Chemosphere 348 (2024) 140761

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Abundance and characterization of microplastic pollution in the wildlife reserve, Ramsar site, recreational areas, and national park in northern Jakarta and Kepulauan Seribu, Indonesia

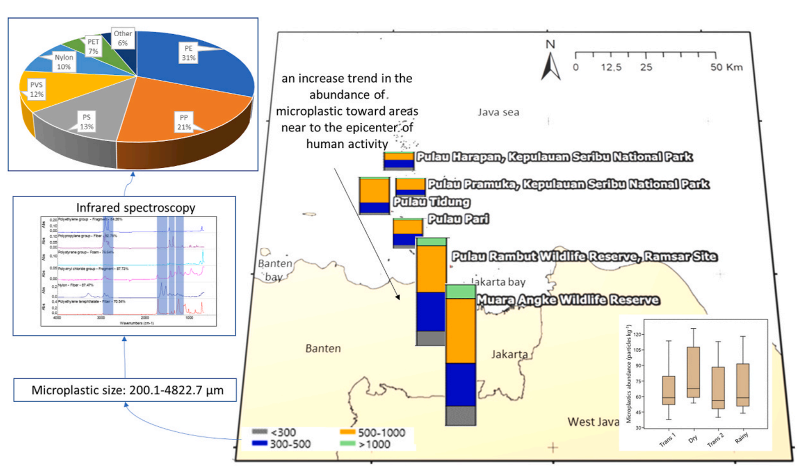
Muhammad Reza Cordova [a,*], Yaya Ihya Ulumuddin [a], Triyoni Purbonegoro [a], Rachma Puspitasari [a], Ricky Rositasari [a], Deny Yogaswara [a], Muhammad Taufik Kaisupy [a], Singgih Prasetyo Adi Wibowo [a], Riyana Subandi [a], Sofia Yuniar Sani [a], S. Sulistiowati [b], Intan Kusumastuti Nugraheni [b], Lucky Rahman [b], Rahmawati [b], Safitri Al Rahmadhani [b], Tyara Aprilani Khoirunnisa [b], Nurhasanah [c], Ahmad Muhtadi [d], Swietenia Puspa Lestari [e], Simon M. Cragg [f,g]

[a] Research Center for Oceanography, National Research and Innovation Agency Republic of Indonesia, Jl. Pasir Putih 1, Ancol, 14430, Jakarta, Indonesia
[b] Graduate School of Fisheries and Marine Science, IPB University, Jl. Agatis Gedung Fakultas Perikanan dan Ilmu Kelautan, Kampus IPB Darmaga, Bogor, 16680, Indonesia
[c] Environmental Studies Graduate Program, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang Tangerang Selatan, 15418, Indonesia
[d] Department of Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara. Jl. Prof. A. Sofyan No. 3, Medan, 20222, Indonesia
[e] Divers Clean Action, Jl. RS Fatmawati No. 72 Jakarta Selatan, 12450, Indonesia
[f] Institute of Marine Sciences, University of Portsmouth, Portsmouth, United Kingdom
[g] Centre for Blue Governance, University of Portsmouth, Portsmouth, United Kingdom

HIGHLIGHTS

- Microplastic abundance was shown to be lower as distance from the center of human activity decreased.
- Most microplastics in sediments are tiny (300–1000 m) and derived from secondary sources.
- Polyethylene and polypropylene are the most popular types of polymer found everywhere.
- Near the mainland, the polymer groups polystyrene and polyvinyl chloride are recognized.
- Nylon group Polymers are prevalent in the national park zone and may be linked to fishing activity.

GRAPHICAL ABSTRACT



* Corresponding author.
E-mail addresses: muhammad.reza.cordova@brin.go.id, cordova@marpol.id (M.R. Cordova).

https://doi.org/10.1016/j.chemosphere.2023.140761
Received 8 February 2023; Received in revised form 26 April 2023; Accepted 17 November 2023
Available online 21 November 2023

ARTICLE INFO

Handling editor: Derek Muir

Keywords:
Microplastic
Beach sediment
Wildlife reserve
Ramsar site
National park
Indonesia

ABSTRACT

This is the first study to evaluate the presence and distribution of microplastics in sediments in the regions with a unique degree of complexity, such as wildlife reserve areas, a Ramsar site that connects directly to Greater Jakarta's mainland, recreational islands, and a marine national park. Microplastics of varying sizes and shapes are found in all places, with an increase trend in the abundance toward areas near to the epicenter of human activity. Comparatively to other marine protected areas, the amount of microplastics discovered is comparable; however, there is an upward trend. Season influences microplastic accumulation, with the dry season causing the greater accumulation. Small-sized microplastics and microplastics resulting from large plastic fragments were predominantly discovered. The properties of microplastics in the study region are dominated by polyethylene, polypropylene, polystyrene, polyvinyl chloride, and nylon. Additional in-depth research and waste reduction from all sources that involve all stakeholders are required to reduce the amount of contaminants entering the protected area.

1. Introduction

In the past two decades, there has been a rise in research and investigations pertaining to litter, especially in coastal and marine ecosystems. Plastic is the form of waste material that generates the most concerns among the numerous types of litter (GESAMP, 2015). Plastic consumption is currently at a record high as a relatively new material that has been mass-produced since 1950s (Matsuguma et al., 2017). Plastic waste pollutes the environment on a vast scale, particularly the marine environment, as a result of inadequate waste management and the reliance of most landfills on open-dumping systems (He et al., 2019; Hopewell et al., 2009; Mrowiec, 2018). In recent decades, plastics' flexible qualities, incredible durability, lightweight, and low manufacturing costs have led to significant growth in plastic consumption and rendered plastics major pollution (Andrady, 2015; Ryan, 2015; van Emmerik et al., 2018). The various sizes of plastic litter found in nature are commonly categorized as follows: megaplastics (>100 cm), macroplastics (>2.5 cm), mesoplastics (>0.5 cm), microplastics (<0.5 cm), and nanoplastics (<1 μm) (GESAMP, 2015).

Plastic litter that is typically dumped, discarded or abandoned in bigger pieces will be fragmented by ultraviolet radiation, mechanical forces, oxidation and hydrolysis reactions, and biodegradation due to microbes' roles (Agamuthu et al., 2019; Cooper and Corcoran, 2010; Muthukumar and Veerappapillai, 2015). In addition, there are small-sized plastics designed from the beginning for cosmetics, personal care, material scrubbers for cleaning, and industrial products (Acosta-Coley and Olivero-Verbel, 2015; Hanvey et al., 2017). The microscopic size of plastic litter, which is more commonly referred to as microplastics, contributes to the global challenge of the plastic litter because it spreads and has several negative impacts on the environment and organisms (Galgani et al., 2015; Krause et al., 2021). Due to their easily dispersible nature, microplastics can be found from the Tropics to the Arctic and Antarctic, as well as in river estuaries, on the surface of the sea, and in the deep sea (Cordova et al., 2020; Mu et al., 2019; Riani and Cordova, 2022; Rios-Mendoza et al., 2021; Suaria et al., 2020). Therefore, microplastics are also discovered in terrestrial, coastal, pelagic, and benthic animals (Da Costa et al., 2019; Eerkes-Medrano et al., 2015). Based on investigations of microplastic exposure, it has been determined that microplastics can be physically and chemically hazardous to an acute degree of mortality (Buteler et al., 2022; Gray and Weinstein, 2017; Sobhani et al., 2021). Despite the fact that environmental conditions differ from laboratory conditions, this remains a threat to life on Earth (Lehtiniemi et al., 2018), both in areas of intensive human activity and in conservation zones.

Protected areas are zones established to preserve biodiversity (land, water, coastal, and marine), restrict exploitation, and reduce human influences on the core zone (Luna-Jorquera et al., 2019). Internationally, protected areas include the areas that meet the requirements for IUCN management categories, Biosphere Reserves, Ramsar sites, and World Heritage sites (Kutralam-Muniasamy et al., 2021). Specifically for marine protected areas that also aim to preserve marine variety, boost fisheries resilience, and protect ecosystem services; it has already reached 8.2% of the world's coastal and marine areas (IUCN, UNEP-WCMC, 2022). Indonesia, which is situated in the core of the Coral Triangle, is one of the nations that has rapidly established marine protected areas. In January 2020, Indonesia's marine protected areas covered 239,000 km^2, protecting 7.3% of the country's sea area (Amkieltiela et al., 2022). However, solid waste threatens areas that should be well protected. Because plastic litter is growing increasingly ubiquitous, marine plastic litter is becoming a major problem in this areas (Luna-Jorquera et al., 2019; Nunes et al., 2023b). Research on marine litter, particularly microplastics, is very sparse in marine protected areas. There are only 168 publications pertaining to microplastics in this domain (Nunes et al., 2023b). There are only two articles that provide chemical characterization analysis and four publications that describe the characterization of microplastics in detail (Nunes et al., 2023a). Even though there are conceivable to be a number of marine protected areas in Indonesia, only one publication has reportedly been published there (Nunes et al., 2023b). It is essential to research microplastics in Indonesia's marine protected areas since these regions directly interact with anthropogenic activities, one of which is located in the metropolitan area of Greater Jakarta.

There are several marine protected areas in the greater Jakarta region, including the Muara Angke wildlife reserve, the Pulau Rambut Ramsar site, and the Kepulauan Seribu national park. The 25.02-ha Muara Angke wildlife reserve is located on the northern coast of Jakarta. This region is predominantly a mangrove forest. The Pulau Rambut Ramsar site is approximately 30 km north of Jakarta, in Jakarta Bay. Pulau Rambut is a mangrove island that provides habitat and resting areas for fourteen species of waterbirds. The 107.50-ha Kepulauan Seribu national park protects not only the Hawksbill Turtle (*Eretmochelys imbricata*) and the Giant Clam (*Tridacna gigas*) but also the coral reef and mangrove ecosystems. Between the Pulau Rambut Ramsar site and the Kepulauan Seribu national park are many islands that act as buffer zones for marine protected areas, including the islands of Pulau Pari and Pulau Tidung. Currently, the two islands are used for maritime leisure. This marine protected area consists predominantly of sandy beaches. This intertidal zone is essential for marine protected area ecosystems; hence, research is required. Consequently, the aim is to evaluate microplastics on sandy beaches in marine protected areas close to human activities from adhering to the mainland (Muara Angke wildlife reserve), near the estuary (Pulau Rambut Ramsar site), two marine recreation area islands (Pulau Pari and Pulau Tidung), and the national park area (Pulau Pramuka and Pulau Harapan). We offer the novelty of this research by providing the first and most recent data on the abundance of microplastics in the three marine protected areas near the most densely populated areas, the Greater Jakarta, i.e., Muara Angke Wildlife Reserve, Pulau Rambut Ramsar Site and Kepulauan Seribu Marine National Park. Our research represents the first seasonal examination of microplastics in marine protected areas in this region. It is imperative to assess numerous factors that affect the dispersion of microplastics in shoreline sediments; however, this could lead to convoluted outcomes. Therefore, our research primarily quantifies microplastics' prevalence and spatial arrangement from proximate areas near Jakarta's mainland to distant locales. This dataset enables us to decipher prevailing trends and patterns using existing literature as a reference point. As per prior research, ocean currents and hydrodynamics play a role in resuspending microplastic particles within the upper layer of sediments during rainy seasons. This phenomenon has enabled the identification of seasonal trends and patterns. The hypothesis is that the greater the distance from the mainland, the smaller the number of microplastics; also, the dispersion of microplastics is impacted by the season. Data gaps can be filled through this study, and Indonesia's waste management improved, particularly in marine protected areas.

2. Materials and methods

2.1. Study area

The research was done in six sampling areas (Fig. 1), including a wildlife reserve (Muara Angke wildlife reserve), a Ramsar site (Pulau Rambut), a recreational area (Pulau Pari and Pulau Tidung), and a national park (Pulau Pramuka and Pulau Harapan). Muara Angke wildlife reserve is a relic of Jakarta's huge mangrove forests. The Muara Angke region receives quite considerable amounts of debris discharge (1.12 ± 0.22 tons per day; Cordova and Nurhati, 2019) and microplastic flows (5.94 ± 0.69 particles per m^3; Cordova et al., 2022a,b) from the Angke river, which are highly likely to accumulate in the region's coastal sediments. Pulau Rambut, situated northwest of Jakarta Bay, is one of Indonesia's seven Ramsar sites. Pulau Rambut has mangrove vegetation and is home to 13 species of waterbirds (Mardiastuti, 2022). Pulau Tidung and Pulau Pari are inhabited islands primarily serving as marine tourism destinations. Pulau Pramuka and Pulau Harapan represent the Kepulauan Seribu Marine National Park's study area. These islands are both inhabited islands. The park is a haven for coral reefs, mangroves, the Hawksbill Turtle (*Eretmochelys imbricata*), and the Giant Clam (*Tridacna gigas*). All sampling locations are in permanent interference with anthropogenic activities, such as fishing and tourism, resulting in the potential to be influenced by waste. Administratively, the six sampling areas are in the Province of Jakarta, allowing for periodic waste management by the local government. However, ocean currents provide a risk of transboundary litter traveling through and accumulating in all sampling locations (Iskandar et al., 2021, 2022).

2.2. Sampling methods

Four different times were chosen to collect sediment samples to reflect the four distinct seasons: the rainy season (November–December), the first transitional season (January–February), the dry season (July), and the second transitional seasons (September). A 30 m transect line is installed in the mid-tide zones and strandlines of each area's coastlines. In addition, sampling was carried out every 5 m in a 25 × 25 cm^2 square transect along the line transect. Five to 10 cm of the top layer of sediment were sampled using a spatula made of stainless steel. The samples were thereafter placed in a sealed glass container. Before the extraction analysis method, the samples were kept at 4 °C.

2.3. Extraction, identification and characterization procedure

The laboratory procedure for assessing microplastics in the sediment was adopted from prior research (Abayomi et al., 2017; Curren et al., 2021). In brief, sediment samples (490–510 g) were dried in an oven at 40 °C for 72–96 h to minimize the moisture contents without deforming plastic material and causing minimal structural damage to the polymer composition. The sediment was then treated with a $ZnCl_2$ solution (ρ = 1.5 g/ml, Merck Millipore EMSURE®, ACS, ISO, Reag. Ph Eur), stirred, and left overnight. The supernatant solutions were then transferred to a test tube (Pyrex, 100 ml) and dried at 40 °C for 24 h. Fenton's reagent prepared from Fe(II)solution (20 ml $Fe(II)SO_4$, 10 mg/ml Merck Millipore, EMSURE® ACS, ISO, Reag. Ph Eur) and H_2O_2 (20 ml, 30% Merck Millipore, Emprove® Essential, Ph Eur, BP, USP) was applied to dried samples in a test tube. The test tube was incubated in a water bath

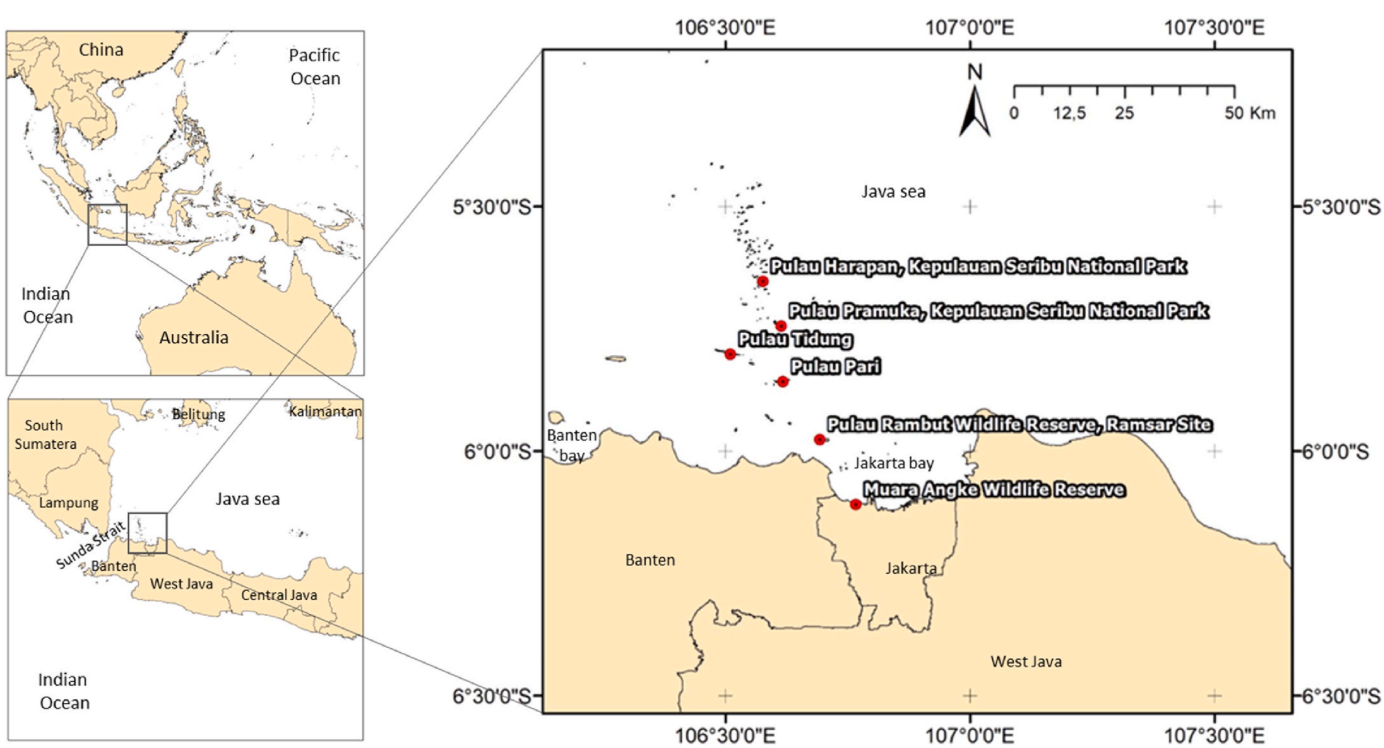


Fig. 1. Sampling location in the northern Jakarta and Kepulauan Seribu region.

(Shibata water bath WB-6C) at 40 °C for 24–48 h. Afterward, the samples were then transferred to sterile filter paper (Merck Whatman™ cellulose nitrate filter paper 47 mm, pore size 0.45 m, grid) and covered with a sterile Petri dish at room temperature prior to form, size, and chemical composition analysis. The filter paper membrane was observed using a microscope (Oympus CX31) and a camera (Sony IMX307).

We recognized probable microplastics using previously developed identification techniques (Cordova et al., 2019; Dehaut et al., 2019; Piehl et al., 2018). The recognized particles were identified based on the following characteristics: uniform tone, absence of biological or cellular features, and lack of segmentation (Cole et al., 2013; Cordova et al., 2022a; Peng et al., 2017). We documented the identified particles' shape and size promptly. This study's size detection limit was 200 μm, slightly smaller than the corresponding fraction of the size fraction limit (212 μm) highlighted in Lao and Wong's (2023) analysis conducted on four environmental matrices. The smallest microplastic observed through microscopy, verified with ATR- FTIR procedure, measures 200.1 μm, while the largest measured at 4822.7 μm. From the samples, a representative of the identified microplastic particles was selected (25%, 1072 out of 4259 particles), and its chemical composition was evaluated using an Attenuated Total Reflectance - Fourier Transform Infrared Spectrometer (ATR-FTIR, diamond crystal material, Agilent Cary 630 with Microlab Expert Software). The 1072 particles used for the chemical composition analysis were collected using a method of systematic random sampling that represented each sampling area and season. Table S1 in the Supplementary Materials demonstrates the proportion of the tested particles. The FTIR was set to a resolution of 4 cm^{-1} with 32 scans in the 650–3000 cm^{-1} band region spectrum range. Polymers were detected by examining the presence of a prominent peak in specific band areas in order to identify the bending vibration of CH_2, the stretching vibration of CF_2, the stretching vibration of C=O, and the stretching vibrations of $CH/CH_2/CH_3$ groups. The identification of polymers was achieved through the investigation of distinct peak occurrences in various band regions (Cordova et al., 2019; De Frond et al., 2021; Käppler et al., 2016; Löder and Gerdts, 2015), specifically at 1174-1087 cm-1, denoting stretching vibration of CF2, 1400–1480 cm-1 indicating bending vibration of CH2, and at 1670–1760 cm-1 as well as 1740–1800 cm-1 signifying stretching vibrations of C=O. Additionally, the presence of stretching vibrations from CH/CH2/CH3 groups within a range spanning from 2780 to 2980 cm-1 further contributed to identifying polymer types. For an illustration on how chemical composition analysis can be conducted for microplastic particle identification purposes using this method, refer to Fig. S1 presented in Supplementary Materials. The results of the chemical composition study were compared to polymer standard libraries from Agilent, Thermo-scientific, and Shimadzu; FLOPP Spectral Libraries of Plastic Particles (De Frond et al., 2021); and the plastic standard from the Research Center for Geosciences, University of Bayreuth, Germany.

2.4. Quality control and quality assurance

Prior to sampling, the spatula was washed three times with seawater and three times with filtered water (using sterile filter paper) to prevent cross-contamination. All glassware was rinsed with filtered water and covered in aluminum foil. In addition, we wore 100% cotton clothes and used glass laboratory supplies, wrapping samples promptly after treatments and sanitizing and cleaning all instruments before conducting laboratory studies. Using sterile filter paper, all chemical solutions were filtered to eliminate any residual microparticles. To ensure the performance of the employed microplastics extraction treatment, a recovery test was done (Cordova et al., 2022b; Way et al., 2022; Weber and Kerpen, 2022). Briefly, seven types of synthetic polymers (size 400–1000 μm) that are commonly used worldwide (PlasticsEurope, 2021) are mixed homogeneously with pure water (Milli-Q®) and 6 mg/l Now Solution® Red Clay Powder, which is equivalent to the average total suspended solid content in Jakarta Bay (Koagouw et al., 2021). The material mixture was then subjected to the same procedures as the sample, including density separation (using $ZnCl_2$ solution) and biological digestion (using Fenton's reagent). Using a combination of two repetitions of the density separation procedure and one biological digestion protocol, the recovery rate of all polymers was 100%. To decrease sampling and analytical errors, a method for estimating the amount of contamination introduced throughout the sampling and laboratory work using blank samples, was developed. Our procedure blank samples from field sampling (N = 3) and laboratory analyses (N = 12) contained exclusively cotton fiber (size range 932.01–7373.2 μm).

2.5. Statistical analyses

The software PAST4 (version 4.0.3) was used to perform statistical analysis and generate graph plots. Units were expressed in number of particles kg^{-1} sediment. We performed non-parametric statistical analysis (Kruskal-Wallis test for equal medians with Mann-Whitney pairwise post hoc) to investigate and compare the abundance of microplastics at each sampling location, at each sampling period, and across the four seasons. Tests were considered statistically significant at a p-value of 0.05.

3. Results

Microplastics were identified in all six locations' sediment samples and throughout each sampling interval. The average microplastic abundance for the entire research area is 70.91 ± 23.88 particles kg^{-1} sediment (Fig. 2). The highest abundance of microplastics was found at the station in Angke (111.93 ± 5.82 particles kg^{-1} sediment), while the lowest was found in Pulau Pramuka (50.74 ± 5.45 particles kg^{-1} sediment). Kruskal–Wallis analysis followed by Mann–Whitney pairwise post-hoc revealed significant differences across all sampling locations ($p < 0.05$), although there were no significant differences ($p > 0.05$) between neighboring islands (i.e., Pulau Harapan and Pulau Pramuka; Pulau Tidung and Pulau Pari).

The pattern of microplastic abundance increases with distance from the mainland (Fig. 2). The highest abundance is found in the Angke region, which is a wildlife reserve, and tends to be slightly higher than the abundance of microplastic at the Ramsar site (Pulau Rambut, 90.75 ± 11.25 particles kg^{-1} sediment). The pattern of microplastic abundance then declined on Pulau Pari, Pulau Tidung (a recreational area), Pulau Pramuka, and Pulau Harapan (a national park), with abundances of 59.30 ± 5.98, 61.44 ± 6.66, 50.74 ± 5.45, 51.32 ± 6.86 particles kg^{-1} sediment, respectively.

The number of microplastics varied with the season, as seen in Fig. 2. Based on the sampling period, the maximum microplastic abundance was 9.86 ± 24.71 particles kg^{-1} sediment during the Dry season, whereas the lowest was found during both transitional one seasons (67.16 ± 22.46 particles kg^{-1} sediment) and transitional two seasons (67.16 ± 24.43 particles kg^{-1} sediment). During the rainy season, the average number of microplastic particles was slightly greater, reaching 69.47 ± 22.66 particles kg^{-1} sediment. In addition, we discovered a greater variation in microplastic abundance throughout the rainy season compared to the other seasons. Similar results were found based on an in-depth comparison of the abundance of microplastics at each research location to the sampling period during each season. During the dry season, the abundance of microplastics at each sampling location was greater than at other times of the year, whereas the lowest microplastic abundance was distinct to each location. The same phenomena when examined through the perspective of the variability of microplastics. Based on the study of significant differences analysis, the abundance of microplastics at each sampling location during the dry season differs from that of other sampling seasons ($p < 0.05$) (see Fig. 3).

In all samples, microplastics of varied sizes and forms were detected. In accordance with the microplastics' size, we classified them into four categories: <300 μm, 300–500 μm, 500–1000 μm, and >1000 μm

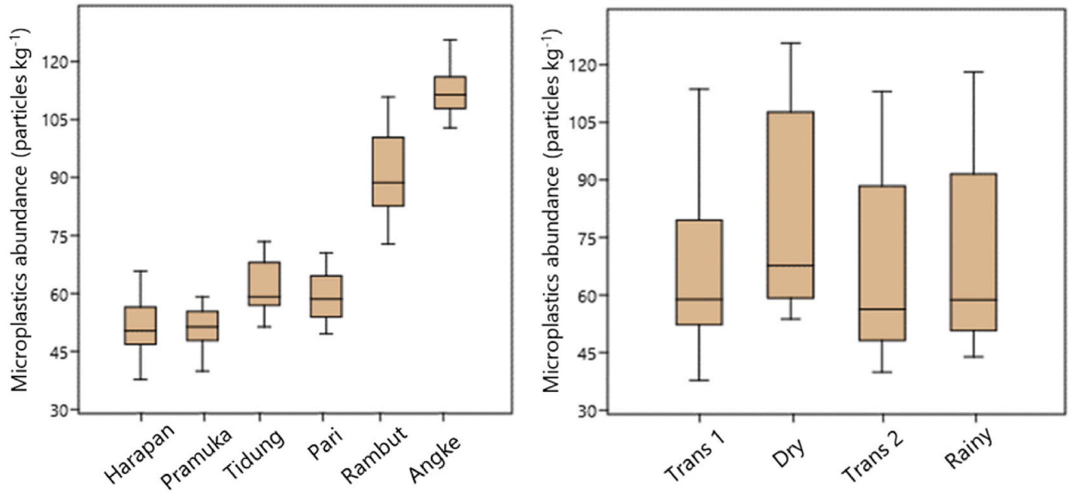


Fig. 2. Spatiotemporal microplastics abundance in the northern Jakarta and Kepulauan Seribu region.

(Fig. 4). Our investigation revealed that the length of discovered microplastics ranges from a minimum of 200.1 μm to a maximum of 4822.7 μm, with an average length of 1039.04 μm. 90% of partially identified microplastics in each study location were between 200 and 1000 μm in size. There is just one particle in Pulau Pramuka with a size >2000 μm (Fragment size: 3411.8 μm) and two particles in Angke (Foam size: 4822.7 μm and Fiber size: 3165.2 μm). Thus, it can be stated that the vast majority of microplastics detected are small-microplastic categories (50–2000 μm). With an average composition of 81.30%, the majority of microplastics are between 300 and 1000 μm in size. In greater detail, the 500–1000 μm range dominates the microplastics detected on almost all islands (43.26% on Pulau Rambut and 62.60% on Pulau Tidung). There was a notable contrast in Pulau Harapan as microplastic sizes ranging from 300 to 5000 μm dominated the proportion at approximately 39.81%. We categorized microplastics into four form categories based on their morphological features, namely fragment, foam, fiber, and granule, and their proportions are shown in Fig. 4. The majority of the particles found are fragments (36.09%). Foams and fibers made up 27.87% and 23.18%, correspondingly. According to the sampling period, there was no size or shape distinction amongst microplastics. In all seasons, 500–1000 μm microplastic particles were the most prevalent (44.51%), followed by 300–500 μm particles (31.9%). The majority of detected microplastics consist of fragments (37.70%), followed by foam (26.43%) and fiber (21.1%).

Out of a total of 4259 items observed in samples, 1072 items (about 25%) were chosen for FTIR spectroscopy identification. These 1072 particles comprised 41.60 % fragments, 15.21 % foams, 30.13 % fibers, and 13.06 % granules. A high proportion of the recognized shapes of microplastics were composed of the polyethylene group (30.97%), polypropylene group (21.36%), polystyrene group (12.41%), polyvinyl chloride group (11.85%), nylon (10.17%), polyethylene terephthalate (7.18%), and other (6.06%) polymers, respectively. Other polymers include polybutadiene, polyurethane, cellophane, polycarbonate, rayon, and polymer blend or combinations.

The abundance of microplastic particles on the windward and leeward beaches was 73.91 ± 24.29 and 67.92 ± 23.28 particles kg^{-1} sediment, respectively (Fig. 5). There was no statistically significant difference between the two groups of beaches (Kruskal-Wallis test for equal medians $p = 0.531$). Moreover, the variance of windward was higher than that of leeward.

4. Discussions

This is the first investigation to analyze the occurrence and distribution of sediment microplastic in regions with a unique complexity, including wildlife reserve areas, a Ramsar site that connects directly with Greater Jakarta's mainland, recreational islands, and marine national parks. All sand beach samples collected from all research sites contained microscopically sized synthetic polymers, demonstrating that microplastics have infiltrated coastal ecosystems in marine protected areas. In comparison to coastal sediments from Malaysia (Matsuguma et al., 2017), China (Xiong et al., 2018; Yu et al., 2016), India (Tiwari et al., 2019), Europe (Lots et al., 2017), and Africa (Vetrimurugan et al., 2020), the average amount of microplastic in beach sediment (range: 37.70 to 125.70 particles kg^{-1} sediment) is low to moderate. However, compared to marine protected areas worldwide, the abundance of microplastics in this research region is considerably higher than that of the Playa El Verde Camacho natural reserve in Mexico, which comprises 0.4–1.3 particles kg^{-1} sediment (Rios-Mendoza et al., 2021); Santuario per i Mammiferi Marini marine protected area in the Tyrrhenian Sea Italy with an abundance of microplastic 8–73 particles kg^{-1} sediment (Mistri et al., 2020); Hancock County Marsh Coastal Preserve and Jourdan River Preserve in Mississippi Gulf Coast tidal marshes USA which has an abundance of microplastic 0–104 and 0–16 particles kg^{-1} sediment, respectively (Weitzel et al., 2021); Shankou Mangrove Nature Reserve in China with abundant microplastics 34–88 particles kg^{-1} sediment (Zhou et al., 2020); and the Western Ghats World Heritage Site in India which has an abundance of 86 particles kg^{-1} sediment (Cheng et al., 2021). Compared to the 2015 sampling, the abundance of microplastics in the Muara Angke nature reserve increased by three to five times. During the second transitional seasons of 2015, monitoring revealed an average abundance of 35.01 ± 8.13 (range 23.93–47.79) particles kg^{-1} sediment (Cordova et al., 2021). In a similar zone in 2020–2021, the abundance of microplastic particles increased to 111.93 ± 5.82 (range 102.88–125.70) particles kg^{-1} sediment. Regrettably, to the best of our knowledge, similar research has not been conducted in other investigated areas, particularly between the Pulau Rambut Ramsar site and the Kepulauan Seribu National Park, so it is difficult to determine whether there has been a decrease or an increase in the abundance of microplastics in this location. We hypothesize that the introduction of microplastics to the marine protected area in the Northern Jakarta has increased as a result of an increase in land-based microplastics, particularly during the Covid-19 pandemic (Cordova et al., 2021, 2022b). Ocean currents in the regions also aid in the drifting of marine debris including microplastics, stranded away from mainland Jakarta (Iskandar et al., 2021, 2022). The growing threat of microplastics in marine protected areas, which directly and indirectly support biodiversity (Clukey et al., 2017; Compa et al., 2022) and the economy (Carvache-Franco et al., 2021; Clifton et al., 2021), necessitates that all stakeholders consider this concerning issue. Moreover, future research

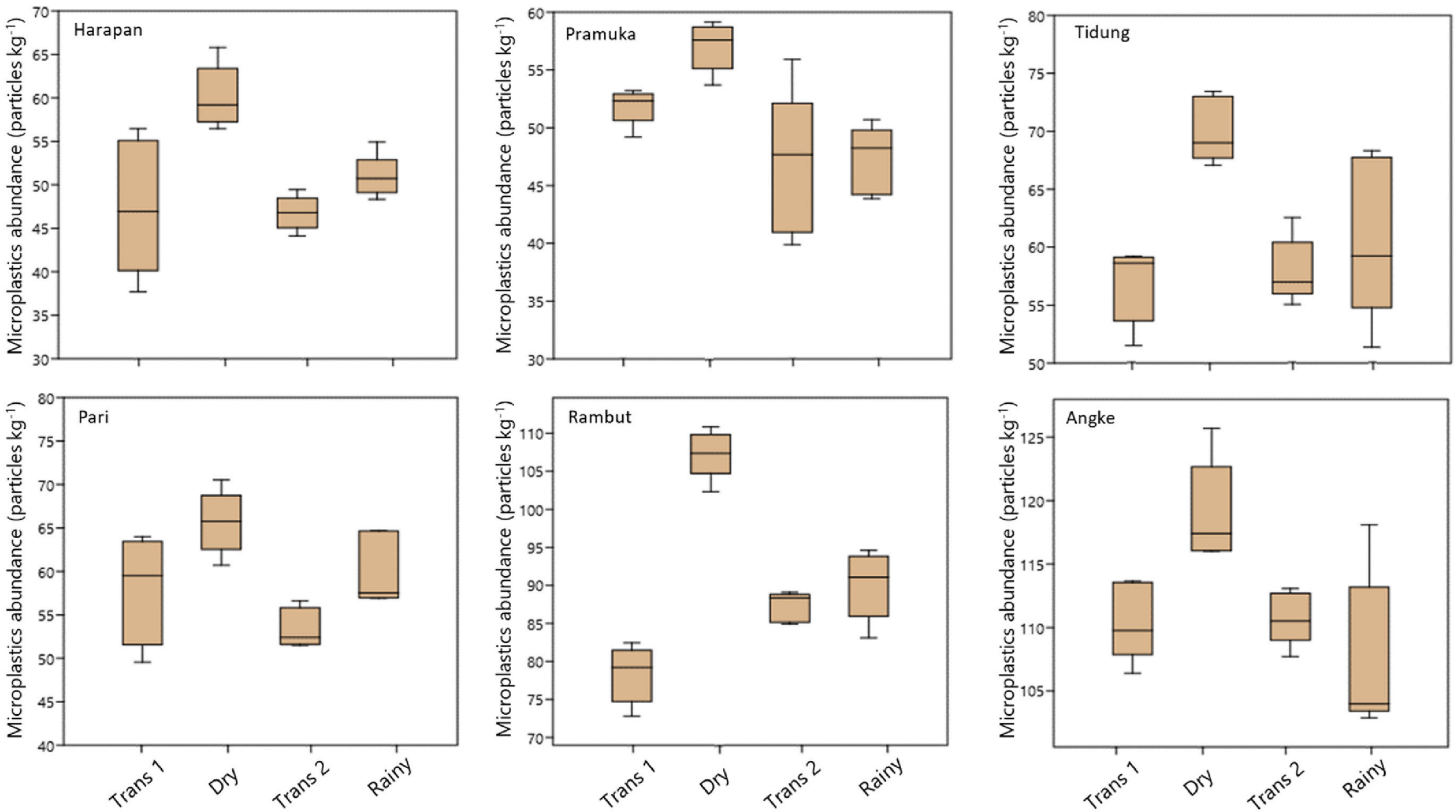


Fig. 3. Temporal variations on microplastics in all sampling areas in the northern Jakarta and Kepulauan Seribu region.

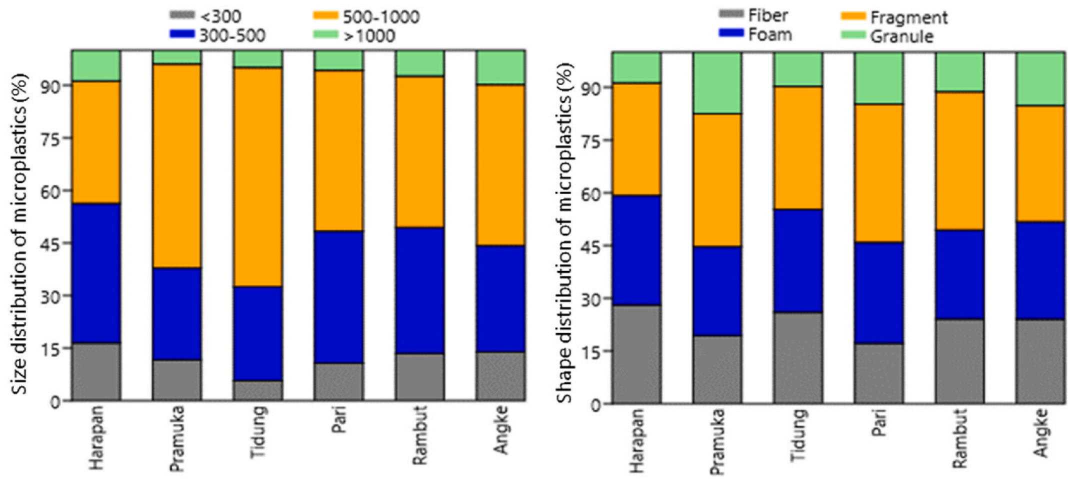


Fig. 4. Temporal distribution of microplastics by size (left) and forms (right) in the northern Jakarta and Kepulauan Seribu region.

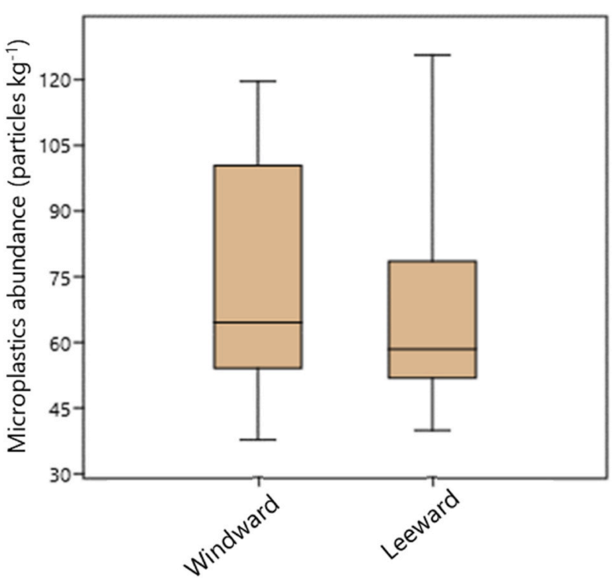


Fig. 5. The abundance of microplastic in windward and leeward beaches in northern Jakarta and Kepulauan Seribu region.

would benefit from monitoring microplastics in the marine protected area, not only in Jakarta but in all marine protected areas, in conjunction with the implementation of a waste management and water filter system and the collection of large plastic waste that has been scattered throughout the environment.

All of our research areas, despite being located within a marine protected area, i.e., wildlife reserve IUCN management category Ia, Ramsar site IUCN management category Ib, and marine national park IUCN management category II (Salman et al., 2020), are surrounded by a broad range of activities, including fishing, marine tourism, and other forms of recreation. This most likely exposes synthetic polymers ascribed to a number of marine and domestic applications (Simon-Sánchez et al., 2019). The wildlife reserve and Ramsar site in the north of Greater Jakarta are in direct contact with the rivers that flow into this region. In addition, the type of beach sediment in Muara Angke and Pulau Rambut near the major river mouths is sandy-muddy sediment, which causes more microplastics to be adsorbed by the sediments than sandy sediment, which has larger size than sandy-muddy sediment (Cordova et al., 2020; Enders et al., 2019; Eo et al., 2018). In accordance with a previous study (Xu et al., 2020), the abundance of microplastics was greater in estuarine locations (i.e., Muara Angke and Pulau Rambut) than on somewhat relatively more outlying islands (i.e., Pulau Pari, Pulau Tidung, Pulau Pramuka, and Pulau Harapan). This is associated with turbulence and ocean currents, which transport numerous substances, minerals, and pollutants (McLusky, 1989; Simon-Sánchez et al., 2019). Freshwater and saltwater mingle in estuaries, resulting in changes to the estuary's ecosystem (Dris et al., 2020; McLusky, 1989). This study was conducted during ebb tides, which represent the release of water, sediment, and materials, including microplastics carried by seawater into the coastal environment (Gallagher et al., 2016), and could be reintroduced during flood tides (Defontaine et al., 2020). Unfortunately, this study's limitation is that it was not conducted at ebb and flood tides. To gain a more comprehensive understanding of the influence of tide cycle on microplastic variations in beach sediment, additional research is required.

Seasonal variables influence the abundance of microplastics in marine protected area sediments. The hydrodynamic mechanism is regarded as the most significant driver in the release of particulate from sediment through the water (Pang et al., 2020). Our study's findings were consistent with literature regarding microplastics accumulated more in the beach sediments during the dry season than the rainy season (Horton and Dixon, 2018; Kobayashi et al., 2021). During the rainy season, there are reportedly more microplastics in rivers and tributaries (Piehl et al., 2020; Preston-Whyte et al., 2021; W. Zhao et al., 2020). It has been observed that during the rainy season, plastic and microplastics in the surface waters of the nine major rivers that flow into Jakarta bay were higher due to their transport by river water (Cordova et al., 2022b; Cordova and Nurhati, 2019). Due to complex currents and hydrodynamics, it is more difficult to suspend particles, particularly microplastics, during the rainy season than during the dry season. Hence, microplastics transported by water will be easier to accumulate during the dry season, when rivers and ocean currents slow down (X. Zhao et al., 2020). Resuspension processes, which become reiterated every season, can enable the movement of microplastics from the sediment to the water above, resulting in a decrease in the quantity of microplastics in the sediment (Tang et al., 2020). In addition, the number of particulate particles in the water above increases dramatically as the perturbation intensity rises (Orlins and Gulliver, 2003; Pang et al., 2020). This is alarming since it indicates that microplastics can continuously accumulate in sediments and float back to the water's surface. In this process, it is conceivable that other contaminants in the environment will be adsorbed by a rising prevalence of microplastics, creating a more considerable potential hazard than newly introduced microplastics (Xia et al., 2021).

Small sizes and secondary-source-like forms dominate the microplastic characteristics observed in this study. This study revealed that the greater the distance from the mainland and rivers, the greater the fraction of smaller microplastics. This occurs because the smaller the microplastics, the higher the probability of a resuspension process resulting from hydrodynamic processes (Chubarenko et al., 2018; Xia et al., 2021). It is believed that this microplastic arose through the fragmentation of bigger plastics (Wang et al., 2020). Moreover, regular and irregular types of microplastics (Li et al., 2018) have been identified in this study. Granule form (also classified as nurdles, pellets, spherules, or beads) includes regular microplastics, a type of plastic produced in small sizes and used in the manufacturing industry, cosmetics, and personal care products (Fok et al., 2017; Li et al., 2018; Sundt et al., 2014). In contrast, fragments, foam, and fiber are irregular forms resulting from the breakdown of plastic in nature (Khatmullina and Isachenko, 2017; Riani and Cordova, 2022). This study discovered a smaller fraction of granules than other kinds. This is consistent with a statement by Priya et al. (2022) that irregular microplastics are the most common type of microplastic discovered in the environment. Large litter plastics will break at a faster pace the more they are exposed to ultraviolet radiation and the higher the temperature (Lambert et al., 2013; Lambert and Wagner, 2016). Consequently, growth in secondary microplastics in the environment can stimulate the process of fragmenting plastics into smaller sizes, specifically nanoplastics, which will increase the possibility of being ingested or directly absorbed in the body, increase the bioaccumulation and bioavailability potential hazard, and raises the risk for the adhesion of hazardous contaminants or microbes that are harmful to health (Galloway et al., 2017; Karkanorachaki et al., 2022; Meng et al., 2021). The worrying thing is that Indonesia's tropical climate encourages these conditions, and it will be exacerbated if large-sized plastic waste is improperly managed and enters the ecosystem or is simply dumped in landfills (Nurhasanah et al., 2021).

Our research on the chemical composition of microplastics in marine protected zones will bridge knowledge gaps regarding their properties. Out of 168 publications in the marine protected area, only two relating to polymer analysis from microplastic particles were identified (Nunes et al., 2023b). A combination of polyethylene group, polypropylene group, polystyrene group, and polyvinyl chloride group was shown to be the predominant form of synthetic polymer (76.59%) discovered in microplastics in sediments from coastal protected zones. Polymer groups are utilized to define common polymer types because the precise sorts of synthetic polymer constituents of each of these groups are incredibly diverse (Int et al., 2021; Mintenig et al., 2020). From the four prominent polymer groups observed in the research region, polyethylene and polypropylene are reasonably evenly distributed (and dominant) in six sampling locations. In contrast, polystyrene and polyvinyl chloride tend to be more prevalent in regions adjacent to the mainland and rivers (i.e., Muara Angke wildlife reserve and Pulau Rambut Ramsar site). In the Kepulauan Seribu national park section (Pulau Pramuka and Pulau Harapan), a significant amount of nylon polymer was discovered (up to 23% of the total found in the section). Polyethylene group and polypropylene group are the most widely used polyolefins in a wide range of applications (Zhang et al., 2017) and are, therefore, the two synthetic polymers prevalent in marine environments, including in Indonesia (Vriend et al., 2021). The form of foam represents polystyrene, which is commonly used for cushioning, padding as well as disposable food and beverage packaging (Chitaka and von Blottnitz, 2019; Way et al., 2022). The majority of the foam discovered by our study is a sort of expanded polystyrene that is light, easily broken, and quickly transported by wind and water (Carpenter et al., 1972; Song et al., 2017). The Muara Angke wildlife reserve and Pulau Rambut Ramsar sites are mangrove habitats, resulting in high amounts of polystyrene along the beaches of these two locations. Mangroves become sinks and traps for land-based debris, particularly plastic (Garcés-Ordóñez et al., 2019; Ivar do Sul et al., 2014).

Our monitoring of the mangrove region in the research area revealed a significant number of Styrofoam-like debris. Due to the high complexity of mangrove ecosystems, a considerable mechanical abrasion process, and microbial activity, the possibility for plastic waste to become fragmented more rapidly (Luo et al., 2021; Martin et al., 2020). Martin et al. (2019) and Luo et al. (2021) stated that there is more large-sized plastic litter in the mangrove region than on the beach and added that the mangrove region is a hotspot for the creation of microplastics. This investigation indicated that the polyvinyl chloride group was also widespread in the Muara Angke wildlife reserve and the Pulau Rambut Ramsar research areas. Polyvinyl chloride is commonly used for pipelines, wires, building materials, and medical supplies (Ye et al., 2017). Polyvinyl chloride is a substantially more dense synthetic polymer than other synthetic polymers (Nanda and Berruti, 2021). We assume that the high abundance of polyvinyl chloride in the research area is due to the fact that this type of polymer is the most unstable since it is susceptible to ultraviolet radiation (Fernández-González et al., 2022). In contrast, the research area is a tropical region where its deterioration will be accelerated. Moreover, the majority of households around river basins in Indonesia employ polyvinyl chloride pipelines and discharge their sanitary sewage via piping directly into the river (Nurhasanah et al., 2021). Therefore, it is possible that considerable amounts of polyvinyl chloride plastic could be detected in rivers and the ocean. In this study, however, it remains an open question whether microplastic forms of polyvinyl chloride are increasingly disappearing from the mainland and estuaries. Possible factors include the fact that polyvinyl chloride has a higher specific gravity, meaning that without massive river flows and ocean currents, it cannot be transported further (Teuten et al., 2009). In addition, technical underestimations of polyvinyl chloride in the environment are probable. Fernández-González et al. (2022) reported that the longer polyvinyl chloride has been present in nature, the more the spectrophotometer reading is disrupted, making the identification findings resemble polyethylene. According to our research, younger polyvinyl chloride was also allegedly identified. In order to ensure that the results of the investigation of microplastics, particularly the type of polyvinyl chloride, are not underestimated, it is necessary to do additional and comprehensive research on this topic. The other intriguing aspect of our research is the generally higher quantity of microplastic types of nylon in the Kepulauan Seribu national park area. We speculate that the nylon discovered corresponds to abandoned, lost, or discarded fishing gear. Traditional fisherman predominantly populates Pulau Pramuka and Pulau Harapan. Nylon is the fundamental, most common, robust, flexible, and inexpensive material for fishing gear. Traditional fishermen may patch fishing gear back together if it is damaged; therefore, the older the fishing gear is, the more microplastics it is likely to produce. In order to reduce fishing gear waste, which is a source of microplastics, we propose a more in-depth inquiry into the design of eco-friendly, sustainable equipment, as well as the recycling of fishing gear.

Our findings indicate that the microplastic abundance on the windward is higher than that on the leeward, although there is no significant difference between the two. The findings of this study support prior research conducted in Pacific ocean (Ivar do Sul et al., 2009; Monteiro et al., 2020) and Atlantic ocean (Monteiro et al., 2018). We divide each island's additional research regions into windward and leeward. Windward sites are more exposed to waves during the east and west monsoon, but leeward sites are more protected from waves. This condition demonstrates the influence of surface currents that transport microplastics and finally deposit them on beach sand (Rey et al., 2021). Microplastics are similar in size and form to sand. Hence their mobility will impact the sediment deposition process in this location (Monteiro et al., 2020). However, there was no difference in the microplastic abundance between the two sites, and the higher variance of microplastic in the windward position suggested that the accumulation of sediments in this area was unaffected by wave activity (Monteiro et al., 2018). For a clearer understanding of the distribution of microplastics in windward and leeward locations, additional research, including sediment traps, is required.

This study discovered an accumulation of microplastics in marine protected zones in close proximity to human activities. The marine protected area that is the primary focus of this study is the management of the aquatic domain for conservation purposes (Lamb et al., 2016). However, according to our research findings, there is a bigger threat to zones that should be free of disturbance and potentially safeguard susceptible biota and ecosystems (Carvache-Franco et al., 2021). In comparison to research conducted in wildlife reserve areas, Ramsar sites, national parks, and other IUCN management areas, the abundance of microplastics in the northern part of Jakarta is comparable. However, because of an increase in threats, the abundance of microplastics is now almost equivalent to coastal locations with greater anthropogenic activity (Nunes et al., 2023b). Indeed, the likelihood of eradicating microplastics from the marine environment, particularly in marine protected areas, is improbable due to the impossibility of eliminating plastic consumption entirely (Bonanno, 2022). What can be done now is to eradicate the core source of plastic pollution by maximizing waste management, quitting open-dumping landfills, and altering one's thinking to raise environmental consciousness. In addition, there is a need for regional and global coordination among diverse stakeholders, as well as an increase in law enforcement.

5. Conclusions

This is the first study to examine microplastics in marine protected areas near Indonesia's most densely populated area, the Greater Jakarta. Microplastics were detected in the top layer of beach sediments across the sampling locations. Microplastic abundance was frequently lower in locations far from the Jakarta mainland. Muara Angke wildlife reserve and Pulau Rambut Ramsar site, which are close to the mainland, had a greater abundance of microplastics than the maritime leisure areas (i.e., Pulau Pari and Pulau Tidung) and marine national park areas (Pulau Pramuka and Pulau Harapan), which are far from the mainland. There were seasonal effects on the abundance of microplastics in each sampling location, with the dry season demonstrating the largest accumulation of microplastics in the sediments. Smaller-sized microplastics from secondary sources were more frequent in marine protected and recreational areas. With percentages of >74% and >60%, fragment-shaped microplastics with a size range of 300–1000 μm predominated at all sampling locations. Polyethylene and polypropylene polymers were dominant in each sampling location. Polystyrene and polyvinyl chloride groups were abundant in the sediment of sampling locations near the mainland, while nylon dominated the polyethylene and the polypropylene groups in the marine national park. The presence of microplastics in the marine national park revealed that marine debris had reached the areas which is ideally free from environmental pressures, like marine debris accumulation. If the current situation continues, it could have major environmental effects in the near future. However, this can be mitigated by retaining plastic waste at its sources, for example, by consuming plastic more wisely and optimizing waste management. Finally, collaboration with local, national, regional, and international stakeholders would make the measures more effective.

CRediT authorship contribution statement

Muhammad Reza Cordova: Cordova, Conceptualization, Writing – original draft, preparation, Writing – review & editing, Resources, Investigation, Methodology, Formal analysis, Visualization, Data curation, Funding acquisition, Project acquisition, Supervision. **Yaya Ihya Ulumuddin:** Investigation, Resources, Validation, Writing – review & editing. **Triyoni Purbonegoro:** Investigation, Resources, Validation. **Rachma Puspitasari:** Investigation, Resources, Validation. **Ricky Rositasari:** Investigation, Resources, Validation. **Deny Yogaswara:** Investigation, Resources, Validation. **Muhammad Taufik Kaisupy:** Investigation, Resources, Validation. **Singgih Prasetyo Adi Wibowo:** Investigation, Resources, Validation. **Riyana Subandi:** Investigation, Resources, Validation. **Sofia Yuniar Sani:** Investigation, Resources, Validation. **S. Sulistiowati:** Investigation, Resources, Validation. **Intan Kusumastuti Nugraheni:** Investigation, Resources, Validation. **Lucky Rahman:** Investigation, Resources, Validation. **Rahmawati:** Investigation, Resources, Validation. **Safitri Al Rahmadhani:** Investigation, Resources, Validation. **Tyara Aprilani Khoirunnisa:** Investigation, Resources, Validation. **Nurhasanah:** Investigation, Resources, Funding acquisition, Project acquisition. **Ahmad Muhtadi:** Investigation, Resources, Validation. **Swietenia Puspa Lestari:** Investigation, Funding acquisition, Project acquisition. **Simon M. Cragg:** Writing – review & editing, Funding acquisition, Project acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

We would like to appreciate the fishers, residents, workers and officials of the Muara Angke wildlife reserve, the Pulau Rambut Ramsar site, and the Kepulauan Seribu national park for their assistance. This research funded by NERC UKRI funding scheme for Simon M. Cragg and Muhammad Reza Cordova (Grant No. NE/V009516/1) and partially funded by Universitas Terbuka funding scheme 2022 (Grant No. B/284/UN31.LPPM/PT.March 01, 2022 and B/410/UN31.LPPM/PT.March 01, 2022) for Nurhasanah and Muhammad Reza Cordova. Muhammad Reza Cordova is the main contributor to this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2023.140761.

References

Abayomi, O.A., Range, P., Al-Ghouti, M.A., Obbard, J.P., Almeer, S.H., Ben-Hamadou, R., 2017. Microplastics in coastal environments of the arabian Gulf. Mar. Pollut. Bull. 124, 181–188. https://doi.org/10.1016/j.marpolbul.2017.07.011.

Acosta-Coley, I., Olivero-Verbel, J., 2015. Microplastic resin pellets on an urban tropical beach in Colombia. Environ. Monit. Assess. 187 https://doi.org/10.1007/s10661-015-4602-7.

Agamuthu, P., Mehran, S.B., Norkhairah, A., Norkhairiyah, A., 2019. Marine debris: a review of impacts and global initiatives. Waste Manag. Res. 37, 987–1002. https://doi.org/10.1177/0734242X19845041.

Amkieltiela, Handayani, C.N., Andradi-Brown, D.A., Estradivari Ford, A.K., Beger, M., Hakim, A., Muenzel, D.K., Carter, E., Agung, F., Veverka, L., Iqbal, M., Lazuardi, M. E., Fauzi, M.N., Tranter, S.N., Ahmadia, G.N., 2022. The rapid expansion of Indonesia's marine protected area requires improvement in management effectiveness. Mar. Pol. 146, 105257 https://doi.org/10.1016/j.marpol.2022.105257.

Andrady, A.L., 2015. Persistence of plastic litter in the oceans. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 57–72. https://doi.org/10.1007/978-3-319-16510-3_3.

Bonanno, G., 2022. Marine-protected areas and plastic pollution. In: Bonanno, G., Orlando-Bonaca, M.B.T.-P.P., C, M. (Eds.), Plastic Pollution and Marine Conservation: Approaches to Protect Biodiversity and Marine Life. Academic Press, pp. 249–273. https://doi.org/10.1016/B978-0-12-822471-7.00010-9.

Buteler, M., Alma, A.M., Stadler, T., Gingold, A.C., Manattini, M.C., Lozada, M., 2022. Acute toxicity of microplastic fibers to honeybees and effects on foraging behavior. Sci. Total Environ. 822 https://doi.org/10.1016/j.scitotenv.2022.153320.

Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters (80- Science 178, 749–750. https://doi.org/10.1126/science.178.4062.749.

Carvache-Franco, M., Carvache-Franco, W., Manner-Baldeon, F., 2021. Market segmentation based on ecotourism motivations in marine protected areas and national parks in the galapagos islands, Ecuador. J. Coast Res. 37, 620–633. https://doi.org/10.2112/JCOASTRES-D-20-00076.1.

Cheng, M.L.H., Lippmann, T.C., Dijkstra, J.A., Bradt, G., Cook, S., Choi, J.G., Brown, B.L., 2021. A baseline for microplastic particle occurrence and distribution in Great Bay Estuary. Mar. Pollut. Bull. 170 https://doi.org/10.1016/j.marpolbul.2021.112653.
Chitaka, T.Y., von Blottnitz, H., 2019. Accumulation and characteristics of plastic debris along five beaches in Cape Town. Mar. Pollut. Bull. 138, 451–457. https://doi.org/10.1016/j.marpolbul.2018.11.065.
Chubarenko, I., Esiukova, E., Bagaev, A., Isachenko, I., Demchenko, N., Zobkov, M., Efimova, I., Bagaeva, M., Khatmullina, L., 2018. Behavior of Microplastics in Coastal Zones, Microplastic Contamination in Aquatic Environments. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813747-5.00006-0.
Clifton, J., Osman, E.O., Suggett, D.J., Smith, D.J., 2021. Resolving conservation and development tensions in a small island state: a governance analysis of Curieuse Marine National Park, Seychelles. Mar. Pol. 127 https://doi.org/10.1016/j.marpol.2019.103617.
Clukey, K.E., Lepczyk, C.A., Balazs, G.H., Work, T.M., Lynch, J.M., 2017. Investigation of plastic debris ingestion by four species of sea turtles collected as bycatch in pelagic Pacific longline fisheries. Mar. Pollut. Bull. 120, 117–125. https://doi.org/10.1016/j.marpolbul.2017.04.064.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T. S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655. https://doi.org/10.1021/es400663f.
Compa, M., Alomar, C., Morató, M., Álvarez, E., Deudero, S., 2022. Spatial distribution of macro- and micro-litter items along rocky and sandy beaches of a Marine Protected Area in the western Mediterranean Sea. Mar. Pollut. Bull. 178, 113520 https://doi.org/10.1016/j.marpolbul.2022.113520.
Cooper, D.A., Corcoran, P.L., 2010. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai. Hawaii. Mar. Pollut. Bull. 60, 650–654. https://doi.org/10.1016/j.marpolbul.2009.12.026.
Cordova, M.R., Iskandar, M.R., Muhtadi, A., Nurhasanah Saville, R., Riani, E., 2022a. Spatio-temporal variation and seasonal dynamics of stranded beach anthropogenic debris on Indonesian beach from the results of nationwide monitoring. Mar. Pollut. Bull. 182, 114035 https://doi.org/10.1016/j.marpolbul.2022.114035.
Cordova, M.R., Nurhati, I.S., 2019. Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. Sci. Rep. 9, 18730 https://doi.org/10.1038/s41598-019-55065-2.
Cordova, M.R., Nurhati, I.S., Riani, E., Nurhasanah Iswari, M.Y., 2021. Unprecedented plastic-made personal protective equipment (PPE) debris in river outlets into Jakarta Bay during COVID-19 pandemic. Chemosphere 268, 129360. https://doi.org/10.1016/j.chemosphere.2020.129360.
Cordova, M.R., Purwiyanto, A.I.S., Suteja, Y., 2019. Abundance and characteristics of microplastics in the northern coastal waters of Surabaya, Indonesia. Mar. Pollut. Bull. 142, 183–188. https://doi.org/10.1016/j.marpolbul.2019.03.040.
Cordova, M.R., Riani, E., Shiomoto, A., 2020. Microplastics ingestion by blue panchax fish (Aplocheilus sp.) from Ciliwung Estuary, Jakarta, Indonesia. Mar. Pollut. Bull. 161, 111763 https://doi.org/10.1016/j.marpolbul.2020.111763.
Cordova, M.R., Ulumuddin, Y.I., Purbonegoro, T., Puspitasari, R., Afianti, N.F., Rositasari, R., Yogaswara, D., Hafizt, M., Iswari, M.Y., Fitriya, N., Widyastuti, E., Harmesa, Lestari, Kampono, I., Kaisupy, M.T., Wibowo, S.P.A., Subandi, R., Sani, S. Y., Sulistyowati, L., Nurhasanah Muhtadi, A., Riani, E., Cragg, S.M., 2022b. Seasonal heterogeneity and a link to precipitation in the release of microplastic during COVID-19 outbreak from the Greater Jakarta area to Jakarta Bay, Indonesia. Mar. Pollut. Bull. 181, 113926 https://doi.org/10.1016/j.marpolbul.2022.113926.
Cordova, M.R., Ulumuddin, Y.I., Purbonegoro, T., Shiomoto, A., 2021. Characterization of microplastics in mangrove sediment of Muara Angke Wildlife Reserve, Indonesia. Mar. Pollut. Bull. 163, 112012. https://doi.org/10.1016/j.marpolbul.2021.112012.
Curren, E., Kuwahara, V.S., Yoshida, T., Leong, S.C.Y., 2021. Marine microplastics in the ASEAN region: a review of the current state of knowledge. Environ. Pollut. 288, 117776 https://doi.org/10.1016/j.envpol.2021.117776.
Da Costa, J.P., Paço, A., Santos, P.S.M., Duarte, A.C., Rocha-Santos, T., 2019. Microplastics in soils: assessment, analytics and risks. Environ. Chem. 16, 18–30. https://doi.org/10.1071/EN18150.
De Frond, H., Rubinovitz, R., Rochman, C.M., 2021. Matr-FTIR spectral libraries of plastic particles (FLOPP and FLOPP-e) for the analysis of microplastics. Anal. Chem. 93, 15878–15885. https://doi.org/10.1021/acs.analchem.1c02549.
Defontaine, S., Sous, D., Tesan, J., Monperrus, M., Lenoble, V., Lanceleur, L., 2020. Microplastics in a salt-wedge estuary: vertical structure and tidal dynamics. Mar. Pollut. Bull. 160 https://doi.org/10.1016/j.marpolbul.2020.111688.
Dehaut, A., Hermabessiere, L., Duflos, G., 2019. Current frontiers and recommendations for the study of microplastics in seafood. TrAC Trends Anal. Chem. 116, 346–359. https://doi.org/10.1016/j.trac.2018.11.011.
Dris, R., Tramoy, R., Alligant, S., Gasperi, J., Tassin, B., 2020. Plastic debris flowing from rivers to oceans: the role of the estuaries as a complex and poorly understood key interface. In: Handbook of Microplastics in the Environment, pp. 1–28. https://doi.org/10.1007/978-3-030-10618-8_3-1.
Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 75, 63–82. https://doi.org/10.1016/j.watres.2015.02.012.
Enders, K., Käppler, A., Biniasch, O., Feldens, P., Stollberg, N., Lange, X., Fischer, D., Eichhorn, K.-J., Pollehne, F., Oberbeckmann, S., Labrenz, M., 2019. Tracing microplastics in aquatic environments based on sediment analogies. Sci. Rep. 9, 15207 https://doi.org/10.1038/s41598-019-50508-2.
Eo, S., Hong, S.H., Song, Y.K., Lee, Jongsu, Lee, Jongmyoung, Shim, W.J., 2018. Abundance, composition, and distribution of microplastics larger than 20 μm in sand beaches of South Korea. Environ. Pollut. 238, 894–902. https://doi.org/10.1016/j.envpol.2018.03.096.
Fernández-González, V., Andrade-Garda, J.M., López-Mahía, P., Muniategui-Lorenzo, S., 2022. Misidentification of PVC microplastics in marine environmental samples. TrAC Trends Anal. Chem. 153, 116649 https://doi.org/10.1016/j.trac.2022.116649.
Fok, L., Cheung, P.K., Tang, G., Li, W.C., 2017. Size distribution of stranded small plastic debris on the coast of Guangdong, South China. Environ. Pollut. 220, 407–412. https://doi.org/10.1016/j.envpol.2016.09.079.
Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. In: Marine Anthropogenic Litter, pp. 29–56. https://doi.org/10.1007/978-3-319-16510-3_2.
Gallagher, A., Rees, A., Rowe, R., Stevens, J., Wright, P., 2016. Microplastics in the Solent estuarine complex, UK: an initial assessment. Mar. Pollut. Bull. 102, 243–249. https://doi.org/10.1016/j.marpolbul.2015.04.002.
Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1 https://doi.org/10.1038/s41559-017-0116.
Garcés-Ordóñez, O., Castillo-Olaya, V.A., Granados-Briceño, A.F., Blandón García, L.M., Espinosa Díaz, L.F., 2019. Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta, Colombian Caribbean. Mar. Pollut. Bull. 145, 455–462. https://doi.org/10.1016/j.marpolbul.2019.06.058.
GESAMP, 2015. Sources, Fate and Effects of Microplastics in the Marine Environment: a Global Assessment", Reports and Studies GESAMP - Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. https://doi.org/10.13140/RG.2.1.3803.7925.
Gray, A.D., Weinstein, J.E., 2017. Size- and shape-dependent effects of microplastic particles on adult daggerblade grass shrimp (Palaemonetes pugio). Environ. Toxicol. Chem. 36, 3074–3080. https://doi.org/10.1002/etc.3881.
Hanvey, J.S., Lewis, P.J., Lavers, J.L., Crosbie, N.D., Pozo, K., Clarke, B.O., 2017. A review of analytical techniques for quantifying microplastics in sediments. Anal. Methods 9, 1369–1383. https://doi.org/10.1039/c6ay02707e.
He, P., Chen, L., Shao, L., Zhang, H., Lü, F., 2019. Municipal solid waste (MSW) landfill: a source of microplastics? -Evidence of microplastics in landfill leachate. Water Res. 159, 38–45. https://doi.org/10.1016/j.watres.2019.04.060.
Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Philos. Trans. R. Soc. B Biol. Sci. 364, 2115–2126. https://doi.org/10.1098/rstb.2008.0311.
Horton, A.A., Dixon, S.J., 2018. Microplastics: an Introduction to Environmental Transport Processes, vol. 5. Wiley Interdiscip. Rev. Water, p. e1268. https://doi.org/10.1002/wat2.1268.
Int, Veen, I., Nogueira, P., Isigkeit, J., Hanel, R., Kammann, U., 2021. Positively buoyant but sinking: polymer identification and composition of marine litter at the seafloor of the North Sea and Baltic Sea. Mar. Pollut. Bull. 172 https://doi.org/10.1016/j.marpolbul.2021.112876.
Iskandar, M.R., Cordova, M.R., Park, Y.-G., 2022. Pathways and destinations of floating marine plastic debris from 10 major rivers in Java and Bali, Indonesia: a Lagrangian particle tracking perspective. Mar. Pollut. Bull. 185, 114331 https://doi.org/10.1016/j.marpolbul.2022.114331.
Iskandar, M.R., Surinati, D., Cordova, M.R., Siong, K., 2021. Pathways of floating marine debris in Jakarta Bay, Indonesia. Mar. Pollut. Bull. 169 https://doi.org/10.1016/j.marpolbul.2021.112511.
IUCN, UNEP-WCMC, 2022. The world database on protected areas [online], december/2022. World Wide Web Electron. Publ. www.protectedplanet.com.
Ivar do Sul, J.A., Costa, M.F., Silva-Cavalcanti, J.S., Araújo, M.C.B., 2014. Plastic debris retention and exportation by a mangrove forest patch. Mar. Pollut. Bull. 78, 252–257. https://doi.org/10.1016/j.marpolbul.2013.11.011.
Ivar do Sul, J.A., Spengler, Â., Costa, M.F., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1236–1238. https://doi.org/10.1016/j.marpolbul.2009.05.004.
Käppler, A., Fischer, D., Oberbeckmann, S., Schernewski, G., Labrenz, M., Eichhorn, K.J., Voit, B., 2016. Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both? Anal. Bioanal. Chem. 408, 8377–8391. https://doi.org/10.1007/s00216-016-9956-3.
Karkanorachaki, K., Tsiota, P., Dasenakis, G., Syranidou, E., Kalogerakis, N., 2022. Nanoplastic generation from secondary PE microplastics: microorganism-induced fragmentation. Microplastics 1, 85–101. https://doi.org/10.3390/microplastics1010006.
Khatmullina, L., Isachenko, I., 2017. Settling velocity of microplastic particles of regular shapes. Mar. Pollut. Bull. 114, 871–880. https://doi.org/10.1016/j.marpolbul.2016.11.024.
Koagouw, W., Arifin, Z., Olivier, G.W.J., Ciocan, C., 2021. High concentrations of paracetamol in effluent dominated waters of Jakarta Bay, Indonesia. Mar. Pollut. Bull. 169 https://doi.org/10.1016/j.marpolbul.2021.112558.
Kobayashi, T., Yagi, M., Kawaguchi, T., Hata, T., Shimizu, K., 2021. Spatiotemporal variations of surface water microplastics near Kyushu, Japan: a quali-quantitative analysis. Mar. Pollut. Bull. 169 https://doi.org/10.1016/j.marpolbul.2021.112563.
Krause, S., Baranov, V., Nel, H.A., Drummond, J.D., Kukkola, A., Hoellein, T., Sambrook Smith, G.H., Lewandowski, J., Bonet, B., Packman, A.I., Sadler, J., Inshyna, V., Allen, S., Allen, D., Simon, L., Mermillod-Blondin, F., Lynch, I., 2021. Gathering at the top? Environmental controls of microplastic uptake and biomagnification in freshwater food webs. Environ. Pollut. 268, 115750 https://doi.org/10.1016/j.envpol.2020.115750.
Kutralam-Muniasamy, G., Pérez-Guevara, F., Elizalde-Martínez, I., Shruti, V.C., 2021. How well-protected are protected areas from anthropogenic microplastic contamination? Review of analytical methods, current trends, and prospects. Trends Environ. Anal. Chem. 32 https://doi.org/10.1016/j.teac.2021.e00147.

Lamb, J.B., Wenger, A.S., Devlin, M.J., Ceccarelli, D.M., Williamson, D.H., Willis, B.L., 2016. Reserves as tools for alleviating impacts of marine disease. Philos. Trans. R. Soc. B Biol. Sci. 371 https://doi.org/10.1098/rstb.2015.0210.

Lambert, S., Sinclair, C.J., Bradley, E.L., Boxall, A.B.A., 2013. Effects of environmental conditions on latex degradation in aquatic systems. Sci. Total Environ. 447, 225–234. https://doi.org/10.1016/j.scitotenv.2012.12.067.

Lambert, S., Wagner, M., 2016. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere 145, 265–268. https://doi.org/10.1016/j.chemosphere.2015.11.078.

Lao, W., Wong, C.S., 2023. How to establish detection limits for environmental microplastics analysis. Chemosphere 327, 138456. https://doi.org/10.1016/j.chemosphere.2023.138456.

Lehtiniemi, M., Hartikainen, S., Näkki, P., Engström-Öst, J., Koistinen, A., Setälä, O., 2018. Size matters more than shape: ingestion of primary and secondary microplastics by small predators. Food Webs 17, e00097. https://doi.org/10.1016/j.fooweb.2018.e00097.

Li, J., Zhang, H., Zhang, K., Yang, R., Li, R., Li, Y., 2018. Characterization, source, and retention of microplastic in sandy beaches and mangrove wetlands of the Qinzhou Bay, China. Mar. Pollut. Bull. 136, 401–406. https://doi.org/10.1016/j.marpolbul.2018.09.025.

Löder, M.G.J., Gerdts, G., 2015. Methodology used for the detection and identification of microplastics—a critical appraisal. In: Marine Anthropogenic Litter, pp. 201–227. https://doi.org/10.1007/978-3-319-16510-3_8.

Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. 123, 219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057.

Luna-Jorquera, G., Thiel, M., Portflitt-Toro, M., Dewitte, B., 2019. Marine protected areas invaded by floating anthropogenic litter: an example from the South Pacific. Aquat. Conserv. Mar. Freshw. Ecosyst. 29, 245–259. https://doi.org/10.1002/aqc.3095.

Luo, Y.Y., Not, C., Cannicci, S., 2021. Mangroves as unique but understudied traps for anthropogenic marine debris: a review of present information and the way forward. Environ. Pollut. 271 https://doi.org/10.1016/j.envpol.2020.116291.

Mardiastuti, A., 2022. Waterbird community in Pulau Rambut wildlife sanctuary, Jakarta bay: review on species composition and population size after thirty years. In: IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/950/1/012031.

Martin, C., Almahasheer, H., Duarte, C.M., 2019. Mangrove forests as traps for marine litter. Environ. Pollut. 247, 499–508. https://doi.org/10.1016/j.envpol.2019.01.067.

Martin, C., Baalkhuyur, F., Valluzzi, L., Saderne, V., Cusack, M., Almahasheer, H., Krishnakumar, P.K., Rabaoui, L., Qurban, M.A., Arias-Ortiz, A., Masqué, P., Duarte, C.M., 2020. Exponential increase of plastic burial in mangrove sediments as a major plastic sink. Sci. Adv. 6 https://doi.org/10.1126/sciadv.aaz5593.

Matsuguma, Y., Takada, H., Kumata, H., Kanke, H., Sakurai, S., Suzuki, T., Itoh, M., Okazaki, Y., Boonyatumanond, R., Zakaria, M.P., Weerts, S., Newman, B., 2017. Microplastics in sediment cores from asia and Africa as indicators of temporal trends in plastic pollution. Arch. Environ. Contam. Toxicol. 73, 230–239. https://doi.org/10.1007/s00244-017-0414-9.

McLusky, D.S., 1989. In: McLusky, D.S. (Ed.), The Estuarine Environment BT - the Estuarine Ecosystem. Springer Netherlands, Dordrecht, pp. 1–48. https://doi.org/10.1007/978-94-011-7616-3_1.

Meng, M., Yang, L., Wei, B., Cao, Z., Yu, J., Liao, X., 2021. Plastic shed production systems: the migration of heavy metals from soil to vegetables and human health risk assessment. Ecotoxicol. Environ. Saf. 215 https://doi.org/10.1016/j.ecoenv.2021.112106.

Mintenig, S.M., Kooi, M., Erich, M.W., Primpke, S., Redondo- Hasselerharm, P.E., Dekker, S.C., Koelmans, A.A., van Wezel, A.P., 2020. A systems approach to understand microplastic occurrence and variability in Dutch riverine surface waters. Water Res. 176 https://doi.org/10.1016/j.watres.2020.115723.

Mistri, M., Scoponi, M., Granata, T., Moruzzi, L., Massara, F., Munari, C., 2020. Types, occurrence and distribution of microplastics in sediments from the northern Tyrrhenian Sea. Mar. Pollut. Bull. 153 https://doi.org/10.1016/j.marpolbul.2020.111016.

Monteiro, R.C.P., Do Sul, J.A.I., Costa, M.F., 2020. Small microplastics on beaches of fernando de noronha island, tropical atlantic ocean. Ocean Coast. Res. 68, 1–10. https://doi.org/10.1590/S2675-28242020068235.

Monteiro, R.C.P., Ivar do Sul, J.A., Costa, M.F., 2018. Plastic pollution in islands of the Atlantic ocean. Environ. Pollut. 238, 103–110. https://doi.org/10.1016/j.envpol.2018.01.096.

Mrowiec, B., 2018. Plastics in the circular economy (CE). Environ. Prot. Nat. Resour. J. Inst. Environ. Prot. Res. Institute. 29, 16–19. https://doi.org/10.2478/oszn-2018-0017.

Mu, J., Zhang, S., Qu, L., Jin, F., Fang, C., Ma, X., Zhang, W., Wang, J., 2019. Microplastics abundance and characteristics in surface waters from the northwest pacific, the bering sea, and the chukchi sea. Mar. Pollut. Bull. 143, 58–65. https://doi.org/10.1016/j.marpolbul.2019.04.023.

Muthukumar, A., Veerappapillai, S., 2015. Biodegradation of plastics – a brief review. Int. J. Pharm. Sci. Rev. Res. 31, 204–209.

Nanda, S., Berruti, F., 2021. Thermochemical conversion of plastic waste to fuels: a review. Environ. Chem. Lett. 19, 123–148. https://doi.org/10.1007/s10311-020-01094-7.

Nunes, B.Z., Huang, Y., Ribeiro, V.V., Wu, S., Holbech, H., Moreira, L.B., Xu, E.G., Castro, I.B., 2023a. Microplastic contamination in seawater across global marine protected areas boundaries. Environ. Pollut. 316, 120692 https://doi.org/10.1016/j.envpol.2022.120692.

Nunes, B.Z., Moreira, L.B., Xu, E.G., Castro, Í.B., 2023b. A global snapshot of microplastic contamination in sediments and biota of marine protected areas. Sci. Total Environ. 865, 161293 https://doi.org/10.1016/j.scitotenv.2022.161293.

Nurhasanah, Cordova, M.R., Riani, E., 2021. Micro- and mesoplastics release from the Indonesian municipal solid waste landfill leachate to the aquatic environment: case study in Galuga Landfill Area, Indonesia. Mar. Pollut. Bull. 163, 111986 https://doi.org/10.1016/j.marpolbul.2021.111986.

Orlins, J.J., Gulliver, J.S., 2003. Turbulence quantification and sediment resuspension in an oscillating grid chamber. Exp. Fluid 34, 662–677. https://doi.org/10.1007/s00348-003-0595-z.

Pang, W., Dai, Z., Ma, B., Wang, J., Huang, H., Li, S., 2020. Linkage between turbulent kinetic energy, waves and suspended sediment concentrations in the nearshore zone. Mar. Geol. 425 https://doi.org/10.1016/j.margeo.2020.106190.

Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., Li, D., 2017. Microplastics in sediments of the changjiang estuary, China. Environ. Pollut. 225, 283–290. https://doi.org/10.1016/j.envpol.2016.12.064.

Piehl, S., Atwood, E.C., Bochow, M., Imhof, H.K., Franke, J., Siegert, F., Laforsch, C., 2020. Can water constituents Be used as proxy to map microplastic dispersal within transitional and coastal waters? Front. Environ. Sci. 8 https://doi.org/10.3389/fenvs.2020.00092.

Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C., Laforsch, C., 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Sci. Rep. 8 https://doi.org/10.1038/s41598-018-36172-y.

PlasticsEurope, E.P.R.O., 2021. Plastics - the Facts 2021 an Analysis of European Plastics Production. demand and waste data. Plastics Europe (the Association of Plastics Manufacturers in Europe) and EPRO (the European Association of Plastics Recycling and Recovery Organisations), Brussels, Belgium.

Preston-Whyte, F., Silburn, B., Meakins, B., Bakir, A., Pillay, K., Worship, M., Paruk, S., Mdazuka, Y., Mooi, G., Harmer, R., Doran, D., Tooley, F., Maes, T., 2021. Meso- and microplastics monitoring in harbour environments: a case study for the Port of Durban, South Africa. Mar. Pollut. Bull. 163 https://doi.org/10.1016/j.marpolbul.2020.111948.

Priya, A.K., Jalil, A.A., Dutta, K., Rajendran, S., Vasseghian, Y., Qin, J., Soto-Moscoso, M., 2022. Microplastics in the environment: recent developments in characteristic, occurrence, identification and ecological risk. Chemosphere 298. https://doi.org/10.1016/j.chemosphere.2022.134161.

Rey, S.F., Franklin, J., Rey, S.J., 2021. Microplastic pollution on island beaches, Oahu, Hawai'i. PLoS One 16. https://doi.org/10.1371/journal.pone.0247224.

Riani, E., Cordova, M.R., 2022. Microplastic ingestion by the sandfish Holothuria scabra in Lampung and Sumbawa, Indonesia. Mar. Pollut. Bull. 175, 113134 https://doi.org/10.1016/j.marpolbul.2021.113134.

Rios-Mendoza, L.M., Ontiveros-Cuadras, J.F., Leon-Vargas, D., Ruiz-Fernández, A.C., Rangel-García, M., Pérez-Bernal, L.H., Sanchez-Cabeza, J.A., 2021. Microplastic contamination and fluxes in a touristic area at the SE Gulf of California. Mar. Pollut. Bull. 170 https://doi.org/10.1016/j.marpolbul.2021.112638.

Ryan, P.G., 2015. Does size and buoyancy affect the long-distance transport of floating debris? Environ. Res. Lett. 10, 84019 https://doi.org/10.1088/1748-9326/10/8/084019.

Salman, M.M., Kharroubi, S., Itani, M., Talhouk, S.N., 2020. Using IUCN protected areas management categories as a tool to assess youth preferences for local management of an Important Plant Area (IPA) in Lebanon. In: Land Use Policy, vol. 99. https://doi.org/10.1016/j.landusepol.2020.105035.

Simon-Sánchez, L., Grelaud, M., Garcia-Orellana, J., Ziveri, P., 2019. River Deltas as hotspots of microplastic accumulation: the case study of the Ebro River (NW Mediterranean). Sci. Total Environ. 687, 1186–1196. https://doi.org/10.1016/j.scitotenv.2019.06.168.

Sobhani, Z., Panneerselvan, L., Fang, C., Naidu, R., Megharaj, M., 2021. Chronic and transgenerational effects of polystyrene microplastics at environmentally relevant concentrations in earthworms (Eisenia fetida). Environ. Toxicol. Chem. 40, 2240–2246. https://doi.org/10.1002/etc.5072.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., 2017. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ. Sci. Technol. 51, 4368–4376. https://doi.org/10.1021/acs.est.6b06155.

Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020. Floating macro- and microplastics around the southern ocean: results from the antarctic circumnavigation expedition. Environ. Int. 136 https://doi.org/10.1016/j.envint.2020.105494.

Sundt, P., Schultze, P.-E., Syversen, F., 2014. Sources of microplastic- pollution to the marine environment. Mepex, Nor. Environ. Agency 1–108.

Tang, C., Li, Y., He, C., Acharya, K., 2020. Dynamic behavior of sediment resuspension and nutrients release in the shallow and wind-exposed Meiliang Bay of Lake Taihu. Sci. Total Environ. 708 https://doi.org/10.1016/j.scitotenv.2019.135131.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philos. Trans. R. Soc. B Biol. Sci. 364, 2027–2045. https://doi.org/10.1098/rstb.2008.0284.

Tiwari, M., Rathod, T.D., Ajmal, P.Y., Bhangare, R.C., Sahu, S.K., 2019. Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. Mar. Pollut. Bull. 140, 262–273. https://doi.org/10.1016/j.marpolbul.2019.01.055.

van Emmerik, T., Kieu-Le, T.C., Loozen, M., Oeveren, K. van, Strady, E., Bui, X.T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P.D., Schwarz, A., Slat, B., Tassin, B., 2018. A methodology to characterize riverine macroplastic emission into the ocean. Front. Mar. Sci. 5 https://doi.org/10.3389/fmars.2018.00372.

Vetrimurugan, E., Jonathan, M.P., Sarkar, S.K., Rodríguez-González, F., Roy, P.D., Velumani, S., Sakthi, J.S., 2020. Occurrence, distribution and provenance of micro plastics: a large scale quantitative analysis of beach sediments from southeastern coast of South Africa. Sci. Total Environ. 746 https://doi.org/10.1016/j.scitotenv.2020.141103.

Vriend, P., Hidayat, H., van Leeuwen, J., Cordova, M.R., Purba, N.P., Löhr, A.J., Faizal, I., Ningsih, N.S., Agustina, K., Husrin, S., Suryono, D.D., Hantoro, I., Widianarko, B., Lestari, P., Vermeulen, B., van Emmerik, T., 2021. Plastic pollution research in Indonesia: state of science and future research directions to reduce impacts. Front. Environ. Sci. 9, 187. https://doi.org/10.3389/fenvs.2021.692907.

Wang, J., Qin, X., Guo, J., Jia, W., Wang, Q., Zhang, M., Huang, Y., 2020. Evidence of selective enrichment of bacterial assemblages and antibiotic resistant genes by microplastics in urban rivers. Water Res. 183 https://doi.org/10.1016/j.watres.2020.116113.

Way, C., Hudson, M.D., Williams, I.D., Langley, G.J., 2022. Evidence of underestimation in microplastic research: a meta-analysis of recovery rate studies. Sci. Total Environ. 805 https://doi.org/10.1016/j.scitotenv.2021.150227.

Weber, F., Kerpen, J., 2022. Underestimating microplastics? Quantification of the recovery rate of microplastic particles including sampling, sample preparation, subsampling, and detection using µ-Ramanspectroscopy. Anal. Bioanal. Chem. https://doi.org/10.1007/s00216-022-04447-z.

Weitzel, S.L., Feura, J.M., Rush, S.A., Iglay, R.B., Woodrey, M.S., 2021. Availability and assessment of microplastic ingestion by marsh birds in Mississippi Gulf Coast tidal marshes. Mar. Pollut. Bull. 166 https://doi.org/10.1016/j.marpolbul.2021.112187.

Xia, F., Yao, Q., Zhang, J., Wang, D., 2021. Effects of seasonal variation and resuspension on microplastics in river sediments. Environ. Pollut. 286 https://doi.org/10.1016/j.envpol.2021.117403.

Xiong, X., Zhang, K., Chen, X., Shi, H., Luo, Z., Wu, C., 2018. Sources and distribution of microplastics in China's largest inland lake – qinghai Lake. Environ. Pollut. 235, 899–906. https://doi.org/10.1016/j.envpol.2017.12.081.

Xu, Q., Xing, R., Sun, M., Gao, Y., An, L., 2020. Microplastics in sediments from an interconnected river-estuary region. Sci. Total Environ. 729, 139025 https://doi.org/10.1016/j.scitotenv.2020.139025.

Ye, L., Qi, C., Hong, J., Ma, X., 2017. Life cycle assessment of polyvinyl chloride production and its recyclability in China. J. Clean. Prod. 142, 2965–2972. https://doi.org/10.1016/j.jclepro.2016.10.171.

Yu, X., Peng, J., Wang, J., Wang, K., Bao, S., 2016. Occurrence of microplastics in the beach sand of the Chinese inner sea: the Bohai Sea. Environ. Pollut. 214, 722–730. https://doi.org/10.1016/j.envpol.2016.04.080.

Zhang, Y., Yuan, Z., Xu, C., 2017. Bio-based resins for fiber-reinforced polymer composites. In: Natural Fiber-Reinforced Biodegradable and Bioresorbable Polymer Composites, pp. 137–162. https://doi.org/10.1016/B978-0-08-100656-6.00008-X.

Zhao, W., Huang, W., Yin, M., Huang, P., Ding, Y., Ni, X., Xia, H., Liu, H., Wang, G., Zheng, H., Cai, M., 2020. Tributary inflows enhance the microplastic load in the estuary: a case from the Qiantang River. Mar. Pollut. Bull. 156 https://doi.org/10.1016/j.marpolbul.2020.111152.

Zhao, X., Chen, H., Jia, Q.L., Shen, C.S., Zhu, Y., Li, L., Nie, Y.H., Ye, J.F., 2020. Pollution status and pollution behavior of microplastic in surface water and sediment of urban rivers. Huanjing Kexue/Environmental Sci. 41, 3612–3620. https://doi.org/10.13227/j.hjkx.201912236.

Zhou, Q., Tu, C., Fu, C., Li, Y., Zhang, H., Xiong, K., Zhao, X., Li, L., Waniek, J.J., Luo, Y., 2020. Characteristics and distribution of microplastics in the coastal mangrove sediments of China. Sci. Total Environ. 703 https://doi.org/10.1016/j.scitotenv.2019.134807.