finer grain sizes. To summarise, these findings provide evidence that the distribution and behaviour of MPs in this tropical river-estuarine system are influenced by particle physical properties and the environmental conditions of the surrounding habitat.

Sediments appear to be a significant sink for MPs, especially for particles of higher density or those with biofouled surfaces, as evidenced by the greater abundance of MPs in sediments than in water. This is in agreement with previous studies that found that fine-grained sediments are more likely to retain MPs due to the lower-energy environment and the larger surface area of fine sediments that can act as trapping sites for MPs. In addition, the high correlation between MPs and silt fractions confirms the importance of the sediment texture in the accumulation process. Fiber MPs consistently dominated the water and sediment compartments throughout the sampling month, indicating a combination of sustainable anthropogenic inputs and typical particle transport characteristics along the river–estuary continuum [6,32,33]. The dominance of this fiber fraction is mainly related to continuous emissions from domestic wastewater, textile-related activities, and widespread atmospheric deposition, which collectively supply filament-like MPs to fluvial systems in high and relatively constant quantities [6,32,33].

The filament morphology and high aspect ratio of the fibers provide hydrodynamic benefits that allow these particles of standard size to be kept in suspension, transported downstream more efficiently, and achieve a vertical distribution within the water column. Such conditions promote continuous exchanges between the suspended and benthic phases through processes including aggregation with fine sediments, biofouling, and resuspension, especially in estuarine turbidity zones, where hydrodynamic activity is strong. The observed accumulation of fibers in surface sediments in this study is consistent with previous studies. It implies that cohesive substrates in estuaries and other sedimentary environments are effective long-term accumulators of filamentary MPs. The presence of the identified fibers is consistent with well-established theoretical models and empirical studies that show their high environmental persistence and the need to consider chronic exposure to MPs in riverine and estuarine environments.

Fragmented MPs exhibited different temporal dynamics in sediments than in waters, with gradual increases and higher spatial variability in sediments. This trend results from cumulative retention and local reworking. This pattern is mainly attributed to the in-situ fragmentation of larger plastic debris by ultraviolet radiation, mechanical abrasion, and biofilm-mediated decay on the surfaces of riverbeds, riverbanks, and estuaries. As a result, the deposition environment continuously generates new fragments [34,35]. Once created, fragments tend to deposit faster and travel shorter distances than fiber-shaped MPs, increasing the likelihood of settling in low energy zones, fine sediments and areas of flow convergence throughout the river-estuary continuum. Repeated resuspension and redeposition processes favour the vertical integration of fragments in the sediment.

In contrast, biophysical flocculation with cohesive sediments and organic matter improves deposition and accumulation efficiency at the local scale[27,36,37]. The combination of these mechanisms results in an increasingly patchy distribution of fragments in sediments over time, consistent with field observations in various river and estuary systems that show an increase in fragment load in calm-water habitats or in fine sediments, even though water concentrations fluctuate [28,38,39]. In contrast, water experiences more intense vertical flushing and mixing due to hydrological influences, thereby limiting long-term storage and reducing the formation of spatial gradients. This ultimately results in weaker temporal amplification and lower fragment heterogeneity compared to sediments [28,38,39]

As a result, sediments recorded local, short-lived accumulation peaks, consistent with previous findings that identified foam MPs as indicators of responsiveness to extreme events rather than as persistent fractions in sedimentation environments [40]. In contrast, granular MPs consistently account for only a small fraction and show limited variation in both the water and sediments. This low contribution reflects the limited resources as well as the transport behavior of grains that closely resemble natural sand particles [41,42]. The almost spherical shape and relatively high deposition speed cause the grain to move quickly as the base load, with a short dwell time in the suspended phase. At the same time, ongoing burial and manipulation within dynamic sediment layers limit the episodic enrichment or significant accumulation of materials under varying hydrodynamic conditions. As a result, the stability and restricted presence of the detected granular MPs align with the sediment analogy framework, which views their movement and retention mainly as functions of grain size and flow energy. The statistically significant differences in the types of MPs identified, as revealed by the Kruskal-Wallis test, are reflected in their environmental behavior. This variation is mainly related to particle shape, contrast, density, and size, which together control the particle's ability to remain suspended, the transport distance, and the retention rate in the sediment across the various compartments. MPs dominated by fibers are more prevalent in the water, consistent with high aspect ratios, large resistance forces, and low effective deposition rates, allowing these particles to remain in suspension longer and be transported downstream under various discharge conditions conditions [6,26,33].

In contrast, fragment and film MPs accumulate more in sediments. This suggests that they have relatively short transport distances and are more effectively captured through higher deposition rates. Factors contributing to this include their tendency to cluster with fine particles and their selective retention in low-energy deposition areas along river-estuary gradients [27,36,37]. This type-dependent behavior results in a convergent distribution pattern, characterized by increased concentrations of MPs in both the water and sediments downstream, in response to the accumulation of anthropogenic inputs and hydrodynamic convergence around the estuary transition zone [6,43,44]. Nevertheless, the opposite pattern also emerges, particularly in sediments, where MPs loads form patchy hotspots that are not always aligned with the concentration in the overlying water. These conditions indicate strong local controls, including base shear stress, sediment grain characteristics, biofouling processes, and cycles of episodic resuspension and deposition. These factors selectively retain denser or irregularly shaped particles close to the bottom of the water [28,38,39]. This contrast indicates that suspended MPs and sediment-associated MPs capture different temporal and spatial signals of fluvial and estuarine dynamics, rather than responding uniformly to hydrological constraints.

Based on various studies conducted worldwide and in Indonesia, MPs have been widely detected in both river waters and sediments, with highly variable concentrations. In general, the abundance of MPs in sediments is higher than in the water because sediments act as long-term accumulation sites or reservoirs for MPs. A study of the Elbe River in Germany reported an abundance of MPs in the water of approximately 5.57 particles/m^3. In contrast, in sediments it reached 3.35×10^6 particles/m^3, indicating that sediments can contain MPs concentrations far higher than those found in the water [27]. Studies in several other rivers show similar patterns. In the St. Lawrence River, Canada, MPs abundance in the water ranged from 0.006 to 0.02 particles/L, while sediment concentrations ranged from 52 to 1,900 particles/kg [34]. Meanwhile, in the Milwaukee River system extending to Lake Michigan, the abundance of MPs in the water was relatively low, ranging from 0.02 to 0.08 particles/L, whereas sediment concentrations could reach 500–2,800 particles/kg [35]. These differences indicate that MPs tend to undergo deposition processes influenced by polymer density, particle size, and hydrodynamic conditions in the aquatic environment.

In Indonesia, MPs have also been found in many rivers, with concentrations that vary with the level of surrounding human activity. A study of the Tallo River in Makassar reported MP abundance in the water ranging from 0.74 to 3.41 items/m^3 and in sediment ranging from 16.7 to 150 items/kg [45]. These values are relatively lower than those of rivers in highly urbanized areas. For example, the Ciliwung River in Jakarta shows significantly higher MPs abundance, with concentrations of approximately 320–741 particles/L in the water and 6,560–10,630 particles/kg in sediments, which are closely related to high population density and domestic and industrial activities along the river [46].

Another study conducted in the Opak River, Yogyakarta, reported MPs abundance ranging from 4.15 to 12.3 particles/L in the water and from 960 to 3,080 particles/kg in sediments [47]. This finding indicates that even in areas with mixed rural and urban characteristics, MPs are still present across all sampling locations. In addition, research on sediments in the Progo River reported MPs abundance ranging from 209 to 1,173 particles/kg, with a tendency to increase from upstream to downstream areas [48]. This pattern suggests that MPs tend to accumulate in downstream sections of rivers due to the concentration of pollution sources and reduced water flow velocity.

The significant spatial differences in total MPs abundance observed in the water column during June and July, together with the absence of significant differences in surface sediments, indicated that MPs responded differently to environmental processes across the PT–KR–SK river–estuary continuum. Water samples exhibited more pronounced spatial variability because suspended MPs responded rapidly to changes in local inputs and hydrodynamic conditions. In contrast, surface sediments reflected the cumulative deposition of particles over longer periods. Consequently, the abundance of sediment MPs remained relatively similar among station groups despite differences detected in the water column.

This pattern agreed with previous studies reporting that MPs in river and estuarine waters exhibited greater spatial and temporal variability than those retained in surface sediments, which tended to integrate deposition and therefore displayed more stable spatial patterns [26,49,50]. The longitudinal classification of the study area into PT (upstream), KR (middle reach), and SK (estuarine zone) likely reflects distinct sources and transport conditions that drive the distribution of suspended MPs. In the upper reaches, residential activity was linked to the middle reaches, which served as transitional transport areas. Tidal mixing and port activities at estuarine locations may influence particle transport and redistribution. Similar trends were observed in river-estuarine systems, where changes in water-column MPs were associated with changes in

human inputs and hydrodynamic transport. In contrast, the distribution of sediment was more significantly influenced by depositional processes and sediment retention [50–52]. These findings suggested that water samples were more sensitive indicators of short-term spatial variation in MPs pollution. In contrast, sediment samples better represented the integrated accumulation of MPs within the river–estuary continuum. These results highlighted that the water column captured spatial differences in MP contamination more effectively than surface sediments across the Jawi River–Kakap estuarine continuum, reflecting the greater responsiveness of suspended MPs to local environmental conditions.

Conclusions

The Jawi River-Kakap Estuary exhibited a distinct compartment-dependent distribution of MPs, with significantly higher quantities found in sediment (491–2,807 particles/kg) compared to water (371–738 particles/m^3). The high abundance of fibres in the water and fragments in the sediments indicates a clear decoupling of transport and accumulation pathways, with low-density particles remaining in suspension and being transported downstream and higher density particles accumulating in fine-grained substrates. This pattern is further supported by multivariate analysis (PCA) which reveals sediment-associated MPs are tightly correlated to silt fractions while waterborne MPs are controlled by gradients in dissolved oxygen and salinity, emphasising the role of hydrodynamics in controlling their distribution. The spatial clustering suggests that MPs variability across the continuum is controlled by anthropogenic inputs and estuarine processes. These results indicate that suspended MPs are more sensitive to local environmental conditions, so that the water column better reflected the spatial variability of MP pollution along the Jawi River–Kakap estuarine continuum than surface sediments.

Author Contributions

GTP: Conceptualization, Methodology, Software, Investigation, Writing, Review, Editing; **AMSM**: Writing – Review, Editing, Supervision; **BK**: Writing, Review, Editing; and **PBU**: Writing, Review, Editing.

AI Writing Statement

During the preparation of this work, the authors used Grammarly to paraphrase and proofread the sentences. After using this service, they must take full responsibility for the publication's content.

Conflicts of Interest

The authors declare no conflicts of interest.

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