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Microplastics in tropical coastal and river sediments in a non-industrial urban area: Correlations with land use and potential sources

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ABSTRACT

This study investigated the complex relationships among environmental factors in coastal settings and identified potential sources of microplastics in tropical coastal and river sediments within a non-industrial urban area. The research was conducted along the northern coast of Aceh, Indonesia, encompassing two river estuaries: the Krueng Aceh and Krueng Lamnyong. The results indicate that land use, population density, and distance from the river estuary influence the distribution of microplastics in coastal sediments. The Krueng Aceh River, which is associated with a higher population density, exhibited greater levels of microplastic contamination than the Krueng Lamnyong River. The formation of estuarine turbidity maxima (ETM) is considered a key factor controlling microplastic distribution along the Krueng Aceh River, whereas distribution patterns in the Krueng Lamnyong River appear to be more strongly influenced by local anthropogenic activities and environmental conditions. The study area is distinctive because, despite the absence of major industrial sources, identifying microplastic origins remains complex. In coastal zones, tourist sites tend to exhibit lower microplastic abundances, likely due to stricter waste management practices, whereas non-tourist areas show higher levels of contamination. This study provides new insights into the distribution and potential sources of microplastics in tropical non-industrial urban environments and offers a foundation for developing more effective mitigation strategies for microplastic pollution.

1. Introduction

In 2019, approximately 368 million metric tons of plastic were produced globally, with nearly half of

this amount generated in Asia. Projections suggest that by 2050, cumulative plastic waste could reach 12 billion metric tons [1], highlighting a rapid escalation of the global plastic pollution crisis.

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As global plastic production continues to increase, microplastics—plastic particles smaller than 5 mm—have emerged as a major threat to marine environments worldwide.

These particles originate both from the fragmentation of larger plastic debris (secondary microplastics) and from primary sources such as industrial pellets, synthetic fibers, and microbeads, used in consumer and industrial products. Microplastics can adversely affect marine ecosystems and may enter the human food chain, posing potential health risks that remain insufficiently understood [2, 3]. Recent studies indicate that the distribution and accumulation of microplastics in marine environments are strongly influenced by environmental factors such as climate, land use, and pollution sources [4, 5].

Numerous studies have documented the widespread occurrence of microplastics across diverse marine environments. Huang et al. [6] and Gurumoorthi and Luis [7] reported the presence of microplastics in global ocean systems, including polar regions. Li et al. [8] demonstrated that ocean currents play a major role in transporting microplastics and influencing their ecological impacts. Other studies estimate that substantial quantities of plastic enter the oceans annually, with the majority originating from densely populated and industrialized coastal urban areas [9, 10].

Environmental conditions also play a critical role in shaping microplastic distribution. Akyildiz et al. [11] reported higher microplastic abundances in areas characterized by intense human activity. Bao et al. [12] mapped global microplastic transport pathways, demonstrating the capacity of plastics to disperse widely from multiple sources. Hee et al. [13] further showed that tropical rivers contribute significantly to marine plastic pollution, emphasizing the importance of fluvial transport processes.

Tropical climates strongly influence hydrological processes that mobilize microplastics from land to coastal waters. Previous studies have shown that high rainfall, intense surface runoff, and strong river discharge accelerate the transport of plastic particles from terrestrial sources—including settlements, agriculture, and industry—into river systems and eventually into coastal zones [14–16].

In addition, elevated temperatures in tropical regions can accelerate plastic degradation, promoting fragmentation into smaller microplastic particles. Under these conditions, tropical environments act as catalysts for both the transport and transformation of plastic debris.

Tropical coastal zones are also characterized by high population densities and concentrated human activities [13, 15]. Rivers in tropical regions have been identified as major pathways for plastic transport to the ocean [17], and heavily industrialized tropical urban areas often become hotspots of microplastic accumulation due to large inputs of both primary and secondary plastics [17, 18]. These factors, combined with hydrodynamic conditions and local oceanographic processes, contribute to complex spatial patterns of microplastic accumulation in tropical coastal sediments.

Despite growing attention to microplastic pollution, most existing studies have focused on heavily industrialized riverine and coastal systems (e.g., Xu et al. [4]; Ronda et al. [19]; Wootton et al. [20]; Erkan et al. [21]). In contrast, microplastic dynamics in non-industrial tropical urban catchments remain comparatively understudied. Such environments are typically characterized by rapid population growth, mixed land use, and limited waste-management infrastructure, yet lack major industrial inputs. Consequently, the pathways and retention mechanisms controlling microplastic accumulation may differ substantially from those in industrialized systems. In tropical regions, high rainfall, strong runoff, and estuarine mixing processes may enhance both the mobilization and trapping of particulate pollutants. Hydrodynamic processes such as estuarine turbidity maxima (ETM), together with land use and population density, are therefore expected to play key roles in controlling microplastic distribution.

Previous sedimentological and environmental magnetic studies in the Krueng Aceh estuary have reported elevated suspended sediment loads, turbidity anomalies, and contaminant accumulation patterns consistent with particle-retention processes in estuarine transition zones [22, 23]. These findings provide indirect evidence of hydrodynamic convergence and sediment trapping

within the estuary, processes that may also influence microplastic accumulation.

In the present study, ETM-related retention is interpreted as a plausible mechanism consistent with observed spatial distribution patterns rather than a directly measured process. Direct measurements of turbidity, suspended sediment concentration, salinity gradients, or tidal phase were not conducted; therefore, hydrodynamic interpretations are made cautiously and in reference to previously documented estuarine behavior in the same system.

This study investigates microplastic abundance and composition in river and coastal sediments along the northern coast of Aceh, Indonesia, representing a non-industrial tropical urban setting. The study examined how land use, population density, and distance from river mouths interact with estuarine processes to influence spatial patterns of microplastic accumulation.

Beyond providing baseline regional data, this study proposes a process-oriented interpretation linking land-use-derived inputs, population density, and estuarine retention processes in a non-industrial tropical system. By integrating spatial analysis, statistical correlation, and previously documented hydrodynamic characteristics, this work offers a conceptual framework for understanding microplastic transport and retention in rapidly urbanizing tropical catchments lacking major industrial sources.

This integrative approach extends current understanding of microplastic distribution beyond heavily industrialized systems and highlights the importance of interactions between hydrodynamic and anthropogenic factors in shaping microplastic accumulation in tropical coastal environments.

2. Materials and methods

2.1. Location and samples

Sampling was conducted at multiple coastal and riverine locations along the northern coast of Aceh, Indonesia, in June 2023. The study area includes coastal zones within Banda Aceh City and Aceh Besar Regency, which represent non-industrial urban environments with relatively high population densities. Banda Aceh, the provincial capital, has an estimated population of 260,000–280,000, and

a population density of approximately 5,000 inhabitants km^{-2} . Aceh Besar Regency, which encompasses a broader coastal area, has a population of approximately 400,000 with an average density of ~ 300 inhabitants km^{-2} . However, population density in the coastal urban sectors of Aceh Besar could be considerably higher, particularly in areas adjacent to Banda Aceh, indicating strong population concentrations around major economic and administrative centers.

A total of 13 coastal stations (39 sampling points) were established along the shoreline, including four tourist sites. Additional sediment samples were collected from the Krueng Aceh and Krueng Lamnyong rivers, both of which discharge into the northern coast of Aceh. The population density within the buffer zone of the Krueng Aceh River is substantially higher than that of the Krueng Lamnyong River. Fifteen sampling points were established along the Krueng Aceh River and twelve along the Krueng Lamnyong River. All sampling locations are shown in Figure 1 and in Supplementary Figure S1.

Surface sediment samples were collected using a sediment corer in river and beach environments, and a Van Veen grab sampler in estuarine areas. Samples were taken from the upper 0–5 cm of the sediment layer. Sampling was conducted during low tide between 12:00 and 15:00 local time to maintain consistency across sites. Weather conditions were recorded during fieldwork to minimize potential external influences on sampling conditions.

For river and estuarine sites, samples were collected by boat. At each sampling station, a minimum of five subsamples were collected and homogenized to produce one composite sample for subsequent analysis.

2.2. Magnetic characterization of river sediments

Magnetic susceptibility measurements were performed on a subset of river sediment samples collected from the Krueng Aceh (KA stations) and Krueng Lamnyong (KL stations) to provide qualitative information on sediment properties along the river–estuary continuum. After air-drying and homogenization, low-field magnetic susceptibility was measured using a Bartington

MS2B sensor at low frequency (χ_{LF} , 0.465 kHz) and high frequency (χ_{HF} , 4.65 kHz).

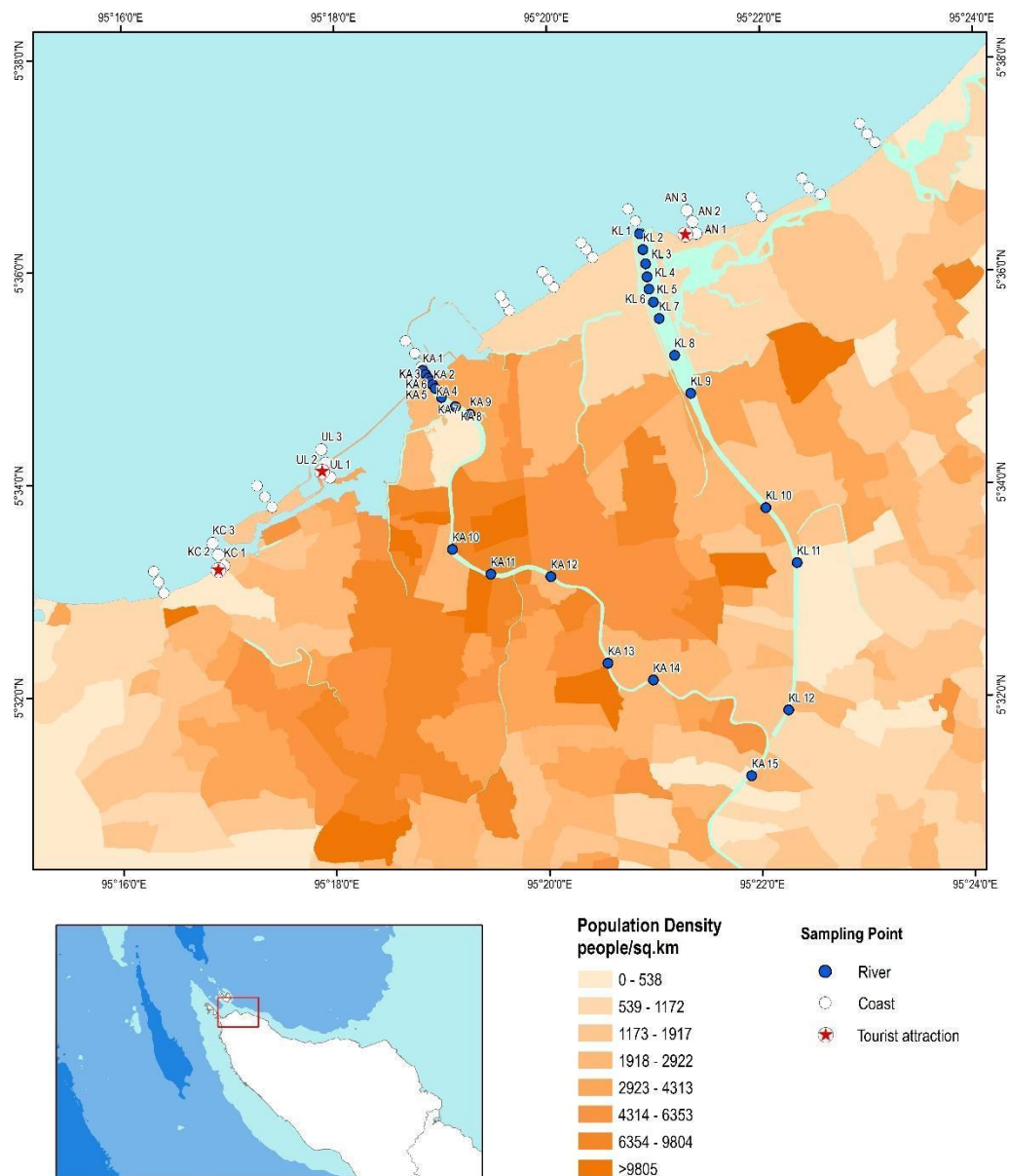


Fig. 1. Sampling locations along the northern coast of Aceh, including coastal, riverine, and tourist-site stations. Different symbols indicate sampling points from each environment.

Mass-specific susceptibility was calculated by normalizing instrument readings to the dry mass of each sample. Frequency-dependent susceptibility (χ_{FD}) was calculated as $((\chi_{LF} - \chi_{HF}) / \chi_{LF}) \times 100$ and used as a qualitative indicator of fine magnetic grain enrichment [22]. The use of magnetic parameters in this study is based on previous findings showing that frequency-dependent susceptibility (χ_{FD}) is closely associated with fine-

grained sediment fractions and depositional conditions in tropical river-estuary systems. In such environments, χ_{FD} has been applied as a qualitative proxy for identifying zones of enhanced fine-particle accumulation, which may be related to the formation of estuarine turbidity maxima (ETM) [22, 23]. In the present study, magnetic measurements were conducted only on river sediment samples and are used as supporting

environmental proxies to aid the interpretation of sedimentary conditions that may influence microplastic retention. These measurements are not intended as a quantitative grain-size analysis but rather as contextual indicators of fine-particle enrichment along the river–estuary system.

2.3. Water parameter measurements

Water samples were collected exclusively at river sampling stations along the Krueng Aceh and Krueng Lamnyong rivers using a horizontal grab sampler (TESS Technologies Ltd., Indonesia). Turbidity was measured *in situ* using a portable turbidity meter (Amtast AMT21) in accordance with Indonesian National Standard (SNI) procedures. Total suspended solids (TSS) were determined using standard gravimetric methods following established protocols [24]. Salinity was measured *in situ* at each river station using a handheld conductivity–salinity meter (Horiba, Japan), which is widely used for rapid assessment of freshwater–seawater mixing conditions. These parameters were measured to provide supporting information on suspended particulate matter and mixing conditions in the river system and to assist in the interpretation of sediment and microplastic distribution along the river–estuary continuum.

2.4. Microplastic identification

After collection, sediment samples were oven-dried at 60 °C until completely dry and, subsequently, sieved through a 5 mm mesh to remove large debris. Microplastics were separated from the sediment using a high-density saturated sodium chloride (NaCl) solution, allowing low-density particles to float and be collected for further analysis. This density-separation procedure follows widely applied protocols for extracting microplastics from sediments [25]. The supernatant containing suspected microplastics was then filtered through Whatman filter paper with a pore size of 0.45 µm.

No chemical or enzymatic digestion was applied prior to density separation; therefore, some particles may have retained residual organic matter or biofilms. To minimize potential misidentification, samples were thoroughly oven-dried before separation, and conservative visual criteria were applied during particle identification.

Particles retained on the filter papers were examined using a binocular microscope (Olympus CX23LED) and classified according to shape and morphology. Identification followed established visual criteria, including homogeneous structure, absence of cellular or biological features, and consistent color and thickness [25].

Fourier-transform infrared spectroscopy (FTIR; PerkinElmer) was used on a subset of larger particles to confirm polymer composition, following the approach described by Hossain et al. [26]. FTIR analyses were conducted on representative particles selected from each morphological category (fibers, films, and fragments) and from multiple sampling locations. Approximately 15–20% of visually identified particles were analyzed using FTIR, with the proportion varying slightly among sites and particle types to ensure representative coverage. Larger and morphologically intact particles were prioritized, as very small particles often produce weak or noisy spectra that are difficult to interpret reliably. This strategy follows common practice in sediment microplastic studies, where spectroscopic confirmation is applied to representative particles to validate visual identification while maintaining analytical feasibility [25].

The primary purpose of the FTIR analysis in this study was to confirm polymer types and reduce the likelihood of false positives in visual classification rather than to analyze every isolated particle. Because the same identification protocol was applied consistently across all samples, spatial comparisons of microplastic abundance are considered internally consistent.

2.5. Quality Control

To ensure the reliability and accuracy of the results, a series of quality control (QC) procedures was implemented from field sampling through laboratory analysis. Sampling equipment, including sediment corers and grab samplers, was inspected and thoroughly cleaned prior to use to minimize the risk of cross-contamination. Field operators followed standardized procedures based on written protocols. Samples were collected using clean gloves and sterile tools and were stored in tightly sealed, clearly labeled containers.

In the laboratory, additional precautions were taken to prevent contamination during sample processing. Procedural blanks were included during drying, filtration, and density-separation steps to monitor potential contamination. All reagents, including NaCl solutions, were checked for purity prior to use. Each sample was analyzed in duplicate to reduce measurement uncertainty, and any substantially divergent results were reexamined. Microplastic particles were identified and counted under a stereomicroscope and independently verified by two analysts. A subset of larger particles was further analyzed using FTIR to confirm polymer composition.

Microplastic abundance data were statistically screened to identify potential anomalies or outliers, and questionable results were reviewed and reanalyzed where necessary. All field and laboratory procedures were documented in detail using laboratory notebooks and digital records, including sampling conditions, equipment used, and analytical results.

2.6. Analysis of data

Spearman rank correlation analysis was used to evaluate relationships between microplastic abundance and environmental variables, including distance from river mouths, population density, and land-use composition. Spearman's correlation coefficient (r) was calculated for each variable pair, with values ranging from -1 to 1 . Values approaching 1 indicate a strong positive correlation, values approaching -1 indicate a strong negative correlation, and values near 0 indicate little to no correlation. Statistical significance was assessed using p -values, with $p < 0.05$ considered statistically significant. Correlation results are presented as a correlation matrix and interpreted to examine relationships between microplastic abundance and the tested environmental factors [27].

Distances between sampling points and river mouths were measured using geographic information system (GIS) software to ensure spatial accuracy. Microplastic abundance data from river sediments were analyzed by distinguishing estuarine sections from upstream sections less influenced by tidal dynamics, and distances from river mouths were calculated for each station.

To evaluate the influence of surrounding land use on microplastic distribution, spatial analysis was conducted using GIS software [27].

Land-use data, represented as polygon layers for urban, agricultural, forest, and industrial areas, were obtained from the Aceh Province land office. Coastal and river sediment sampling points were georeferenced and linked to surrounding land-use polygons using a spatial join procedure. For each sampling point, the dominant land-use type and proportional land-use composition within a defined buffer radius were calculated to assess potential relationships with microplastic abundance.

The Kruskal–Wallis test was applied to evaluate differences in microplastic abundance among coastal locations. All statistical analyses were conducted using standard statistical software.

3. Results and discussion

3.1. Longitudinal variations in salinity, suspended particulates, and magnetic properties along the river–estuary system

Based on Figure 2, longitudinal variations in salinity, turbidity, total suspended solids (TSS), and frequency-dependent magnetic susceptibility (χ_{FD}) reveal clear differences in hydrodynamic behavior between the Krueng Aceh and Krueng Lamnyong rivers. Collectively, these parameters reflect interactions among freshwater discharge, tidal intrusion, and suspended particle dynamics along the river–estuary continuum and therefore provide indirect indicators for identifying potential estuarine turbidity maximum (ETM) zones [28, 29].

In the Krueng

Aceh River (Figure 2a–b), salinity increases markedly from upstream stations toward the lower estuary, indicating strong seawater intrusion and active mixing between freshwater and marine water masses.

This increase coincides with a pronounced rise in turbidity and TSS between stations KA3 and KA6, with peak values observed around KA4–KA5. The co-occurrence of elevated salinity and suspended particulate concentrations in this reach is consistent with conditions typically associated with ETM formation, where hydrodynamic convergence, tidal pumping, and density-driven circulation promote retention and repeated resuspension of fine particles [28, 30].

The observed increase in turbidity and TSS can be attributed to the transition from river-dominated to tide-influenced flow conditions. As saline water

intrudes upstream, increasing ionic strength enhances aggregation and flocculation of fine sediments and organic matter [31].

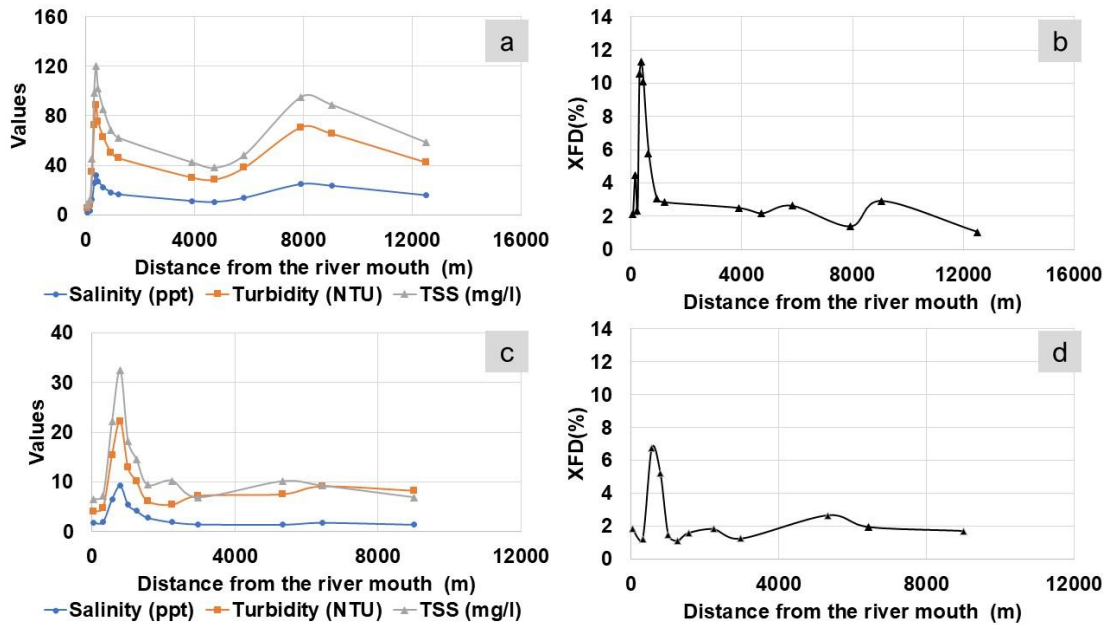


Fig. 2. Longitudinal variation of hydrodynamic parameters and magnetic proxies along the river–estuary systems. Panels (a–b) represent the Krueng Aceh River, and panels (c–d) represent the Krueng Lamnyong River. Profiles include salinity, turbidity, TSS, and frequency-dependent magnetic susceptibility (χ_{FD}).

These flocs tend to settle more rapidly; however, tidal turbulence and bidirectional flow can maintain them in suspension within a restricted reach of the estuary. This process results in a localized maximum in suspended sediment concentration. The decrease in turbidity and TSS both upstream and downstream of this reach suggests reduced particle trapping efficiency outside the convergence zone [32, 33].

The χ_{FD} profile shows a similar spatial pattern, with elevated values occurring within the same reach where turbidity and TSS peak. Frequency-dependent susceptibility is sensitive to fine superparamagnetic grains commonly associated with clay–silt fractions and surface-active particles [22]. The spatial coincidence of elevated χ_{FD} with high turbidity suggests enrichment of fine suspended sediments in this zone. This pattern is consistent with enhanced fine-particle retention in the lower Krueng Aceh estuary and supports the interpretation of a localized particle retention zone. Upstream of this section, the influence of saline intrusion weakens, and suspended particles are transported more efficiently, resulting in lower turbidity and χ_{FD} values.

In contrast, the Krueng Lamnyong River (Figure 2c–d) shows more limited salinity intrusion and generally lower turbidity and TSS values along the longitudinal profile. Although a localized increase in turbidity and χ_{FD} occurs around stations KL3–KL4, the magnitude and spatial extent of these peaks are considerably smaller than those observed in the Krueng Aceh River. This pattern suggests a weaker and potentially more transient convergence zone.

The reduced salinity gradient in the Krueng Lamnyong system likely limits flocculation and density-driven circulation, which are key processes in sustaining strong ETM development [34]. Without persistent hydrodynamic trapping, suspended particles are transported more uniformly downstream, resulting in lower retention efficiency and reduced accumulation of fine sediments [35]. The modest increase in χ_{FD} around KL3–KL4 may indicate temporary accumulation of fine particles; however, the absence of a broad and sustained turbidity maximum suggests that a well-developed ETM is less evident in this river compared with the Krueng Aceh system.

Overall, the combined behavior of salinity, turbidity, TSS, and χ_{FD} along both rivers indicates that particle retention processes are strongly influenced by the intensity of salinity intrusion and hydrodynamic convergence. In the Krueng Aceh River, the co-occurrence of strong salinity gradients, elevated suspended sediment concentrations, and increased χ_{FD} values suggests the presence of a well-defined fine-particle retention zone in the lower estuary. Such zones are commonly associated with enhanced accumulation of fine sediments and particle-bound contaminants, including microplastics, due to repeated cycles of aggregation, settling, and resuspension. In contrast, the Krueng Lamnyong River exhibits only localized and weaker increases in these parameters, indicating less efficient trapping of suspended particles. Taken together, the spatial patterns shown in Figure 2 support the interpretation that particle retention associated with ETM-like conditions is more pronounced in the Krueng Aceh estuary than in the Krueng Lamnyong system. The integration of hydrological measurements and magnetic proxies provides a useful qualitative framework for identifying zones of enhanced particle retention along tropical river-estuary systems, even in the absence of continuous tidal or current measurements.

3.2. Distribution of microplastics in river sediments

The types of microplastics found consisted of fibers, films, and fragments. The microplastics were identified as polymers, such as high-density polyethylene (HDPE), polyamide (PA), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS). Polymers with densities higher than seawater ($\sim 1.025 \text{ g cm}^{-3}$), including PET (1.37 g cm^{-3}), PS (1.05 g cm^{-3}), and PVC (1.38 g cm^{-3}), are expected to settle more readily in sediments due to their intrinsic density. However, microplastics composed of lower-density polymers, such as PP ($0.90\text{--}0.92 \text{ g cm}^{-3}$) and HDPE (0.94 g cm^{-3}), may also accumulate in sediments through secondary processes such as aggregation with dissolved organic matter (DOM), biofilm formation, attachment to clay minerals, and interactions with fine suspended particles, which increase their effective density and promote sinking and retention in riverbed sediments [36]. Based on

Figure 3, it can be seen that the distribution of microplastics in the two rivers shows significant differences. The observed spatial pattern in the Krueng Aceh River suggests the possible influence of hydrodynamic retention processes commonly associated with estuarine turbidity maxima (ETM), although direct measurements of turbidity, suspended sediment concentration, or salinity gradients were not conducted in this study. Therefore, the role of ETM is interpreted here as a plausible mechanism rather than a directly measured driver. In contrast, the distribution in the Krueng Lamnyong River is more likely influenced by changes in weather and human activities. This interpretation is supported by the presence of a localized microplastic concentration anomaly in the Krueng Aceh River, whereas a similar mid-reach concentration peak is not observed in the Krueng Lamnyong River, indicating differences in hydrodynamic retention conditions between the two systems. Estuarine turbidity maxima typically occur in transition zones where freshwater and seawater interact, generating turbulence and promoting the trapping of fine suspended particles. Such processes can enhance the retention of microplastics within specific river reaches [35, 36].

However, in the present study, this mechanism is inferred from spatial distribution patterns and previous sediment-based observations rather than from direct hydrodynamic measurements. In the Krueng River, Aceh, the most dominant type of microplastic is fiber. This finding is consistent with previous studies showing that fibers are commonly the dominant microplastic type in aquatic environments and can originate from a variety of sources, including domestic wastewater, textile washing, and fishing-related activities [11, 37, 38]. In the present study area, both residential inputs and river-based activities such as fishing and small-scale aquaculture may contribute to the observed fiber abundance. Therefore, fiber sources are interpreted as mixed and context-dependent rather than attributable to a single dominant source. The fiber distribution shows the highest abundance at sampling point KA5, which is 36,782 meters from the estuary, with 1,101 items/kg, and decreases at points closer to the estuary, such as KA1, with only 12 items/kg. Apart from fiber, plastic

film is also found in significant quantities in the Krueng River, Aceh. These findings are consistent with patterns of high single-use plastic use in Southeast Asia [39]. The distribution of film-type

microplastics shows the highest concentration at point KA5, with 379 items/kg, and decreases at points closer to the estuary.

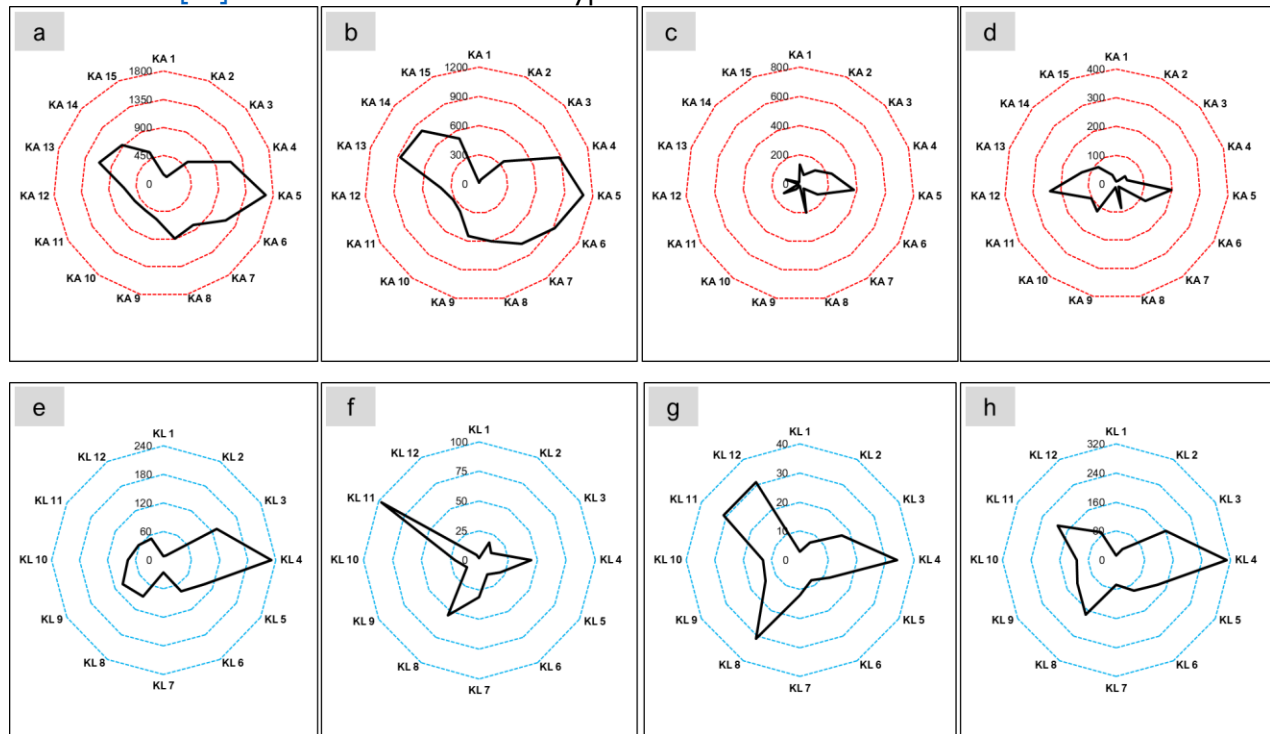


Fig. 3. Distribution of microplastic types (total, fiber, film and fragments) along the Krueng Aceh River (a-d) and Krueng Lamnyong River (e-h). The data shows the abundance of microplastics at various sampling points at different distances from the estuary.

Plastic fragments also show distribution patterns similar to those of fibers and films. At point KA5, fragment abundance reached 198 items/kg, indicating a significant concentration in this area. Fragments tend to decrease with increasing distance from the estuary, but some points, such as KA12, show high concentrations depending on local hydrodynamic factors. The distribution of microplastics in the Krueng Lamnyong River, in contrast, exhibits a different pattern that is more influenced by variations in human activity and local environmental conditions than by ETM mechanisms. It was found that fiber was the most common type, with 231 items/kg at point KL4 and only 8 items/kg at point KL1. This suggests that human activities, such as the disposal of household and industrial waste, have a greater impact on the distribution of microplastics. Film and fragment microplastic types in these rivers show significant but inconsistent variations, reflecting the uneven influence of human activities and local environmental conditions. Based on Table 1, fiber-

type microplastics in the Krueng Aceh River show a very strong positive correlation with total microplastics (0.97), indicating that fiber is the main component of the total microplastics in this river. Additionally, fiber has a moderate correlation with fragments (0.43) and films (0.31). In the Krueng Lamnyong River, fiber shows a strong correlation with total microplastics (0.81), indicating the dominance of fiber in the microplastic composition in this river.

Fiber also has a moderate correlation with fragments (0.58) and a low correlation with films (0.24). Correlations between other types of microplastics are also significant, with fragments showing a strong correlation with total microplastics (0.80) and a moderate correlation with films (0.44).

The contrasting patterns observed between the Krueng Aceh and Krueng Lamnyong rivers indicate that ETM-related processes influence microplastic transport differently in each system. In the Krueng Aceh River, local hydrodynamic conditions and

channel morphology appear to favor the development of a more persistent turbidity maximum, where strong river discharge interacts with saline intrusion and tidal forcing. Such

interactions enhance vertical and horizontal mixing, producing zones of elevated turbulence that facilitate the retention of suspended particles, including microplastics [40].

Table 1. Spearman correlation coefficient matrix between population density and types of microplastics (fiber, film, fragments) in the Krueng Aceh and Krueng Lamnyong Rivers.

	Population density	Fiber	Film	Fragment	Total
Krueng Aceh					
Population density	1.00	-0.61	0.14	-0.09	-0.53
Fiber	-0.61	1.00	0.31	0.43	0.97
Film	0.14	0.31	1.00	0.17	0.36
Fragment	-0.09	0.43	0.17	1.00	0.52
Total	-0.53	0.97	0.36	0.52	1.00
Krueng Lamnyong					
Population density	1.00	0.01	0.29	0.01	0.12
Fiber	0.01	1.00	0.24	0.58	0.81
Film	0.29	0.24	1.00	0.44	0.62
Fragment	0.01	0.58	0.44	1.00	0.80
Total	0.12	0.81	0.62	0.80	1.00

In estuarine settings with stronger tidal influence, repeated mixing between freshwater and seawater can intensify flocculation and particle trapping within a limited reach, increasing the likelihood of localized microplastic accumulation [41]. By comparison, the Krueng Lamnyong River exhibits weaker salinity intrusion and less pronounced mixing, suggesting that ETM-related trapping mechanisms are less developed and may occur only intermittently or over shorter spatial scales.

In contrast, the Krueng Lamnyong River does not show a significant ETM zone influence, possibly due to its more stable and unresponsive morphology as well as weaker interactions with seawater. With a lower abundance of microplastics, the influence of ETM in the Krueng Lamnyong River was not strong enough to create the same distribution pattern. The study by Akyildiz et al. [11] showed that the distribution of microplastics in urban rivers is more influenced by direct human activities than by hydrodynamic phenomena such as ETM. This indicates that industrial factors can have a greater impact than natural mechanisms in certain contexts. In comparison, research by Li et al. [8] found that variability in microplastic distribution around rivers is more influenced by land use and local pollution sources. These findings support the idea that human activities play a significant role in the distribution patterns of microplastics in the Krueng Lamnyong River. Therefore, further analysis

is needed to examine other factors, such as population density and land use around rivers, to fully understand the distribution of microplastics in this region.

3.3. Correlation of population density

The population density around the Krueng Aceh River and the Krueng Lamnyong River shows significant differences, with 308,853 people/km² in the Krueng Aceh River buffer and 94,736 people/km² in the Krueng Lamnyong River buffer, which influences their level of microplastic contamination. Moreover, the cities of Banda Aceh and Aceh Besar, through which these two rivers pass, do not have a domestic waste processing system. As a result, all household and commercial waste is discharged into canals and ends up in rivers.

In the Krueng Aceh River, high population density directly contributes to high levels of microplastic contamination. With a denser population, the volume of plastic waste produced and disposed of in the environment is also greater. Household and commercial activities in areas with high population density usually lack waste management, resulting in more microplastics being released into rivers. Previous research has shown that areas with high population density tend to have a greater abundance of microplastics, especially in nearby aquatic environments [8, 42].

In contrast, the lower population density around the Krueng Lamnyong River could potentially explain the lower levels of microplastic contamination compared to the Krueng Aceh River. With a smaller population, the volume of plastic waste produced and disposed of also tends to be lower. Table 1 shows the results of the Spearman correlation analysis, which supports this finding. In the Krueng Aceh River, there is a significant positive correlation between population density and microplastic abundance, though the hydrodynamic mechanisms of the river also play a major role. This positive correlation indicates that a combination of hydrodynamic and population density mechanisms affects the distribution of microplastics in the Krueng Aceh River.

In the Krueng Lamnyong River, the correlation between population density and types of microplastics is relatively weak. Correlations were almost non-existent between population density and fibers (0.01) and fragments (0.01), while correlations with films (0.29) and total microplastics (0.12) were also low. These results indicate that the distribution of microplastics in this river is more influenced by factors other than population density. Human activities may play a more dominant role in determining the distribution of microplastics in the Krueng Lamnyong River. Therefore, further analysis is needed to observe these factors in detail to understand the distribution of microplastics in these rivers.

3.4. Correlation with land use

Figure 4 shows a comparison of the abundance of microplastics in the Krueng Aceh River and the Krueng Lamnyong River based on land use in the surrounding area. These land use data reveal significant differences between the buffers of the two rivers that influence the distribution of microplastics. In the Krueng Aceh River, residential land dominates with a percentage of 68.16%, compared to only 46.21% in the Krueng Lamnyong River. The high percentage of residential land around the Krueng Aceh River may contribute to a greater abundance of microplastics in this river compared to the Krueng Lamnyong River. Household activities and less effective waste management in dense residential areas are the

main sources of microplastic fibers, films, and fragments entering rivers. Previous studies support these findings, showing that urban areas with high residential density are major sources of microplastic pollution [27]. In contrast, the Krueng Lamnyong River buffer shows a higher proportion of land use for agriculture (25.44%) and fish ponds (12.69%). The presence of significant fish ponds along the Krueng Lamnyong River can be an additional source of microplastics, especially from plastic materials used in fishing equipment and fish farming processes [26]. The use of plastic mulch in agriculture can also contribute to microplastic pollution through agricultural waste that ends up in rivers. According to Hao et al. [43], small farms are more prone to producing microplastics compared to large-scale farms, which strengthens the influence of this type of land use on microplastic abundance.

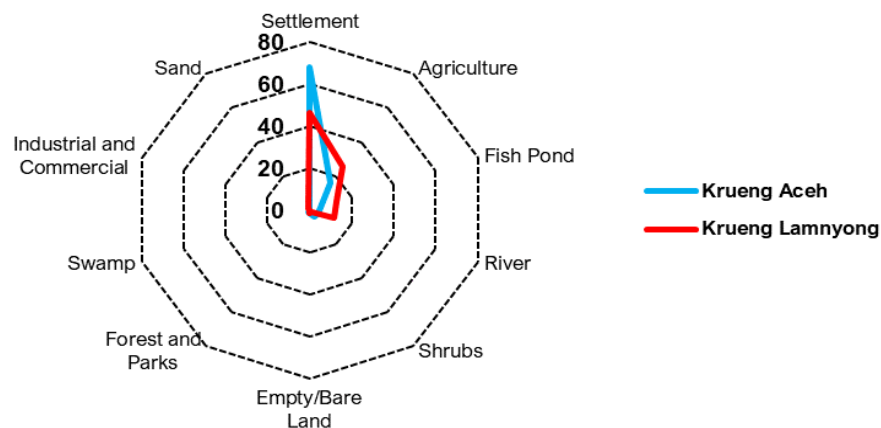
The Spearman correlation analysis between land use and the amount of microplastics in the Krueng Lamnyong and Krueng Aceh estuaries (Table 2) shows that the relationship is complicated and varied. In the Krueng Lamnyong estuary, settlements showed a strong positive correlation with the abundance of all types of microplastics: fiber ($r = 0.57$), film ($r = 0.34$), fragments ($r = 0.41$), and total microplastics ($r = 0.62$). This indicates that settlement activities contribute significantly to increasing microplastic pollution in this estuary. In contrast, sandy areas showed a strong negative correlation with all types of microplastics: fiber ($r = -0.39$), film ($r = -0.38$), fragments ($r = -0.55$), and total microplastics ($r = -0.52$).

This is logical, as there is no activity in this area. Fish ponds also showed a positive correlation with microplastic abundance, including fiber ($r = 0.37$), film ($r = 0.42$), and total microplastics ($r = 0.26$), although their contribution was smaller compared to settlements.

This means that empty land and trading activities are less likely to be sources of microplastics in the Krueng Lamnyong River. The negative correlations found for empty land were: fiber ($r = -0.09$), film ($r = -0.22$), fragments ($r = -0.56$), and total microplastics ($r = -0.27$). For trading areas, the correlations were: fiber ($r = -0.53$), film ($r = -0.18$), fragments ($r = -0.44$), and total microplastics ($r = -0.44$).

Table 2. Spearman's Correlation between Land Use Type and Microplastic Abundance in the Krueng Lamnyong and Krueng Aceh Rivers (items/kg).

	Abundance in Krueng Lamnyong (items/kg)				Abundance in Krueng Aceh (item/kg)			
	Fiber	Film	Fragment	Total	Fiber	Film	Fragment	Total
Agriculture	-0.28	-0.30	0.06	-0.13	0.36	0.15	-0.29	0.28
Settlement	0.57	0.34	0.41	0.62	0.05	-0.51	0.54	0.06
River	0.00	0.09	-0.52	-0.22	0.41	0.34	-0.03	0.35
Fish Pond	0.37	0.42	0.10	0.26	0.34	0.40	-0.30	0.30
Sand	-0.39	-0.38	-0.55	-0.52	0.00	0.00	0.00	0.00
Forest and Parks	0.00	0.00	0.00	0.00	-0.39	-0.27	0.46	-0.30
Empty/Bare Land	-0.09	-0.22	-0.56	-0.27	0.43	0.69	-0.16	0.42
Shrubs	-0.08	-0.14	-0.24	-0.10	0.18	0.60	-0.21	0.14
Commerce	-0.53	-0.18	-0.44	-0.44	-0.10	0.59	-0.45	-0.13

**Fig. 4.** Comparison of microplastic abundance of the Krueng Aceh and Krueng Lamnyong Rivers based on land use.

On the other hand, in the Krueng Aceh River, agricultural activities show a positive correlation with fiber abundance ($r = 0.36$) and total microplastics ($r = 0.28$), indicating that agriculture around this river contributes to increasing microplastic pollution. However, microplastic fragments showed a negative correlation with agriculture ($r = -0.29$), suggesting that this type of microplastic may be more influenced by other activities.

Trading in the Krueng Aceh estuary had a positive relationship with film abundance ($r = 0.59$) but a negative relationship with fiber ($r = -0.10$), fragments ($r = -0.45$), and total microplastics ($r = -0.13$). This means that trade only makes some types of microplastics more common.

Strong positive correlations between fish ponds and microplastic abundance were also seen in this estuary, with fiber ($r = 0.34$), film ($r = 0.40$), and total microplastics ($r = 0.30$), confirming that fish ponds are an important source of microplastics.

Additionally, forests and parks showed a negative correlation with microplastic abundance in the Krueng Aceh estuary, with fiber ($r = -0.39$), film ($r = -0.27$), and total microplastics ($r = -0.30$), while fragments showed a positive correlation ($r = 0.46$). These findings demonstrate the importance of considering land use variations in the analysis of microplastic distribution. The study by Huang et al. [44] in urban rivers in China also found that residential land contributed significantly to the abundance of microplastics, supporting our findings in the Krueng Aceh River. Additionally, research by Kabir et al. [45] on Japanese rivers shows that small-scale agricultural activities tend to increase microplastic contamination in water bodies, in line with our observations on the Krueng Lamnyong River.

These results confirm that land use and human activities are critical factors in the distribution of microplastics. More effective waste management and strict regulations for activities that contribute

to microplastic pollution in coastal and river areas are needed to reduce the negative impact of microplastics on ecosystems. By considering the findings from these studies, mitigation strategies can be designed more specifically and effectively to address microplastic pollution.

3.5. Distribution of microplastics on the coast

Based on microplastic data obtained from several points on the coast, descriptive analysis showed significant variations in the distribution of microplastic components. For the fiber component ($n=39$), the average value was 115.54 ± 92.91 items/kg, indicating a highly variable distribution. The maximum value reached 480 items/kg, far above the third quartile of 145.5 items/kg, indicating the existence of several points with very high fiber concentrations.

The fragment component ($n=39$) had an average value of 132.31 ± 109.26 items/kg. The minimum value was 0 items/kg, indicating the presence of points with no fragments at all, while the maximum value reached 451 items/kg. Fragment distribution showed significant variation with high standard deviations.

For the film component ($n=39$), the average value was 10.56 ± 21.57 items/kg. The majority of data showed low values, with the median and first quartile both at 0 items/kg, indicating many points without film. However, the maximum value reached 79 items/kg, indicating that there were several points with high film concentrations.

The total abundance of microplastics ($n=39$) had an average value of 178.54 ± 128.38 items/kg. The minimum value was 14 items/kg, and the maximum value reached 583 items/kg. High variations in total abundance indicated significant differences in microplastic concentrations at different points.

Analysis by location showed that microplastic concentrations vary depending on activity and local environmental characteristics. At tourist locations, fibers ($n = 9$) had a lower average value (67.33 ± 35.63 items/kg) compared to non-tourist locations (106.21 ± 64.59 items/kg). However, fragments in tourist locations had a higher average value (246.56 ± 78.35 items/kg) compared to non-tourist locations (85.88 ± 78.35 items/kg). This pattern may be associated with common tourist-

related activities, such as recreational boating, fishing, shoreline recreation, and the use of single-use food and beverage packaging, which can introduce plastic debris that subsequently fragments through physical abrasion, UV exposure, and mechanical breakdown in dynamic coastal environments. Films in both locations had low average values, but were slightly higher in non-tourist locations.

Around river mouths, the distribution of microplastics showed striking variations. Near the mouth of the Krueng Aceh River, fibers ($n = 3$) had the highest average value (240.33 ± 89.44 items/kg) compared to other locations, followed by fragments (173.33 ± 89.44 items/kg) and films (0.67 ± 1.15 items/kg). The total abundance around the mouth of the Krueng Aceh River was also the highest (336.00 ± 233.85 items/kg). These results suggested that river mouths act as important convergence zones for land-derived plastic debris, where hydrodynamic mixing, tidal influence, and sedimentation processes could enhance the retention and accumulation of microplastics before their transport to coastal waters.

In contrast, near the mouth of the Krueng Lamnyong River, the average value of fibers was 210.00 ± 233.88 items/kg, fragments was 120.00 ± 121.24 items/kg, and films was 8.33 ± 8.08 items/kg. These results indicate that human activities, especially in tourist areas and around river mouths, contributed significantly to variations in microplastic concentrations. Tourist sites, although having lower fiber concentrations, had higher fragment concentrations, likely due to intensive recreational activities. Meanwhile, areas around river mouths showed very high concentrations of microplastics, indicating that river mouths may be the main entry point for microplastics from land to sea. These findings are in line with previous studies showing that human activities and river flows are the main sources of microplastic pollution in coastal environments [19]. This research emphasizes the importance of management strategies adapted to local characteristics to reduce microplastic pollution in coastal environments.

3.6. Potential sources of microplastics on coasts

This study found that the type of location (tourist vs. non-tourist) and distance to the river mouth (Krueng Lamnyong vs. Krueng Aceh) had a significant influence on the abundance of microplastics in coastal areas. Land use data reveal that non-tourist areas have a higher abundance of microplastics compared to tourist areas. Figure 5 shows that non-tourist areas have a higher median

and wider distribution in terms of total abundance of microplastics, fibers, fragments, and films. This may be due to differences in human activities and waste management practices. Tourist areas usually have more supervision and stricter waste management policies to maintain cleanliness and attract tourists, while non-tourist areas may have less supervision, resulting in higher levels of littering.

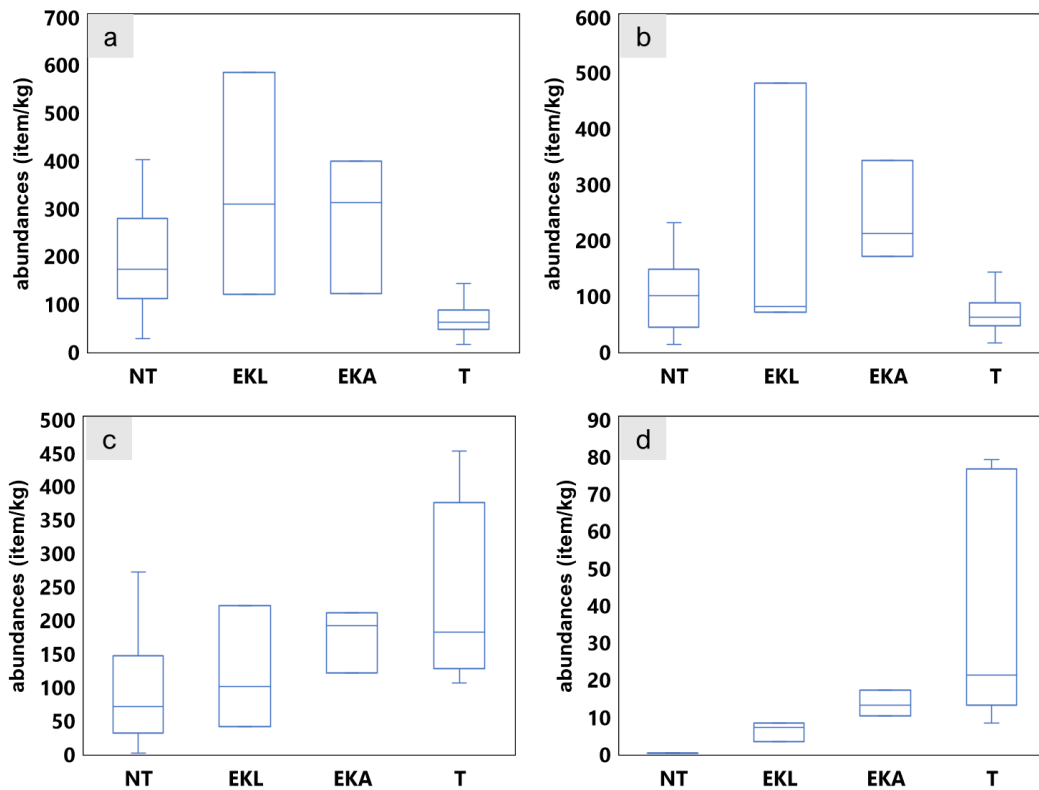


Fig. 5. Data visualization of total microplastic abundance (a) fiber (b), film (c), fragments (d) in various types of coastal locations, tourist (T), non-tourist (NT), Krueng Lamnyong estuary (EKL) and Krueng Aceh (EKA).

The results of statistical tests support these findings by showing significant differences in the abundance of microplastics between various locations. The Kruskal-Wallis test revealed that for fiber-type microplastics, the statistical value was 8.0153 ($p = 0.0457$), for fragment-type microplastics 13.3405 ($p = 0.0040$), and for film-type microplastics 36.7435 ($p = 5.213821e-08$). The total abundance of microplastics also showed a significant difference with a statistical value of 14.6670 ($p = 0.0021$). These results clearly indicate that location has a significant influence on the abundance of microplastics.

Further analysis showed that the distance of sampling from the mouth of the Krueng Aceh River

had a more significant influence on the abundance of microplastics compared to the distance from the mouth of the Krueng Lamnyong River. A moderate negative correlation was found between the distance to the Krueng Aceh estuary and fiber abundance ($r = -0.492$), as well as a weak negative correlation with the total abundance of microplastics ($r = -0.204$). This indicates that as the distance from the Krueng Aceh estuary increased, the abundance of fiber and total microplastics tended to decrease. In contrast, the distance to the Krueng Lamnyong estuary showed a very weak correlation with microplastic abundance, meaning that distance from this estuary had no significant

effect on microplastic abundance across the study sites.

These findings confirm that land use type and distance to river mouths play an important role in determining the abundance of microplastics in coastal areas. Non-tourist areas, which are less organized in terms of waste management, show a higher abundance of microplastics. Additionally, the Krueng Aceh estuary appears to function as the main transport route for microplastic fragments and films, whereas the Krueng Lamnyong estuary is more associated with microplastic fibers. Therefore, microplastic pollution mitigation strategies must be tailored to the specific conditions of each location and consider factors such as location type and distance to river mouths to reduce the negative impact of microplastics on coastal ecosystems.

The results of previous studies in the same area (Sungai Krueng Aceh) showed a similar contaminant distribution pattern, where microplastics, heavy metals such as lead (Pb), nickel (Ni), and cobalt (Co), as well as chemical and physical water quality parameters, showed higher concentrations in urban areas with intense human activity.

The similar distribution patterns of microplastics and heavy metals, along with decreased water quality, confirm the correlation between poor environmental quality and a high abundance of microplastics. Thus, pollution mitigation strategies must consider various types of contaminants holistically to improve the overall environmental quality in these tropical non-industrial urban areas [23].

4. Conclusion

This study investigated the distribution and potential sources of microplastics in river and coastal sediments within a non-industrial tropical urban system along the northern coast of Aceh, Indonesia. By integrating spatial analysis, environmental parameters, and qualitative sediment proxies, the results demonstrate that microplastic accumulation in such environments is controlled by a combination of land-use intensity, population density, and estuarine retention processes rather than by direct industrial inputs.

Clear differences were observed between the two river systems.

The Krueng Aceh River, which is characterized by higher population density and stronger hydrodynamic mixing near the estuary, exhibited higher microplastic abundances than the Krueng Lamnyong River. Fibers were the dominant microplastic type in river sediments, followed by films and fragments. Their spatial distribution corresponds to zones of enhanced suspended particulate retention in the lower Krueng Aceh estuary, consistent with conditions typically associated with estuarine turbidity maximum (ETM) formation. In contrast, the Krueng Lamnyong River showed lower microplastic abundances and more localized inputs, likely reflecting a weaker salinity gradient, reduced particle retention, and a stronger influence of local domestic activities.

Land-use analysis indicates that densely populated residential areas surrounding the Krueng Aceh River are a major contributor to microplastic inputs. Around the Krueng Lamnyong River, additional inputs from agricultural areas and aquaculture ponds were identified, although their relative contributions appear smaller. These findings highlight that even in the absence of major industrial sources, population density and mixed land use can generate substantial microplastic inputs to river–estuary systems.

In coastal sediments, microplastic abundance was generally higher in areas influenced by discharge from the Krueng Aceh River, particularly in non-tourist coastal zones. Differences between sites near river mouths and managed tourist areas suggest that both land-use type and distance from fluvial sources play key roles in shaping coastal microplastic distribution. These patterns support the interpretation that river-derived inputs and estuarine retention processes together control microplastic accumulation in adjacent coastal environments.

Overall, this study provides baseline evidence that microplastic transport and retention in non-industrial tropical urban catchments are governed by the interaction of anthropogenic inputs and hydrodynamic processes. By linking land-use patterns, population density, and estuarine particle-retention conditions, the study offers a

process-oriented framework for understanding microplastic distribution in rapidly urbanizing tropical systems lacking major industrial sources. These findings contribute to a growing body of research emphasizing the importance of river-estuary dynamics in microplastic accumulation and provide a basis for developing targeted mitigation strategies for tropical urban coastal environments.

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Author's contribution

Abd Mujahid Hamdan: Conceptualization, methodology, field investigation, supervision, data interpretation, writing – original draft, writing – review and editing, project administration, and funding acquisition. Syafrina Sari Lubis: Methodology, field investigation, laboratory analysis, data curation, formal analysis, and writing – review and editing. Yunasar Yunasar: Field investigation, laboratory assistance, data processing, visualization, and writing – review and editing. Sudarningsih Sudarningsih: Methodological validation, scientific supervision, data interpretation, and writing – review and editing. All authors have read and approved the final version of the manuscript..

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of Using Generative AI

Generative AI tools were used solely to support language refinement, readability improvement, and manuscript formatting. The authors carefully reviewed, verified, and approved all content and take full responsibility for the scientific accuracy, interpretation, and integrity of the manuscript

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