ISSN 2413-5577, Ecological Safety of Coastal and Shelf Zones of Sea, 2025, No. 2, pp. 99–117.

Original paper

Assessment and Characterization of Microplastics in Aquatic Environments near Pekalongan (Indonesia)

S. Widada [1], Kunarso [1], E. Indrayanti [1], R. Widiaratih [1], A. Ismanto [1], M. Zainuri [1, 3] *, T. Hadibarata [2], M. A. Anindita [1], T. Tristanova [1], M. S. Jihadi [1, 3]

[1] *Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Semarang, Indonesia*
[2] *Environmental Engineering Program, Faculty of Engineering and Science, Curtin University Malaysia, Miri, Malaysia*
[3] *Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University Jl. Prof. Soedarto SH., Tembalang, Semarang, Central Java, Indonesia*
* *e-mail: muhammadzainuri@lecturer.undip.ac.id*

Abstract
The occurrence of microplastics in the marine environment and their impact on the environment, biodiversity, and human life is concerning. Pekalongan is an industrial city with various anthropogenic activities such as fisheries, aquaculture, household, and most notably the batik textile industry. This research was carried out to determine the spatial distribution and characteristics of microplastics in the water and sediment of the Pekalongan coastal area. Water samples were collected at 10 stations (at 5 of them sediments were sampled as well) in the Sengkarang River estuary and its surroundings. Microplastics were identified using the optical microscopy method, followed by Fourier transform infrared spectroscopy (FTIR) testing to determine the polymer of microplastics. Microplastics were characterized using a Motic SMZ-161 microscope, then photographed using a Moticam A5 and counted based on each characteristic. In this study, we found polymers such as polystyrene, polyethylene, polyamide, and polyester. The abundance of microplastics in seawater was 214.4 particles/L and 300 particles/kg in suspended sediments. The microplastics types included fibers, fragments, films, and pellets of various colors and sizes. The dominant microplastic type in seawater and sediments was fiber (44%, 44%), followed by fragments (28%, 25%), foam (15%, 13%), and pellets (7%, 16%). White was the dominant color in seawater (54%) and sediments (53%), blue (21%, 18%), and red (15%, 17%), while yellow, green, and black were also found in small portions. The size of microplastics ranged from 1 μm to 10 mm, and the dominant size range was in the 50–250 μm group. The highest concentration of microplastics in the seawater was found in site *B5* with a concentration of 360 particles/L, while the highest concentration of microplastics in sediments was found in site B4 (389 particles/kg). Site *B5* is located in the midwater area but still close to the estuary, where the pollution from the surrounding areas flows to the location. Site *B4* is in the littoral-intertidal zone where the water is affected by tides and is prime location for sedimentation to occur.

Keywords: microplastics, Pekalongan, North Java Coast, estuary, pollution

Acknowledgments: This work was supported by the Research for International Publications program managed by the Universitas Diponegoro, and that fund was sourced other than APBN UNDIP Number 609-64/UN7.D2/PP/VIII/2023. Collaboration from Curtin University Malaysia is highly appreciated.

For citation: Widada, S., Kunarso, Indrayanti, E., Widiaratih, R., Ismanto, A., Zainuri, M., Hadibarata, T., Anindita, M.A., Tristanova, T. and Jihadi, M.S., 2025. Assessment and Characterization of Microplastics in Aquatic Environments near Pekalongan (Indonesia). *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 99–117.

Оценка и характеристики микропластика в водной среде в районе Пекалонгана (Индонезия)

С. Видада [1], Кунарсо [1], Э. Индраянти [1], Р. Видиарати [1], А. Исманто [1], М. Зайнури [1, 3] *, Т. Хадибарата [2], М. А. Аниндита [1], Т. Тристанова [1], М. Ш. Джихади [1, 3]

[1] *Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University, Semarang, Индонезия*

[2] *Environmental Engineering Program, Faculty of Engineering and Science, Curtin University Malaysia, Miri, Малайзия*

[3] *Center for Coastal Rehabilitation and Disaster Mitigation Studies, Diponegoro University Jl. Prof. Soedarto SH., Tembalang, Semarang, Central Java, Индонезия*

* *e-mail: muhammadzainuri@lecturer.undip.ac.id*

Аннотация

Присутствие микропластика в морской среде и его воздействие на окружающую среду, биоразнообразие и жизнь человека вызывают обеспокоенность. Пекалонган – промышленный город, в котором ведется разнообразная хозяйственная деятельность, например рыболовство, аквакультура, домашнее хозяйство и особенно текстильная промышленность (производство батика). Цель исследования – определить пространственное распределение и характеристики микропластика в воде и донных отложениях прибрежной зоны Пекалонгана. Пробы воды были отобраны на 10 станциях; на пяти из них также взяты пробы донных отложений. Район отбора проб охватывал устье реки Сенгкаранг и прилегающие территории. Микропластик идентифицировали методом оптической микроскопии, а полимерный состав определяли методом инфракрасной спектроскопии с преобразованием Фурье (*FTIR*). Микропластик характеризовали с помощью микроскопа *Motic SMZ*-161, затем фотографировали на камеру *Moticam A*5 и подсчитывали по каждой категории. В ходе исследования были идентифицированы полимеры: полистирол, полиэтилен, полиамид и полиэстер. Концентрация микропластика составила 214.4 част/л в морской воде и 300 част/кг в донных отложениях. Выделены следующие типы частиц: волокна, фрагменты, пленки и гранулы различных цветов и размеров. Во всех средах преобладали волокна (44 в воде и 44 % в отложениях), за ними следовали фрагменты (28 и 25 % соответственно), вспененный материал (15 и 13%) и гранулы (7 и 16 %). Наиболее распространенным был белый цвет пластика (54 в воде, 53 % в отложениях), затем синий (21 и 18 %) и красный (15 и 17 %). Желтый, зеленый и черный цвета встречались реже. Размер частиц варьировался от 1 мкм до 10 мм, при этом наиболее частым был диапазон 50–250 мкм. Максимальная концентрация микропластика в морской воде зафиксирована на ст. *B1* (360 част/л), а в донных отложениях – на ст. *B4*. Это объясняется расположением станции *B1* на реке вблизи насосной станции, куда поступают загрязнения с прилегающих территорий. Станция *B4* находится в литоральной зоне, подверженной влиянию приливно-отливных течений, что способствует интенсивному накоплению отложений.

Ключевые слова: микропластик, Пекалонган, северное побережье Явы, эстуарий, загрязнение

Благодарности: работа выполнена в рамках программы Research for International Publications Университета Дипонегоро и финансировалась из источников, не являющихся APBN UNDIP № 609-64/UN7.D2/PP/VIII/2023. Авторы высоко ценят сотрудничество с Университетом Кертина, Малайзия.

Для цитирования: Assessment and Characterization of Microplastics in Aquatic Environments of Pekalongan Waters / S. Widada [et al.] // Экологическая безопасность прибрежной и шельфовой зон моря. 2025. № 2. С. 99–117. EDN VHKNLA.

Introduction

Waste has been dumped into the ocean for centuries, but recently the composition of marine debris has drastically changed. Most garbage used to be composed of organic biodegradable items some decades ago. Synthetic materials including plastics, are now prevalent in solid waste. Plastic is one of the major non-organic waste segments in our daily output of municipal solid waste production [1]. Bottles of plastic, ropes, tarpaulins, and synthetic fishing lines float freely, decay slowly, and break into smaller pieces [2]. As the characteristics of microplastic is buoyant and durable, they accumulate on beaches, ocean eddies, and enclosed or semi-enclosed seas where surface water is held for extended periods [3]. Plastic is highly buoyant; thus, it can be carried out for thousands of miles by currents and dispersed across the marine environment, which can be detrimental to marine ecosystems [4–6].

Microplastics are solid particles of polymer with regular or irregular shape and size between 1 μm and 5 mm. Plastic breaks down into finer particles [7–9]. Microplastics made up approximately 92% of the 5.25 trillion plastic particles present at global scale in the ocean [10–12]. Research on microplastics in the Java Sea was first conducted by Purba et al. in 2016 [13] with results of 0.2 mg/L microplastics detected in Java Sea water. Various human activities on land, coastal, and marine areas are the main sources of microplastics present in the Java Sea waters. It is believed that around 75–95% of plastic waste in the marine environment comes from land-based sources, and the remaining 5–25% comes from the ocean [14] like unintentional loss or illegal disposal during offshore drilling or fishing [10]. Because microplastics can be consumed by marine life, and eventually kill them, their effects on the marine biota are concerning [15]. Microplastics can also potentially reduce aquaculture's economic benefits by causing oxidative stress in aquaculture products, altering their behaviour, growth, and reproduction, and even causing them to die [16].

Pekalongan is a coastal industrial and tourist city covering 45.25 km^2 and has population of 315,997 people. The city has various anthropogenic activities including 364 companies that process fish, with ponds and cultivation areas cover 331,292 ha; 634 batik industries, and up to 75 medium- to large-sized companies that make food, textiles, plastics, and shipyard activities (BPS Pekalongan, 2022). Due to this, the garbage produced in Pekalongan City each day approaches 140 tons, or 0.46 kg per resident (Pekalongan City, 2023). The city of Pekalongan's industries use plastic materials in their operations and output. A hazardous consequence of microplastics in sediments and waterways is the disturbance of the ecosystem's biotic and abiotic water ecology [17, 18]. This research was carried out to determine the spatial distribution and also to identify the abundance, shape, size, color, and polymer type of microplastics in water and suspended sediment samples in Pekalongan waters.

Materials and Methods

The research location was in Pekalongan Waters, Central Java, in the Sengkarang River estuarine area and the surrounding waters. The purposive field sampling method was used to determine 10 sampling sites for microplastics in seawater and 5 sampling sites for sediment samples (sites *B1–B4*, and *B9*), as shown in Fig. 1. The sites were defined as such to represent the coastal environment, both on the seaward, estuary, and riverine areas.

Collection of samples was conducted during the dry season with three replications. The upstream and downstream areas of the Sengkarang River are located within residential areas, textile industries, tourist attractions, fishing grounds, and wastewater treatment plants.

During the collection of samples, half of the 108 μm plankton net was dipped into the surface. The volume of filtered water taken was 10 m^3 (the collected water discharge was calculated using a flow meter). The sediment samples were taken using a grab sampler at each location sites with a total sample of 400 grams.

Water samples were filtered using a vacuum pump and then mixed with 30% Fe (II) solution and H_2O_2 to remove organic matter that was still contained in the sample. The density of the microplastic in the water samples was increased by using NaCl. Each sediment sample was extracted through the process of density separation method using $ZnCl_2$ solution (1.6 $g \cdot L^{-1}$), and the sediment-salt mixture solution was mixed with a spatula [19], HCl was used to remove organic matter that was still contained. The method of testing water and sediment samples refers to the National Oceanic and Atmospheric Administration (NOAA) method with minor adjustments [1)].

Multiple measures were implemented to minimize the possibility of microplastics contamination during the microplastics analysis procedure. Sampling equipment and glassware were rinsed with purified water several times and were dried before use. There were no plastic consumables used in the process of sample collection and extraction. The filters, laboratory consumables, and the solvent were always covered with aluminium foil during the sample extraction procedure. Latex gloves and cotton laboratory coats were used during the microplastics sampling and extraction process. Sample separation was performed by filtration using 0.45 μm cellulose filter membranes. The filter paper was observed under a microscope using the sweeping method to see each type of microplastic. Microplastics were identified using the optical microscopy method [20]. Optical microscopy was the first method of characterization used to observe microplastics [21], followed by Fourier Transform Infrared Spectroscopy (FTIR) testing to determine the polymer of microplastics [22]. Polymer identification was done by dissolving microplastics that is already filtered, and then the solution is pipetted and placed under the FTIR.

[1)] Masura, J., Baker, J., Foster, G., Arthur, C. and Herring, C., 2015. *Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments*. Silver Spring, MD, USA: NOAA, (NOAA Technical Memorandum NOS-OR&R-48).

Microplastic shape, size, and color identification was performed using a Motic SMZ-161 microscope. After that, the microplastics found were photographed using a Moticam A5 and counted based on each characteristic. Statistical data analysis was conducted on the type, size, color, number, and abundance of microplastics. The results of data analysis will be displayed in graphical form for each sample. The distribution of microplastics was visualized in the spatial map.

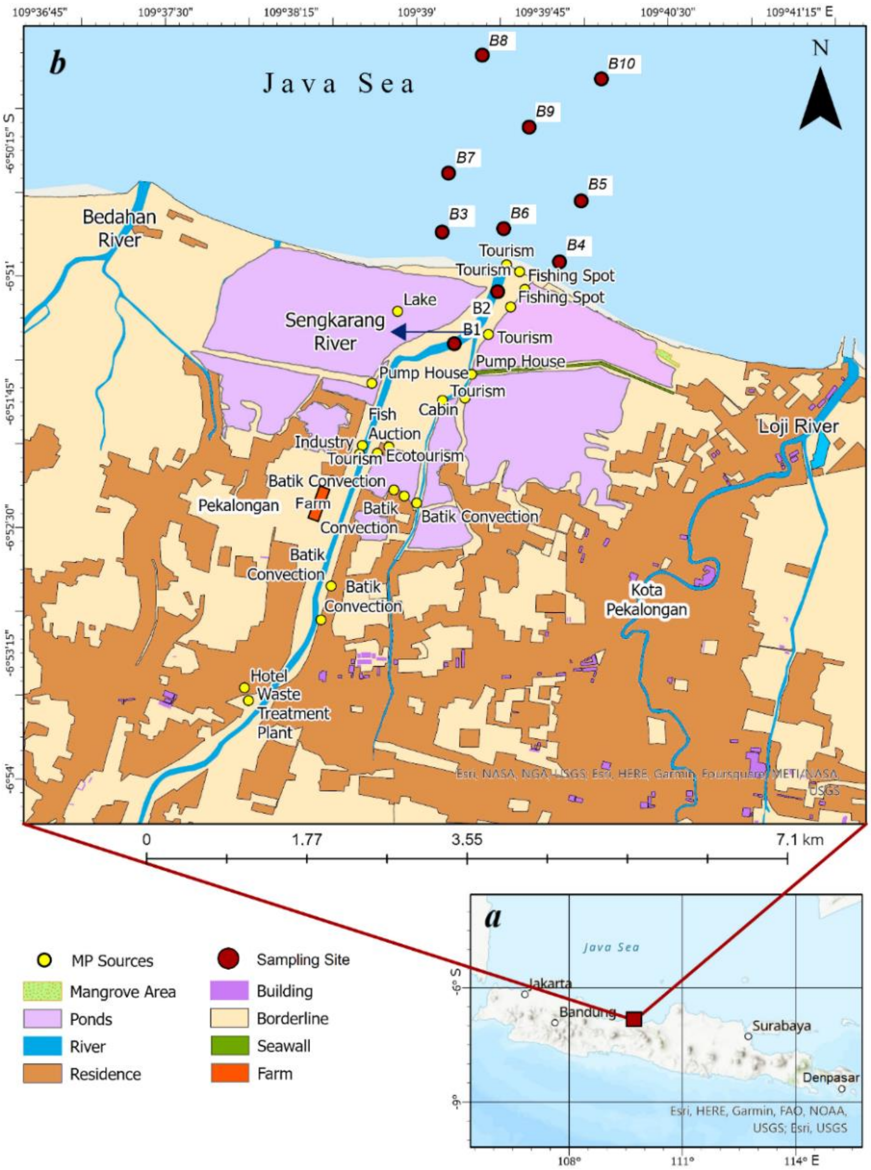
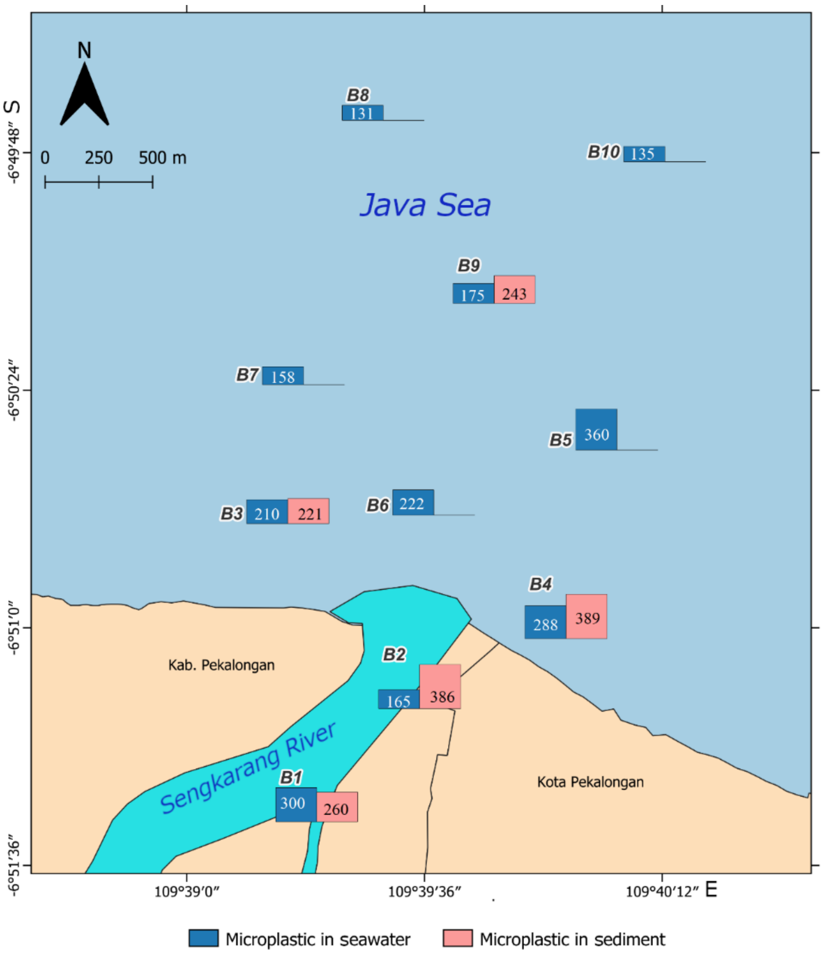


Fig. 1. Map of Java Island, the red square denotes the area of interest (*a*), the enlarged image of the area of interest (*b*)

Results

The spatial abundance of microplastics in seawater and sediment in Pekalongan waters is shown in Fig. 2. The average abundance of MPs in seawater was 214.4 particles/L and 300 particles/kg in suspended sediment. Site *B1* was located in the Sengkarang River, close to the pump house, tourist area, fish auction, and ponds. Site *B2* is located in the Sengkarang estuarine area, close to the beach and fishing grounds. The littoral or intertidal area is represented by sites *B3*, *B4* (close to the mangrove area), and *B6*. Sites *B5* and *B7*, were in the middle water area, and sites B8, *B9* and *B10* were in deep water quite far from anthropogenic activities other than marine fishing (Table 1). The abundance of microplastics in seawater and sediment has significant differences. The abundance of MPs in sediments had higher numbers.

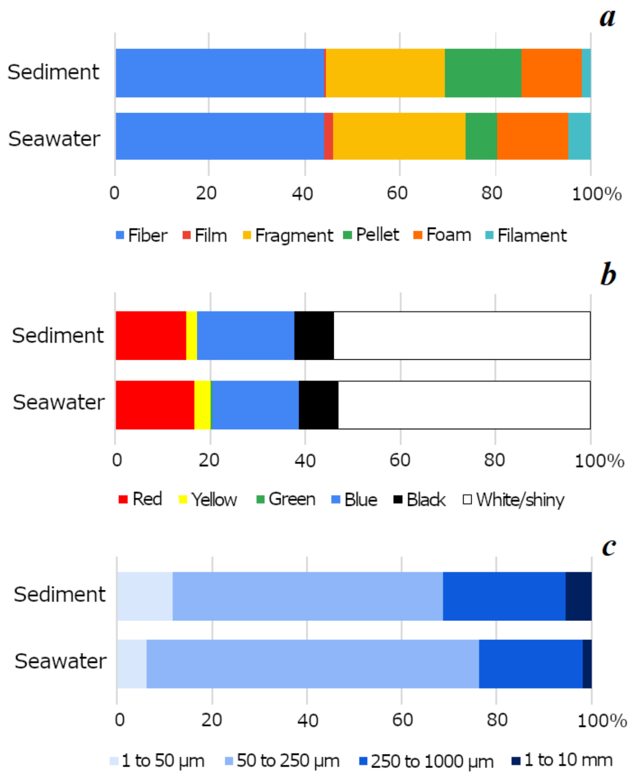


F i g . 2 . Microplastics abundance in water, particle/L, and sediments, particle/kg

T a b l e 1 . Abundance of microplastics in seawater, particles/L, and sediments, particles/kg, at different sampling sites

Site	Abundance of microplastics		Description of sampling location
	in seawater	in sediments	
B1	300	260	Sengkarang River area, near pump house, tourism area, fish auction, ponds
B2	165	386	Mouth or estuarine of Sengkarang River, tourism area, fishing spot area /
B3	210	221	Near coastal area
B4	280	389	Near coastal area, mangrove area
B5	360	–	Midwater water area
B6	220	–	Near coastal area
B7	158	–	Midwater area
B8	175	–	Open water
B9	131	243	Open water
B10	135	–	Open water

In this research, the types of microplastics shown in Fig. 3, *a* were found. Fiber types were most prevalent in seawater samples (44%) and sediment samples (44%). The second most prevalent type found in Pekalongan waters was the fragment type, which constituted 28% of seawater samples and 25% of sediment samples. In the samples, 15% of foam types were found in seawater samples and 13% in sediments. The pellet type in seawater amounted to 7%, and in sediment it amounted to 16%.



F i g . 3 . Percentage of microplastics types (*a*), colors (*b*), and size (*c*) in seawater near Pekalongan

Figure 3, *b* shows the percentage of microplastic color in seawater and sediment samples. The MPs color in seawater and sediment was dominated by white/ shiny at 54% in seawater samples and 53% in sediment samples. The second most common color was blue at 21% in water samples and 18% in sediment samples, followed by red at 15% in water samples and 17% in sediment samples. In this study, yellow and black MPs were also found, as well as green ones. The size distribution of microplastics is depicted in Fig. 3, *c*, where size groups include 1–50 µm, 50–250 µm, 250–1000 µm, and 1–10 mm. Microplastics between 50 and 250 µm dominated the samples with 57% in seawater and 70% in sediment. Followed by the 250–1000 µm size group, with 26 % in seawater samples and 22% in sediment samples. The 1–50 µm size was only found in 12% of all seawater samples and 6% of all sediment samples. Microplastics with sizes 1–10 mm were rarely found, only 6% of the total seawater MP and 6% of the total sediment MP. Figure 4 is a bar graph displaying the color and size distribution at each station in Pekalongan waters.

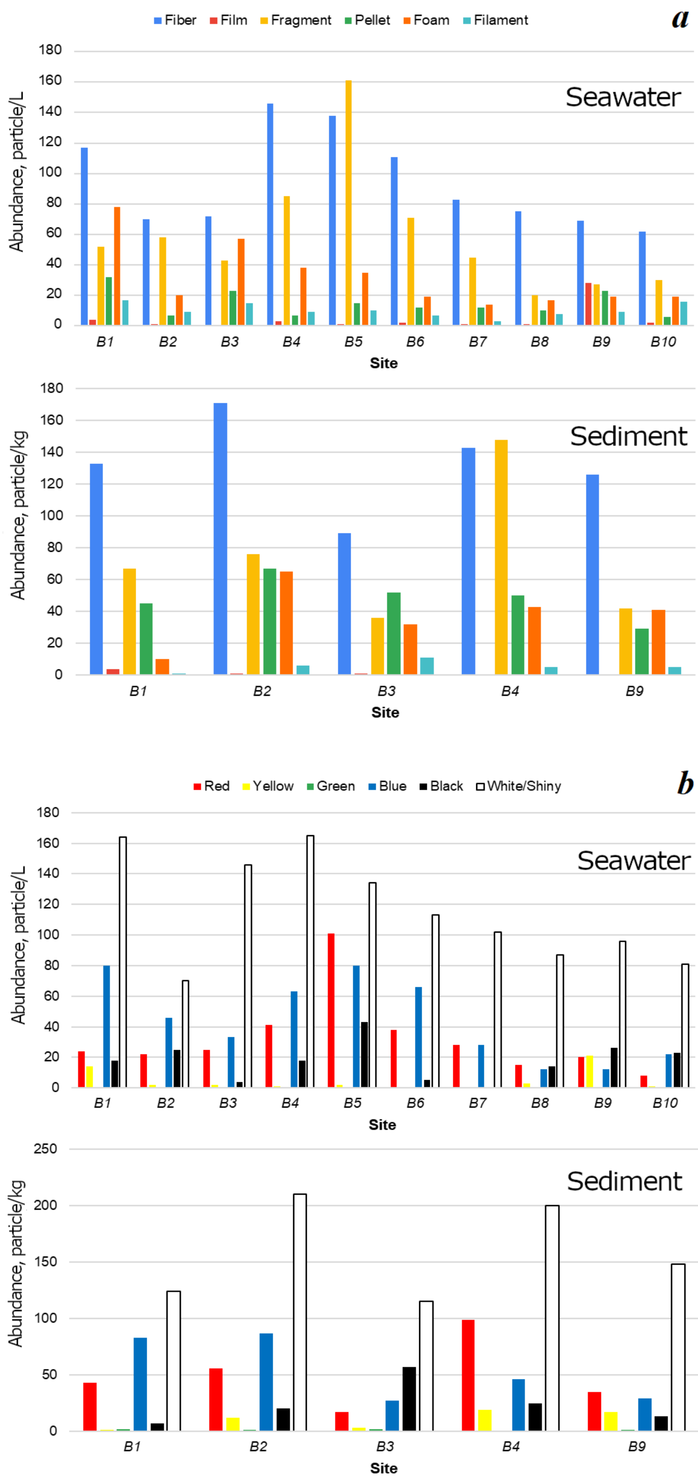
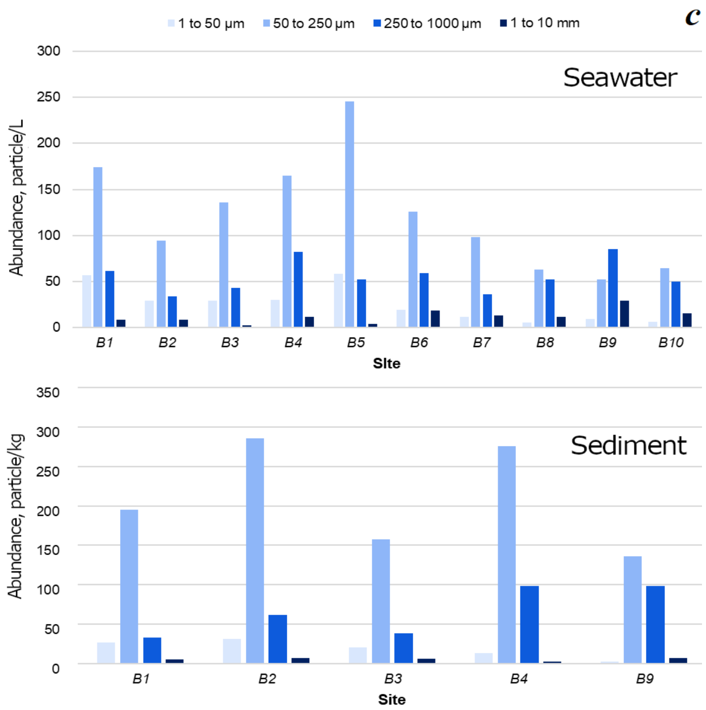


Fig. 4. Distribution chart of microplastics by types (*a*), colors (*b*), and size (*c*) in each site



Continued Fig. 4 / Продолжение Рис. 4

Discussion

The presence of MPs in the water and sediments in Fig. 2 related to the texture of the sediment which affects their ability to capture microplastics. The softer the sediment texture, the better its ability to capture microplastics [23]. Based on the research conducted by Yuanita et al. in 2022 [24], the type of sediment in coastal Pekalongan is non-cohesive sediment dominated by sand. This may affect the number of microplastic particles in Pekalongan sediments. In addition to certain accumulation zones in the high seas, marine debris is often more prevalent in shallow coastal areas [25]. This theory is consistent with the present study, where areas close to anthropogenic activities such as rivers, estuaries and coasts had higher abundance compared to central and deep-water areas. Coastal areas sampled both offshore and nearshore by Montoto et al. in 2020 [26] also showed this difference.

The MPs fibers shown in Fig. 3, *a*, are usually ascribed to terrestrial sources, such as river flow and urban runoff [27]. These fiber microplastics are most likely detached from clothing and fabrics through washing or from fishing lines and ropes used in nearby shipping and fishing operations [28]. While the fragment type present in Fig. 3, *a* were mainly generated by fragmentation of plastic products containing hard plastic polymers, such as packaging (beverage bottles and plastic container) [29]. Microplastics in the form of foam are widely used as packaging materials (food containers) and transportation packaging [30]. In addition, the pellet form had less quantity compared to other groups of microplastic forms. Typically, pellets come from the direct discharge of primary microplastics from manufactured plastic waste and residential waste products used for personal care [31].

The results of ATR-FTIR analysis for Pekalongan waters were similar to the research results by Ismanto et al. (2023) [32] that found polystyrene, polyester, and polyamide in the stream area up to the estuary of the Loji River in Pekalongan. In the present study, the same polymers, polystyrene (PS), polyethlene (PE), polyamide (PA), and polyester (PES) were found. Polyester is the dominant polymer, which is commonly used in textile and product packaging industries [33]. Indications of waste from anthropogenic activities are supported by the dominance of fibers and fragments (secondary microplastics) compared to pellets (primary microplastics) [34]. Density also influences the abundance of MPs as it determines how widely they are distributed throughout the water column [35]. The density of polystyrene foam (PS) 0.01–0.05 g/cm^3 was used as a reference. This polymer is expected to float on the surface of water because its density is lower than that of seawater (1.0267 g/cm^3). However, being denser than water, some polymers, such as solid PS (1.04–1.50 g/cm^3), tend to sink slower in the water column [36].

Previous research on microplastics in marine waters and estuaries in Indonesia is shown in Table 2. The abundance of MPs particles in seawaters and sediments in each region varies significantly. The abundance of microplastics in Pekalongan is higher than in several cases, such as Tambak Lorok, Semarang, Indonesia [37], Jakarta Bay, Indonesia [38], and Trengganu Estuary, Malaysia [39]. Several factors cause the large abundance of microplastics in Pekalongan, namely the anthropogenic waste, small scale industries, and textile industries. Cases with high amounts of microplastics use a mobile water pump with an additional mesh net filter [39]. This method produces an abundance of microplastics comparatively higher than the manual sampling method using a net [34, 40, 41]. Variations in microplastic abundance are greatly affected by the level of pollution, sampling location, and water hydrodynamics in each study area.

Table 2. Previous microplastics research used for comparison

Location	Sample	Methods	Identification tool	Abundance	Ref.
Banten Bay, Indonesia	Sediment	Smith-McIntyre grabs	Nikon Eclipse E600 stereo microscope	267 ± 98 particles/kg	[42]
Tambak Lorok, Semarang, Indonesia	Water and sediment	Gravity corer	Microscope Olympus MD 50	7–111 particles/10 mL seawater and 8–49 particles/g sediment	[37]

Continued Table 2

Location	Sample	Methods	Identification tool	Abundance	Ref.
Bintan Water, Indonesia	Water	Neuston net	Hirox Digital Microscope KH-8700	0.45 pieces per m^3	[40]
Jakarta Bay, Indonesia	Surface Water	Round net	Nikon SMZ 745T stereo microscope	9.729 to 89.164 nm^{-3}, with an average of 48.179 ± 21.960 nm^{-3}	[38]
Lampung and Sumbawa, Indonesia	Sediment and sandfish	Van Veen grab & local fishers	Nikon Eclipse Ni–U microscope	72.64 ± 25.28 particles/kg (sediments) 2.01 ± 1.59 particles /individual (fish)	[43]
Brantas Water, Indonesia	*Gambusia affinis*	Random sampling	Olympus CX-23 Lighting System	Downstream (209.18 ± 48.85 particles/g) upstream (24.44 ± 0.14 particles/g)	[44]
Ciliwung Estuary, Indonesia	Water and *Aplocheilus* sp.	Manta trawl net & randomly collected	Nikon DF-12 stereo microscope	River flow (9.37 ± 1.37 particles/m^3), coastal waters (8.48 ± 9.43 particles/m^3), and in 75% samples of *Aplocheilus* sp. (1.97 particles/individual)	[41]

End of Table 2

Location	Sample	Methods	Identification tool	Abundance	Ref.
Benoa Bay, Bali, Indonesia	Surface water	Mini manta trawl net equipped with flow-meter	Stereo microscope Nikon Eclipse Ni-U	1.41–1.88 particles/m^3	[34]
Trengganu Estuary, Malaysia	Seawater & zoo-plankton	Mobile water pump & 2000 µm mesh net filter	Olympus SZX7, Olympus CX21	545.8 particles/m^3	[39]
Yellow Sea, China	Surface water	Manta trawl net	Stereo microscope M205FA	0.63 ± 0.57 particles/m^3	[45]
Northern Indian Ocean	Surface water	Manta net	Nikon SMA800N	Pre-monsoon 15,200 ± 7999 no./km^2, monsoon 18,223 ± 14,725 no./km^2 and post monsoon 72,381 ± 77,692 no./km^2	[46]

Conclusion

The assessment and characterization of microplastics in the waters around Pekalongan showed that both seawater and sediment samples were polluted with microplastics. The average microplastics abundances were 214.4 particles/m³ in seawater and 300.0 particles/kg in suspended sediments. The highest concentration of microplastics in the seawater was found in site *B5* with a concentration of 360 particles/L, while the highest concentration of microplastics in sediments was found in site *B4* (389 particles/kg). Site *B5* is located in the located in the midwater area but still close to the estuary, where the pollution from the surrounding areas flows to the location. Site *B4* is in the littoral-intertidal zone where the water is affected by tides and is prime location for sedimentation to occur.

Four main types of microplastics were identified: fibers (44% both in water and sediments), fragments (28% in water and 25% in sediments), foam (15% in water and 13% in sediments), and pellets (7% in water and 16% in sediments). The prevalent fibers are likely to have detached from clothing and fabric or fishing lines and ropes, while the fragments primarily come from the degradation of hard plastic products (bottles, containers).

The dominant color was white, accounting for 54% in water and 53% in sediments. The most widespread size range was 50–250 μm (57 and 70% in water and sediments, respectively).

The detection of various polymers (polystyrene, polyethylene, polyamide and polyester) suggests that the microplastics originate from diverse anthropogenic activities, including urban runoff, fisheries, batik industries.

The existence of widely distributed microplastics in the environment is the reason for the concern about water quality, ecosystems, and human health. Fourteen million tons of microplastics are estimated to be accumulated in the bottom of the ocean [47]. Aquatic biotas, ranging from plankton to large marine mammals, are likely to ingest microplastics. Humans are being exposed to microplastics through the ingestion of contaminated seafood and other foods and beverages, or through the inhalation of airborne microplastics. Along with increasing scientific understanding of the risks caused by plastic pollution and greater policy attention to reduce these risks, multiple governments are now looking at ways to address the emission of microplastics into the environment.

In response to growing concerns over the risks related to plastic pollution, Indonesia has introduced measures to reduce plastic widespread into the environment, mainly through better waste management policies, a ban on single-use plastics that are often discarded carelessly, and restrictions on the manufacture and distribution of personal care products and cosmetics which contain microplastics. Indonesia has carried out a priority program to improve waste management in several tourist locations, including marine national parks, to prevent and collect plastic waste in the sea for recycling, as well as address the issue of the impact of plastic waste and microplastics. In 2017, monitoring and surveys of plastic waste in the sea were carried out, using UNEP and NOAA guidelines in 18 coastal areas in 18 cities/districts, from 25 priority cities/districts, and will continue in the following years. As with the waste management target following Presidential Regulation Number 97 of 2017, namely reducing waste from the source by 30% and waste handling by 70% by 2025, Indonesia is adapting its commitment at the international level, with a target of reducing marine waste by 70% by 2025 (KLHK (Ministry of Environment and Forestry) press release, 2018). Mitigation efforts from residents can be done through the 6 R movement: Reduce, Reuse, Recycle, Repair, Refuse, Rethink [48], separating the types of waste from the beginning, encouraging the role of government through education and regulation, research and technology support and increase the comfort of the local civilian and visitors so that the function of Pekalongan waters remains sustainable.

REFERENCES

1. Kibria, M.G., Masuk, N.I., Safayet, R., Nguyen, H.Q. and Mourshed, M. 2023. Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management. *International Journal of Environmental Research*, 17, 20. https://doi.org/10.1007/s41742-023-00507-z
2. Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L. and Suh, S., 2020. Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry and Engineering*, 8(9), pp. 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635
3. Lassen, C., Hansen, S.F., Magnusson, K., Hartmann, N.B., Rehne Jensen, P., Nielsen, T.G. and Brinch, A., 2015. *Microplastics: occurrence, effects and sources of releases to the environment in Denmark*. Danish Environmental Protection Agency, 207 p. Available at: https://backend.orbit.dtu.dk/ws/portalfiles/portal/118180844/Lassen_et_al._2015.pdf [Accessed: 28 May 2025].
4. Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. and Law, K.L., 2015. Plastic Waste Inputs from Land into the Ocean. *Science*, 347(6223), pp. 768–771. https://doi.org/10.1126/science.1260352
5. Nchimbi, A.A., Shilla, D.A., Kosore, C.M., Shilla, D.J., Shashoua, Y. and Khan, F.R., 2022. Microplastics in Marine Beach and Seabed Sediments along the Coasts of Dar es Salaam and Zanzibar in Tanzania. *Marine Pollution Bulletin*, 185, 114305. https://doi.org/10.1016/j.marpolbul.2022.114305
6. Sheavly, S. and Register, K., 2007. Marine Debris and Plastics: Environmental Concerns, Sources, Impacts and Solutions. *Journal of Polymers and the Environment*, 15, pp. 301–305. https://doi.org/10.1007/s10924-007-0074-3
7. McEachern, K., Alegria, H., Kalagher, A.L., Hansen, C., Morrison, S. and Hastings, D., 2019. Microplastics in Tampa Bay, Florida: Abundance and Variability in Estuarine Waters and Sediments. *Marine Pollution Bulletin*, 148, pp. 97–106. https://doi.org/10.1016/j.marpolbul.2019.07.068
8. Park, H. and Park, B., 2021. Review of Microplastic Distribution, Toxicity, Analysis Methods, and Removal Technologies. *Water*, 13(19), 2736. https://doi.org/10.3390/w13192736
9. Wulandari, S.Y., Radjasa, O.K., Bambang, Y., Aris, I., Muslim, M., Jarot, M., Siagian, H. and Siti, M., 2021. Microplastics Model Distribution in Semarang Waters. *Research Journal of Chemistry and Environment*, 25(1), pp. 109–120. Available at: https://www.researchgate.net/publication/348379282 [Accessed: 28 May 2025].
10. Coyle, R., Hardiman, G. and Driscoll, K.O., 2020. Microplastics in the Marine Environment: A Review of their Sources, Distribution Processes, Uptake and Exchange in Ecosystems. *Case Studies in Chemical and Environmental Engineering*, 2, 100010. https://doi.org/10.1016/j.cscee.2020.100010
11. Auta, H.S., Emenike, C.U. and Fauziah, S.H., 2017. Distribution and Importance of Microplastics in the Marine Environment: a Review of the Sources, Fates, Effects and Potential Solutions. *Environment International*, 102, pp. 165–176. https://doi.org/10.1016/j.envint.2017.02.013

12. Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G. and Reisser, J., 2014. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS One*, 9(12), e111913. https://doi.org/10.1371/journal.pone.0111913

13. Pangestu, I.F., Purba, N.P. and Syamsudin, M.L., 2016. Microplastic Condition in Indramayu Waters, West Java. In: E. Afrianto [et al.], eds., 2016. *Proceedings of the National Seminar on Fisheries and Maritime Affairs: Technology, Law and Policy Synergy on Fisheries and Marine Sciences Toward Food Sovereignty in AEC (Bandung, Indonesia)*. 382.

14. Duis, K. and Coors, A., 2016. Microplastics in the Aquatic and Terrestrial Environment: Sources (with a Specific Focus on Personal Care Products), Fate and Effects. *Environmental Sciences Europe*, 28, 2. https://doi.org/10.1186/s12302-015-0069-y

15. Chatterjee, S. and Sharma, S., 2019. Microplastics in our Oceans and Marine Health. *Field Actions Science Reports*, (19), pp. 54–61. Available at: https://journals.openedition.org/factsreports/5257 [Accessed: 28 May 2025].

16. Wu, H., Hou, J. and Wang, X., 2023. A Review of Microplastic Pollution in Aquaculture: Sources, Effects, Removal Strategies and Prospects. *Ecotoxicology and Environmental Safety*, 252, 114567. https://doi.org/10.1016/j.ecoenv.2023.114567

17. Yap, H.S., Shukor, M.Y. and Yasid. N.A., 2022. The Microplastics Occurrence and Toxic Effects in Marine Environment. *Journal of Environmental Microbiology and Toxicology*, 10(2), pp. 1–6. https://doi.org/10.54987/jemat.v10i2.733

18. Bhuyan, M.S., 2022. Effects of Microplastics on Fish and in Human Health. *Frontiers in Environmental Science*, 10, pp. 1–17. https://doi.org/10.3389/fenvs.2022.827289

19. Nahian, S.A., Rakib, M.R.J., Kumar, R., Haider, S.M.B., Sharma, P. and Idris, A.M., 2023. Distribution, Characteristics, and Risk Assessments Analysis of Microplastics in Shore Sediments and Surface Water of Moheshkhali Channel of Bay of Bengal, Bangladesh. *Science of the Total Environment*, 855, 158892. https://doi.org/10.1016/j.scitotenv.2022.158892

20. Sierra, I., Chialanza, M.R., Faccio, R., Carrizo, D., Fornaro, L. and Pérez-Parada, A., 2019. Identification of Microplastics in Wastewater Samples by Means of Polarized Light Optical Microscopy. *Environmental Science and Pollution Research*, 27, pp. 7409–7419. https://doi.org/10.1007/s11356-019-07011-y

21. Wang, Z.M., Wagner, J., Ghosal, S., Bedi, G. and Wall, S., 2017. SEM/EDS and Optical Microscopy Analyses of Microplastics in Ocean Trawl and Fish Guts. *Science of the Total Environment*, 603–604, pp. 616–626. https://doi.org/10.1016/j.scitotenv.2017.06.047

22. Kalaronis, D., Ainali, N.M., Evgenidou, E., Kyzas, G.Z., Yang, X., Bikiaris, D.N. and Lambropoulou, D.A., 2022. Microscopic Techniques as Means for the Determination of Microplastics and Nanoplastics in the Aquatic Environment: A Concise Review. *Green Analytical Chemistry*, 3, 100036. https://doi.org/10.1016/j.greeac.2022.100036

23. Watters, D.L., Yoklavich, M.M., Love, M.S. and Schroeder, D.M., 2010. Assessing Marine Debris in Deep Seafloor Habitats Off California. *Marine Pollution Bulletin*, 60(1), pp. 131–138. https://doi.org/10.1016/j.marpolbul.2009.08.019

24. Yola, Yuanita, N., Kurniawan, A., Nugroho, E.O., Martin, R.J., Muhammad, I.F., Wijaya, F.S. and Fauzi, N., 2022. Coastal Protection System Design at the Indonesian Mangrove Center in Pekalongan, Central Java–Indonesia. In: IOP, 2022. *IOP Conference Series: Earth and Environmental Science. The Fourth International Conference on Sustainable Infrastructure and Built Environment 08/03/2022–09/03/2022 Online. ITB, Bandung, Indonesia*. IOP Publishing. Vol. 1065, iss. 1, 012062. https://doi.org/10.1088/1755-1315/1065/1/012062

25. Katsanevakis, S., 2008. Marine Debris, a Growing Problem: Sources, Distribution, Composition, and Impacts. In: T. N. Hofer, ed., 2008. *Marine Pollution: New Research*. New York: Nova Science Publishers, pp. 53–100.
26. Montoto-Martínez, T., Hernández-Brito, J.J. and Gelado-Caballero, M.D., 2020. Pump-Underway Ship Intake: An Unexploited Opportunity for Marine Strategy Framework Directive (MSFD) Microplastic Monitoring Needs on Coastal and Oceanic Waters. *PLoS ONE*, 15(5), e0232744. https://doi.org/10.1371/journal.pone.0232744
27. Qu, J., Wu, P., Pan, G., Li, J. and Jin, H., 2022. Microplastics in Seawater, Sediment, and Organisms from Hangzhou Bay. *Marine Pollution Bulletin*, 181, 113940. https://doi.org/10.1016/j.marpolbul.2022.113940
28. Tien, C., Wang, Z. and Chen, C.S., 2020. Microplastics in Water, Sediment and Fish from the Fengshan River System: Relationship to Aquatic Factors and Accumulation of Polycyclic Aromatic Hydrocarbons by Fish. *Environmental Pollution*, 265, part B, 114962. https://doi.org/10.1016/j.envpol.2020.114962
29. Shim, W.J., Hong, S.H. and Eo, S., 2018. Chapter 1 – Marine Microplastics: Abundance, Distribution, and Composition. In: E. Y. Zeng, ed., 2018. *Microplastic Contamination in Aquatic Environments*. Elsevier, pp. 1–26. http://dx.doi.org/10.1016/B978-0-12-813747-5.00001-1
30. Wang, T., Zou, X., Li, B., Yao, Y., Zang, Z., Li, Y., Yu, W. and Wang, W., 2019. Preliminary Study of the Source Apportionment and Diversity of Microplastics: Taking Floating Microplastics in the South China Sea as an Example. *Environmental Pollution*, 245, pp. 965–974. https://doi.org/10.1016/j.envpol.2018.10.110
31. Di, M. and Wang, J., 2018. Microplastics in Surface Waters and Sediments of the Three Gorges Reservoir, China. *Science of the Total Environment*, 616–617, pp. 1620–1627. https://doi.org/10.1016/j.scitotenv.2017.10.150
32. Ismanto, A., Hadibarata, T., Kristanti, R.A., Sugianto, D.N., Widada, S., Atmodjo, W., Satriadi, A., Anindita, M.A., Al-Mohaimeed, A.M. and Abbasi, A.M., 2023. A Novel Report on the Occurrence of Microplastics in Pekalongan River Estuary, Java Island, Indonesia. *Marine Pollution Bulletin*, 196, 115563. https://doi.org/10.1016/j.marpolbul.2023.115563
33. Avio, C.G., Gorbi, S. and Regoli, F., 2017. Plastics and Microplastics in the Oceans: from Emerging Pollutants to Emerged Threat. *Marine Environmental Research*, 128, pp. 2–11. https://doi.org/10.1016/j.marenvres.2016.05.012
34. Suteja, Y., Atmadipoera, A.S., Riani, E., Nurjaya, I.W., Nugroho, D. and Cordova, M.R., 2021. Spatial and Temporal Distribution of Microplastic in Surface Water of Tropical Estuary: Case Study in Benoa Bay, Bali, Indonesia. *Marine Pollution Bulletin*, 163, 111979. https://doi.org/10.1016/j.marpolbul.2021.111979
35. Flores-Ocampo, I.Z. and Armstrong-Altahatrin, J.S., 2023. Abundance and Composition of Microplastics in Tampico Beach Sediments, Tamaulipas State, Southern Gulf of Mexico. *Marine Pollution Bulletin*, 191, 114891. https://doi.org/10.1016/j.marpolbul.2023.114891
36. Crawford, C.B. and Quinn, B., 2016. *Microplastic Pollutants*. Elsevier Science, 336 p.
37. Khoironi, A., Hadiyanto, H., Anggoro, S. and Sudarno, S., 2020. Evaluation of Polypropylene Plastic Degradation and Microplastic Identification in Sediments at Tambak Lorok Coastal Area, Semarang, Indonesia. *Marine Pollution Bulletin*, 151, 110868. https://doi.org/10.1016/j.marpolbul.2019.110868
38. Purwiyanto, A.I.S., Prartono, T., Riani, E., Naulita, Y., Cordova, M.R., and Koropitan, A.F., 2022. The Deposition of Atmospheric Microplastics in Jakarta-Indonesia: The Coastal Urban Area. *Marine Pollution Bulletin*, 174, 113195. https://doi.org/10.1016/j.marpolbul.2021.113195

39. Taha, Z.D., Amin, R.M., Anuar, S.T., Nasser, A.A.A. and Sohaimi, E.S., 2021. Microplastics in Seawater and Zooplankton: A Case Study from Terengganu Estuary and Offshore Waters, Malaysia. *Science of the Total Environment*, 786, 147466. https://doi.org/10.1016/j.scitotenv.2021.147466

40. Syakti, A.D., Hidayati, N.V., Jaya, Y.V., Siregar, S.H., Yude, R., Suhendy, Asia, L., Wong-Wah-Chung, P. and Doumenq, P., 2018. Simultaneous Grading of Microplastic Size Sampling in the Small Islands of Bintan Water, Indonesia. *Marine Pollution Bulletin*, 137, pp. 593–600. https://doi.org/10.1016/j.marpolbul.2018.11.005

41. Cordova, M.R., Riani, E. and Shiomoto, A., 2020. Microplastics Ingestion by Blue Panchax Fish (Aplocheilus sp.) from Ciliwung Estuary, Jakarta, Indonesia. *Marine Pollution Bulletin*, 161, 111763. https://doi.org/10.1016/j.marpolbul.2020.111763

42. Falahudin, D., Cordova, M.R., Sun, X., Yogaswara, D., Wulandari, I., Hindarti, D. and Arifin, Z., 2020. The First Occurrence, Spatial Distribution and Characteristics of Microplastic Particles in Sediments from Banten Bay, Indonesia. *Science of the Total Environment*, 705, 135304. https://doi.org/10.1016/j.scitotenv.2019.135304

43. Riani, E. and Cordova, M.R., 2022. Microplastic Ingestion by the Sandfish Holothuria scabra in Lampung and Sumbawa, Indonesia. *Marine Pollution Bulletin*, 175, 113134. https://doi.org/10.1016/j.marpolbul.2021.113134

44. Buwono, N.R., Risjani, Y. and Soegianto, A., 2021. Distribution of Microplastic in Relation to Water Quality Parameters in the Brantas River, East Java, Indonesia. *Environmental Technology and Innovation*, 24, 101915. https://doi.org/10.1016/j.eti.2021.101915

45. Zhang, W., Zhang, S., Qu, L., Ju, M., Huo, C. and Wang, J., 2023. Seasonal Distribution of Microplastics in the Surface Waters of the Yellow Sea, China. *Marine Pollution Bulletin*, 193, 115051. https://doi.org/10.1016/j.marpolbul.2023.115051

46. Janakiram, R., Keerthivasan, R., Janani, R., Ramasundaram, S., Martin, M.V., Venkatesan, R., Ramana Murthy, M.V., and Sudhakar, T., 2023. Seasonal Distribution of Microplastics in Surface Waters of the Northern Indian Ocean. *Marine Pollution Bulletin*, 190, 114838. https://doi.org/10.1016/j.marpolbul.2023.114838

47. Barrett, J., Chase, Z., Zhang, J., Holl, M.M.B., Willis, K., Williams, A., Hardesty, B.D. and Wilcox, C., 2020. Microplastic Pollution in Deep-Sea Sediments from the Great Australian Bight. *Frontiers in Marine Science*, 7, 576170. https://doi.org/10.3389/fmars.2020.576170

48. Muhsin, Ahmad, S.W., Yanti, N.A., Mukhsar and Safitri, A.N., 2021. Distribution and Mitigation Efforts for Microplastic Pollution in Kendari Bay as the Mainstay Coastal Tourism Area of Southeast Sulawesi. *Journal of Physics: Conference Series 2021*, 1899, 012012. https://doi.org/10.1088/1742-6596/1899/1/012012

Submitted 11.08.2024; accepted after review 03.10.2024; revised 25.03.2025; published 31.03.2025

About the authors:

Sugeng Widada, Lecturer, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), DSc (Marine Science)

Kunarso, Lecturer, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), DSc (Marine Science)

Elis Indrayanti, Lecturer, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), DSc (Marine Science)

Rikha Widiaratih, Lecturer, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), DSc (Marine Science)

Aris Ismanto, Lecturer, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), DSc (Marine Science)

Muhammad Zainuri, Professor, Department of Oceanography, Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), Center for Coastal Rehabilitation and Disaster Mitigation Studies (CoREM) (Jl. Prof. Soedarto, Tembalang, Kec. Tembalang, Kota Semarang, 50275, Jawa Tengah), DEA (Biol.), **Scopus Author ID: 57188871982**, **ORCID ID: 0000-0001-8131-8448**, *muhammadzainuri@lecturer.undip.ac.id*

Tony Hadibarata, Professor, Environmental Engineering Program, Faculty of Engineering and Science, Curtin University Malaysia (CDT 250, Miri, Malaysia), PhD (Env Eng)

Malya Asoka Anindita, Research Assistant**,** Postgraduate study of Marine Science (Master), Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), BSc (Oceanography)

Tanya Tristanova, Research Assistant, Postgraduate study of Marine Science (Master), Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, 50275, Indonesia), BSc (Oceanography)

Muhammad Shulhan Jihadi, Research Assistant, Postgraduate study of Marine Science (Master), Faculty of Fisheries and Marine Science, Diponegoro University (Jl. Prof. Jacub Rais, Tembalang, Semarang, Indonesia, 50275), Center for Coastal Rehabilitation and Disaster Mitigation Studies (CoREM) (Jl. Prof. Soedarto, Tembalang, Kec. Tembalang, Kota Semarang, 50275, Jawa Tengah), BSc (Oceanography), **ORCID ID: 0009-0003-7193-7298,** *mail.shulhanj@gmail.com*

Contribution of the authors:

Sugeng Widada – lead researcher, supervisor, marine sedimentation and geology expert

Kunarso – supervisor, marine productivity and water quality

Elis Indrayanti – researcher, marine and coastal ecology

Rikha Widiaratih – researcher, physical oceanography, ocean modelling, and microplastics

Aris Ismanto – researcher, physical oceanography, ocean modelling, and microplastics

Muhammad Zainuri – lead researcher, supervisor, manuscript writing, conceptualization

Tony Hadibarata – researcher, environmental health, laboratory analysis, microplastics

Malya Asoka Anindita – researcher, manuscript writing, field data collection, laboratory analysis, Geographic Information System (GIS)

Tanya Tristanova – researcher, manuscript writing, field data collection, laboratory analysis

Muhammad Shulhan Jihadi – researcher, manuscript writing, field data collection, Geographic Information System (GIS)

All the authors have read and approved the final manuscript.