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# Microplastic pollution in beach sediments influenced by fishing and tourism in Cirebon, Indonesia

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## Abstract

Coastal areas support diverse human activities such as fishing, aquaculture, salt farming, and tourism, but are increasingly vulnerable to plastic pollution. This study investigates microplastic (MP) contamination in beach sediments of Cirebon, Indonesia, a densely populated coastal city which plays a significant role in trade, industry, fisheries, port-based commerce, and tourism. Fifteen sediment samples were collected from five sites, representing both fishermen settlements (9 samples) and tourist beaches (6 samples). Samples were collected using a 0.5 × 0.5-meter steel quadrat from the top 1 cm of sediment. MPs were extracted via density separation using a NaCl solution and then identified under a stereomicroscope. Polymer composition was determined using FTIR spectroscopy, while particles too small for FTIR were further analyzed with Raman micro-spectroscopy. The average MP abundance was  $583.33 \pm 166.09$  particles·kg<sup>-1</sup> dry weight. Although particle abundance did not significantly differ among sites, significant variation was observed in MP size. Smaller particles (<1 mm) comprised 51% of total MPs. Films were the dominant morphotype (84%), with white being the most common color (48%). Fourier Transform Infra-Red analysis of MPs sized 2–5 mm identified polyethylene as the most abundant polymer (50%), commonly used in packaging and household products. Raman spectroscopy also revealed organic pigments potentially containing metal-based fouling agents. The dominance of plastic films, especially near settlements, suggests direct household waste discharge into the ocean. These findings highlight the role of human activity and inadequate waste infrastructure in driving coastal MP pollution. Effective waste management strategies and public awareness are essential to mitigate further contamination and protect coastal ecosystems.

## 1. Introduction

Plastic products have become an integral part to modern society, valued for their cost-effectiveness and convenience. Unfortunately, a significant amount of plastic waste ends up in the natural environment due to human activities, accumulating because of poor waste management practices (Jambeck et al., 2015). Research indicates that 80% of oceanic plastics originate from land-based activities, such as inadequate waste management, industrial processes, littering, tourism, and deficient waste disposal systems (Andrady, 2011; Jambeck et al., 2015). In the environment, large plastic items break down into smaller pieces less than 5mm, known as microplastics (MPs), through processes like mechanical wear, ultraviolet

radiation exposure, and thermal breakdown (Andrady, 2011; Kalogerakis et al., 2017). MP are now a widespread concern, found in marine environments worldwide, from densely populated urban areas to remote beaches, coral reefs, mangroves, and deep-sea sediments (Aslam et al., 2020; Cordova et al., 2021; Dowarah and Devipriya, 2019; Utami et al., 2021; Van Cauwenberghe et al., 2013). Their presence and density are notably higher near areas with dense human populations (Utami et al., 2025), highlighting the pressing need for effective waste management.

The ecological and health impacts of MPs have become a focal point of concern. MPs are physical hazards to organisms if ingested, the effect include inflammation, metabolic disruptions, growth and reproduction issues, and even mortality (Rochman et al., 2015). Apart from physical impacts, ingestion of MP can also have chemical effects. Marine plastic debris can be a vector for the absorption or transport of waterborne chemical pollutants, including polychlorinated biphenyls, polycyclic aromatic hydrocarbons (POPs), and organochlorine pesticides (Ivar do Sul and Costa, 2014; Teuten et al., 2009). Marine organisms are particularly vulnerable to plastic pollution through ingestion due to their ubiquity, larger surface area to volume ratio and small size (Barnes et al., 2009). The ecological impact of MPs as emerging contaminants are under intense scrutiny due to their potential to accumulate in ecosystems and pose risks to human health (Rochman et al., 2015; Teuten et al., 2009).

Coastal zones are key areas where the ocean and land interact, providing diverse ecosystem services. While the dense population in these areas brings significant economic advantages, it also places immense pressure on coastal ecosystems. Rapid urbanization and industrialization have had profound negative effects on these ecosystems, such as accumulation of heavy metals on coastal sediment (Nurhidayati et al., 2023). One of the most significant human-induced threats to marine and coastal ecosystems is the accumulation of debris, particularly plastic pollution. Plastic debris littering beaches worldwide poses a direct threat to marine life's health. Therefore, managing MP pollution requires adequate waste management infrastructure and community involvement such as regular waste collection efforts to prevent further degradation and reintroduction into the marine ecosystem (Kalogerakis et al., 2017).

Various factors are responsible for composition, distribution, and quantity of MPs particles in an environment. Recreational activities are one such factor that contributes to an increase in both the quantity and morphological types of MPs found in natural environment. Beaches that have high tourism activity have higher MP density (Chen and Chen, 2020). Fishing practices can significantly influence the prevalence of MPs, especially in areas lacking proper garbage disposal and cleaning systems (Dowarah and Devipriya, 2019; Utami et al., 2021). Fishery activities contribute to MP pollution by releasing plastic polymers fibers and fragments due to accidental loss, intentional abandonment, or the regular wear and tear of fishing equipment and related items (Zhang et al., 2021).

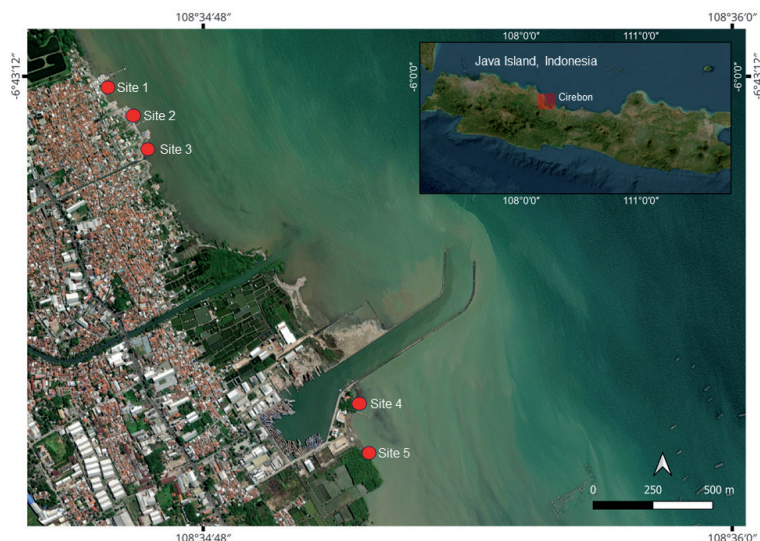
Studies on MP pollution in Indonesian coastal areas have been conducted in various locations. In the Jagir River, Surabaya, the highest MP abundance was found near the river mouth, dominated by fibers. MPs were extracted from five sites using density separation and identified using FTIR. Improper solid waste disposal was identified as the main source of pollution (Firdaus et al., 2020). In Jakarta Bay, MPs were reported in high abundance, with fragments being the dominant type (Manalu et al., 2017). Samples were collected from two locations (Pluit and Ancol) using a van Veen grab, followed by FTIR analysis. High anthropogenic activity along rivers feeding into Jakarta Bay likely serves as a major transport pathway for MPs into coastal sediments. In the Muara Angke mangrove reserve, foams were the most prevalent MP type, with over half measuring  $<1000 \mu\text{m}$  (Cordova et al., 2021). Surface sediments ( $1.5 \times 1.5 \text{ m}^2$  transects) were analyzed using FTIR. The site's proximity to dense urban areas is likely a key factor in MP accumulation. On small reef islands in the Kepulauan Seribu, fiber was the most dominant MP type, with all particles classified as secondary MPs, likely originating from both local and marine sources (Utami et al., 2021). Sediments were collected across reef zones, processed via density separation, and analyzed using  $\mu\text{FTIR}$ . Hence, across diverse ecosystems from rivers to mangroves to coral reef islands, MP contamination in Indonesia consistently reflects strong links to human activity and waste mismanagement.

This study endeavors to contribute to the present knowledge on MP contamination in the marine environment. This study proposes to assess the presence of MPs in beach sediment of a coastal region in Cirebon, Indonesia; to identify the types of polymers; and to confirm the findings by FTIR and Raman spectroscopy. As a densely populated coastal city in the northern Java, Cirebon holds strategic importance in various sectors. It serves as a regional hub for trade and industry, particularly in oil, gas, and manufacturing. The city is also known for its active fishing communities and busy port, which support both local livelihoods and regional commerce. In addition, Cirebon is a well-known cultural and tourism destination, attracting visitors with its rich heritage and coastal attractions. These overlapping human activities make Cirebon a relevant site for studying environmental issues such as MP pollution. By contributing to the current understanding of MP contamination in marine sediments, this research seeks to inform future management and control strategies for MP pollution in coastal regions.

## 2. Study area

Cirebon, located along the northern coastline of Java Island, Indonesia, is strategically located coastal city known for its significance in trade, industry, and tourism. The lithology in the area is dominated by carbonate sandstone (Praptisih et al., 2012). Cirebon region is vulnerable to human activities such as dredging, aquaculture, and waste disposal, as well as natural processes such as sedimentation and erosion, both of which can significantly affect local environment (Hartiningsih et al., 2024). The majority of Cirebon's population lives in coastal areas and depends on the utilization of coastal environmental resources, such as fishing, inland fisheries, salt farming, and marine tourism. With a population of more than 330,000 people (BPS, 2021), Cirebon City produced 74.6 million tons of waste in 2021, of which 19% (14.2 Mt) was plastic (KLHK, 2021). Cirebon is among the coastal cities in Indonesia suffering from pollution due to uncontrolled waste management. About 60% of Indonesia's population lives in coastal areas and is very dependent on marine resources (BPS, 2020). Despite the widespread awareness of the harmful nature of plastics, the accumulation of MPs along Indonesian coastline has not received the attention it deserves.

This study was divided into two main areas, the beach at fisherman settlements and the ecotourism beach with sparse mangrove vegetation (Figure 1). There are in total five sampling sites; sites 1, 2, and 3 represented the settlements, while sites 4 and 5 represented the ecotourism beach. Based on field observations at the five sampling sites, the beach is mainly covered with greyish-black, muddy sand. Data from Cirebon's Port suggest the average sea level is around 139 cm, with the lowest sea level reaching 60 cm below this average (Raharjo and Faturachman, 2003). The region experiences mixed, predominantly semi-diurnal tides (Raharjo and Faturachman, 2003). Surface currents vary slightly between high tide at an average velocity of 0.072 m/s, and low tide at 0.075 m/s. Winds primarily blow from the northeast to the southwest (Raharjo and Faturachman, 2003). The area's current patterns are shaped by a mix of tidal forces, wind direction, and inflow from major rivers (e.g., the Bondet River, Pengarengan River, Bangkaderes River) into the sea (Raharjo and Faturachman, 2003).



**Figure 1.** Map of study area and sampling locations on the coast of Cirebon, north of Java.

### 3. Data and methods

Beach sediments were collected from the wrack line in the five designated sampling sites (Figure 1). At each site, a 100-meter transect was established, and three samples were collected along this transect as a practical approach to ensure the data collected would be representative for analysis (following Aslam et al., 2020). Sample collection was performed using a steel quadrat measuring 0.5 x 0.5 meters. From within each quadrat, only the top 1 cm of sediment was collected using a clean stainless-steel tool. Therefore, for each site, three surface sediment samples (0.5 m × 0.5 m × 1 cm) were obtained for laboratory analysis, resulting in a total of 15 samples across all five sites. The exact positions of the sample sites were recorded using a portable Garmin GPS unit.

15 samples from five locations were selected using a stratified and representative sampling design to capture spatial variability in MP contamination within the limits of time, resources, and analytical capacity. Each site was strategically chosen to reflect distinct environmental pressures such as fishing, tourism, and coastal mangroves (Table 1), ensuring adequate representation of both anthropogenic influence and ecological diversity. Following international recommendations, particularly the GESAMP (2019) guidelines, the focus was placed on sample representativeness rather than quantity, recognizing that smaller, well-chosen sample sets are appropriate for preliminary or baseline assessments.

In the laboratory, the wet sediment samples were first placed in a metal oven safe bowls then dried in an oven set at 70°C for 24 hours to remove moisture. Around 100 grams of the dried sediment was sieved through a 5 mm mesh, with the materials that did not pass through being discarded and the finer particles collected for further analysis (Dowarah and Devipriya, 2019). Visible MPs were handpicked from this refined sediment and stored in petri dishes for detailed examination. For the detection of non-visible MPs, a density separation technique was utilized. A supersaturated NaCl solution was prepared by dissolving 337 g of NaCl in 1 L distilled water to reach a density of 1.2 g/cm<sup>3</sup>, chosen for its safety, neutrality, and cost-efficiency (Coppock et al., 2017). The sediment was mixed with 500 mL of NaCl solution in a 1000 mL glass beaker. The mixture was stirred for five minutes to loosen any MPs particles that might be trapped between the sand particles, and left to settle for two hours under a fume hood. The clear supernatant above the sediment was then carefully transferred to a beaker and was vacuum filtered through a 0.45 µm Whatman membrane filter.

After the density separation process, the particles collected on the filters were carefully examined under a stereomicroscope (Nikon DS-Fi2, Japan) to assess their shape, color, and other physical traits. Fibers were described as filamentous strands or threads, films as two-dimensional shapes, and fragments as three-dimensional objects (Expósito et al., 2021). Characteristics of MPs included unnatural colors, shiny surfaces, and irregular shapes (Martin et al., 2019). The MPs were then photographed at various magnifications to document their specific characteristics.

The Kruskal-Wallis (KW) test was applied among the five surveyed sites to assess if the MP abundance and size varied significantly across the sites. To further identify the sites between which the abundance and size varied significantly, a Post hoc Tukey test was utilized (Dowarah and Devipriya, 2019). Results are presented as mean ± standard error (SE). Statistical significance set at  $p < 0.05$ . All statistical analyses were performed using the PAST software version 3.15 (Hammer et al., 2001).

To reduce the introduction of MP contaminants in the lab, extensive precautions were taken (Lusher et al., 2017). This included the preferential use of non-plastic tools, wearing of cotton garments to minimize contamination, surface cleaning prior to sample handling, and washing all glass with deionized water before and after use.

To determine the polymer composition of the MPs found during the visual examination, Fourier Transform Infrared (FTIR) spectroscopy was employed (Thermo Scientific Nicolet iS5, equipped with a diamond iD5 ATR accessory). Only MPs that were large enough (>2 mm) were analyzed by the FTIR. For the FTIR analysis, 34 representative MPs particle were selected based on their size for easier handling with tweezers. The spectral data were collected in a resolution mode of 8 cm with a range between 600 and 3800 cm<sup>-1</sup>, conducting 16 scans for each sample. The spectra were then analyzed using Open Specy software and its comprehensive spectral library for polymer identification (Cowger et al., 2021). Only

spectra that match with a similarity of 70% or higher with the reference spectra were accepted for determining the polymer types of the samples.

Additionally, Raman micro-spectroscopy was utilized for MP particles that were too small to be examined by FTIR spectroscopy. Raman spectroscopy is known for its surface analysis capability, allows for the investigation of MP particles across a broad range of sizes. This includes very small particles which can be visually sorted and studied in conjunction with microscopy (Araujo et al., 2018). A total of six samples were studied using the Horiba LabRam HR Evolution Raman Spectrometer (Horiba Jobin Yvon). This instrument operates with a laser wavelength of 785 nm. The MP samples were prepared by carefully transferring them from their filters onto microscope slides. The Raman spectra of these samples were recorded across a spectrum range of 50 to 4000  $\text{cm}^{-1}$ . The acquired data was then analyzed using LabSpec 6 software (Horiba Scientific) to identify the MP particles. Only spectra that match with a similarity of 70% or higher with the reference spectra were accepted for determining the polymer types of the samples.

## 4. Results and discussion

### 4.1 MP abundance

Our research across five sites at Cirebon beach revealed an average MP concentration of  $583 \pm 166$   $\text{particle.kg}^{-1}$  DW, as shown in Table 1. The highest level of MP in sediment was observed at Site 1 ( $1,380 \pm 514$   $\text{particle.kg}^{-1}$  DW), with subsequent concentrations noted at Site 3 ( $770 \pm 295.01$   $\text{particle.kg}^{-1}$  DW) and Site 2 ( $543 \pm 203$   $\text{particle.kg}^{-1}$  DW). These sites, located near fishermen's residences and utilized as mooring spots for small boats, contrast with the lower concentrations found at the more touristic Sites 5 and 4, which had  $153 \pm 113$   $\text{particle.kg}^{-1}$  DW and  $70 \pm 25$   $\text{particle.kg}^{-1}$  DW, respectively. Sites 4-5 were tourist beaches with sparse mangrove vegetation. Despite the differing levels, the Kruskal-Wallis H test ( $KW = 8.867$ ,  $p\text{-value} = 0.06$ ) and the subsequent Tukey post hoc test ( $p > 0.05$ ) indicated a lack of statistically significant differences in MP abundance across the sites.

**Table 1.** MP abundance in the Cirebon coast.

MP ( $\text{particle.kg}^{-1}$ DW) in beach sediment			
Location	Site description	Average of each site ( $\pm$ SE)	Total average ( $\pm$ SE)
Site 1	Fishermen residence	$1,380 \pm 514$	$583 \pm 166$
Site 2	Fishermen residence	$543 \pm 202$	
Site 3	Fishermen residence	$770 \pm 295$	
Site 4	Touristic, localized mangrove	$70 \pm 25$	
Site 5	Touristic, localized mangrove	$153 \pm 113$	

Table 2 compares results from various beaches using similar sampling methods and the same units of measurement. While local conditions may differ, this global comparison provides context for understanding where our result fit relative to other studies. The average MP concentration in Cirebon beach sediment is comparable to global averages. In Asia, Qinzhou Bay, China (Li et al., 2018), and Thailand (Bissen and Chawchai, 2020) have reported higher average MP levels in beach sediments. Notably, the highest concentrations were found in sediment samples near areas of intense human activity along the coast, including aquaculture, fisheries, and tourism zones (Bissen and Chawchai, 2020; Li et al., 2018). Fishing have been identified as a major contributor to MP pollution in the marine sediment due to large involvement of plastic gear (Dowarah and Devipriya, 2019; Lusher et al., 2017; Utami et al., 2021). Similarly, coastal tourism and recreational activities are also major contributors to the MP problem in the coasts mainly due to the use of single use plastics (Dowarah and Devipriya, 2019; Ronda et al., 2023).

This study found high concentrations of MPs in sites near fishermen's settlements, primarily due to factors such as high levels of solid waste generation, dense population, intense boating activity, and improper disposal of solid waste (Figure 2). The lack of municipal waste facilities and services is identified as the main cause of MP pollution on the Cirebon fishermen village beach, similar to other local fishing villages in India (Dowarah and Devipriya, 2019) and Indonesia (Firdaus et al., 2020). In contrast, lower levels of MPs were observed on tourist beaches, which can be attributed to better waste management infrastructure, including the

availability of waste bins (Oliveira et al., 2023). The tourist beach examined in this study is government-owned and equipped with proper waste disposal facilities and regular cleaning services. This infrastructure encourages the public to avoid discarding waste directly into the ocean. These bins play a crucial role in promoting sustainable practices, such as proper solid waste management, as daily waste generation and improper storage can lead to environmental contamination and pose risks to human health (Oliveira et al., 2023).

**Table 2.** MPs levels on sandy beaches.

Sampled beach	MP in sediments (particle $\text{kg}^{-1}$ DW)	Reference
Belgium	52.8-213.4	(Claessens et al., 2011)
Slovenia	178	(Laglbauer et al., 2014)
Northeast Atlantic	1 to 3,146	(Maes et al., 2017)
North Yellow Sea, China	$37.1 \pm 42.7$	(Zhu et al., 2018)
Qinzhou Bay, China	3,266	(Li et al., 2018)
Caribbean	261	(Bosker et al., 2018)
Puducherry Coast, India	$720 \pm 191.60$	(Dowarah and Devipriya, 2019)
Tamil Nadu, India	$119 \pm 72$ to $439 \pm 172$	(Sathish et al., 2019)
Dubai	59.71	(Aslam et al., 2020)
Thailand	420 to 200,000	(Bissen and Chawchai, 2020)
Virginia & North Carolina, USA	$1,410 \pm 810$	(Dodson et al., 2020)
Auckland	6	(Bridson et al., 2020)
Taiwan	80-480	(Chen and Chen, 2020)
Vietnam	295	(Hien et al., 2020)
Portugal	100	(Chouchene et al., 2021)
Phuket, Thailand	$188.3 \pm 34.48$	(Akkajit et al., 2021)
Bangladesh	$368.68 \pm 10.65$	(Hossain et al., 2021)
Argentina	$1133.3 \pm 811.3$	(Ronda et al., 2023)
Jakarta Bay, Indonesia	18,405 to 38,790	(Manalu et al., 2017)
Jagir estuary, Indonesia	414	(Firdaus et al., 2020)



**Figure 2.** (A) Plastic bags found on the beach adjacent to fishermen's settlement due to improper waste disposal. (B) Localized mangroves on the touristic beach.

Mangrove vegetation at Site 4-5 to some extent may contribute to lower MP concentration since mangroves are known to trap marine plastic debris (Figure 2) (Cordova et al., 2021; Ivar do Sul and Costa, 2014; Martin et al., 2019; Mohamed Nor and Obbard, 2014). Mangrove region in Cirebon exhibited higher MP levels (Table 1) compared to the mangrove wildlife reserve in Muara Angke, Jakarta, Indonesia which amount for  $28.09 \pm 10.26$  particle. $\text{kg}^{-1}$  DW (Cordova et al., 2021). The findings in Muara Angke mangrove wildlife reserve matched those reported in both the Singapore coastal mangrove area ( $36.8 \pm 23.6$  particle. $\text{kg}^{-1}$  DW) (Mohamed Nor and Obbard, 2014) and the north coast of the Persian Gulf ( $19.5 - 34.5$  particle. $\text{kg}^{-1}$  DW) (Naji et al., 2019). The lower levels of MPs found in Muara Angke mangrove

wildlife reserve were linked to Jakarta's successful river and coastal cleanup efforts (Cordova et al., 2021).

#### 4.2 MP characteristics: shape, color, and size

This study categorized the identified MPs into three morphological types: fibers, films, and fragments (Figure 3A). Film is the most abundance MPs in terms of shape (84%), followed by fibers (14%), and fragment (1%). The abundance of MP particles in terms of colours are white (48%), blue (28%), green (11%), red (6%), black (5%), and yellow (2%). The MP particles found in this study typically measured between 5.0-0.5 mm.

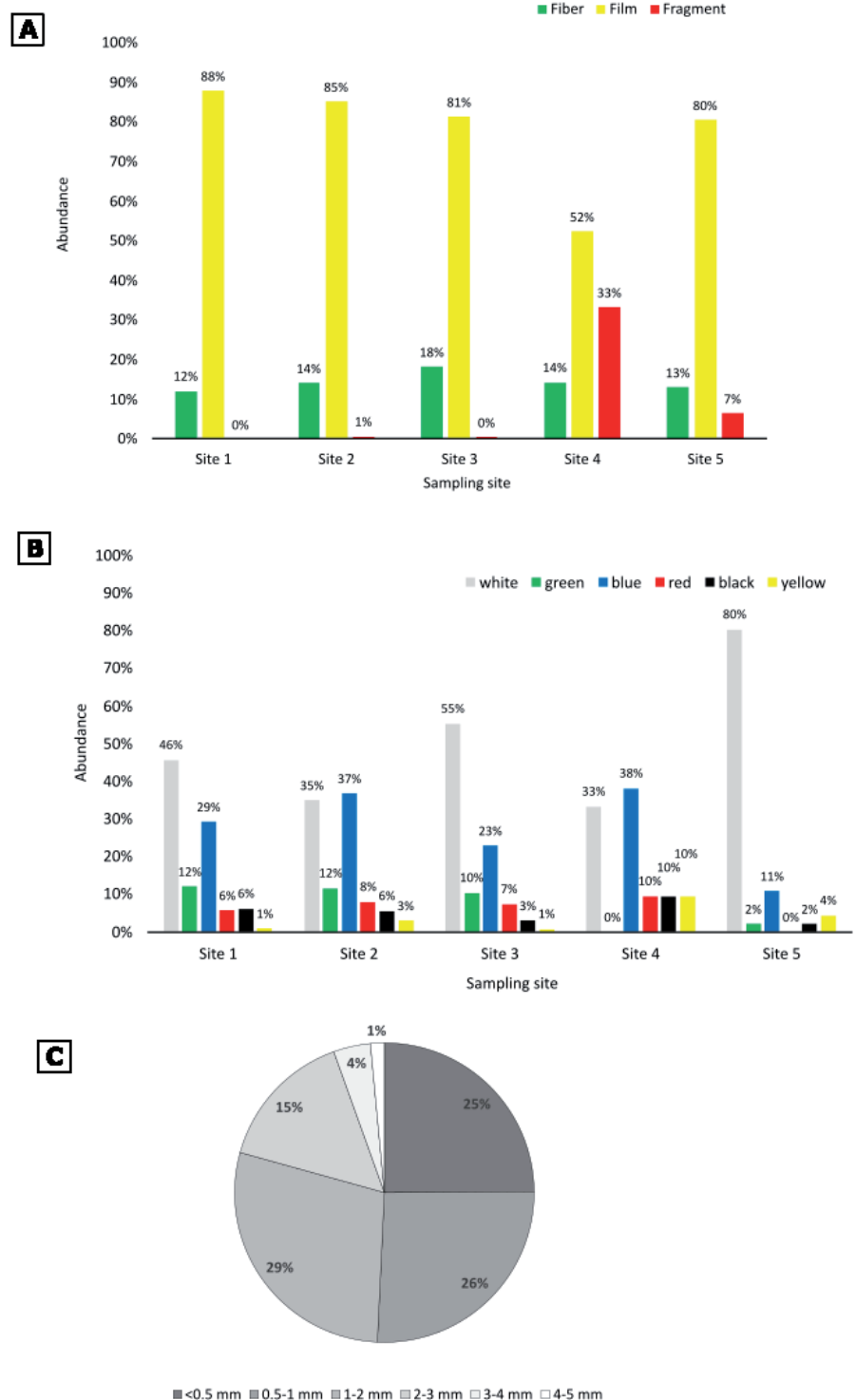
The diversity of MP shapes observed along Cirebon's beaches may reflect the area's range of human activities. The significant presence of MP films in the study area is believed to originate from the degradation of household waste, including plastic bags and food packaging. Based on field observations, these litter were often found to be disposed directly into the sea especially at the beach near the settlement. Beach sediments in the North Yellow Sea of China are heavily contaminated with MP films, primarily due to discarded non-degradable plastic bags, despite regulatory limits on their use (Zhu et al., 2018). Experimental studies have shown that plastic bags left outdoors on sand bed can fragment into MPs within six months due to sunlight and mild mechanical stress (Kalogerakis et al., 2017). The process of plastic degradation is accelerated by high temperatures and the intense UV light typical of tropical climates (Lambert et al., 2013). Consequently, plastics degrade more rapidly on beaches, where sand can reach higher temperatures than seawater, facilitating quicker light-induced oxidative degradation (Arthur et al., 2009). Study implied that beached plastic debris should be regularly collected from the seashore before they are weathered by sunlight and returned to the sea as MPs. Considering the extensive use of plastic film, it's crucial to raise public awareness about MP pollution in marine ecosystems caused by improper disposal of plastic films.

The least MP content identified in this study was fragments, accounting for approximately 1% of the total MP composition. Although present in small quantities, the presence of fragments is environmentally significant. Fragments typically originate from the breakdown of larger plastic items, such as packaging materials, containers, or household waste. Their presence indicates ongoing degradation of macroplastic debris in the environment, reflecting long-term plastic pollution and the persistence of plastic waste in coastal areas. Even in low concentrations, fragments can pose ecological risks due to their irregular shapes and potential to adsorb harmful pollutants.

Research indicates that the color of MPs plays a significant role in attracting marine organisms to ingest them (Abayomi et al., 2017). The color of MPs not only reveals their synthetic origin but also influences their interaction with marine life (Retama et al., 2016). This study found white MP as the most prevalent (Figure 3B). Studies found that fish feeding on zooplankton are more likely to consume MPs that mimic their natural prey in color, such as white, tan, yellow, and translucent (Cole et al., 2011). Colorless and white plastic fragments are reported as the predominant type of plastics responsible for the deaths of sea turtles due to ingestion (Bugoni et al., 2001).

This study found that 49% of the particles identified were large MPs, defined as those larger than 1 mm, while 51% were small MPs (Figure 3C). The size of the MP particles vary significantly among sites (KW = 14.39,  $p$ -value = 0.005). Post hoc Tukey Test showed that the MP levels varied significantly at  $p < 0.05$  between the following sites combinations: Site1 vs Site 4 ( $p = 0.002$ ) and Site 1 vs Site 5 ( $p = 0.004$ ). Numerous factors affect the breakdown of MPs and can alter their size. These factors include mechanical crushing, temperature fluctuations, pH levels, exposure to UV radiation, duration in the environment, and the type of polymer involved (Liu et al., 2022). The size of MPs plays a crucial role in their potential impact on the ecosystem. It not only affects how they behave in the environment but also determines their ultimate fate, as different sizes have varying impacts on ecosystem biota. This size factor is particularly significant because MPs can be ingested by various marine organisms (Cole et al., 2011). MPs measuring below 0.04 mm are of particular concern because they can easily enter the trophic web, given their similarity in size to most micro and nanoplankton (Moore et al., 2001). Once ingested by organisms, MPs may find their way into the human food chain.

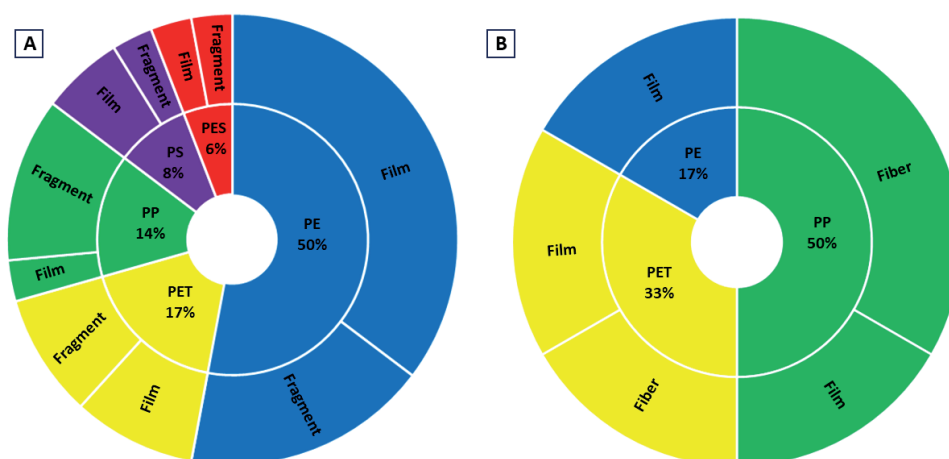
The observed differences in MP size among the sampling sites may be attributed to several local factors. In areas near fishermen’s settlements (e.g., Site 1), higher levels of physical activity such as boat docking, net dragging, and waste disposal could accelerate the fragmentation of larger plastic debris into smaller particles through mechanical abrasion. In contrast, sites with lower human disturbance, like the touristic beaches (Sites 4 and 5), may experience less frequent physical degradation. Environmental conditions, including UV exposure, tidal movement, and sediment grain size, also influence the rate of plastic breakdown (Arthur et al., 2009; Lambert et al., 2013; Liu et al., 2022). Beaches with prolonged sun exposure may promote faster photo-oxidative degradation (Kalogerakis et al., 2017; Lambert et al., 2013). These combined factors likely contribute to the variation in MP size distribution across the sites.



**Figure 3.** MP abundance (in percentage) in terms of different shape, color, and size.

### 4.3 MP polymer

Of the 34 representative particles tested with FTIR, all could be confirmed as polymers. These MPs were either films or fragments (Figure 4). The tested samples were predominantly consisted of polyethylene (PE, 50%), followed by polyethylene terephthalate (PET, 17%), polypropylene (PP, 14%), polystyrene (PS, 8%), and polyesters (PES, 6%). Additionally, six samples analysed using micro-Raman spectroscopy revealed the presence of PP (50%), PET (33%), and PE (17%). The samples for Raman were films and fibers (Figure 4). Differences in polymer compositions between FTIR and Raman analyses were observed in this study due to factors related to the shape and size of the samples. While fragments and films were found to consist of PE, PET, PP, PS, and PES, fibers were observed to consist of only PP and PET.



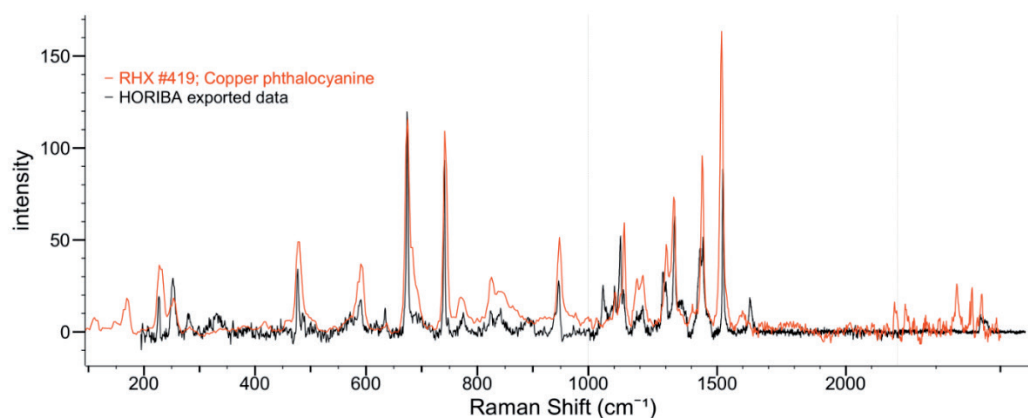
**Figure 4.** Distribution of polymer of the selected MPs based on (A) FTIR and (B) Raman analyses. The central circle indicates the polymers type, while the outer circle specifies the MP' shape corresponding to each polymer type.

Most polymers identified in this study are used in the manufacture of various fishing equipment and gear and single use plastics. PE, PET, and PP are commonly found in reusable bags, food packaging, disposable containers, fishing gear and are abundant in estuarine sediments and sandy beaches around the world (Akkajit et al., 2021; Dodson et al., 2020; Utami et al., 2023). PE and PP also were the most leading polymer in plastic production covering 50% of the European plastic demand (PlasticsEurope, 2021). Polystyrene is used in cool boxes, containers, and floats (Dowarah and Devipriya, 2019). Polyester fibers can be released into the marine environment from washing clothes made of synthetic materials (Napper et al., 2022).

Research conducted at the river estuaries in Cirebon has shown that the area is significantly polluted with solid waste, predominantly thin plastic packaging, stemming from socio-economic activities including households, tourism, and fishing (Astuti et al., 2023). Improper disposal of both organic and inorganic waste at the Cirebon sea near fishermen's residence has led to a decrease in dissolved oxygen levels, potentially impacting marine life in the area (Sudirman and Husrin, 2014). In Muara Angke (Jakarta, Indonesia), polystyrene was identified as the predominant polymer in sediment samples, a result of the accumulation of Styrofoam fragments (Cordova et al., 2021). Similarly, in Surabaya's coastal sediment, polyester was the most common MP polymer which mainly originating from textiles and fishing gear (Firdaus et al., 2020). The varied distribution of MPs across Indonesian locations, such as PE films in Cirebon, PS foams in Jakarta, and PES fibers in Surabaya, reflects the distinct sources of pollution in each area but underscores the broader issue of waste from human activities.

Additionally, six samples were tested using micro-Raman spectroscopy. The pigment copper phthalocyanine (blue pigment) was detected in one of the fibre samples (Figure 5). Copper phthalocyanine is an organic pigment that does not occur naturally, suggesting the sample's anthropogenic origin (Van Cauwenberghe et al., 2013). Such pigments are extensively utilized in the plastics industry (Lewis, 2004), further indicating that the fiber is a plastic particle. Polymer dyeing is becoming a necessity when it comes to the customer market. However,

dyes and additives are harmful to the environment as they can leach from the particles and pose threat to biota. Research reveals that paints containing metal fouling agents such as copper-based compounds can contribute to heavy metal pollution that may impact marine life and the environment, therefore monitoring marine litter associated with antifouling paints should be an important concern in the current marine framework (Brennecke et al., 2016).



**Figure 5.** Raman spectroscopy identified the widely used pigment copper phthalocyanine (blue pigment) in one of the samples from Cirebon beach.

## 5. Conclusions

The results of this study indicate that MP particles are present on the beach of Cirebon, associated with settlement and recreational activity. The average density of MP at all sites was  $583.33 \pm 166.09$  particle.kg<sup>-1</sup> DW. There was no significant difference in MP abundance among sampling sites, but there was a significant difference in MP size among sites. The predominant type of MPs was film and the major color was white. Small MP dominated in the sediment (<1mm). The major chemical composition of the MP (>2mm) was PE. Additionally, one sample exhibited the presence of organic pigment copper phthalocyanine. The primary driver behind the abundance of MPs in the study area is the improper disposal of waste into the ocean due to lack of waste management facilities and services.

Further investigation is needed to explore the occurrence of MPs in the local wildlife and understand its potential effects on them. The subtidal sediment could serve as a potential MPs reservoir; hence, its presence needs thorough examination. Authorities should enforce strict waste disposal regulations. Moreover, promoting environmental education campaigns can help prevent improper garbage disposal practices among the public.

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