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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

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ABSTRACT

To reduce microplastic contamination in the environment, we need to better understand its sources and transit, especially from land to sea. This study examines microplastic contamination in Jakarta's nine river outlets. Microplastics were found in all sampling intervals and areas, ranging from 4.29 to 23.49 particles m^{-3}. The trend of microplastic contamination tends to increase as the anthropogenic activity towards Jakarta Bay from the eastern side of the bay. Our study found a link between rainfall and the abundance of microplastic particles in all river outlets studied. This investigation found polyethylene, polystyrene, and polypropylene in large proportion due to their widespread use in normal daily life and industrial applications. Our research observed an increase in microplastic fibers made of polypropylene over time. We suspect a relationship between COVID-19 PPE waste and microplastic shift in our study area. More research is needed to establish how and where microplastics enter rivers.

1. Introduction

Plastic is one of the most successful industrial materials ever invented. Plastic is relatively inexpensive, easy to make, versatile, and impermeable to water, making these materials ideal for a wide range of applications (Hopewell et al., 2009). Plastic manufacturing has reached an estimated 8.3 billion metric tons, and it is growing faster than any other synthetic material except cement and steel (Geyer et al., 2017). There has been an increase in the amount of plastic produced; PlasticsEurope and EPRO (2021) suggests that 367 Million tonnes of plastic were being produced in 2021, an increase of 32 Million tonnes from 2016. However, the usage of plastics has several negative environmental

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consequences due to their manufacture and inefficient waste management. The entire volume of collected plastic waste is expected to be only between 45 and 50 % of total consumption (Frost and Sullivan, 2021). Moreover, current recycled plastics make up <10 % of the global plastics market, and recycling rates are reported to be <20 % globally, with a significant variance within nations (OECD, 2018). As a result, a significant amount of plastic waste ends up in the environment.

Plastic pollution is becoming a worldwide issue, with an increase in its prevalence across all ecosystems, particularly in the oceans. Numerous studies have demonstrated that plastic waste have a harmful impact on the environment (Araújo and Costa, 2019; Barnes et al., 2009; Cordova, 2020; Derraik, 2002; Gall and Thompson, 2015; Horton et al., 2018; Omeyer et al., 2022). Besides the direct ingestibility dangers, all plastic waste increases the likelihood that harmful compounds will be discharged into the environment and end up in trophic-level (Bouwmeester et al., 2015; Gallo et al., 2018; Häder et al., 2020; Hahladakis et al., 2018; Teuten et al., 2009; vom Saal and Hughes, 2005). One significant issue is that larger plastic objects can fragment into smaller ones (Duis and Coors, 2016; GESAMP, 2015; Koelmans et al., 2017; Thompson et al., 2004). Microplastics are formed as a result of various processes and are derived from a variety of sources with a length of <5 mm (Arthur et al., 2009; Thompson et al., 2004). Microplastics are derived from two major sources, i.e., primary and secondary. Primary sources are small-sized plastics such as pellets and microbeads that are manufactured from the origin (De Falco et al., 2019; GESAMP, 2015), whereas secondary sources are larger-sized plastics that are fragmented in nature (Andrady, 2017; Sundt et al., 2014).

Microplastics have been detected in a wide variety of foods and beverages (Diaz-Basantes et al., 2020; Van Raamsdonk et al., 2020; Weber et al., 2021) and nearly every ecosystem in the world (Cordova et al., 2022; Ding et al., 2019; He et al., 2021; Isobe et al., 2021; Jiao et al., 2022; Qi et al., 2022; Simon-Sánchez et al., 2019); as a result, microplastics have been found in animals (Iwalaye et al., 2020; Mohsen et al., 2019; Naidoo et al., 2020; Walkinshaw et al., 2020), plants (Huang et al., 2022; Yin et al., 2021; Yu et al., 2021), and humans (Ragusa et al., 2021; Schwabl et al., 2019). Although microplastics have distinct physical properties (Miller et al., 2021), their widespread existence may pose a threat to organisms through a variety of routes, including inhalation (Amato-Lourenço et al., 2020; Baensch-Baltruschat et al., 2020), ingestion (Bulleri et al., 2021; Naidoo et al., 2020), bioaccumulation (Sfriso et al., 2020; Van Raamsdonk et al., 2020), and the process of biomagnification (Krause et al., 2021; Saley et al., 2019; Walkinshaw et al., 2020). These tiny plastic particles can adsorb other toxic contaminants (Khalid et al., 2021; Liu et al., 2022) and attachment media for alien species and pathogens (Feng et al., 2020; Naik et al., 2019). Moreover, microplastics can also release certain additive materials (Celino-Brady et al., 2021; Herrera et al., 2022). Microplastics may pose a risk to human health because they can migrate through the food supply chain (Hartmann et al., 2019; Wright and Kelly, 2017). Thus, it is vital to understand microplastics' prevalence, behavior, and fate in natural ecosystems.

Microplastics research, particularly ecological dynamics, has grown at an exponential rate since the term was first used, and it has received extensive attention for more than a decade (Sutherland et al., 2019). However, there is still a lack of knowledge on the composition, primary sources, and ecological significance of microplastics found in freshwater ecosystems (e.g., rivers) specifically urban rivers. It is strongly presumed that rivers are major transporters of microplastics; therefore, it is critical to understand plastic's fate in the aquatic environment. Up to this point, only six Indonesian freshwater microplastic investigations have been completed, one river on Sumatera island and five rivers on Java island (Cordova et al., 2022; Sulistyowati et al., 2022). Baseline data on microplastics is critical for environmental management in Indonesia (Riani and Cordova, 2022), particularly in light of the probability of an increase in microplastics in the aquatic environment as a result of the usage of Personal Protective Equipment (PPE) in response to the COVID-19 pandemic (Hu et al., 2022; Ray et al., 2022). Consequently, it is imperative that we expand our understanding of urban river pollutant microplastics and develop effective ways and strategies to alleviate the conflicting effects of microplastic pollution on the ecosystem and human health.

Thus, the purpose of this study was to determine the seasonal variation in the number and type of polymers detected in the surface water of nine urban rivers. Additionally, we sought to determine the most prevalent polymers in order to ascertain which sources of plastic are creating the most microplastic pollution in these regions. Due to human involvement, we hypothesized that the east side of the greater Jakarta area would have a much higher abundance of microplastics than the west due to increased anthropogenic activities. Additionally, we hypothesized a correlation between high rainfall and microplastics. Additionally, it was hypothesized that an increase in microplastics was caused by PPE use during the pandemic. This investigation may produce a comprehensive report on microplastic contamination in the nine river outflows to Jakarta Bay, which may improve the management and prevention of microplastic contamination in freshwater towards marine ecosystems.

2. Method

2.1. Study area

Jakarta Bay spans 514 km^2 and boasts a coastline of around 72 km. The Jakarta Bay is an estuary formed by multiple rivers that run through the Greater Jakarta area, including Jakarta, Bogor, Depok, Tangerang, and Bekasi. Tangerang's Cisadane River estuary forms the eastern border of Jakarta Bay, while Bekasi's Citarum River forms the western border. Jakarta Bay supports the activities of Greater Jakarta's 33 million inhabitants. The existence of densely inhabited areas, industry, fisheries, international ports, commerce, and terrain changes along the Jakarta Bay shoreline contribute to the growing environmental load. Between 2010 and 2018, the coastline of Jakarta Bay changed by 5.2–30.1 ha and 100.2 ha, respectively, due to sedimentation and land reclamation. Land reclamation is also predicted to alter coastal currents, lowering the pollution that enters Jakarta Bay's natural flushing ability towards the Java Sea.

2.2. Sampling methods

On a quarterly basis, from March 2020 to December 2020, we sampled the microplastics entering Jakarta Bay from Greater Jakarta's nine river outlets (Fig. 1), which are part of three different administrative areas. Seven river outlets (Angke, Pluit, Ciliwung, Kali Item, Koja, Cilincing and Marunda River) located in Jakarta, one river each in Tangerang (Dadap River) and Bekasi (Bekasi River), respectively.

The sampling method for microplastics in Greater Jakarta's nine river outlets was following with earlier research (Cordova et al., 2020; Herrera et al., 2020; Pan et al., 2019; Suteja et al., 2021). Microplastic sampling in water was carried out using a mini manta trawl net (mesh size 200 μm, net length 1.5 m, rectangular opening area 450 cm^2) provided with a flowmeter (Hydro-Bios, model 438–115) set in the opening's center. We collected samples from each river by lowering a manta net from the last bridges prior to the river mouth. We collected samples from the same sampling station throughout the sampling campaign. We took samples from three distinct sampling points (on the river's left, middle, and right sides). The manta trawl was installed opposite the river flow at low tide (Table S1), with five repetitions lasting 20 min. Manta trawl net installation should be <60 min to avoid clogging the net with organic and suspended material, which may account for the low level of microplastic obtained (Tamminga et al., 2018). Following the pulling, the mini manta trawl net was carefully cleaned with riverine water from the outside and Double Distillate Deionized Water (DDDW) from inside to ensure that all microplastics settled into the cod-end

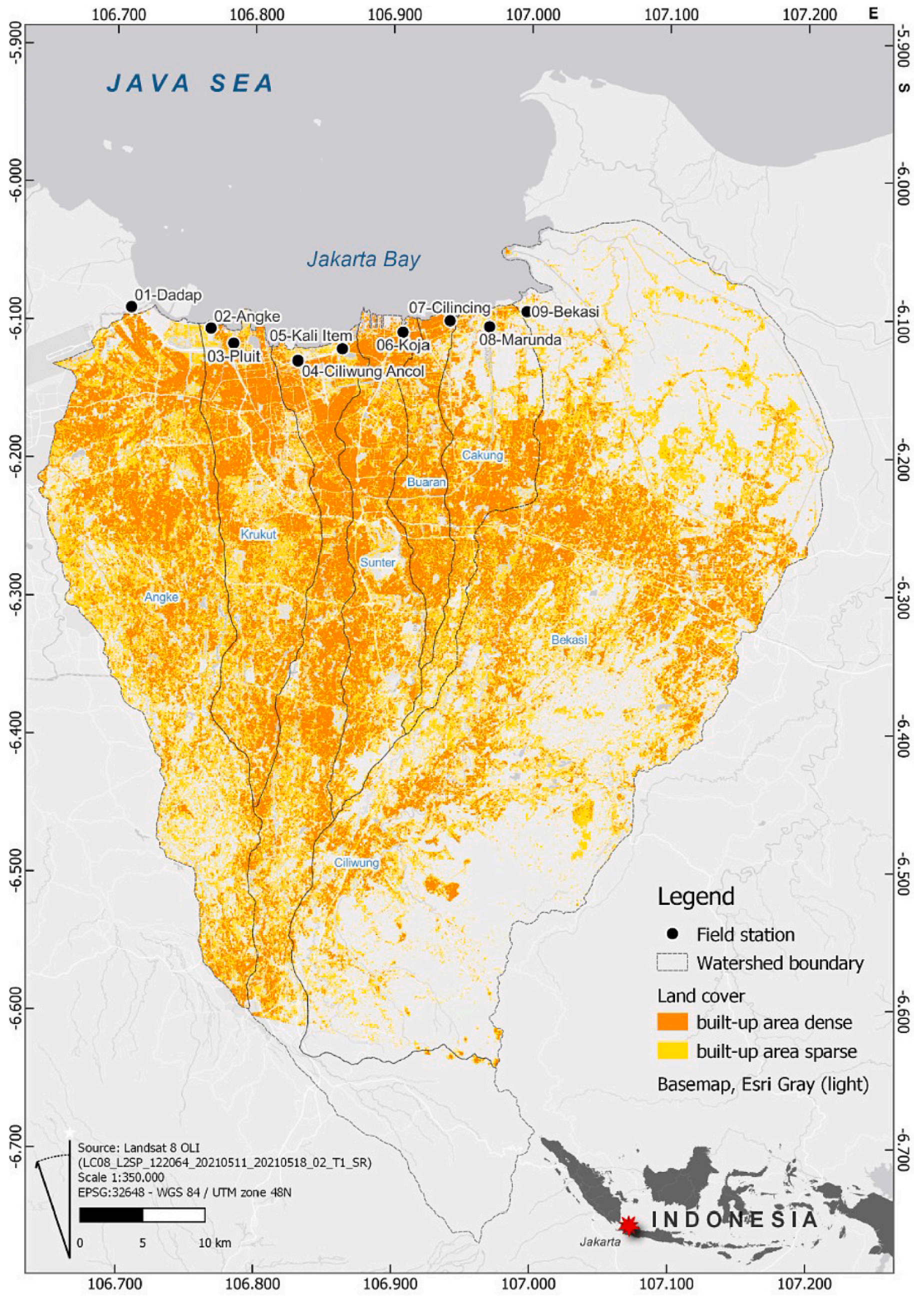

Fig. 1. Microplastics sampling location in river outlet to Jakarta Bay.

bucket.

The samples were filtered using two stages of steel sieve (3-inch Ø) with mesh sizes of 5000 μm and 200 μm. The samples were transferred carefully to a sterile petri dish using a tweezer, a dropper, and a glass spatula taking care not to overfill the petri dish with water. For laboratory examination, the petri dishes were sealed with ParaFilm® sealing film and stored at 4 ± 2 °C for further analysis.

2.3. Sample treatment and microplastics identification

Microplastics were extracted from aqueous samples using a previously documented process (Falahudin et al., 2020; GESAMP, 2019; Lusher et al., 2017b; Masura et al., 2015; Michida et al., 2019; Nurhasanah et al., 2021; Sulistyowati et al., 2022), that involved mixing materials with high-density solvents for density separation protocols and biological digestion operations. Briefly, samples of filtered water were dried for 72–96 h at 50 °C before being treated with a highly saturated NaCl solution (1.2 g cm^{-3}). It was necessary to repeat the separation process six times (please see QA/QC section for microplastic recovery test) due to the possibility of variation in the extraction of high-density microplastics when NaCl is used (Cutroneo et al., 2021; Li et al., 2019). A 50 ml Pyrex test tube was filled with the samples, then dried in an oven at 50 °C for 48 h within sterile conditions. Fenton reagent, prepared from 30 % H_2O_2 (20 ml, Merck Millipore, Emprove® Essential, Ph Eur, BP, USP) and Fe(*II*)SO_4 (10 ml, 10 mg/ml, Merck Millipore, EMSURE® ACS, ISO, Reag. Ph Eur) was added to the test tube. Afterwards, we heated the test tube in a water bath at 50 °C for 48 to 72 h. The samples were then subjected to gridded filter paper (Merck Whatman™ cellulose nitrate, sterile, diameter 47 mm and pore size 0.45 μm) for identification and characterization examination.

A microscope (Nikon Eclipse Ni—U) with a camera (Nikon DS-L4) was used to observe the filter paper membrane. We identified suspected microplastics using previously developed identification methods (Cordova et al., 2019; Lares et al., 2019; Mohamed Nor and Obbard, 2014), recorded shape, size and images shortly after their presence. The particle was identified using the following criteria: uniform color, lack of organic or cellular features, and lack of segmentation (Cole et al., 2013; Cordova et al., 2020; Hidalgo-Ruz et al., 2012).

Finally, a representative suspected microplastics (35.06 %, 162 out of 462 particles) was chosen from the samples, and its chemical structure was determined using an Attenuated Total Reflectance - Fourier Transform Infrared Spectrometer (ATR-FTIR, diamond crystal material, Thermo Fisher Scientific Nicolet™ iS5 with OMNIC™ FTIR Software). The FTIR was adjusted to a 4 cm^{-1} resolution with 32 scans and in the band region spectrum range of 650–3000 cm^{-1}. According to previous studies (Andreassen, 1999; Cordova et al., 2019; Crawford and Quinn, 2017; Käppler et al., 2015; Kotha and Shirbhate, 2015; Löder and Gerdts, 2015; Tagg et al., 2015), polymers were identified by investigating the existence of a significant peak in band regions (Andreassen, 1999; Käppler et al., 2016, 2015; Löder et al., 2015) at 1174–1087 cm^{-1} (stretching vibration of CF_2), 1400–1480 cm^{-1} (bending vibration of CH2), 1670–1760 cm^{-1} (stretching vibration of C═O), 1740–1800 cm^{-1} (stretching vibration of C═O), and at 2780–2980 cm^{-1} (stretching vibrations of $CH/CH_2/CH_3$ groups).

2.4. Quality assurance and quality control (QA/QC)

To avoid cross - contamination throughout sampling, the manta trawl was cleaned three times with river water and three times with DDDW before the next sampling. DDDW was used to rinse the sieve in a clean beaker glass wrapped in aluminum foil. To minimize sampling and analytical mistakes, a blank sample approach was designed to estimate the amount of contamination introduced during the experiment. Microplastic contamination was determined to be absent from the blank samples. Additionally, we wore 100 % cotton clothing and used glass laboratory supplies, immediately wrapping materials following treatments and rinsing and sanitizing all instruments prior to doing laboratory analyses in the laboratory. All chemical solutions were filtered via sterile filter paper to remove any remaining microparticles.

Microplastic recovery tests were performed on several commonly used polymers (PlasticsEurope, 2020). Nine different polymers (i.e., high-density polyethylene, low-density polyethylene, polyamide, polyurethane, polystyrene, polypropylene, polyvinyl chloride, acrylonitrile butadiene styrene, and styrene-acrylonitrile resin) ranging in size from 400 μm to 1000 μm, were added to pure water (Milli-Q®) and 6 mg/l Now Solution® Red Clay Powder (the average total suspended solid content in Jakarta Bay, Koagouw et al., 2021). A density separation approach with highly saturated NaCl and a biological digestion protocol (with Fenton reagent) were used to complete the recovery process. For three repetitions of the density separation procedure combined with one iteration of the biological digestion treatment, the overall recovery rate is 90.91 %. By comparison, the recovery rate for six repetitions of the density separation procedure followed by one iteration of the biological digestion treatment was 100 %.

2.5. Statistical analyses

PAST4 software (version 4.0.3) was used to conduct statistical analysis and create graph plots. The link between rainfall (Table S2) and variance in microplastic abundance was examined using linear regression analysis (Fig. S1). At a p-value of 0.05, statistical tests were considered significant.

3. Result

Microplastics were discovered in each sampling interval and throughout the entire sampling area. (Fig. 2). The abundance of microplastic in the nine rivers outlet to Jakarta ranged from 4.29 to 23.49 particles m^{-3}, with an average (± standard deviation) of 9.02 ± 4.68 particles m^{-3}. The highest microplastic abundance was 9.80 ± 4.79 particles m^{-3} in March 2020, while the lowest was 8.01 ± 4.82 particles m^{-3} in September 2020. As illustrated in Fig. 2A, the number of microplastics varied by season. Microplastics were more abundant throughout the rainy season (March 2020 and December 2020) than during the dry season (June 2020 and September 2020). However, we found no significant difference in microplastic abundance between sampling times ($p = 0.2868$). Moreover, the linear regression analysis revealed a strong relationship between variance in microplastic concentration and 14 days of average rainfall before sampling time ($R^2 = 0.8241$, $p < 0.001$).

As illustrated in Fig. 2B, all sampling locations contained microplastics, indicating that the pattern of microplastic pollution tends to increase towards the eastern part of the estuary flow towards Jakarta Bay. We found the highest amount of microplastic particles from nine rivers outlet to Jakarta Bay were in the Marunda River and the Bekasi River outlet with the average number of microplastic particles m^{-3} varying from 15.49 ± 4.28 and 15.97 ± 6.05, respectively. In our study, the Cilincing river and Dadap river outlets rank third and fourth with an average number of microplastic particles of 10.88 ± 2.79 and 7.16 ± 1.76 particles m^{-3}. Four river outlets in the middle of north Jakarta

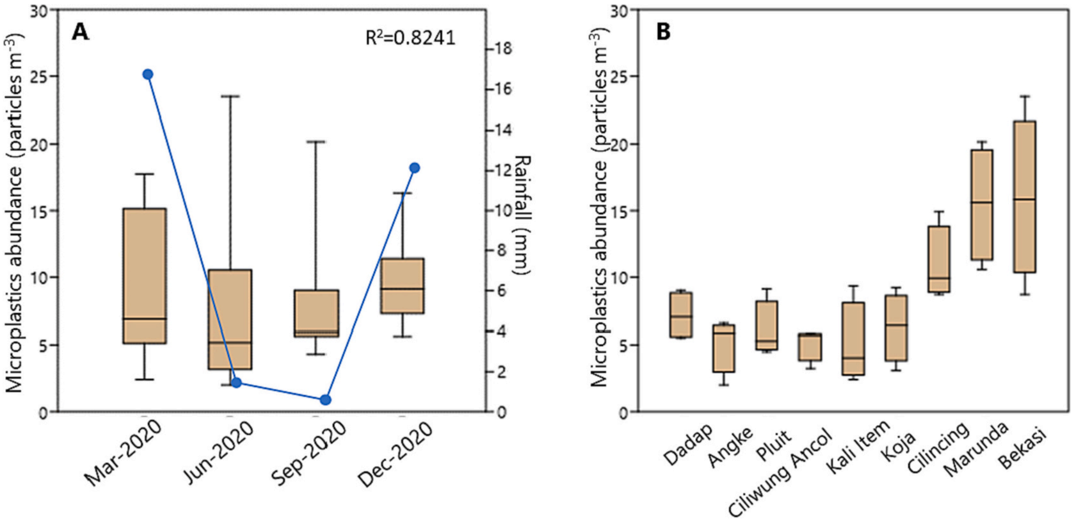

Fig. 2. Spatiotemporal microplastics abundance in nine rivers outlet to Jakarta Bay.

(Pluit, Ciliwung Ancol, Kali Item, and Koja) had an abundance of microplastics varied from 6.18 ± 1.98, 6.05 ± 0.85, 6.51 ± 2.11, and 7.04 ± 1.51 particles m^{-3}, respectively. Lastly, the Angke River outlet samples had the least abundance of microplastic particles (5.94 ± 0.69 particles m^{-3}). There were significant differences in microplastic abundance between Cilincing, Marunda, and the Bekasi River outlet (Kruskal-Wallis's test $p < 0.001$; Dunn's Post Hoc $p < 0.05$) compared to other sampling locations.

We classified microplastics into four shape categories based on their morphological properties, i.e., fragment, foam, fiber, and granule, and their percentages are presented in Fig. 3. In general, fragments (49.20 % with average 4.44 ± 3.37 particles m^{-3}) predominated in all nine river outflows, followed by foam (29.22 %, 2.64 ± 2.13 particles m^{-3}), fiber (19.02 %, 1.72 ± 1.29 particles m^{-3}), and granule (2.56 %, 0.23 ± 0.57 particles m^{-3}). At each location, the shape distribution is highly heterogeneous. Fragment, foam, and fiber are abundant at all sites, whereas granules are discovered only at the Cilincing, Marunda, and Bekasi River outlets. There were significant differences in this study between the types of microplastics, specifically between fragments with fibers and granules and between foam and granules (Kruskal-Wallis's test, $p < 0.001$; Dunn's Post Hoc, $p < 0.05$).

The intriguing finding in our research is that fiber shape grew from 3.33 % (0.37 ± 0. 47 particles m^{-3}) in March 2020 to 15.48 % (1.48 ± 0. 73 particles m^{-3}) in June 2020, then increased again by 24.42 % (2.02 ± 0.94 particles m^{-3}) in September 2020 until December 2020, when it reached 29.46 % (2.99 ± 1.11 particles m^{-3}). Fig. 4 shows fiber shape increase in all research locations, particularly in the Jakarta administrative area (Angke to Marunda). The distribution of fragments and foam, on the other hand, is about constant throughout all study locations.

According to the size of the microplastics, we divided them into four categories, e.g., 300–500 μm, 500–1000 μm, and > 1000 μm (Figs. 3 and 4). 46.54 % of the samples contained microplastics with a size of 500–1000 μm (average of 4.20 ± 2.77 particles m^{-3}), followed by larger size (>1000 μm; 33.15 %, 2.99 ± 2.90 particles m^{-3}) and smaller (300–500 μm; 18.07 %, 1.63 ± 1.45 particles m^{-3}) microplastics, and < 300 μm microplastics (lower limit of 226 μm), which made up the rest (2.24 %, 0.20 ± 0.41 particles m^{-3}). In comparison to large-scale microplastic debris (>1000 μm), the fraction of small-scale microplastic debris (<1000 μm) was significantly high. Microplastics with a size of <1000 μm were the most abundant (>66 %) over the majority of this investigation's duration. There were significant differences across sizes in this study, notably between 500 and 1000 μm and > 1000 μm (Kruskal-Wallis's test, $p < 0.001$; Dunn's Post Hoc, $p < 0.05$).

The pattern of seasonal variation in microplastic size did not alter substantially (Fig. 4). However, the pattern tended to decrease (not significant, Kruskal-Wallis test $p = 0.2775$) for sizes <300 μm. For sizes 300–500 μm, the abundance of microplastics was higher in March and September (~26 % proportion) and declined in June and December 2020 (proportion of 11.90 % and 7.14 %, respectively). The pattern was similar for 500–1000 μm microplastics, relatively lower in June and December 2020 (~41 %) and comparatively high in March and September 2020 (with ~51 % proportion). Different patterns were discovered in >1000 μm size microplastics. In March and September 2020, the proportion of abundance of microplastics was lower (18–19 %) than in June and September 2020, with the proportions of 44.05 % and 50.00 %, respectively.

FTIR spectroscopy determined the chemical composition for 162 of the detected microplastic particles (35.06 % of the total recovered particles). We randomly select particles with a uniform shape and size distribution across all samples. All 162 particles were identified as being made of a synthetic polymer. We identified nine different forms of microplastic polymers (Table 1 and Fig. 5). Polypropylene (36.42 %), polyethylene (21.60 %), and polystyrene (13.58 %) dominated the chemical composition analyses, accounting for 71.60 % of total microplastics. The remaining polymers (28.40 %) included polyvinyl chloride (9.26 %), polybutadiene (6.17 %), polyurethanes (4.32 %), polyethylene terephthalate (3.09 %), nylon 6 and 9 (5.56 %). We also investigated the chemical composition of fiber-type microplastics in this study because their number expanded from the beginning till the end of the study. We discovered 40 fiber particles, four of which were nylon-6 and nylon-9, from the March 2020 sampling time. While 31 fiber particles were determined to be polypropylene and 5 to be polyethylene. The 36 fiber particles were obtained from June, September, and December 2020 sampling periods.

4. Discussion

Rivers are a significant source of plastic pollution in the world's seas, and the amount of plastic in the water varies according to human activities in river basins (Cordova et al., 2022; Cordova and Nurhati, 2019; Kapp and Yeatman, 2018; Kataoka et al., 2019). Microplastics were detected in every surface water sample taken from nine river outlets, which is unsurprising given their pervasive distribution (Horton et al., 2018; Horton and Dixon, 2018). Our investigations of microplastic pollutant emissions in nine rivers that flow into Jakarta Bay reveal a

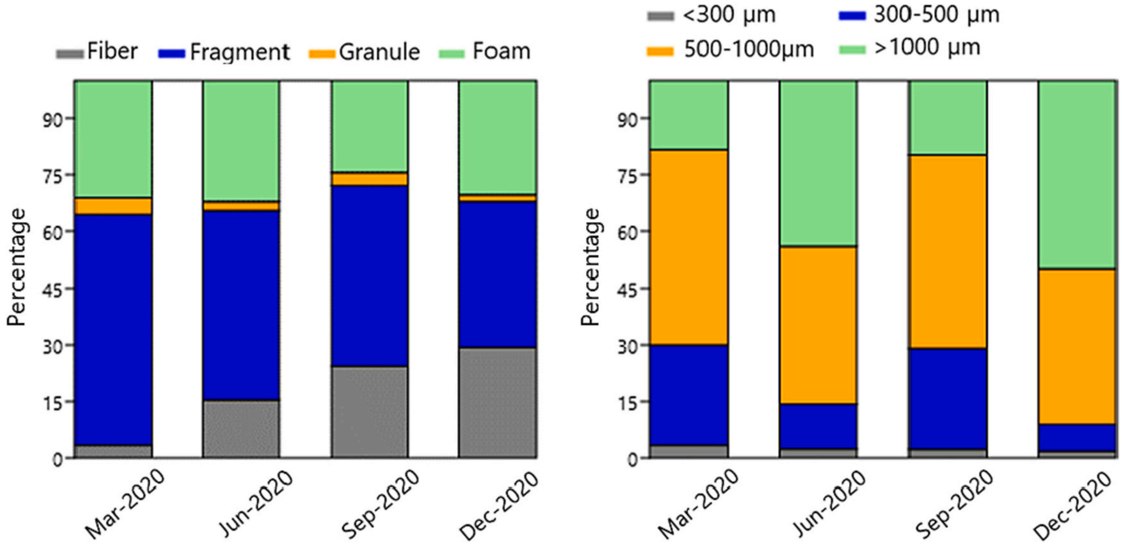

Fig. 3. Seasonal microplastics characteristics, by shape (left) and size (right), in nine rivers outlet to Jakarta Bay.

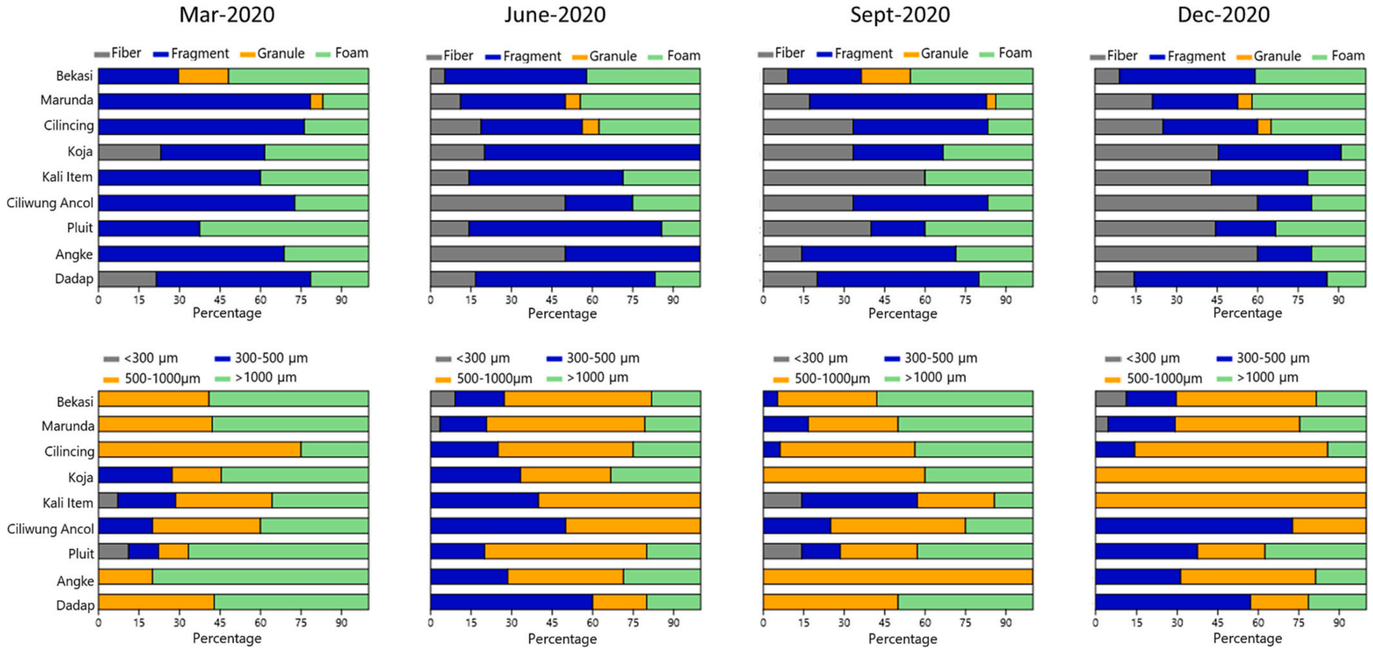

Fig. 4. Spatiotemporal microplastics characteristics, by shape (top) and size (bottom), in nine rivers outlet to Jakarta Bay.

Table 1
Chemical composition from recovered microplastics in nine rivers outlet to Jakarta Bay.

No	Polymer types	Total samples	%
1	Nylon 6 and 9	9	5.56
2	Poly vinyl chloride	15	9.26
3	Polybutadiene	10	6.17
4	Polyethylene	35	21.60
5	Polypropylene	59	36.42
6	Polystyrene	22	13.58
7	Polyurethanes	7	4.32
8	Polyethylene terephthalate	5	3.09
Total		162	100

reasonably low level of microplastic pollution in the water from these areas. In Table 2, we compare our findings to those of other river outlets using a similar approach, including identification of the chemical composition of the particles using FTIR or Raman spectroscopy. It is difficult to directly compare the abundance of microplastics in Table 2 due to the varied sampling techniques employed. Previous research has evaluated various sample techniques for microplastic analysis, which may result in differences in microplastic abundances of orders of magnitude (Zheng et al., 2021). This comparison enables us to conclude that the nine rivers that flow into Jakarta Bay are polluted with microplastics, albeit to a lesser extent than other regions' river outflows. However, microplastic pollution entering Jakarta Bay on a daily basis will result in microplastics being carried and accumulating into Java's north shore and Sumatra's south coast as a result of microplastic pollution. As a result of the marine litter pathway model developed by Iskandar et al. (2021), microplastics are technically possible to be transported and aggregated throughout the Indian Ocean region.

Our research demonstrates a positive association between rainfall and the abundance of microplastic particles observed in all rivers tested. Multiple other studies have identified a correlation between an increase in rainfall and an increase in microplastic particles in rivers, including the Tamsui River in Taiwan (Wong et al., 2020), the Goiana estuary in Brazil (Lima et al., 2015), the Los Angeles River in the United States of America (Moore et al., 2011), the Seine River in France (Dris et al., 2015), the Levantine coast in Turkey (Gündoğdu et al., 2018), the Venoge River in Switzerland (Faure et al., 2015), and the Lake Donghu in China (Xia et al., 2020). Hydrological processes in a river system convey runoff from rainfall (Mamo et al., 2019; Wang et al., 2017). During the dry season, when river discharge is reduced, microplastics are deposited in sediments and riverbanks; however, during the rainy season, when rainfall is abundant, the deposited and deposited microplastics are reactivated, leading to a high abundance of microplastic in the river (Hurley et al., 2018). According to multiple studies, microplastics can also originate from land-atmosphere interactions (Cai et al., 2017; Dris et al., 2016; Enyoh et al., 2019; Purwiyanto et al., 2022; Wright et al., 2020), and have a positive correlation with precipitation (Allen et al., 2019; Ganguly and Ariya, 2019; Purwiyanto et al., 2022). This allows microplastics in rivers to also originate from airborne microplastics. The limitations of our study include the small number of samples collected per time unit, which means they are not completely representative of the system, and the correlation is very likely to underestimate the quantity of microplastic contamination. We urge that high-frequency samples be collected in transects across rivers to ensure that the results are reliable and persuasive.

We discovered microplastic particles in variable levels in all river outlets and examined samples. This result implies widespread microplastic pollution in the catchment areas of all rivers in our research area, which is consistent with previous findings (Constant et al., 2020; Nizzetto et al., 2016; Su et al., 2020). Non-point and point sources of microplastic pollution can contribute to the problem (Siegfried et al., 2017). Human activities have been identified as a major source of microplastics in aquatic habitats in the research area (Eriksen et al., 2013). The statistical analysis findings revealed that the number of microplastic particles in the analyzed rivers varies depending on location, with the highest concentrations found in the east part of the North Jakarta coastline area. This study's findings align with those of Wang et al. (2017), who found a link between population density and the abundance of microplastics. A large abundance of microplastics in the environment may be linked to poor water quality caused by certain economic activities (Browne et al., 2011; Zhao et al., 2015). Given that each location in our study has a unique catchment area, this is to be expected. Land use and population density within the catchment areas may have a role to play in the differences in microplastic particle abundance found in different rivers (Huang et al., 2021; Karlsson et al.,

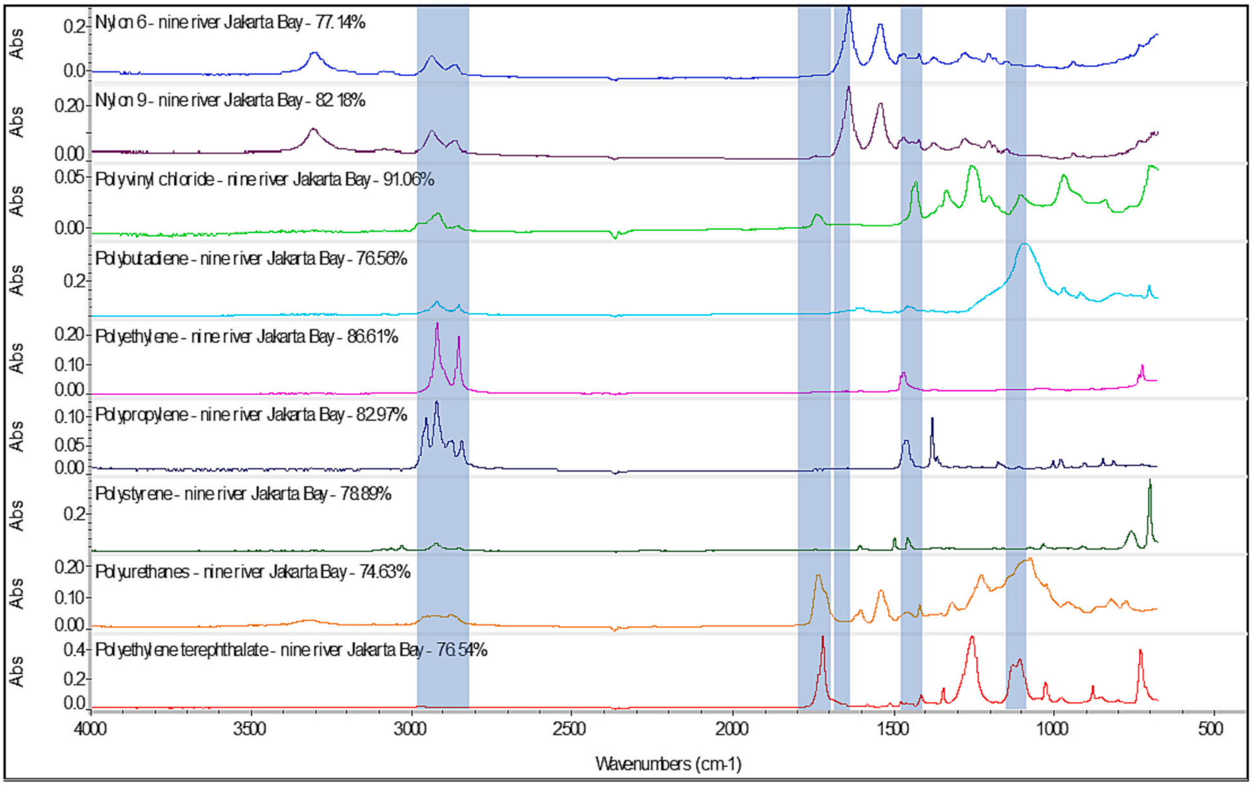

Fig. 5. Identification of microplastic polymer types using FTIR spectra analysis.

2018; Lozoya et al., 2016; Mani et al., 2015). Our findings indicate that the east part of the North Jakarta coastal area has a higher abundance of microplastic particles than the west part of the area (Cordova et al., 2021c, 2020). A similar pattern can be observed in the proportional increase in the number of enterprises and industrial parks (including Tanjung Priok port, Indonesia's biggest and busiest port), higher in the eastern catchment region than in the western catchment area of Northen Jakarta's catchment area (Cordova et al., 2020). This study's lowest abundance of microplastic occurred at the Angke river outlet, a relic of Jakarta Bay's mangrove forests. This result is consistent with the study findings that the mangrove ecosystem is a sink for microplastics (Jiao et al., 2022; Li et al., 2022). Martin et al. (2019) indicated that the developed root system and high net primary productivity contributed significantly to the trapping of riverine plastic litter. However, some other research suggests that hydrodynamic factors primarily determine the blocking of small particles (Zhang et al., 2020). This means that no definitive conclusions can be drawn about what factors had the most significant influence on intercept rates. Our research confirmed that human activities cause plastic contamination in freshwater systems, ultimately ending up in the ocean.

Microplastics' shape properties, size distribution, and chemical composition have been proposed as associative links for source identification (Auta et al., 2017). As a source of fragments and foam, secondary microplastic is commonly used in various applications, including packaging, disposable food and beverage containers, insulation, cushions, and other materials (Andrady, 2017; Lehtiniemi et al., 2018; Nurhasanah et al., 2021; Sulistyowati et al., 2022). These plastics, which are often single use, are brittle and have a low fracture resistance (Jin et al., 2019). After being abandoned and exposed to the environment, these forms of plastic are at a higher hazard of rapidly deteriorating into little particles of plastic waste (Cordova et al., 2021b, 2020; Falahudin et al., 2020). Moreover, the fraction of large-sized microplastics with a size of 500-1000 μm and > 1000 μm was considerable (79.69 %). The predominance of somewhat large microplastics implies that the level of weathering for plastic litter was similarly high (Cooper and Corcoran, 2010; Zbyszewski and Corcoran, 2011). Due to the weathering of plastic wastes and subsequent transportation into rivers via surface runoff, plastic litter may have degraded in the rivers (Chubarenko et al., 2018; Song et al., 2017), that flowed into Jakarta Bay. This finding emphasizes the critical nature of keeping larger bits of plastic from deteriorating once they reach the environment. The significant quantities of polyethylene, polystyrene, and polypropylene (almost two-thirds) discovered in this study were attributed to their ubiquitous use in everyday life and industrial operations (Au et al., 2017; Hahladakis et al., 2018). The three leading polymers accounted for more than half of global plastic consumption (PlasticsEurope, 2020; Stachowitsch, 2019). These three major synthetic polymer groups are used in plastic manufacture, and their copolymers are widely used in various applications, including packaging, various disposable dinnerware, textiles, and fishing equipment (Cordova et al., 2021c; Fotopoulou and Karapanagioti, 2015; Fries et al., 2013; Xiong et al., 2018; Zhang et al., 2019).

Our investigation found that the amount of microplastics in the shape of fibers has increased over time. The increase in the proportion from 3.33 % in March 2020 to nearly 30 % in December 2020 demonstrates that secondary plastic comes from a different source. We presume a linkage between COVID-19 waste, i.e., PPE, particularly face masks and the increase of microplastics in our research area. This result is consistent with Cordova et al. (2021a) findings that face mask waste accounted for 9.83 % of all riverine debris in Jakarta discovered in March 2020. Polypropylene is the primary polymer used in the medical mask (Chen et al., 2021; De-la-Torre et al., 2022; Fadare and Okoffo, 2020; Rathinamoorthy and Balasaraswathi, 2022). The chemical composition of fiber-shaped microplastics in March 2020 was determined to be nylon 6 and 9, which are commonly used in fisheries industry (De Witte et al., 2014; Lusher et al., 2017a; Silva-Cavalcanti et al., 2017; Sulistyowati et al., 2022). Interestingly, the chemical composition of the fiber-shaped microplastic identified during three consecutive sampling periods (June, September, and December 2020) was

Table 2
The abundance of microplastics found in this study compared to other river areas.

Sampling location	Riverine outlet area	River length (km)	Microplastic abundance (particles m^{-3})	Size range (μm)	Sampling method	Sampling depth (cm)	References
Banten, Jakarta,West Java, Indonesia	9 river outlets to Jakarta Bay	6.09–124.75	9.02 ± 4.68	226–2917	Trawling (mini manta trawl net)	15	This study
Banten, Indonesia	Dadap River	6.56	7.16 ± 1.76	297–2001	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Angke River	91.25	5.94 ± 0.69	288–1298	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Pluit River	19.6	6.18 ± 1.98	275–2401	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Ciliwung Ancol River	124.75	6.05 ± 0.85	236–2917	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Kali Item River	5.97	6.51 ± 2.11	232–2468	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Koja River	55.58	7.04 ± 1.51	226–1789	Trawling (mini manta trawl net)	15	This study
Jakarta, Indonesia	Cilincing River	44.97	10.88 ± 2.79	296–1096	Trawling (manta trawl net)	15	This study
Jakarta, Indonesia	Marunda River	23.5	15.49 ± 4.28	287–2784	Trawling (manta trawl net)	15	This study
West Java, Indonesia	Bekasi River	6.09	15.97 ± 6.05	296–1640	Trawling (manta trawl net)	15	This study
Banten, Indonesia	Cisadane River	138	61.33 ± 18.50	146–2680	Filtering	50	(Sulistyowati et al., 2022)
Bambe to Jagir, East Java, Indonesia	Surabaya River	43.2	4.47–21.16	300–5000	Trawling (manta trawl net)	16	(Lestari et al., 2020)
Citarum downstream area, West Java, Indonesia	Citarum River	270	3.35 ± 0.54	201–4983	Trawling (manta trawl net)	15	(Cordova et al., 2022)
Citarum downstream area, West Java, Indonesia	Citarum River	270	0.057 ± 0.025	50–2000	Trawling (manta trawl net)	45	(Sembiring et al., 2020)
Ciliwung downstream area, Jakarta, Indonesia	Ciliwung River	119	9.37 ± 1.37	300–5000	Trawling (manta trawl net)	15	(Cordova et al., 2020)
Lower reaches section of Yangtze River, China	Yangtze River	6300	983.3 ± 234.7	500–5000	Trawling (manta trawl net) and filtering	Not available (surface)	(He et al., 2021)
Yangtze River estuary, China	Yangtze River	6300	1838.9 ± 1041.9	500–5000	Trawling (manta trawl net) and filtering	Not available (surface)	(He et al., 2021)
Hangzhou, China	Qiantang river	494	1183 ± 269	45–5000	Filtering	50	(Zhao et al., 2020)
Fujian, China	Zhangjiang River	258	50–725	300–5000	Filtering using manta net	Not available (surface)	(Pan et al., 2020)
Ho Chi Minh City, Vietnam [fiber shape]	Saigon River	225	172,000–519,000	50–4850	Trawling (plankton net)	70	(Lahens et al., 2018)
Ho Chi Minh City, Vietnam [fragment shape]	Saigon River	225	10–223	50–4850	Trawling (plankton net)	70	(Lahens et al., 2018)
Greater Melbourne Area, Australia	Watersheds of Port Phillip and Western Port Bays	n.a.	30–1700	1.26 ± 0.93	Filtering	0–5	(Su et al., 2020)
Arkhangelsk Region, Russia	Northern Dvina River	744	0.003–0.010	333–5000	Trawling (neuston net)	15	(Zhdanov et al., 2022)

polypropylene. Indonesia began implementing a partial lockdown and the requirement to wear masks when going out in public during these three sampling periods; however, management is still inefficient, resulting in a significant amount of mask waste being scattered in the environment (Cordova et al., 2021a). After being retrieved from the environment, polypropylene surgical face masks showed considerable crystallinity loss and rupture of their fibrous microstructure (De-la-Torre et al., 2022). Photooxidation of polypropylene causes it to become embrittled, resulting in fragmentation and the generation of microplastics (Fayolle et al., 2000; Forero-López et al., 2021). Shen et al. (2021) states that after two months of exposure to the environment, the masks degrade into extremely delicate fragments and microplastics. Microplastics emitted from UV-irradiated masks in an aquatic environment with constant agitation have been estimated to reach hundreds of thousands of particles per mask (Morgana et al., 2021; Rathinamoorthy and Balasaraswathi, 2022; Saliu et al., 2021). However, our research on the abundance of microplastics is still in its earliest stages. Additional research is required to determine how the mask fragments as a result of exposure to UV radiation, heat, the effect of hydrodynamic activity, and waves. A previous study indicates that masks discarded on the beach degrade fully into microscopic fiber particles and aggregates in less than two years, while additional research on a longer timescale is required to test this assumption (Saliu et al., 2021). Another factor to consider in the future is the type of microplastic fiber that results from the fragmentation of the mask. If not adequately handled, this form of microplastic fiber would raise environmental pressure and jeopardize the environment. As a result, strict legislation, public education, and campaigns are necessary to promote correct disposal methods and systemic changes in plastic waste management, particularly single-use plastics. Additionally, additional research is necessary to determine how these microplastics particles infiltrate the aquatic ecosystem and their sources, including residential, industry, agricultural runoff, and other potential microplastic sources activity.

5. Conclusion

Microplastic particles were found in all nine river outlets studied in our study. The presence of microplastic particles in all tests indicates that Jakarta Bay is contaminated with microplastics. Based on our findings and field observations, we believe that the origin of microplastic particles in all river outlets is very likely due to the breakdown of macroplastic within the aquatic ecosystem and the combination of land-based sources. Through the seasonal analysis from March to December 2020, this study established a strong correlation between rainfall and microplastic abundance in the surface water of nine river outlets to Jakarta Bay. Our analysis discovered that an increase in polypropylene fiber-shaped microplastics could result from COVID-19 PPE waste, notably face masks. As a result, proper waste management is crucial for minimizing microplastics emissions into the environment. It should be emphasized that extensive studies into microplastic pollution in Indonesia's freshwater and marine ecosystems are necessary.

CRediT authorship contribution statement

Muhammad Reza Cordova: Writing - Original draft preparation, Writing - Review & Editing, Conceptualization, Resources, Investigation, Methodology, Formal analysis, Visualization, Data curation, Funding acquisition, Supervision.

Yaya Ihya Ulumudin: Investigation, Resources, Validation.

Triyoni Purbonegoro: Investigation, Resources, Validation.

Rachma Puspitasari: Investigation, Resources, Validation.

Nur Fitriah Afianti: Investigation, Resources, Validation.

Ricky Rositasari: Investigation, Resources, Validation.

Deny Yogaswara: Investigation, Resources, Validation.

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Marindah Yulia Iswari: Investigation, Resources, Validation.

Nurul Fitriya: Investigation, Resources, Validation.

Ernawati Widyastuti: Investigation, Resources, Validation.

Harmesa: Investigation, Resources, Validation.

Lestari: Investigation, Resources, Validation.

Irfan Kampono: Investigation, Resources, Validation.

Muhammad Taufik Kaisupy: Investigation, Resources, Validation.

Singgih Prasetyo Adi Wibowo: Investigation, Resources, Validation.

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Nurhasanah: Funding acquisition, Project acquisition.

Ahmad Muhtadi: Investigation, Resources, Writing - Review & Editing.

Etty Riani: Investigation, Visualization, Data curation, Funding acquisition, Project acquisition, Writing - Review & Editing.

Simon M. Cragg: Funding acquisition, Project acquisition, Writing - Review & Editing.

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.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: https://doi.org/10.1016/j.marpolbul.2022.113926. These data include the Google map of the most important areas described in this article.

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