
Spatial Distribution Of Microplastics In Sediments Of The Karangsong Mangrove Ecotourism Area, Indramayu

Fitriani¹⁾, Zahidah Hasan²⁾, Roffi Grandiosa³⁾, Mochamad Candra Wirawan Arief⁴⁾

^{1,2,3,4)} Fisheries Study Program, Faculty of Fisheries and Marine Sciences, Padjadjaran University

*Corresponding Author

Email : pipit5fitriani@gmail.com

Abstract

Karangsong Mangrove Ecotourism Area is an area in Indramayu Regency that has various activities such as tourism, fishing and anthropogenic. These activities produce waste such as plastic which is then fragmented into small particles (microplastics). This research aims to determine the distribution and abundance of microplastics caused by different activities around the Karangsong Indramayu Mangrove Ecotourism area. The environmental factors used in this research are temperature and pH taken in situ and current data obtained from the Copernicus marine. Sediment samples were taken using a piston core once a week for one month. Furthermore, laboratory tests were carried out to see the abundance and characteristics of microplastics. The data that has been obtained is then tested with oneway ANOVA with a significance level of 5%. The highest abundance of microplastics was found at Station 3 (Beach) with a concentration of 15.87 ± 1.05 particles/g and the lowest abundance was identified at Station 1 (Ecotourism Area) with a concentration of 1.25 ± 0.04 particles/g. The dominating characteristics at each station are the types of Fragments and Films, yellow and transparent colors, and microplastics <1mm in size.

Keywords: Activity, Characteristics, Microplastics.

INTRODUCTION

Plastic is one of the most widely discussed global environmental issues. The increasing population and intensity of human activities have led to a high dependence on plastic products. Moreover, the production of single-use plastic packaging contributes to the continuous accumulation of waste over time. Plastic waste is a type of inorganic waste that requires a very long time to decompose. Plastic degradation takes approximately 500–1,000 years, and it is estimated that two generations are needed to significantly reduce the lifespan of plastic waste (Kalsum *et al.* 2023). Plastic bags require about 10–20 years to break down, while detergent packaging may take 50–80 years to decompose (Kalsum *et al.* 2023). This indicates that the degradation of plastic waste takes far longer than the average human lifespan, which ranges from 60–70 years.

Indonesia ranks second after China as the world's largest contributor to marine plastic waste (Jambeck *et al.* 2015). According to Purba *et al.* (2022) the sources of plastic waste in Indonesia are primarily land-based, transported to the ocean through river systems. Other sources include human activities in coastal and marine areas, such as fishing, ecotourism, and aquaculture, waste discharged from boats, and debris carried by ocean currents from outside Indonesian waters. Plastic waste transported by currents undergoes degradation into smaller fragments known as microplastics. When distributed within the water column, these microplastics tend to settle into sediments, as their distribution in sediments occurs more slowly compared to the water column (Ambarsari dan Anggiani 2022).

Microplastics are plastic particles smaller than 5 mm in size with a weight ranging from 0.1 to 8.8 mg (Ambarsari dan Anggiani 2022). They are classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured for use in products such as cleaning agents, textiles, and cosmetics, and they may enter aquatic environments due to improper handling or disposal. Secondary microplastics, on the other hand, are formed through the fragmentation of larger plastic debris (Ambarsari dan Anggiani 2022).

Sediments are considered the primary sink for microplastics because transport processes within sediments are slower than in the water column. Consequently, sedimentation processes significantly influence microplastic abundance. Before settling, microplastic particles are dispersed throughout the water column, where they may be ingested by marine organisms. Some sediments may also be

resuspended and transported by currents before permanent deposition, indicating that hydrodynamic conditions play an important role in the transport and accumulation of microplastics in sediments.

Karangsong Village has a coastline of approximately 2 km and is located in a coastal area. Sedimentation at the river estuary is a recurring issue due to the flow of the Karangsong River toward the estuary. Inappropriate land use within the Karangsong watershed, such as residential areas and aquaculture ponds, has contributed to erosion, resulting in high sedimentation rates in the Karangsong River. According to Adrianto *et al.* (2017) reported a sedimentation rate of 101.3 g/m²/day at the Karangsong River estuary. The high sedimentation rate is attributed to sediment input from the Karangsong River and tidal influences from the sea entering the estuary. The Karangsong area is also a tourist destination that features mangrove ecosystems as its main attraction. Increased human activities within the mangrove ecosystem are likely to generate more waste from visitors, which is suspected to increase the abundance of microplastics that have not yet fully degraded.

RESEARCH METHODS

This study employed a survey method with direct sediment sampling conducted in the Karangsong Mangrove Ecosystem, which comprised three stations: the mangrove area, the Karangsong River estuary, and Karangsong Beach. The stations were determined using *purposive sampling* based on the influence of river flow, tourism activities, and tidal dynamics, while the sampling replication points were established through *random sampling*. The research procedures included the stages of preparation, sediment sampling of 150 grams with four replications at each station, laboratory sample processing for sediment grain-size and microplastic analyses, and data analysis. Sample processing involved drying, granulometric analysis using a sieve shaker and classification based on the Wentworth scale, as well as the extraction and identification of microplastics according to their abundance and characteristics (size, color, and shape) using density separation methods and microscopic observation. The data were analyzed using descriptive comparative analysis to compare the abundance and characteristics of microplastics among stations and were further supported by a One-Way ANOVA test to determine significant differences in microplastic abundance.

RESULTS AND DISCUSSION

General Conditions of the Study Area

The Karangsong area hosts a Mangrove Ecotourism Zone that has been operating since 2015 (Oni *et al.* 2019). The economic benefits arising from tourism activities have been accompanied by an increase in solid waste generation. This is consistent with Tsururi (2022) who reported that waste generation in Indramayu is relatively high and that its management remains suboptimal. Consequently, at Station 1, microplastic abundance is primarily derived from anthropogenic activities, particularly tourism. In addition, plastic waste at this station also originates from river flow passing through the ecotourism area.

Sources of pollution at Station 2 (Song River Estuary) are associated with anthropogenic activities such as batik production, salted-fish processing, and vessel traffic in the estuarine area. These activities potentially contribute to plastic waste pollution. Meanwhile, Station 3, which represents the coastal zone, receives pollutants from current-driven transport of microplastics, tourism-related waste, and inputs from the river estuary.

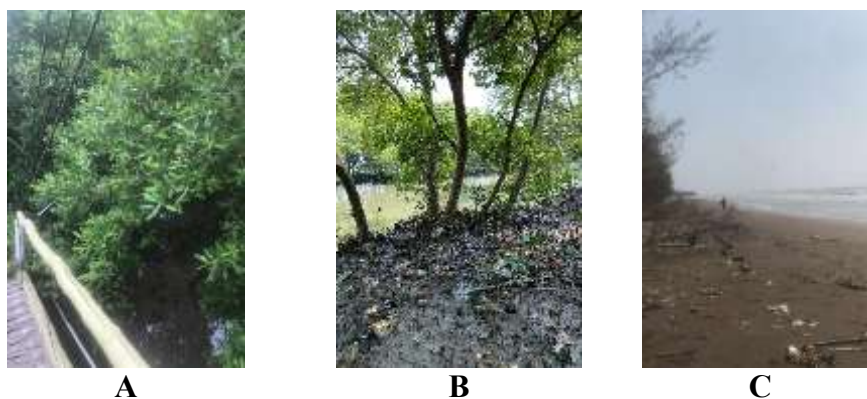


Figure 1. Locations of the sampling stations: (A) Mangrove Ecotourism Area, (B) River Estuary, and (C) Coastal Area.

Tabel 1. Vegetation Type

Research Station	Substrate Type	Vegetation Type	Plant Species
Mangrove Ecotourism Area	Slightly Gravelly Sandy Mud	Mangrove Vegetation	<i>Rhizophora mucronata</i> and <i>Avicennia marina</i>
River Estuary	Slightly Gravelly Sandy Mud	Mangrove Vegetation	<i>Rhizophora mucronata</i> and <i>Avicennia marina</i>
Coastal Area	Slightly Gravelly Sand	Coastal Pine Vegetation	<i>Casuarina equisetifolia</i>

At Station 1, which represents the Karangsong Mangrove Ecotourism Area in Indramayu, the vegetation is dominated by mangrove species *Rhizophora mucronata* and *Avicennia marina*, primarily in tree form. At this station, plastic waste originates not only from tourist activities but also from river flow passing through the Karangsong Mangrove Ecotourism area. Station 2 corresponds to the Song River estuary, which receives pollution inputs from anthropogenic activities such as batik production, salted-fish processing, and vessel traffic in the estuarine zone. In addition, mangrove vegetation dominated by *Rhizophora mucronata* and *Avicennia marina* is also present in the estuary. Station 3 represents the coastal area located north of Indramayu City. This station is influenced by pollution sources derived from marine currents transporting microplastics, tourism-related waste generation, and inputs from the river estuary.

Sediment Types

Based on grain-size analysis using Excel Gradistat, Stations 1 (Mangrove Ecotourism Area) and 2 (River Estuary) are dominated by mud. The high mud concentration at these stations is attributed to the low current velocities in the Karangsong area, ranging from 0.051 to 0.057 m/s. This finding is consistent with Taqwa et al. (2014), who stated that river estuaries with low current velocities are dominated by muddy substrates, whereas areas with strong current velocities are dominated by sandy substrates. This is because weak currents are unable to transport large sediment particles; therefore, areas with low current strength tend to be dominated by muddy substrates (Sihombing et al., 2021). Therefore, at Station 1 (Mangrove Ecotourism Area) and Station 2 (Song River Estuary), the substrate type is dominated by mud.

At Karangsong Beach Station, the analysis results indicate that the dominant substrate type is sand. According to Mulyadi et al. (2015), the direction of sediment distribution is influenced by physical factors such as waves and currents. The sand fraction identified at the coastal station is caused by strong tidal current velocities, which result in a higher settling rate of sand particles.

Tabel 2. Fraksi Sedimen

Station	Sediment Fraction Concentration		
	Gravel	Sand	Silt
Mangrove Ecotourism (I)	1.4%	44.2%	54.4%
Song River Estuary (II)	0.9%	43.8%	55.3%
Coastal Area (III)	0.2%	95.3%	4.5%

In coastal areas, sediments are highly dynamic due to continuous processes of erosion, transportation, and deposition occurring across both spatial and temporal scales. Sediment distribution in coastal environments is influenced by ocean currents, waves, and tidal processes, all of which affect sediment characteristics (Purba *et al.* 2022). In estuarine areas, sediment supply originates from river discharge as well as tidal seawater intrusion that transports sediments. According to Tampubolon *et al.* (2022) variations in current velocity significantly influence sediment movement. The minimum current velocity capable of mobilizing sediments with a grain size of 1 mm is 0.5 m/s (Tampubolon *et al.* 2022). therefore, research locations characterized by weak currents are only able to distribute fine-grained sediments.

According to Alhusban (2024) the entry of microplastics into sediments begins with plastic waste originating from terrestrial sources that enters river surfaces and undergoes degradation due to physical and chemical factors. This degradation process produces microplastics that can be incorporated into sediments through deposition and subsequently distributed via continuous sediment transport processes.

Environmental Quality

Based on field observations, water temperatures recorded at the three stations varied, ranging from 29.1 to 35°C. Temperature influences microplastic abundance through photo-oxidative degradation processes, whereby degradation products are transported into aquatic environments via currents and coastal erosion. Ulufil *et al.* (2023), stated that the degradation of macroplastics into smaller particles requires elevated temperatures facilitated by exposure to ultraviolet (UV) radiation. Consequently, waters with higher temperatures are predicted to exhibit higher microplastic abundance (Yani *et al.* 2021).

The pH values recorded during the observation period ranged from 6.35 to 7.75. Acidity level (pH) is a chemical parameter required by microorganisms to facilitate microplastic degradation processes (Ulufil *et al.* 2023). Microplastic surfaces can serve as new habitats for microorganisms, which subsequently form slimy biofilms (Dewi, 2022). According to Jiang *et al.*, (2024) factors influencing microplastic biodegradation in aquatic environments include pH, nutrient levels, and seasonal variation. pH affects biodegradation processes by influencing biofilm-producing bacterial activity. The pH of aquatic environments can be affected by several factors, such as acid rain, wastewater discharge into water bodies, and water hardness (Gazali *et al.* 2013). Higher pH values in aquatic environments are associated with higher microplastic abundance at a given location (Ulufil *et al.* 2023).

Table 3. Average Environmental Quality

Station	Average Environmental Quality	
	Temperature	pH
Mangrove Ecotourism (I)	31,125 °C ± 2,35	6,5 ± 0,38
Song River Estuary (II)	31 °C ± 0,98	6.35 ± 1,07
Coastal Area (III)	33,75 °C ± 1,92	7.75 ± 0,48

According to Vida (2019) Current velocity categories can be classified as very fast (> 1 m/s), fast (0.5–1 m/s), moderate (0.25–0.5 m/s), weak (0.1–0.25 m/s), and very weak (< 0.1 m/s). Based on Figure 2, current velocities at the research site ranged from 0.051 to 0.057 m/s and were therefore categorized as very weak currents. Currents are a physical factor that plays an important role in microplastic transport, with influencing parameters such as particle density and size (Suteja *et al.* 2024). This is consistent with Huang *et al.* (2023) who stated that currents facilitate microplastic

transport because particles accumulated in bottom sediments can be redistributed spatially by currents toward surface sediments. According to Zhang (2017), surface currents exert a major influence on the horizontal transport of microplastics, with high velocities (> 2 km/h) enabling widespread dispersal of microplastic particles and preventing their accumulation in a single location. As current velocity increases, microplastic particles are less likely to settle into sediments, thereby reducing microplastic abundance in sediments. Suteja *et al.* (2024) explained that this occurs because strong currents resuspend microplastics from sediments back into the water column.

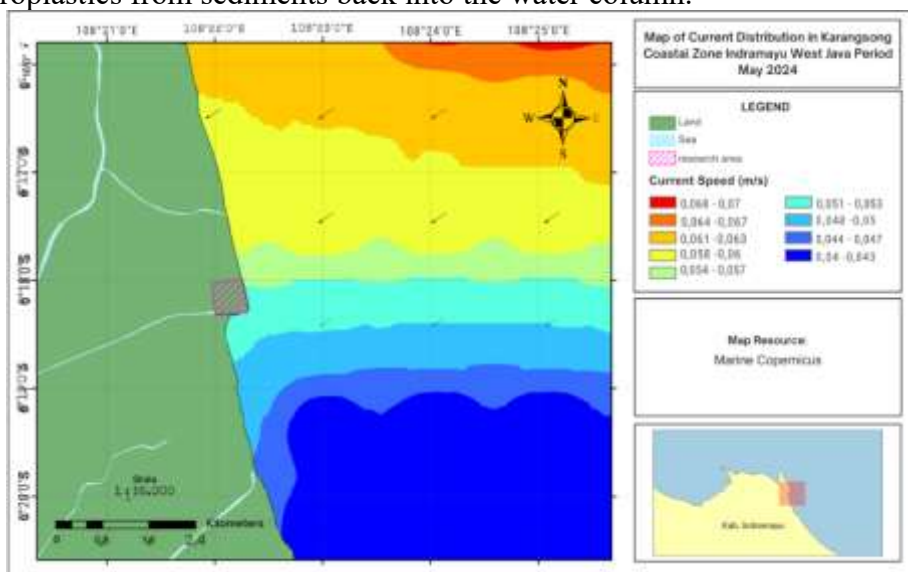


Figure 2. Map of Current Distribution in the Karangsong Coastal Area

Microplastic Abundance

Microplastics identified at each station exhibited different concentrations. Based on one-way ANOVA results, significant differences in microplastic abundance among stations were observed, as indicated by $F > F_{crit}$ and $p\text{-value} < 0.05$. Microplastic abundance was calculated as the number of identified particles per 150 g of sediment.

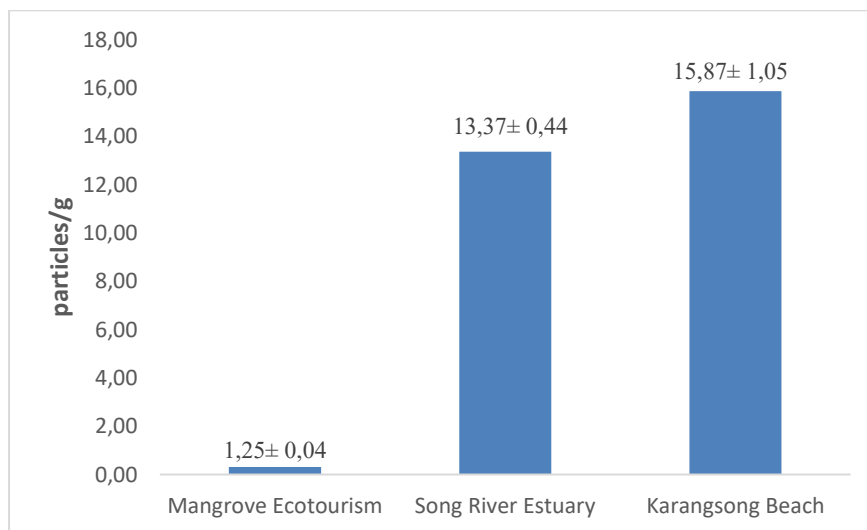


Figure 3. Microplastic Abundance

The highest microplastic abundance was recorded at Station 3, Karangsong Coastal Area, with a concentration of 15.87 ± 1.05 particles/g. Based on Figure 2, the coastal station exhibited relatively low current velocities, ranging from 0.051 to 0.057 m/s. According to Lorenza (2019) low current velocities can lead to the accumulation of microplastics in sediments because microplastics have low density; under high current velocities, microplastics tend to be resuspended and transported back into

the water column. Low current velocities in coastal areas are often associated with human activities, such as tourism and fishing vessel operations. These activities predominantly generate plastic waste originating from packaging materials and fishing gear. This is consistent with field observations at this station, where plastic debris such as beverage bottles, fishing nets, and food packaging was commonly found. In addition to hydrodynamic factors, the high microplastic abundance at this station is also influenced by freshwater input from the Song River estuary, which transports microplastics derived from anthropogenic activities, including small-scale salted fish processing industries, batik textile industries, and vessel traffic in the estuarine and coastal zones.

Microplastic abundance at Station 2, the Song River Estuary, reached a concentration of 13.37 ± 0.44 particles/g. Overall, the abundance at Station 2 did not differ substantially from that at Station 3, as the influencing factors at both stations are relatively similar. The elevated microplastic abundance at Station 2 is attributed to anthropogenic activities in the estuarine area, such as fishing activities and vessel mobilization. In addition, pollution sources include effluents from batik production, salted fish processing, and domestic wastewater. This indicates a correlation between microplastic abundance and human activities, which is consistent with Yonkos *et al.* (2014), who reported that microplastic pollution levels are strongly influenced by human population density.

Another source of microplastic abundance at the estuarine station is vessel anchoring and traffic along the Song River. According to Laila *et al.* (2020) painted vessels (e.g., those coated with polyurethane, alkyd, or epoxy paints) moored in estuarine areas can contribute to increased microplastic abundance due to paint flaking. Microplastics may also originate directly from paint products that enter aquatic environments without prior degradation. In addition, domestic waste generated by local communities significantly contributes to microplastic loads in rivers, which are subsequently transported to offshore waters.

The lowest microplastic abundance was observed at Station 1, the Mangrove Ecotourism Area, with an average abundance of 5.87 ± 0.04 particles/g. The lower abundance at this station is attributed to reduced human activity, as tourism activities are limited to holidays, resulting in fewer plastic materials available for degradation. According to Susanto *et al.* (2023) mangrove ecosystems function physically as natural wave barriers, reducing current velocities toward the shoreline. This condition promotes the trapping and fragmentation of debris within mangrove root systems. Furthermore, Susanto *et al.* (2023) reported that microplastic abundance at the innermost mangrove boundary (0–80 m) is lower than at the outer mangrove boundary. This is also consistent with their findings that microplastic abundance is higher in zones with the highest tidal influence compared to zones with lower tidal influence.

Sediment grain size is another factor influencing microplastic abundance. Based on microplastic identification, the highest abundance was recorded at Station 3 (coastal area), where sediment composition consisted of 95.3% sand, 0.2% gravel, and 4.5% silt. This finding aligns with Hafitri *et al.* (2022) who reported that sediments with higher sand content tend to contain more microplastics. Sandy substrates are more capable of transporting and trapping microplastics within sediments. Similar results were reported by Laila *et al.* (2020) who found that sandy sediments are more effective at retaining microplastics compared to softer sediment textures such as silt and clay. The high microplastic abundance at the coastal station is also attributed to the higher porosity of sand compared to fine sediments, increasing the likelihood of microplastic entrapment.

Environmental conditions, particularly temperature, influence thermal degradation processes. Thermal degradation refers to the breakdown of plastics that occurs concurrently with photodegradation, especially in coastal environments (Zhang *et al.* 2021). This process is driven by ultraviolet (UV) radiation and temperature. Waters with higher temperatures are predicted to exhibit higher microplastic abundance (Yani *et al.* 2021). In addition, acidity (pH) is a chemical parameter required by bacteria for microplastic degradation processes (Ulufil *et al.* 2023). with optimal bacterial activity occurring at pH values ranging from 7 to 8. Consequently, the highest microplastic abundance was observed at Station 3, which exhibited the highest average temperatures among the three stations

(31–35°C) and pH values ranging from 7.2 to 8.5. Furthermore, current velocity also affects sediment transport processes. Based on observations (Figure 7), current velocities in the study area were relatively weak. According to Sigit (2019) waters with weak currents tend to have significantly higher microplastic abundance compared to areas with strong currents. Similar findings were reported by Vianello *et al.* (2013) who observed lower microplastic abundance in areas with strong currents (>100 cm/s) and higher abundance in areas with weak currents. As current velocity increases, microplastic particles are less likely to settle into sediments, thereby reducing microplastic abundance in sediments. According to Suteja *et al.* (2024) this occurs because high current velocities resuspend microplastics from sediments back into the water column.

Microplastic Characteristics

Microplastic Types

Microplastic types were classified following Yusron and Asroul Jaza (2021) into fragments, films, fibers, and pellets. One-way ANOVA was conducted to determine the significance of station-specific effects on microplastic types, with results indicating a significant influence ($F > F$ -critical and p -value < 0.05). Bar charts illustrating the distribution of microplastic types at each station are presented in Figure 4.

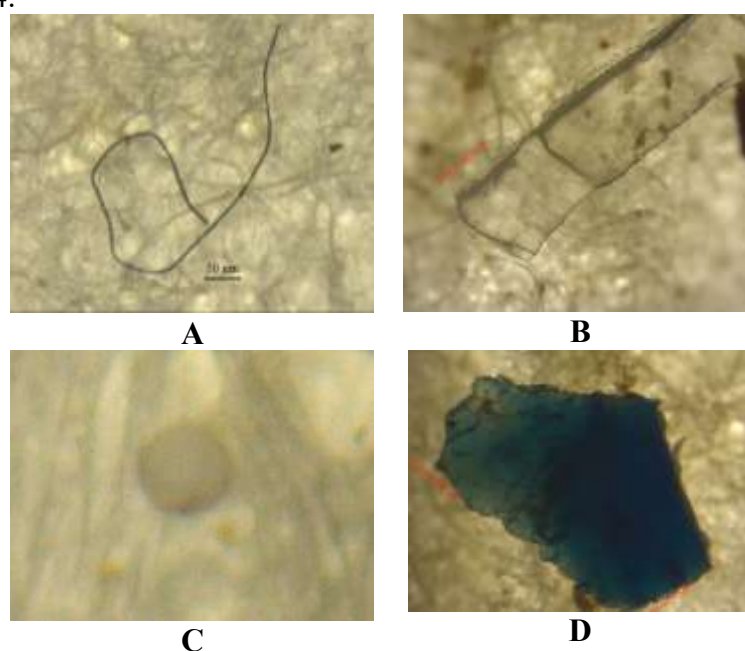


Figure 4. Results of Microplastic Type Observation
(Figure 4A) Fiber type
(Figure 4B) Film type
(Figure 4C) Pellet type
(Figure 4D) Fragment type

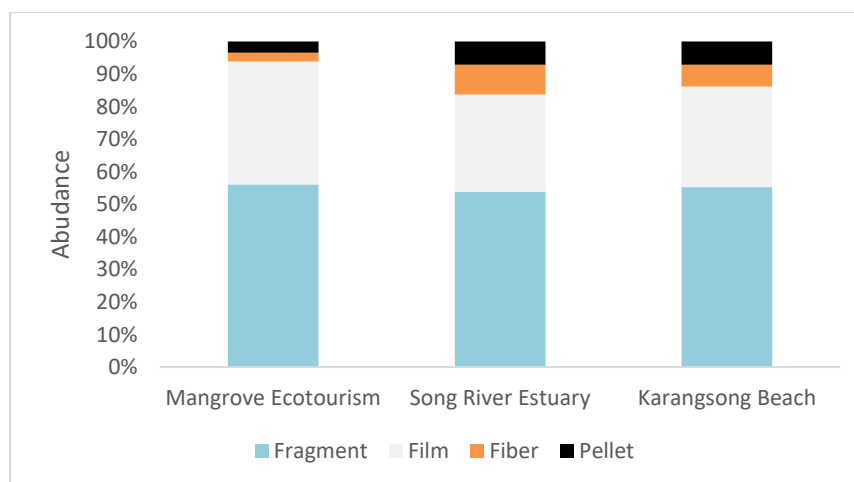


Figure 5. Distribution of Microplastic Types

Based on the identification results, the microplastic types found consisted of fragments, films, fibers, and pellets. This is consistent with Yusron dan Asroul Jaza (2021) who reported that the most commonly encountered microplastic types are fragments, films, fibers, and pellets. As shown in Figure 5, fragments were the dominant type across all three sampling stations. The high abundance of fragments in estuarine and coastal areas is consistent with findings reported by (Díaz-Jaramillo *et al.* 2021; Fok dan Cheung 2015; Gray *et al.* 2018; Horton *et al.* 2017). According to Sulastri *et al.* (2023) fragments originate from larger plastic items that undergo degradation due to ultraviolet (UV) radiation. Similarly, Pamungkas *et al.* (2022) stated that fragments are pieces of durable plastic polymers, such as those derived from beverage bottles and plastic water containers. Furthermore, Susanto *et al.* (2023) explained that the dominance of fragment-type microplastics in aquatic environments is associated with the high presence of dense macroplastics along shorelines, such as plastic bottles and household plastic waste. This observation aligns with field observations at all three stations, where beverage bottles and food packaging were commonly found. The predominance of fragments over other types is often linked to urban, industrial, and commercial activities (Suteja *et al.* 2024). The Mangrove Ecotourism Area also supports tourism activities, batik textile industries, salted fish processing, and residential settlements.

The second most dominant type across all stations was film. The high abundance of film at Station 1 can be attributed to its location at the innermost boundary of the mangrove area. Film particles have lower density compared to other types, making them more easily transported to the inner mangrove zone (Susanto *et al.* 2023). In addition, the high abundance of films is related to their widespread use in daily life, particularly as plastic packaging materials. Films are the result of fragmentation of plastics that readily break down at low density. Film microplastics are defined as thin, transparent sheet-like particles, generally originating from plastic bags and packaging materials with low density (Pamungkas *et al.* 2022). This is consistent with the high amount of plastic packaging and bottles associated with tourism activities at Station 1, which contributed to the greater abundance of film-type microplastics compared to other stations.

Fibers were the third most abundant microplastic type identified during the study. Fiber-type microplastics originate from fragmented fishing nets and synthetic textiles and are characterized by their elongated shape (Pamungkas *et al.* 2022). Generally, fibers in aquatic environments originate from anthropogenic activities, including domestic wastewater from laundry processes and fisheries activities such as fishing using nets. The high abundance of fibers in aquatic systems is attributed to their widespread use as raw materials for clothing, textile fibers, fishing nets, and household products (Susanto *et al.* 2023). This finding is consistent with the results of this study, where fibers were most frequently found at Station 2, which is strongly influenced by anthropogenic and fisheries activities. Based on interviews with the Head of the Pantai Lestari Group, the Song River estuary receives waste

inputs from batik industries, salted fish processing, and fishing vessel operations. Furthermore, the high abundance of fibers at the Song River Estuary and Karangsong Beach is consistent with the findings of Susanto *et al.* (2023) who reported that fibers, fragments, and pellets tend to be more abundant at the outer boundaries of mangrove areas. Materials commonly used in daily life, such as clothing and household furnishings, are made from natural or synthetic fibers, which are subsequently released into the environment. Therefore, these materials represent a major contributor to microplastic pollution. Browne *et al.* (2011) reported that polyester-based fabrics can release more than 1,900 microplastic fibers during a single washing cycle.

Pellets were the least frequently identified type of microplastic. Pellets are characterized by their spherical shape and smooth surface (Sulastri *et al.*, 2023). This type typically originates from cleaning products and raw materials used in plastic manufacturing. According to Hiwari *et al.* (2019) pellets are small, round particles with very low density and can have diameters as small as 1 μm . The low abundance of pellet-type microplastics in the study area is likely due to the absence of large-scale industrial plastic manufacturing facilities, with only small-scale household industries present. This finding is consistent with Sari Dewi *et al.* (2015) who stated that pellet-type microplastics originate from industrial production processes and are classified as primary microplastics.

Microplastic Size

One-way ANOVA testing to assess the effect of station-specific factors on microplastic size revealed a statistically significant influence, as indicated by $F > F\text{-critical}$ and $p\text{-value} < 0.05$. Microplastics identified in this study were predominantly smaller than 1 mm (98.42%) across all stations, compared to those larger than 1 mm (1.58%).

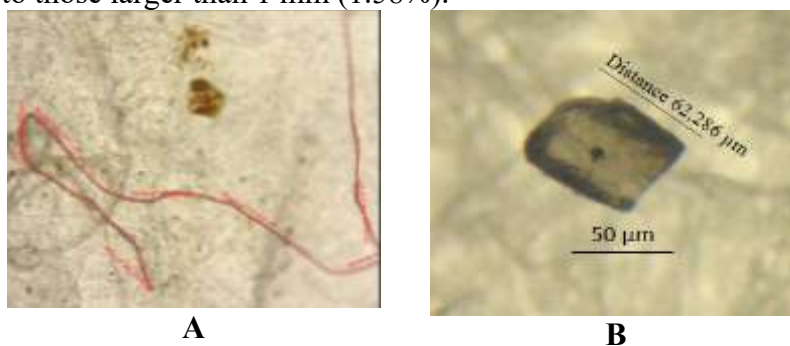


Figure 6. Results of Microplastic Size Observation
 (Figure 6A) Microplastics with a size > 1 mm
 (Figure 6B) Microplastics with a size < 1 mm

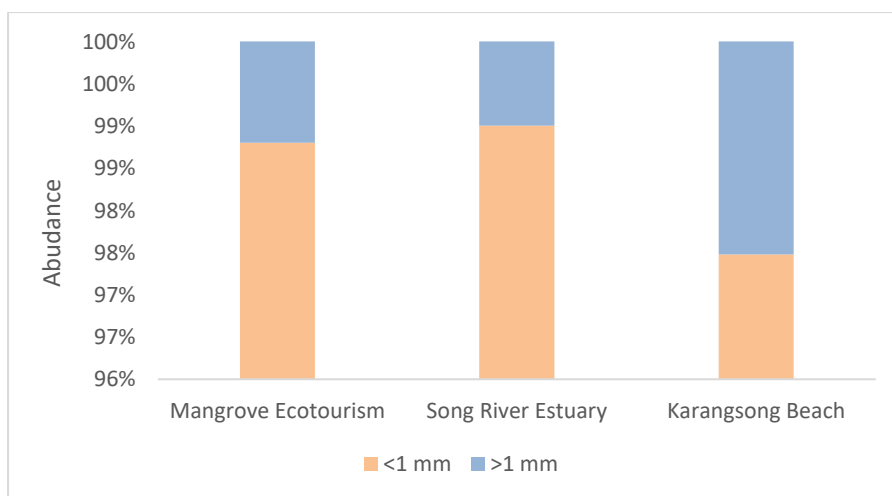


Figure 7. Distribution of Microplastic Sizes

Strock et al. (2015) classified microplastic particle sizes into two categories: particles smaller than 1 mm and particles ranging from 1 to 5 mm. Based on the observations, microplastics with sizes > 1 mm were the least frequently found at all sampling stations. In general, microplastics larger than 1 mm were predominantly composed of fibers. Microplastics smaller than 1 mm were the most dominant size fraction at all stations. According to Uurasjärvi *et al.* (2020), areas with high microplastic concentrations tend to be dominated by small-sized particles. Several studies conducted in Indonesia have also reported a predominance of small-sized microplastics; for example, Hafitri *et al.* (2022) found that 100% of the identified microplastics were < 1 mm in size. The high abundance of small-sized microplastics indicates prolonged degradation processes. According to Claessens *et al.* (2011) the degradation of plastics from macro- to micro-sized particles is driven by ultraviolet radiation, mechanical forces generated by ocean waves, oxidative substances, and the hydrolytic properties of seawater. In addition, Hebner (2020) stated that the prevalence of small-sized microplastics in sediments reflects long-term fragmentation processes, resulting in particles being broken down into smaller sizes. This is further supported by Shamskhany *et al.* (2021) who explained that microplastics initially float for extended periods in the water column before being transported by currents and eventually suspended and deposited in sediments.

Microplastic size is also a key factor determining the extent of its effects on aquatic organisms. Smaller microplastics tend to affect a greater number of biota (Salsabila *et al.* 2023). Numerous studies have reported that microplastics are ingested by aquatic organisms and may subsequently enter the human body through food consumption (Babel & Dork 2021). The micron-scale size of microplastics facilitates ingestion by particulate-feeding organisms, which may mistakenly perceive them as natural food items. Such organisms include zooplankton, mollusks, fish, crustaceans, and other aquatic fauna (Franzellitti *et al.* 2019). Biota that ingest microplastics may experience various physiological disturbances, including digestive tract impairment, inhibited growth, reduced enzyme production, decreased steroid hormone levels, and disruption of reproductive systems (Wright *et al.* 2013)

Microplastic Color

One-way ANOVA testing conducted on sediments from ecotourism areas, estuaries, and beaches indicated that differences in environmental factors at each station had a significant effect on microplastic color distribution ($F > F_{critical}$ and $p\text{-value} < 0.05$). The most dominant colors at all stations were yellow (32.91%) and transparent (30.65%).

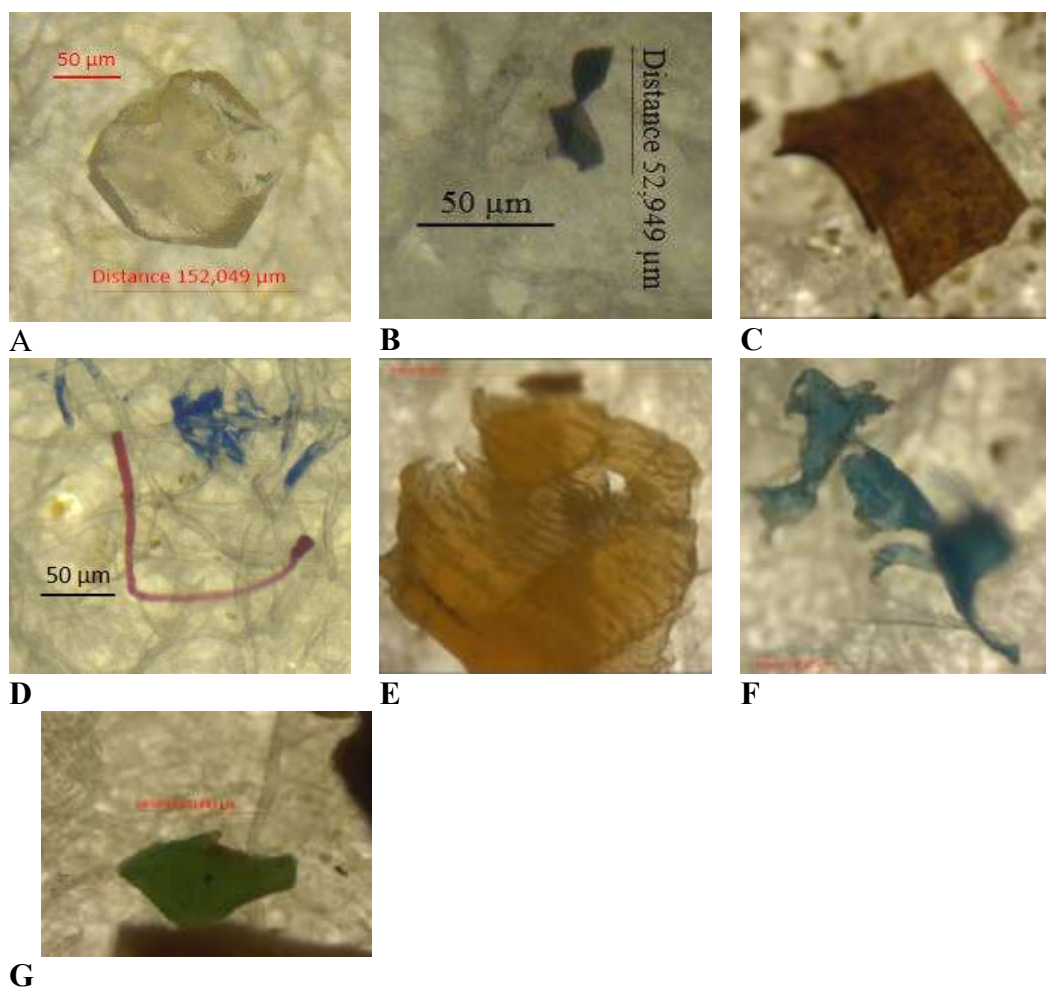


Figure 8. Results of Microplastic Color Identification
(Figure 8A) Transparent-colored microplastics
(Figure 8B) Black-colored microplastics
(Figure 8C) Brown-colored microplastics
(Figure 8D) Red-colored microplastics
(Figure 8E) Yellow-colored microplastics
(Figure 8F) Blue-colored microplastics
(Figure 8G) Green-colored microplastics

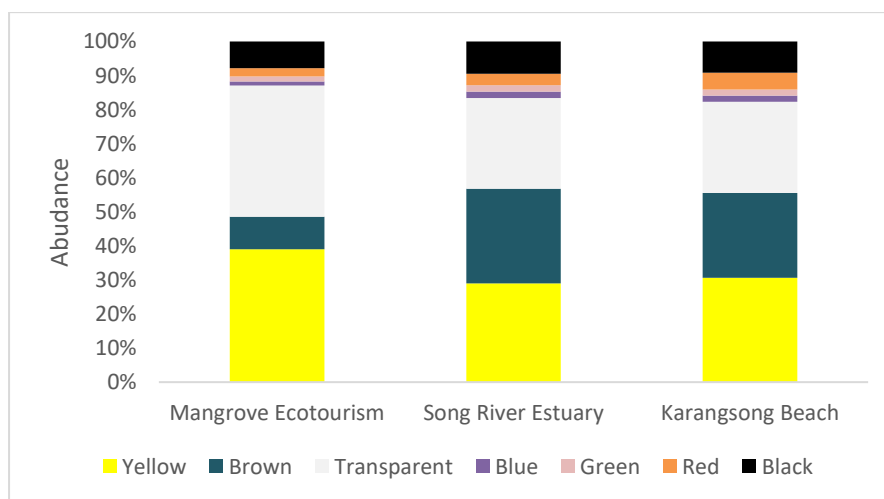


Figure 9. Distribution of Microplastic Colors

Microplastic color can provide information regarding the sources of waste pollution as well as the environmental condition of the microplastics themselves (Putri et al., 2023). Color characteristics also reflect the duration of microplastic exposure to sunlight and oxidative processes, which can induce color changes and result in variations among microplastic particles. Based on the identification results, the highest proportion of microplastic particles was yellow, followed by transparent and brown. Blue and green particles were the least frequently identified. These findings are consistent with the study by Frias and Nash (2019) which reported that the dominant microplastic colors were yellow, transparent, and black.

Photo-oxidative degradation resulting from light absorption and reflection alters the chemical composition as well as the physicochemical properties of microplastic particles (Chamas et al. 2020). Photo-oxidation in microplastics leads to color changes toward yellowing. Prolonged exposure to ultraviolet (UV) radiation can further transform yellow-colored microplastics into brown particles (Daryanto 2023). Yellow microplastics may also originate from packaging bags, fishing lines, or detergent residues (Ibrahim et al. 2023). Particles that were initially white can also turn yellow due to prolonged UV exposure (Frias dan Nash 2019 ; Kowalski et al. 2016).

The second most abundant color identified was transparent. Transparent microplastics may indicate the presence of polypropylene (PP), a polymer that is commonly found in aquatic environments. In addition, transparent microplastics can also reflect the duration of photo-degradation by UV radiation (Hiwari et al. 2019).

In addition to yellow and brown particles, many microplastics were identified in darker and more intense colors such as black, red, green, and blue. Generally, dark-colored microplastics have not undergone significant discoloration (Hiwari et al. 2019). Blue, green, and red microplastics are commonly associated with anthropogenic activities (Putri et al., 2023). Black microplastics have a high capacity to adsorb pollutants and may serve as indicators of absorbed contaminants, which can alter particle surface texture. Black microplastics were originally white, green, blue, red, or orange (bright) in color; however, heating during processing can cause the color to darken (Gunawan et al. 2021).

Brown-colored microplastics indicate prolonged exposure to sunlight and are often associated with the presence of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Salsabila et al. 2023). This is consistent with the statement by (Hidalgo-Ruz et al. 2012) that dark and intense-colored microplastics tend to contain chemical pollutants such as PAH and PCB.

CONCLUSION

Based on the results of the study, the following conclusions can be drawn:

1. The highest abundance of microplastics was found at Station 3 (Beach), with a concentration of 15.87 ± 1.05 particles/g. This condition is attributed to intensive human activities at the station, relatively low current velocity (0.051–0.057 m/s), high temperature (33.75 °C), and a pH value (7.75) that is favorable for the activity of plastic-degrading microorganisms. In contrast, the lowest microplastic abundance was identified at Station 1 (Ecotourism Area), with a concentration of 1.25 ± 0.04 particles/g.
2. All three stations were predominantly composed of fragment-type microplastics (55.04%) and film-type microplastics (32.8%). The dominant microplastic size at each station was <1 mm (98.42%). In addition, the colors identified across all stations included yellow, transparent, brown, black, blue, green, and red, with yellow (32.91%) and transparent (30.65%) being the most dominant.

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