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The correlation between microplastics characteristics and sediment grain size to microplastics accumulation in coral reef sediment in Gede Island, Rembang, Indonesia

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ABSTRACT

In general, microplastics (MPs) have been identified at higher concentrations in marine sediments than in seawater. This is attributed to the trapping effect of sediments on MPs. MPs in the ocean undergo a sinking process, ultimately accumulating in marine sediments. MPs have been identified as a significant threat to marine biodiversity, particularly in coral reef habitats, due to their potential carcinogenic effects. This study examines the correlation between MPs characteristics – specifically, size and shape – and sediment grain size with MPs abundance in adjacent coral reef sediments in Rembang Regency, Central Java, Indonesia. To achieve this, Pearson's correlation and principal component analysis (PCA) methods were employed. The findings indicate that most MPs are concentrated in nearshore regions near anthropogenic sources. Moreover, the correlation based on Pearsons was found to be particularly significant for MPs size, shape, and grain size, with values of 0.84, 0.754, and 0.431, respectively. The PCA result demonstrates that the greater the abundance of MPs in the sediment, particularly those that are MPs smaller in size and compact shape, such as fragments and pellets, the greater the likelihood of their sinking and infiltration into the sediment. This finding highlights the crucial role of MPs size and shape in tight relationship to their density in determining the rate of sinking and infiltration of MPs into the sediment.

Keywords: MPs abundance, size, shape, density, grain size, correlation, PCA.

INTRODUCTION

The presence of microplastics (MPs) has been confirmed in all components of the marine ecosystem, including the coral reef ecosystem. The threat that these tiny plastic particles (less than 5 mm) pose to the coral reef ecosystem worldwide is multifaceted and indirect (Zhang et al., 2023). Previous studies have examined the impact of MPs on the behavior and health of various types of coral. These include investigations into the cleaning mechanisms, feeding interactions, and passive contact between corals and MPs, which can lead to adverse health outcomes for the coral, including necrosis and bleaching (Biswas et al., 2024; Reichert et al., 2018). As coral reefs are fixed habitats, exposure to MPs is inevitable and poses a significant threat to coral biodiversity (Khalid et al., 2021; Pantos, 2022).

Prior research has identified a pattern in which MPs are present at significantly higher concentrations in sediment than in seawater (Scherer et al., 2020; Wang et al., 2019). This phenomenon is primarily attributable to MPs transported from terrestrial sources via rivers and estuaries to the sea. In marine environments, MPs tend to accumulate in proximity to shorelines and on the surface of the water. Due to their lightweight structure, MPs have positive buoyancy, resulting in their tendency to float on the surface. However, MPs occur in complex mechanisms, including biological, chemical, and physical exposure, while floating on the surface. The biofouling process, whereby organisms attach themselves to the surface of MPs, causes the original positive buoyancy of the MPs to be negated. This results in the formation of a heavier, negatively buoyant mass that sinks to the seabed (Waldschläger and Schüttrumpf, 2020). Moreover, the resuspension process facilitates the resettlement of MPs that are trapped deeper in the sediment (Xia et al., 2021). Previous studies have identified the presence of MPs in deep-sea sediment, including in the Southwestern Sumatra waters (Cordova and Wahyudi, 2016), the Northwest Pacific Ocean (Brandt et al., 2020), and at the deepest part in the Mariana Trench (Peng et al., 2018).

The abundance of MPs is generally influenced by a combination of anthropogenic and hydrodynamic factors (Widiaratih et al., 2024). Gede Island, geographically located in Rembang Regency, Central Java, Indonesia, is a recently designated marine tourism area with considerable potential for coral reef tourism. A variety of appealing options are available, including white sand, marine sports, local culinary, and boat tours, which can be classified as anthropogenic factors. The hydrodynamics factors including currents, waves, and tides, serve as facilitators of MPs transportation and distribution. Previous studies in the Rembang area had been identified MPs in seawater, saltwater, sediment and marine biota. For instance, in Karangjahe, Rembang, MPs were found in seawater at a concentration of 140–233 items/m^3, and 33–51 items/kg of sediment (Nainggolan et al., 2022). Additionally, the concentration of MPs in saltwater at Rembang ranges from 1.3 × 10^3 to 1.6 × 10^3 per cubic meter (Nilawati et al., 2023). Furthermore, a study conducted in Gugunung Wetan Village, Rembang Regency, identified 68 items of microplastics in crab (*Portunus pelagicus*), 28 items in seawater, and 33 items in sediment (Rohmaniyah et al., 2023).

As a long-term consequence of this process, MPs will become embedded in sedimentary deposits through a range of mechanisms, including biofouling, adhesion, gravitational settling, resuspension, and others that will significantly impact the health of marine biota. This research aims to examine the relationship between MPs characteristics, including size and shape, and grain size to their occurrence in Gede Island, Rembang Regency.

METHODOLOGY

Study sites description

The location of the sampling site is illustrated in Figure 1. Purposive sampling was employed, with each station designated a representative sample. The stations were selected for analysis of the spatial distribution and to determine the effect of open or closed areas. Stations 1 and 3 represent open areas with numerous exposures to waves, currents, and tides. Stations 2 and 4, in contrast, reflect closed areas. Station 5 was chosen for analysis of the distance effect, as it is the shortest distance to the coastline, which has the highest level of anthropogenic factor (Salsabila et al., 2023).

Methods

The samples were obtained from the surface sediment in a shallow depth area, at a depth of approximately 3–5 meters, by a diver on June 5th, 2022. Surface sediment samples were collected from each station at a depth of approximately ± 5 cm and a mass of up to 1 kg. The samples were placed in zip-lock bags for subsequent analysis. Moreover, the samples were transported to the laboratory for comprehensive examination and analysis. The method employed for the identification of microplastics is that described by (Prata et al., 2019), while the grain size analysis is conducted using a sieve shaker. Hereinafter, the sediment samples were placed in an oven and exposed to temperatures between 70–90 degrees Celsius for the purpose of drying. Furthermore, the dried sediment was weighed in 200-gram increments for subsequent analysis. Microplastic extraction from the dried sediment (~200 g) was conducted using a NaCl solution (1000 ml, ρ = 1.2 g/ml) per sample, based on a modified flotation method (Karlsson et al., 2017). To remove organic material, 20 ml of a 30% H_2O_2 solution

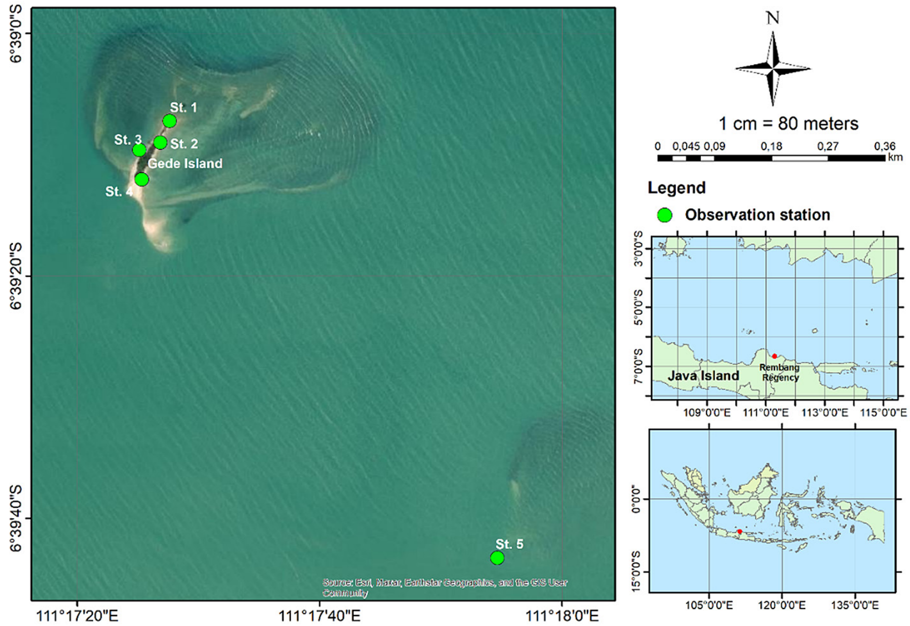

Figure 1. Research area

was added, and the sample was left for 24 hours (Nuelle et al., 2014).

To achieve density separation, a solution of $ZnCl_2$ (100 ml with a density of 1.5 g/ml) was added to the sample, which was then left for a period of 24 hours (Marques Mendes et al., 2021). Furthermore, the solution can be pipetted and filtered using a 0.45 μm Millipore filter paper with a vacuum pump. Hereinafter, MPs filtered on filter paper were observed visually using a stereo microscope to calculate their characteristic features, including abundance, size, color, and shape at 40x zoom magnification (Cordova et al., 2021). Additionally, the type of MPs polymer was identified through Fourier Transform Infrared (FTIR) analysis (Ismanto et al., 2023).

Furthermore, the grain size analysis employed the use of a sieve shaker to categorize seven size groups, including 2 mm, 500 μm, 300 μm, 150 μm, 75 μm, 63 μm and < 63μm. The machine operates on the fundamental principle of reciprocation, whereby an oscillatory movement facilitates the dispersion of the separating particles (Iyasara et al., 2023). (The analysis was performed on 200 grams of dried sediment samples from each station. The correlation levels were determined using Pearson's equation (Liu, 2019) and principal component analysis (PCA), both of which are commonly utilized for the analysis of multidimensional data, including parameters and item locations (Polak et al., 2009).

RESULTS AND DISCUSSION

Abundance and characteristic of microplastics in Gede Island, Rembang Regency

The results regarding the abundance and characteristics of MPs are presented in Table 1. The highest abundance of MPs was observed at Stations 5 and 4, which are situated near the coastal area (Talbot and Chang, 2022). The findings indicate that anthropogenic factors remain a dominant influence, with higher MPs accumulation linked to population density and coastal activities, as documented by (Lin et al., 2022; Widiaratih et al., 2023). Nevertheless, the lowest abundance of MPs was observed in Stations 3 and 1, which located in open areas. Such distributions are influenced by hydrodynamic factors, including currents, waves, and tidal which play a significant role in the dispersion and deposition of MPs in sediments through mechanisms such as suspension and turbulence (Dimante-Deimantovica et al., 2023). Furthermore, the sampling took place on June 5th, 2022, during the east monsoon, where wind direction was from east to west. Consequently, the hydrodynamic factor exerted significant influence over the distribution of marine plastics in the open area, as observed by (Marganita et al., 2022).

The characteristics of MPs, including shape, color, and size, are illustrated in Figure 2. The study area encompassing Gede Island revealed

Table 1. MPs abundance and characteristics including shape, size, and color

Station	MPs abundance (Items/kg)	MPs shape				MPs size				Color					
		Fiber	Fragment	Pellet	Film	1–50 µm	50–250 µm	250–1.000 µm	1–10 mm	Red	Brown	Green	Blue	Black	White/ transparent
Gede St.1	800	555	205	25	15	240	175	100	285	85	120	10	80	405	100
Gede St.2	970	600	345	25	0	185	355	200	230	20	60	5	160	280	445
Gede St.3	310	140	170	0	0	200	90	5	15	20	130	0	25	125	10
Gede St.4	1055	220	780	45	10	745	185	100	25	50	220	5	285	375	120
Gede St.5	1100	130	970	0	0	575	330	140	55	45	805	0	65	145	40

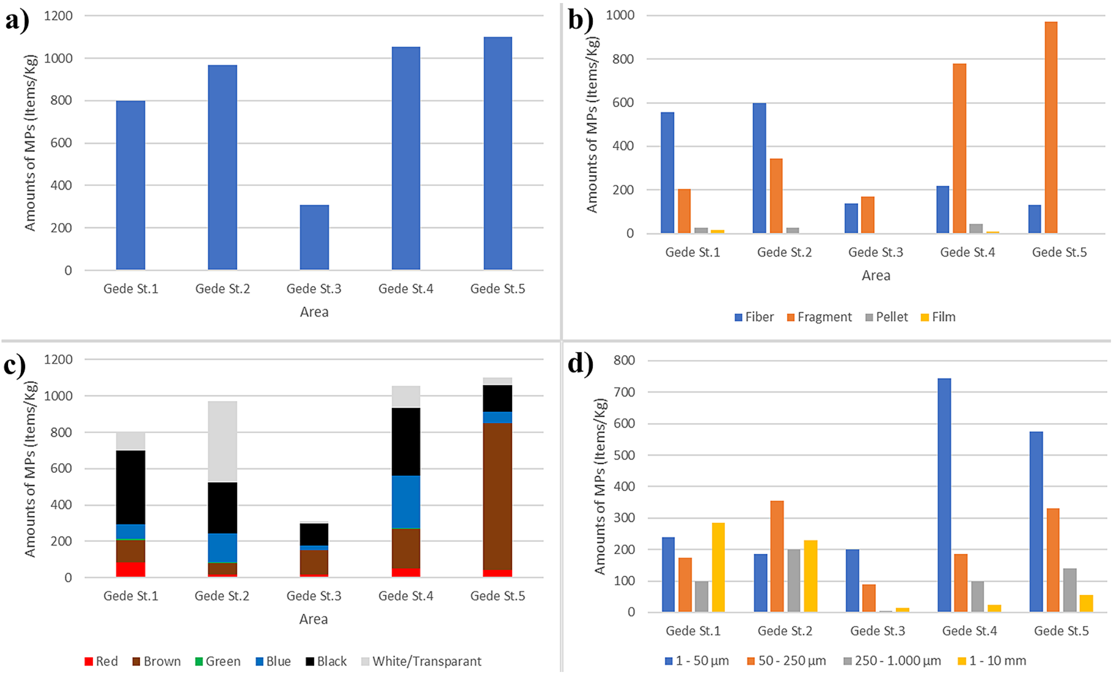

Figure 2. (a) MPs abundance; (b) shape; (c) color; (d) size

the existence of four distinct shapes, namely fragments, fibers, pellets and films. The results show that MPs shape of the fragment and fiber were the most prevalent in the coral reef sediment samples. A notable trend is that fiber is the predominant shape of MP identified in Stations 1 and 2, whereas fragment is the dominant shape found in Stations 4 and 5. In aquatic environments, fragments and fibers constitute most identified shapes. These are predominantly sourced from sewage and subsequently transported to rivers and estuaries (Hope et al., 2021; Na et al., 2024). These finding is in line with geographically, the Gede Island region characterized by a network of river systems that drain into the ocean, with several of these located in proximity to the island itself.

However, the predominant colors identified in the samples are brown and black. The observed phenomenon is attributed to the influence of weathering processes, particularly the phenomenon of tanning that occurs as plastics age and fragment. The fragmentation and alteration in coloration of ocean plastics may be attributed to prolonged exposure to sunlight in the natural environment (Martí et al., 2020). While the second most prevalent color is black, the prevalence of black plastics is largely attributed to the recycling process, which accounts for a considerable portion of the total plastic waste (Huang and Xu, 2022). The color of MPs is significant as it influences the attraction of marine biota, such as turtles and fish, which have been observed to exhibit a preference for consuming colorful MPs over those with darker hues (Sacco et al., 2024).

The predominant size class of the MPs was revealed to be 1–50 µm, with a second most prevalent class at 50–250 µm. These findings are consistent with those of (Enders et al., 2015; Estahbanati and Fahrenfeld, 2016) regarding the influence of MPs surface area on buoyancy. As the surface area of an MP decreases, its tendency to sink increases. Consequently, the smaller the size of an MP, the higher it is likely to be found in the sediment. Figure 3 illustrates the range of MPs shapes observed at each station. Moreover, the MPs polymer type is investigated by Fourier Transform Infrared (FTIR) analysis, as illustrated in Figure 4. The most peak was profound at station 3 and 5, as identified 20 peaks, that is higher than at the other stations, presented in Table 2. The polymer type was analyzed by checking the suitability of the peak absorption that matched

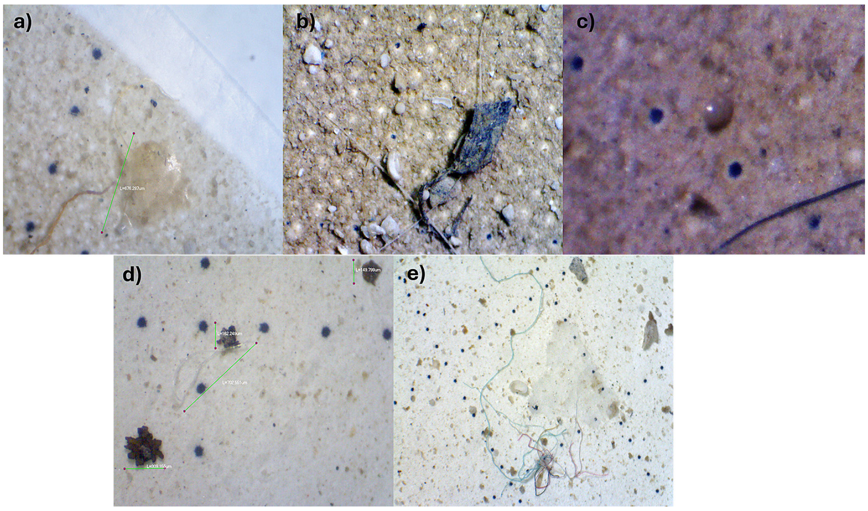

Figure 3. MPs found in Gede Island, Rembang Regency: (a) film – st.1; (b) fragment – st.2; (c) pellet – st.3; (d) fragment – st.4; and (e) fiber – st.5

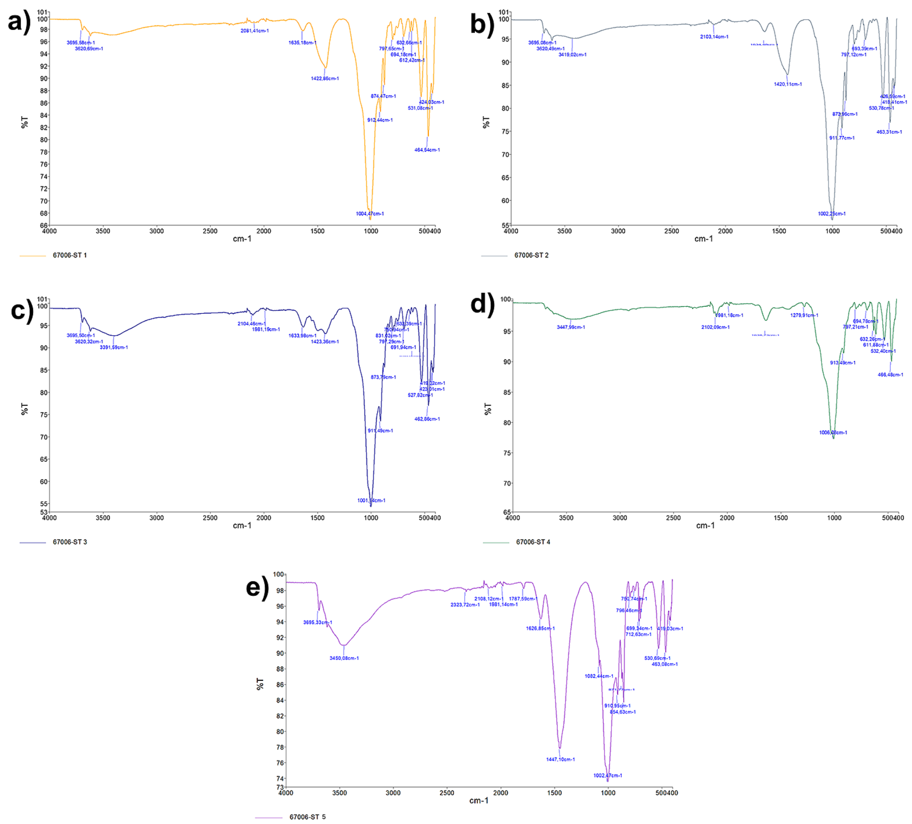

Figure 4. FTIR analysis at: (a) Station 1; (b) Station 2; (c) Station 3; (d) Station 4, and (e) Station 5

using reference data from (Jung et al., 2018). It was found that not all the identified peak absorptions were due to plastic categorized, with some detected as organic matter.

A slight tendency has been observed whereby the MPs polymer type in open areas is found to be lower than in semi-closed areas. This is thought to result from a hydrodynamic mechanism involving processes such as resuspension and biofouling. The most prevalent types of synthetic polymers observed at each station were nylon, high-density polyethylene (HDPE), polypropylene (PP), and acrylic. These MPs were categorized as high-density polymers, which have been observed to sink faster and remain in surface sediment.

The sources of these polymers are diverse, for example, primary MPs, including polyethylene (PE), polylactic acid (PLA), PP, polystyrene (PS), and polyethylene terephthalate (PET), are utilized as scrubbers in certain cosmetic products (e.g., toothpastes and facial cleansers). While pellets are derived from the plastic industry, other polymers, including those composed of acrylic, poly (methyl methacrylate) (PMMA), polyvinyl chloride (PVC), plastic epoxy resin mixtures, melamine and phenolic resin mixtures, are sourced from plastic-based glitters (PBG). In contrast, secondary MPs, such as fibers, are primarily composed of synthetic textiles. These include polyester (PE), polyethylene (PET), acrylic, elastane, and polyamide. These synthetic fibers are derived from the manufacturing of synthetic textiles, whereas PET and polyesters have been identified in plastic bottled water and food packaging materials (RANI, 2022).

The research conducted by (Liu et al., 2022) indicates that the type of MPs polymers plays a pivotal role in the sinking mechanism. This is due to fouling contact area, drag coefficient, and surface area to volume ratio (SA:V) parameters. Furthermore, the biofilm mechanism also results in MPs becoming biofouled and sinking, which is influenced by the polymer type. For instance, PET and PS contain a greater abundance of phototrophic microorganisms than PE (Leiser et al., 2020). Notable examples of high-density polymers include PET and PES, in contrast to low-density polymers such as PE. The tendency for low-density MPs to concentrate at the water surface is contrasted by the accumulation of high-density particles in sediments due to the buoyancy effect (Lenaker et al., 2019). However, the presence of biofouling and inorganic matter can increase the density of low-density microplastics, thereby causing them to sink (Wu et al., 2020). Furthermore, marine aggregates also play a role in transporting low-density microplastics to deeper waters via biofilm formation, although their role may be less significant than anticipated (Eo et al., 2021).

Grain sizes sediment in Gede Island, Rembang Regency

Previous study shown that MPs trapped within sediment was influenced by various factors such as particle density, size, and shape, as well as sediment grain size (Constant et al., 2023). Grain size in five stations at Gede Island, Rembang Regency depicted in Table 3. In this research, the grain size distinguished into 7 categorized such as granule (> 2 mm), coarse sand (2 mm–500 µm), medium sand (500–300 µm), fine sand (300–150 µm), fine

Table 2. Polymer's type of MPs

Location	Total peak absorption	Total polymer type identified	Polymer type	Common example
Station 1	15	13	Nylon, Nitrile, ABS, PS, Acrylic, PP, PVC, CA, PU, Latex, HDPE, PC, CA	Bottle caps, rope, plastic bags, floats, containers, fishing nets, clothing, fishing nets, clothing cigarette filters plastic film clothing plastic bottles, carpet, clothing
Station 2	15	13	Nylon, PS, ABS, Acrylic, PVC, PTFE, LDPE, PP, PU, Latex, HDPE, PC, CA	
Station 3	20	15	Nitrile, Acrylic, PS, Nylon, ABS, PTFE, LDPE, HDPE, CA, EVA, PC, Latex, PU, PVS, PP	
Station 4	13	13	ABS, PS, Nylon, Acrylic, CA, PTFE, PVC, PETE, PU, EVA, PC, PP, LDPE	
Station 5	20	18	PC, Nylon, ABS, Latex, Acrylic, EVA, PC, LDPE, HDPE, PS, PP, PU, PETE, PVC, Nitrile, CA, EVA, PMMA	

Note: Ethylene vinyl acetate (EVA), polycarbonate (PC), poly (methyl methacrylate) (PMMA or acrylic), polytetrafluoroethylene (PTFE), polyurethane (PU), polyethylene terephthalate (PETE), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyurethane (PU), acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), cellulose acetate (CA) sand (159–75 μm), very fine sand (75–63 μm), and Silt/mud (< 63 μm) (Wentworth, 1922).

Table 3 delineates four distinct classes of grain size observed on Gede Island, namely granule, coarse sand, medium sand, and fine sand. The coral reef habitat of Gede Island is primarily characterized by a white sand sediment type. In the outer and open area, station 1 exhibits a predominantly granule composition, with hydrodynamics – including currents, waves, and tides – playing a significant role in this region (Nurkhasanah et al., 2019). The larger granule size remains in this area, while smaller grain sizes are carried by waves, currents, and tides. St.3 and St.5 exhibit comparable grain size (coarse sand) and are classified as semi-closed areas. These areas experience reduced hydrodynamic exposure relative to St.1; the threshold current velocity for grain size 500 μm is approximately 0.28 m/s (Paphitis et al., 2001). However, the fine sand observed in St.2, which is a closed area, has a grain size of 300–63 μm, necessitating a minimum threshold current velocity of 0.007 m/s for sediment movement (Larsen' et al., 1981; Sternberg and Larsen, 1975). Considering this information, the distribution of sediments based on their grain size is associated with hydrodynamic parameters such as currents, tides, and wave patterns. It profound that the greater the hydrodynamic exposure, the larger the size of the sediment that dominates it.

Correlation between MPs abundance to MPs characteristics and grain size sediment

Table 4 presents a summary of the correlation between MPs abundance and MPs characteristics with respect to grain size. MPs trapped in ocean sediments are subject to a multitude of influencing factors. The objective of the present study is to identify the key factors responsible for trapping MPs in sediments, with a particular focus on the Gede Island region in Rembang Regency, which is surrounded by sandy coral reefs. The characteristics of MPs under consideration in this study are their shape and size, while the sediment characteristics pertain to grain size. The results demonstrate a statistically high significant correlation between MP abundance to MP size, followed by MP shape and grain size sediment, particularly.

These correlations are specific to each location and contingent upon the marine environment's chemical, biological, and physical attributes, as well as the coastal morphology. In Gede Island, Rembang Regency, where the coastal environment is dominated by sandy coral reefs, the highest correlation is observed between MPs size 250–1000 μm and r = 0.804. A similar trend emerges with smaller MP sizes, with the range of 50–250 μm and 1–50 μm reaching r = 0.757 and r = 0.623, respectively. These findings indicate that the smallest MPs are the most prevalent and trapped in surface sediments. It can be surmised that the smaller the particle size, the smaller the surface area, which in turn makes them more susceptible to sinking than larger particles.

Furthermore, the shape of microplastics is another factor influencing the correlation coefficient. Fragments exhibit the highest correlation (r = 0.754), suggesting that they may be the most prevalent type of microplastic in this region. These findings demonstrate that in nearly all regions, most MPs are fragments. Pellets also represent a significant proportion of the MPs found, with an r-value of 0.457. This evidence suggests that fragments and pellets tend to sink faster and persist in surface sediments due to their higher density than other types of MPs. However, this behavior is not observed in fibers, which exhibit density-independent sinking tendencies (Lenaker et al., 2019).

Nevertheless, the grain size exhibited a relatively weak correlation with r = 0.431, falling within the medium sand range of 300–500 μm. However, the grain size data indicate inconsistency in the occurrence of MPs, with higher grain sizes

Table 3. Grain size of sediment in coral reef area

Station	MPs abundance (items/kg)	Grain size							Dominant of sediment type
		> 2 mm	500 μm	300 μm	150 μm	75 μm	63 μm	< 63 μm	
Gede St.1	800	355.85	111.3	163.95	346.5	21.5	0.5	0.3	Granule
Gede St.2	970	56.35	141.4	82.9	618.8	96.6	2.35	1.4	Fine sand
Gede St.3	310	133.4	713.65	125.8	20.2	3	0.85	0.4	Coarse sand
Gede St.4	1055	3.8	389.75	536.2	67.95	0.65	0.05	0	Medium sand
Gede St.5	1100	119.95	536.5	212.05	112.9	13.9	2.55	1.25	Coarse sand

Table 4. Correlation MPs abundance to the MPs characteristics and grain size

Variables	Items/kg	2 mm	500 µm	300 µm	150 µm	75 µm	63 µm	< 63 µm	Fiber	Fragment	Pellet	Film	1-50 µm	50-250 µm	250-1.000 µm	1-10 mm
Items/kg	1	-0.291	-0.466	0.431	0.286	0.253	0.321	0.327	0.173	0.754	0.457	0.151	0.623	0.757	0.804	0.160
2 mm	-0.291	1	-0.323	-0.440	0.138	-0.140	-0.188	-0.179	0.373	-0.497	-0.217	0.533	-0.481	-0.288	-0.216	0.610
500 µm	-0.466	-0.323	1	0.098	-0.833	-0.622	-0.002	-0.127	-0.931	0.222	-0.613	-0.535	0.221	-0.404	-0.673	-0.899
300 µm	0.431	-0.440	0.098	1	-0.502	-0.529	-0.567	-0.605	-0.390	0.590	0.649	0.433	0.894	-0.195	-0.102	-0.483
150 µm	0.286	0.138	-0.833	-0.502	1	0.940	0.416	0.548	0.925	-0.350	0.263	0.006	-0.536	0.601	0.761	0.851
75 µm	0.253	-0.140	-0.622	-0.529	0.940	1	0.586	0.706	0.756	-0.258	0.133	-0.311	-0.509	0.687	0.771	0.630
63 µm	0.321	-0.188	-0.002	-0.567	0.416	0.586	1	0.988	0.074	0.283	-0.536	-0.739	-0.194	0.831	0.624	0.121
< 63 µm	0.327	-0.179	-0.127	-0.605	0.548	0.706	0.988	1	0.216	0.191	-0.446	-0.701	-0.275	0.857	0.693	0.236
Fiber	0.173	0.373	-0.931	-0.390	0.925	0.756	0.074	0.216	1	-0.514	0.426	0.353	-0.549	0.319	0.567	0.950
Fragment	0.754	-0.497	0.222	0.590	-0.350	-0.258	0.283	0.191	-0.514	1	0.070	-0.145	0.883	0.479	0.341	-0.485
Pellet	0.457	-0.217	-0.613	0.649	0.263	0.133	-0.536	-0.446	0.426	0.070	1	0.645	0.367	0.001	0.302	0.249
Film	0.151	0.533	-0.535	0.433	0.006	-0.311	-0.739	-0.701	0.353	-0.145	0.645	1	0.183	-0.379	-0.112	0.414
1-50 µm	0.623	-0.481	0.221	0.894	-0.536	-0.509	-0.194	-0.275	-0.549	0.883	0.367	0.183	1	0.103	0.069	-0.568
50-250 µm	0.757	-0.288	-0.404	-0.195	0.601	0.687	0.831	0.857	0.319	0.479	0.001	-0.379	0.103	1	0.939	0.304
250-1.000 µm	0.804	-0.216	-0.673	-0.102	0.761	0.771	0.624	0.693	0.567	0.341	0.302	-0.112	0.069	0.939	1	0.510
1-10 mm	0.160	0.610	-0.899	-0.483	0.851	0.630	0.121	0.236	0.950	-0.485	0.249	0.414	-0.568	0.304	0.510	1

(i.e., > 500 µm) exhibiting opposite negative correlations. This implies that the size of the trapped MPs is contingent upon the grain size. If most of the trapped MPs are of a smaller size, then a medium sand grain size represents an optimal trap. This suggests that the smaller MPs are not capable of being captured by a larger grain size, such as gravel, due to the presence of a greater amount of empty space, which is not as densely packed as that of a smaller grain size. When there are high currents or waves, leading to suspension, the trapped MPs are easily released into the column water, rather than remaining in the surface sediment.

Due to the surrounding coral reef habitat, the sediment composition is predominantly sandy, with a lesser proportion of clay or silt. Despite the relatively minor proportion of silt or clay, the positive correlation (r = 0.327) is evident. This is attributed to the high adhesion of these sediments, which are trapped by MPs. The findings demonstrate that sediments with a smaller grain size exhibit a greater capacity to trap MPs on their surface. The highest concentration of MPs was observed in St. 5 and St. 4, which are predominantly composed of coarse and medium sand and situated in close proximity to the coastline. Additionally, hydrodynamic processes exert a significant influence on the mixing and turbulence of sediments, particularly in areas with limited hydrodynamic exposure.

Further examination of the multivariate parameters was carried out using Principal Component Analysis (PCA). The superiority of PCA is it can simplify complex datasets while preserving the most important information by reducing the number of variables in a dataset by creating new uncorrelated variables called principal components that are linear combinations of the original variables (Patel et al., 2024). Furthermore, it is distinguished by the first and second principal component. Moreover, the first principal component accounts for the largest possible variance in the data. Even though, while reducing dimensionality, PCA strives to retain as much of the original dataset's information as possible (Salem and Hussein, 2019). The goal of PCA is finding the best summary of the data using a limited number of PCs (Lever et al., 2017).

The PCA analysis of MPs abundance in relation to MPs characteristics and grain size are illustrated in Figure 5. A comparative analysis based on the location reveals that St. 5 has a high degree of similarity with St. 4, while St. 1 exhibits greater similarity to St. 2. However, St.3 has its own unique characteristics. A similar observation is noted in the analysis of the abundance of MPs, where St. 5 and St. 4 are found to be more closely correlated than the other locations, with pattern of MPs characterization significantly are the smallest size 1–50

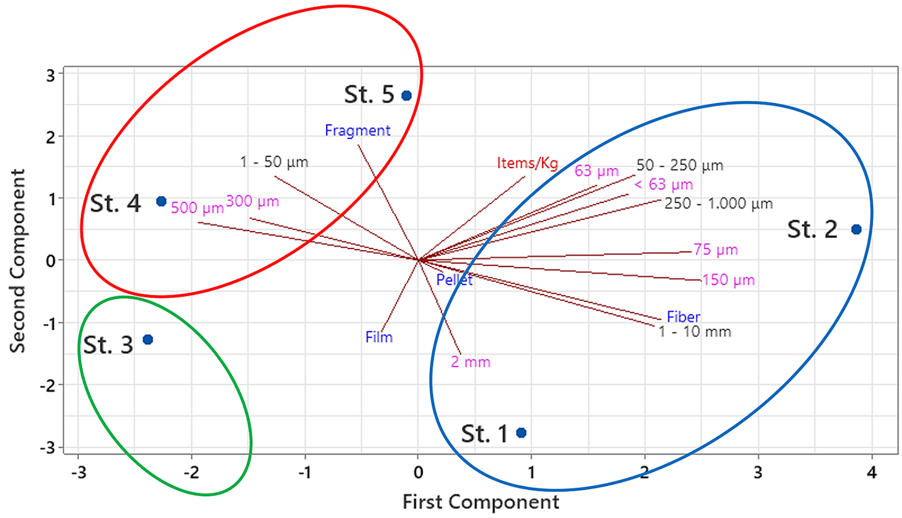

Figure 5. PCA analysis of MPS abundance to MPs characteristics and grain size

µm, fragment shape, and grain size identified as coarse (500 µm) and medium (300 µm) sand. Since, these locations have the highest occurrence of MPs, it is suggested that a smaller grain size (< 300 µm) has a better trap of MPs than higher grain size. Moreover, the hydrodynamics effect is lower due to closed area, the resuspension event also decreasing.

In contrast, St. 1 and St. 2 located in open area, have much more exposure of hydrodynamics pressure, its profound that MPs characteristics have longer size (> 50 µm), MPs shape majority by Fiber and Pellet, and composition of grain size filled by the highest size gravel combination with the smaller size to complement each other. The role of sediment type is well demonstrated in St. 1 as gravel has been linked with a lower occurrence of MPs, as observations have shown it to trap the larger size of MPs, which constitute a small portion. Moreover, this region is subjected to greater hydrodynamic stress, which results in increased resuspension. This enables MPs to migrate to the water column and attain positive buoyancy, thereby ascending to the water's surface.

As St. 3 is situated within a transitional zone from closed to open area, it is characterized by the presence of coarse sand. Furthermore, it experiences a higher degree of hydrodynamic stress due to the east monsoon condition. However, the sediment type in this area is predominantly coarse sand, with minimal presence of fine sand, which lacks the necessary cohesion to effectively trap MPs. Consequently, St. 3 exhibits the lowest occurrence of MPs, with the MPs being the smallest size and identified in fiber and fragment. In summary, St. 3 demonstrates a heightened degree of suspension exposure, resulting in the liberation of MPs from the sediment into the water column.

Moreover, the impact of MPs size on infiltration was investigated. The findings revealed that smaller MPs are more likely to be infiltrated deeper into the sediment, including pellets with a round shape, exhibited deeper infiltration. In contrast, fragments and films showed a reduced penetration due to the capture of angular particles within the pore structure. Given the focus on surface sediment, it can be inferred that this phenomenon may contribute to the accumulation of smaller fragments and larger fibers in sediment. This aligns with the findings of (Waldschläger et al., 2020) who observed that MPs with a ratio of diameter of microplastic particles (dMP) to the diameter of grain size (dGS) exceeding 0.32 exhibited a minimal infiltration.

From another perspective, the MPs particles can be approached by the grain size due to their densities (ratio of mass to volume). The larger MPs can be equivalent to smaller grains with higher densities. If their densities are equal, they can be mobilized by the same level of bed shear stress leading to sediment transport processes (Harris, 2020). This study shows the Pearson correlation generally exhibits a trend like that observed in the PCA, with the greatest abundance of MPs occurring in the presence of smaller MPs, particularly high-density MPs such as fragments and pellets, which can be regarded as the smaller grain size.

CONCLUSIONS

The distribution of MPs in sediment is influenced by numerous factors, including anthropogenic activity, hydrodynamic forces, and the MPs inherent properties such as their size, shape, polymer composition, and color. This research has investigated that the abundance of MPs in sediment is strongly related to the size of these particles. The size of these MPs will typically be linked to the other characteristics, including shape and polymer, because of their respective densities. The density of these MPs will play an important role in the process of MPs becoming trapped in sediment. This is due to their ability to interact with sediment, which can result in deeper infiltration or suspension in surface sediments. A higher density of MPs will tend to sink more rapidly, particularly smaller MPs with a pellet-like shape that can penetrate deeper into sediment. Additionally, smaller grain sizes are more effective at capturing MPs than larger ones that allow space for MP capture. In future studies, examining MPs abundance to depth profiles with a variety of sediment types, such as silt, gray, and gravel, would provide more insight. Furthermore, considering hydrodynamics factors, such as currents, waves, and tides, is crucial as they impact resuspension, sinking mechanisms, and sedimentation rates, allowing for the examination of complex interactions.

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