Microplastics as a sedimentary component in reef systems: A case study from the Java Sea

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ABSTRACT

Microplastic pollution has been reported from coral reef systems all over the tropics. Exposure to microplastics has several negative impacts on coral health, such as bleaching, tissue necrosis, or an impairment of the coral’s immune system. Despite this potential risk for reef systems, the controlling processes for microplastics dispersion and accumulation in reef sediments are still largely under-studied. Presented here is a study of microplastics (125 µm to 5 mm) distribution in two tropic atoll reef platforms in Kepulauan Seribu, Indonesia. Sediment samples were collected in different facies zones within the reef platform. Microplastics were concentrated using density floatation and characterized by light and scanning electron microscopy. Some particles were identified as polypropylene using micro-Fourier transform infrared spectroscopy. All recovered microplastics were classified as secondary microplastics, likely derived from marine and local sources, with fibres as the most abundant type. Microplastics are showing similar transport and accumulation behaviour as fine siliciclastic grains. The abundance of microplastic is controlled by the proximity to the source area of larger plastic debris and hydrodynamic processes. Microplastics are not only present in low energy environments but also high energy settings such as the reef crest. Processes that contribute to accumulation in reef sediments are biofouling, interlocking and the creation of compound grains. Microplastics are present in sediment close to the seafloor (0 to 3.5 cm) but also at depths between 3.5 cm and 7.0 cm. Microplastic particles from below 3.5 cm are unlikely to be remobilized under modal weather conditions in the studied equatorial reefs. Subtidal reef sediment therefore can be regarded as a permanent sink for microplastics. The study shows that microplastics in coral reef environments deserve careful consideration since microplastics pose an additional threat to corals and their ability as framework builders in reef systems.

Keywords Anthropocene, coral reef, Indonesia, microfibre, pollution, sand apron.
INTRODUCTION

The worldwide accumulation of plastic litter in the marine environment has raised international awareness. Since the mass production of plastics in the 1950s, 6.3 billion tonnes of plastic is predicted to be waste (Geyer et al., 2017) and a large amount has entered the global environment. Once introduced to the environment, plastic litter eventually accumulates in the oceans (van Sebille et al., 2015). In 2010, between 4.8 to 12.7 million tonnes of plastic waste entered the ocean and by 2025 this number is predicted to rise by one order of magnitude (Jambeck et al., 2015). Ubiquitous litter in the marine environment consists of microplastics (Van Cauwenberghe et al., 2015); plastic particles and fibres smaller than 5 mm (Arthur et al., 2009) that were either directly manufactured or formed through breakdown of larger plastic waste (Andrady, 2011).

The marine ecosystem and its ecological function are threatened by microplastics (de Carvalho-Souza et al., 2018). Coral reef ecosystems receive increased attention since the discovery that corals might capture and ingest microplastics due to their similarity in size to plankton (Hall et al., 2015; Reichert et al., 2018). Laboratory experiments document that ingestion of microplastics by corals can inhibit food intake (Hall et al., 2015) and reduce their growth rate (Lartaud et al., 2020). Long-term exposure and adhesion to microplastics may have negative effects on corals such as bleaching and necrosis (Reichert et al., 2018). Furthermore, microplastics may promote the transmission of pathogens, which further increases the susceptibility of reef-building corals to diseases (Zettler et al., 2013; Lamb et al., 2018). In the long run microplastics pose a threat to reef corals and their ability to act as framework builders in coral reef systems. The United Nations Environmental Program (UNEP) identified the understanding of the patterns of plastic pollution in and around coral reef environments as one of the most important knowledge gaps associated with reef ecosystems (Sweet et al., 2019).

Only recently, microplastic pollution has been reported from coral reef systems all over the tropics: the South China Sea (Cheang et al., 2018; Ding et al., 2019; Zhang et al., 2019; Tan et al., 2020), the Great Barrier Reef (Hall et al., 2015), Maldives atolls (Imhof et al., 2017; Sallu et al., 2018, 2019), the Belize Barrier Reef (Oldenburg et al., 2021) and the coast of India (Vidyasakar et al., 2018). From popular tourist destinations to remote islands, reefs are affected by microplastic pollution (Imhof et al., 2017; Tan et al., 2020).

Indonesia is part of the Indo-Pacific Coral Triangle, which represents one of the most diverse marine ecoregions. The country is ranked as the second-largest contributor of mismanaged plastic waste to the ocean (Jambeck et al., 2015). In Indonesia, microplastics have been found in fish guts (Rochman et al., 2015), coastal waters (Syakti et al., 2017, 2018), river sediment (Alam et al., 2019), estuaries (Firdaus et al., 2020) and coral reef sediments (Cordova et al., 2018). The Kepulauan Seribu patch reef system close to Jakarta Bay is at risk of microplastic pollution. Urban pressures and pollutants from rivers entering Jakarta Bay have been reported to cause environmental degradation of ecological conditions in Kepulauan Seribu (Farhan & Lim, 2012). Approximately 8 tonnes of plastic litter dominated by styrofoam from the Greater Jakarta Area are entering Jakarta Bay daily (Cordova & Nurhati, 2019). Beach litter in Kepulauan Seribu is also generated from local island tourism, residents and passing ships. Altogether this has resulted in the spread of severe pollution to even more distant parts of the archipelago (Wylloughby et al., 1997).

Despite the global presence of microplastics, its distribution on the seafloor is poorly understood (Martin et al., 2017; Kane & Clare, 2019). Half of all plastics have a density greater than seawater (Morét-Ferguson et al., 2010) and eventually sink to the seafloor, which is considered to be a major sink for global plastic (Van Cauwenberghe et al., 2013; Woodall et al., 2014; Kowalski et al., 2016). Integration of process-based sedimentological knowledge with insights from modern sedimentary systems can provide crucial constraints on the transfer and distribution of microplastics to marine environments (Kane & Clare, 2019). However, the sedimentological processes that govern microplastic transport and distribution are still under-explored (Horton & Dixon, 2018; Kane & Clare, 2019). None of the aforementioned studies of microplastic distribution in reefal environments take the role of sedimentary processes or facies into account. This study wants to close this knowledge gap through the analyses of the distribution of microplastics in different environmental and sedimentary facies of a patch reef from Kepulauan Seribu. The sedimentary and environmental facies of this reef platform was
STUDY AREA AND ENVIRONMENTAL SETTING

Situated in the Java Sea, Kepulauan Seribu (Thousand Islands) consists of more than 300 coral reef platforms. About a quarter of them possess islands ranging in size from a few metres across to lengths greater than 7 km. From about 10 km off the north-west Java coastline, the island chain extends for about 40 km into the Java Sea. The patch reef system of Kepulauan Seribu is located on the shallow Sunda Shelf where it rises from a water depth of 30 to 50 m to the sea surface. A deep and several kilometres wide, east–west oriented channel separates Pari Island to the south from most other islands to its north (Fig. 1). It appears that this channel forms an important hydrological barrier, channelling the sediment-laden coastal waters off Java and Kalimantan away from the reef (Tomascik et al., 1997; Jordan, 1998).

Kepulauan Seribu is located in a relatively sheltered position protected from severe storms and ocean swell because it is surrounded by major land masses such as Sumatra, Java and Kalimantan (Fig. 1). The controlling influence on modern reef growth and morphology in Kepulauan Seribu is believed to be the seasonal change in the wind and current directions which are controlled by the monsoonal climate (Scrutton, 1976). The Java Sea is characterized by the monsoonal wind with a seasonal reversal between the north-west monsoon (December to February) and south-east monsoon (April to October). The seasonal south-east monsoon phase lasts longer but is characterized by lower maximum wind speeds compared to the north-west monsoon. On the interannual timescale of more than five to seven years this relationship reverses with higher wind magnitudes during the south-east monsoon (Poerbandono, 2016). The longer-lasting winds of the south-east monsoon (eight months) are thought to be more important for beach erosion, despite the somewhat lower wind magnitudes on seasonal timescales (Poerbandono, 2016). The tidal range in Kepulauan Seribu is micro-tidal, averaging about 52 cm with a range from 15 to 82 cm and a typical diurnal tidal cycle with one high stand and one low stand per day (Wyrtki, 1962).

The focus of this study is the patch reef systems of Panggang and Semak Daun which are situated in the middle part of the Kepulauan Seribu chain (Fig. 1). Panggang Island has the highest population density in Kepulauan Seribu, with 1000 people per m². It is situated on the north-eastern part of the sand apron, sheltering parts of the reef system from direct wave exposure from the Java Sea. (Fig. 1). Most of the inhabitants of Panggang Island work as fishermen and also practice aquaculture within the lagoon.

The Panggang reef platform has an atoll morphology with an approximate area of 3.2 km² and a central lagoon surrounded by reef and sand apron facies. From the reef flat, the water depth increases from about 1 m to about 20 m in the deepest part of the lagoon. Parts of the reef crest will be exposed during low tide, showing a coral assemblage dominated by platy Acropora and foliated corals. The sand apron on the eastern and western side of the lagoon is roughly two times wider compared to the sand apron on the northern and southern side. Only one small inlet traverses the sand aprons allowing only a very limited connection between the lagoon and the open sea.

Semak Daun Island is a small, uninhabited island (Fig. 1) popular for local, unorganized tourism on a camping ground. The reef platform Semak Daun is characterized by an extensive reef flat surrounding a partially filled shallow lagoon with active coral growth in its centre. Similar to Panggang, the reef flat in Semak Daun is expanded broadly on the eastern and western sides, leaving a narrow reef flat on the northern and southern side. Water exchange between the lagoon and the Java Sea is restricted to a few inlets on its western sides, while the eastern side of Semak Daun is directly exposed to the Java Sea. Semak Down is separated from Panggang towards the south by a shallow inter-reef channel (Fig. 1).

Surface sediments in the study area can be subdivided into four sedimentary facies: coral grainstone, coral packstone/grainstone, coral–mollusc packstone and mollusc wackestone (Utami et al., 2018). The occurrence of mollusc wackestone in the lagoon is controlled by water depth, while the sand apron and reef front do not show significant facies separation with water depth. Environmental facies distribution is
mainly controlled by water depth, the density of seagrass cover and coral abundance (Table 1; Utami et al., 2018). The satellite-derived environmental facies correlated only in the lagoon directly with sedimentary facies. No direct correlation of environmental facies to sedimentary facies exists in the sand apron due to the heterogeneity and complexity of the environment (Utami et al., 2018).

Aragonite is the dominant mineral phase, while low-magnesium calcite and high-magnesium calcite occur in fairly similar amounts in all sedimentary facies. Small amounts of siliciclastic minerals (quartz and smectite) are preferentially deposited in deeper waters below the wave base (Utami et al., 2021).

**METHODOLOGY**

**Sampling**

Sediments were collected in July 2018 from different subtidal and intertidal environments associated with the Panggang and Semak Daun reef platforms (Utami et al., 2018). These
environments include beach, sand apron with dense seagrass and without seagrass, subtidal reef margin and the deeper part of the lagoon (Table 1). For each site, three replicate samples were taken within a radius of ca 5 m. All of the sampling sites were documented photographically by using an underwater camera and geographically using GPS. Water depth was measured using a folding rule or markers on the hand line of the grab sampler. At the beach and in shallow water, the sediment for microplastic extraction was taken by directly ‘coring’ the sediment with a cut-off syringe (Romed Holland, Wilnis, The Netherlands). The modified syringe is placed on the sediment surface, while the tube (3.5 cm diameter) is pushed into the sediment to a depth of 7 cm. While the tube is pushed down into the sediment, the piston stays in place thereby maintaining a vacuum. This way, sediment disturbance is minimized and loss of sediment can be prevented. Subsequently, the tube is excavated and its bottom sealed before the modified syringe is retrieved, resulting in acquisition of 70 ml of sediment. The tube was immediately wrapped with aluminum foil and fastened with a rubber band to avoid contamination. Below a water depth of 10 m, the sediments were taken with a vessel-deployed grab sampler. Once on the boat, it was checked that the grab sampler jaws were tightly closed, preventing wash-out of fines. All samples retrieved with the grab sampler were relatively soft, cohesive fine-grained sediments (silt and very fine sand), allowing the ‘coring’ of the relatively undisturbed central portion of each grab sample before opening the jaws. ‘Coring’ within the grab sampler followed the same procedure as for the beach and shallow water sites. On land, each sample was split into two subsamples of 35 ml each; and the lower and upper 3.5 cm of the sediment column were transferred to separate foil trays. The environmental facies for each sampling site is derived from the facies map in Utami et al. (2018) and was ground-truthed with field observations.

### Grain-size analysis and sedimentary facies

All samples of 35 ml each were dried using an oven (Memmert, Schwabach, Germany) set to 70°C for 7 h. Dried samples were sieved through 125 µm, 250 µm, 500 µm, 1 mm and 2 mm sieves (Retsch GmbH, Haan, Germany). All individual grain-size fractions were weighed. Mean grain size and sorting were calculated using the software Gradistat (Blott & Pye, 2001). The sorting of samples was quantified as graphic standard deviation using the equation of Folk & Ward (1957). Values below 2 indicate moderate sorting, while values <4 and >4 indicate poor and very poor sorting, respectively. Point counting analysis was done on a minimum of 100 grains from the bulk fraction and compared with results from Utami et al. (2018) to derive the sedimentary facies for each sample. Microplastics in the size range from 125 µm to 5 mm were analyzed from bulk samples.

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**Table 1.** Sediment texture, sedimentary facies and water depth for each environmental facies at Panggang, Pramuk and the Semak Daun platform reef (Utami et al., 2018).

| Environmental facies       | Mean grain size (µm) | Sorting (µm) | Water depth (m) | Dunham | Sedimentary facies |
|---------------------------|----------------------|--------------|-----------------|--------|--------------------|
| DSPL/PM                   | 84                   | 5.5          | 9.6             | –      | GST                |
| SSPL/PM                   | 175                  | 7.5          | 6.6             | –      | PST                |
| SRM/SC                    | 441                  | 4.6          | 14.3            | 33%    | WST               |
| SAWWDSG                   | 514                  | 3.8          | 0.7             | 57%    | CG                 |
| SAWSSG                    | 585                  | 3.6          | 0.6             | 71%    | CP/G               |
| SAWSG                     | 614                  | 3.6          | 0.7             | 64%    | C-M P              |

Dunham texture: GST, grainstone; PST, packstone; WST, wackestone. Environmental facies: DSPL/PM, deeper subtidal part of lagoon/platform margin; SSPL/PM, shallower subtidal part of lagoon/platform margin; SRM/SC, subtidal reef margin/sparse coral; SAWWDSG, sand apron with dense seagrass; SAWSSG, sand apron with sparse seagrass; SAWSG, sand apron without seagrass. Sedimentary facies: CG, coral grainstone; CP/G, coral packstone/grainstone; C-M P, coral mollusc packstone; MW, mollusc wackestone.
Distribution analysis

All statistical analyses were performed using PAST (version 3.15) (Hammer et al., 2001). The Levene’s test was used to check if homogeneity of variances was met. The non-parametric Mann-Whitney U test was used for pairwise comparisons between depth and concentration of microplastic. The non-parametric Kruskal Wallis test for independent samples was used to examine the medians of microplastic distribution in different environmental facies. The significance level for all analyses was set at 95%. All samples used for microplastics analysis have an equal volume of 35 ml, but each sample has a slightly different weight due to differences in porosity and composition. Microplastic concentrations for all samples were normalized to a constant weight of one kilogram dry weight. To allow a better comparison to literature data the concentration was additionally normalized to volume (one litre) and area (one square metre).

Procedural contamination protocol

A strict protocol for each procedure was followed to prevent potential post-sampling contamination. Standard non-plastic laboratory equipment was used as much as possible. Clean cotton white lab. coats and nitrile gloves were worn all the time during sample handling. All laboratory procedures were done inside a laminar fume hood. The laminar fume hood was cleaned thoroughly using filtered distilled water and a non-shedding laboratory paper before and after every microplastics extraction. All surfaces and laboratory equipment were cleaned three times with tap water and filtered distilled water, then covered with clean aluminum foil. Only new, filtered NaCl-solution was used for the density separation procedure. Airborne fibres were monitored by placing a dampened filter paper pad inside the laminar fume hood for a 72 h period before and during each extraction (Martin et al., 2017). Additionally, procedural blanks were analyzed to monitor background contamination, using the density separation protocol with NaCl-solution but without sediments. Blanks were analyzed before the first extraction and after every third sample (Coppock et al., 2017). Fibres observed during monitoring were identified as cotton using scanning electron microscopy (SEM) and were excluded from the data analysis. The minimum size of plastic examined in this study was limited to 125 µm since particles below this size are difficult to identify by ATR-µFT-IR. The investigated size spectrum is overlapping with the size of zoo-plankton (200 to 1000 µm), which is ingested by reef corals as food (Houbrèque & Ferrier-Pagès, 2009; Hall et al., 2015) and microplastics used in feeding experiments of corals (Reichert et al., 2018). Some of these feeding experiments indicate that ingestion of microplastics is size-limited and restricted to particles >250 µm in some species of tropical reef corals (Hankins et al., 2018), further justifying the minimum-size limit.

Microplastics extraction

The Sediment Microplastic Isolation (SMI) unit was constructed as an extraction tool that allows rapid, simple and efficient microplastics separation from sediment (Coppock et al., 2017). The SMI unit was chosen due to its practicality in single-step decanting and cleaning to avoid cross-contamination. It also allows rapid processing of numerous replicates of small samples. Two SMI units were used for extraction to minimize the wear of the SMI units. The ball valves of both SMIs were checked regularly to rule out PVC contamination (Nel et al., 2019). The procedure for microplastics extraction from sediment follows Coppock et al. (2017) with one exception: filtered, saturated sodium chloride (NaCl) solution with a density of 1.2 g/cm³, instead of ZnCl₂ solution, was used for density separation. NaCl-solution has the advantage of being non-acidic, non-toxic and cheap. Other commonly used solutions, such as ZnCl₂-solution, have low pH, leading to reaction with the carbonate sediment and hampering effective microplastics extraction. To evaluate the recovery rate of microplastics for this study, microplastics in the size range from 125 µm to 1 mm were produced by cutting a polypropylene rope and sieving the resulting fragments. These fragments were distinctive in both colour and shape to ensure that they are distinguishable from non-spiked plastic. Fifty of these fragments, covering the complete size range, were added to every third sample prior to microplastics extraction. The mean recovery rate for the spiked microplastics was 89%, slightly lower compared to the >95% reported by Coppock et al. (2017) for the SMI unit using ZnCl₂ solution as a flotation media.
Microplastics identification

Visual identification based on morphological and physical characteristics is most widely utilized for microplastics identification in combination with other methods. Optical analysis of the particles in the size range from 125 µm to 5 mm recovered on the filters after density separation was performed using a stereomicroscope (Wild M3Z, Heerbrugg, Switzerland). Microplastic particles were identified and counted following protocols developed by Lusher et al. (2017). Unnatural colours and/or shininess and unnatural forms/structures were used as indicators of potential microplastics (Fries et al., 2013; Martin et al., 2017). Particles with potentially cellular or organic structures and translucent fibres were rejected as microplastics (Martin et al., 2017). Translucent fibres and fibres that were not characterized by three-dimensional bending and uniform thickness were also rejected (Nuelle et al., 2014; Martin et al., 2017). Subsequently, all identified, potential microplastic particles were counted according to shape and colour and photographed.

The application of micro-Fourier transform infrared spectroscopy (µ-FT-IR) methods is technically limited by the diameter of the infrared (IR) beam to the identification of particles larger than ca 20 µm (Galgani et al., 2013). However, obtaining good quality spectra by attenuated total reflectance micro-Fourier transform infrared spectroscopy (ATR-µ-FT-IR) requires close contact between the sample and the crystal surface, which is often difficult to obtain (Konechnaya et al., 2021). In this study, several potential microplastic fragments were selected for ATR-µ-FT-IR spectroscopy analysis based on their size and morphology so that close contact between the sample and the germanium crystal could be obtained. All selected particles were >500 µm, and had at least one even surface to ensure close contact between the particle and the ATR-µ-FT-IR germanium crystal to obtain high-quality spectra. ATR-µ-FT-IR analysis was carried out with a Spotlight™ 400 Series imaging system (Perkin Elmer, Waltham, MA, USA). The imaging system is equipped with a mercury cadmium telluride detector, operating in the 4000 to 650 cm⁻¹ wavenumber range, and was run in reflectance mode. Spectrum™ 10.4.2 software was used to analyze spectroscopy images. A library of the most commonly used polymers was self-generated to serve for comparison and identification of the polymer type according to their IR spectra. The plastics were provided from daily goods, the IR spectra were measured using the same FT-IR tool and verified with the resin identification code symbols on their surface. In addition, all spectra were also compared with published libraries. The spectrum analysis followed the method of Woodall et al. (2014). Matches with a quality index ≥0.7 were accepted. Matches with a quality index <0.7 but ≥0.6 were individually inspected and interpreted based on the proximity of their absorption frequencies to those of chemical bonds in the known polymers. Matches with a quality index <0.6 were rejected.

Microplastic particles and fibres which were too small for ATR-µ-FT-IR analysis were analyzed using scanning electron microscopy with an energy dispersive X-ray spectrometer (SEM-EDX) (n = 17, 13%) to characterize their surface morphology and elemental chemistry. The remaining microplastic particles and fibres were accepted solely through visual identification (visual matches on colour and physical form) to ATR-µ-FT-IR and SEM-EDX confirmed microplastics from the same subsample or corresponding replicate. SEM is known to produce high-resolution images and has been used in several studies for the identification of microplastics (Corcoran et al., 2009; Fries et al., 2013; Van Cauwenbergh et al., 2013; Vianello et al., 2013; Lusher et al., 2017). Microplastic identification based on surface morphology and elemental chemistry was carried out using a SEM-EDX mounted on a FEG-SEM Zeiss SUPRA 55-VP (Carl Zeiss, Oberkochen, Germany). All particles were gold-coated before analysis to prevent sample charging (Corcoran et al., 2009). To obtain the best image resolution, the SEM was operated at 3kV in secondary electron (SE) mode. To obtain information on average atomic numbers and chemical composition of the sample the SEM was operated at 12 kV in backscattered electron (BSE) mode combined with EDX (Vianello et al., 2013).

RESULTS

Microplastics characterization

Four individual microplastic particles were analyzed by ATR-µ-FT-IR. Three microplastic particles were confirmed to be polypropylene (Fig. 2). For one additional microplastic particle the polymer type could not be identified...
unequivocally but the ATR-µ-FT-IR analysis revealed a clear dibutyl phthalate signal. A detailed interpretation and comparison with reference spectra allowed the differentiation from chemically similar polymers, in particular polyethylene terephthalate (PET). Phthalates are known as plasticizers and as ingredients of microplastics in proportions up to 60% of the total plastic product weight (Teuten et al., 2009). Saliu et al. (2019) found appreciable levels of phthalates in the tissue of corals from an atoll reef in the Maldives Archipelago. The sample containing dibutyl phthalate was found on the intertidal beach of Panggang and was assumed to be a fragment of chipped boat paint. Secondary microplastics were identified in samples from all facies and occur predominantly as fibres (98%), while fragments (2%) and film (<1%) are subordinate (Fig. 3). Most microplastic fibres and particles are either blue (44%) or black (36%). Less common colours are red (15%), white (4%) and transparent (1%).

**Microplastics distribution**

Most sediment samples in the study area are grain supported (83%) and can be categorized as grainstone (0 to 10% matrix) or packstone (10 to 50% matrix). Wackestone (50 to 90% matrix) is the only matrix-supported texture (17%). Sorting is generally poor (68%) or very poor (20%), but ‘moderately sorted’ (7%) and ‘moderately well-sorted’ samples (3%) are also present. The grain size of the samples varies between 0.03 mm and 1.3 mm, with a mean grain size of 0.5 mm. The fine fraction (<125 µm) is most abundant in the lagoon, while coarser sediments are mostly found at the reef front of Panggang and Semak Daun (Fig. 4). The sediment composition is nearly identical to previous facies descriptions (Utami et al., 2018, 2021) with corals and molluscs as the dominant skeletal components. Based on their grain size and composition all samples can be attributed to the sedimentary facies defined by Utami et al. (2018). Samples from the two sites within the lagoons of Panggang and Semak Daun belong to the mollusc wackestone facies. The two sites from the reef crest yielded coral packstone/grainstone samples, while sediments from all other sites belonged to the coral grainstone facies (Fig. 4).

A total of 132 microplastic fragments and fibres were recovered from 43 subsamples (including replicates), while 11 subsamples were devoid of microplastic. Fibres are the majority of contaminants in the study area (98%) followed by boat paints (1%) (Fig. 3). Microplastic abundance varied from zero to eight particles/subsample (Fig. 4). High microplastic concentrations were found on the beach of Semak Daun and in the lagoon of Panggang (Fig. 4). The concentration of microplastic shows a statistical significance difference for the two depth intervals in subtidal facies of both reef platforms (independent samples Mann-Whitney U test, \( P < 0.05 \)) (Fig. 5). The beach environment is characterized by relatively constant concentrations with depth on both islands (Fig. 5). Overall, there is no significant difference in microplastic abundance between the uninhabited island of Semak Daun and the densely populated island of Panggang (independent samples Mann-Whitney U test, \( P = 0.26 \)). The mean concentration is higher at Semak Daun, while the highest absolute number is found in a sample from Panggang (Fig. 6). At Semak Daun, the microplastic concentration is significantly higher at the beach compared to all subtidal facies (independent samples Kruskal Wallis test, \( P < 0.05 \)) (Fig. 6). All subtidal facies at Panggang...
Fig. 3. Local sources of contamination and microplastic particles found in the study area. (A) Fish farm in the Panggang lagoon. The approximate height of the building is 4 m. (B) Microplastic fragment from the Panggang lagoon (sample M07, 3.5 to 7.0 cm). (C) Plastic litter from unregulated tourism found on the beach of Semak Daun. The field of view is 5 m. (D) Microplastic fibres of various lengths and colours from the beach at Semak Daun (sample M19, 3.5 to 7.0 cm). (E) Boats on the beach at Panggang used for fishing and tourism. The length of the boat is approximately 4 m. (F) Microplastic fragment from the beach at Panggang (sample M29, 3.5 to 7.0 cm).
show higher concentrations compared to the beach, although the difference is not statistically significant (independent samples Kruskal Wallis test, $P = 0.36$) (Fig. 6). Generally, high microplastic concentrations are restricted to samples with mean sediment grain sizes <100 µm and >50% fine sediment fraction (<125 µm) content (Fig. 7).
Fig. 5. Depth profile of cumulative microplastic abundance in all samples from subtidal facies \((n = 42)\) and the beach \((n = 12)\) of the two reef platforms.

Fig. 6. (A) Box plots and arithmetic mean (x) for microplastics in bulk sediment (35 ml) of Panggang and Semak Daun reef platforms. (B) Comparison of microplastic concentrations between environmental facies.

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DISCUSSION

Comparison with other reef environments

Information on the concentration of microplastic in reef environments is very limited. Saliu et al. (2018) studied microplastic abundance at the beaches of a populated but remote atoll from the Maldives Archipelago. Cheang et al. (2018), Cordova et al. (2018) and Zhang et al. (2019) studied the sediments from subtidal reef environments (Table 2). Saliu et al. (2018) used different procedures for the sampling of non-visible <1 mm and visible (1 to 5 mm) microplastics. Saliu et al. (2018) sampled the larger microplastics fraction (1 to 5 mm) by visual inspection of the beach surface within a 1 m by 1 m grid at the high tide drift line. In contrast, in this study, a size range from 125 µm to 5 mm was analyzed to a depth of 7 cm. Turra et al. (2015) noted that plastic items may occur to a depth of 2 m in beach environments and emphasized that depth of sampling is crucial for a comparison between sites when the abundance of particles is normalized to an area. This is supported by the current study, which shows a similar concentration of microplastics in the upper and lower 3.5 cm of the beach samples (Fig. 5). A direct comparison between the concentration of the 1 to 5 mm fraction reported in Saliu et al. (2018) and data in this study, therefore, is not meaningful. In contrast, a comparison is possible for the non-visible fraction <1 mm, which is normalized to kilograms of sediment. Saliu et al. (2018) reported mean plastic (150 µm to 1 mm) abundances of 156 particles/kg in beach sediments from the Maldives, with only one of six stations showing concentrations of less than 100 particles/kg. These values are higher compared to the present study area, especially if the smaller plastic size range (150 µm to 1 mm) in the study of Saliu et al. (2018) is considered.

For subtidal environments, the microplastic concentration is comparable to other reef systems. Semak Daun shows slightly lower values and Panggang shows slightly higher values when compared to Lombok or several reef systems in the South China Sea. Microplastic concentrations between 40 to 90 particles per kg seem to be the rule for subtidal reef environments. Much higher values from Sanya Lu Hui Tou and the Xisha Island (both in the South China Sea) seem to be exceptional for relatively isolated reef islands and are more similar to reefs in metropolitan areas like Hong Kong (Cheang et al., 2018).

Microplastics source and accumulation at the seafloor

The morphology of recovered microplastics indicates that the breakdown of larger plastic items into secondary microplastics is the primary
source of microplastics in the study area. Styro-foam, plastic cups and thin plastic wrap were reported as the most abundant land-derived marine debris from the Greater Jakarta Area (Cordova & Nurhati, 2019). This is in contrast with the composition of the microplastic assemblage in Kepulauan Seribu. Fibres and flakes of boat paint are the majority of microplastics and indicate a local source of contamination from the islands or of marine origin, i.e. by fishing activity (Fig. 3), instead of a direct impact from the Greater Jakarta Area. A deep submarine channel to the north of Pari (Fig. 1) appears to act as an important hydrological barrier channelling the sediment-laden coastal waters off Java and Kalimantan away from the reefs of Kepulauan Seribu (Tomascik et al., 1997; Jordan, 1998). This seems to be in line with observations of other environmental stressors. Polluted water masses from the Greater Jakarta Area are considered to affect reefs in nearshore areas close to river mouths around Jakarta Bay, while localized effects of anthropogenic stressors are more important for reefs in the northern Kepulauan Seribu (Farhan & Lim, 2012; Baum et al., 2015). The lack of a statistically significant difference between samples from the densely populated (Panggang) and the unpopulated island (Semak Daun) is likely due to mismanaged plastic waste from tourism, as indicated by the abundance of microplastic found on the intertidal beach at Semak Daun which is known as a popular unregulated tourist campsite (Fig. 6). Plastic cups and wraps are the dominant macroplastic litter found along the beach of Semak Daun (Fig. 3), but plastic ropes used to secure tents and hammocks are also common and likely disintegrate to mesoplastics and microplastics.

The difference in abundance of microplastic between the environmental facies shows diverging patterns between the two reef platforms. At Panggang, the highest concentrations are observed in the lagoon, which is used for aquafarming. At Semak Daun, the highest concentrations are coupled to human activity on the beach of the island impacted by tourism. Microplastic abundance seems to be controlled to some extent by the proximity to the source area of larger plastic debris. However, the question remains why the microplastics are deposited and incorporated in the carbonate sediment at all. The microplastic fragments identified using µ-FT-IR analysis proved to be polypropylene (Fig. 2), which should be buoyant in seawater (Hidalgo-Ruz et al., 2012). Biofouling is known to increase the density of microplastics to an extent that allows even buoyant polymers to sink to the seafloor (Kaiser et al., 2017). Biofouling is the process of the buildup of organic matter and successive colonialization of plastic by organisms from bacteria to invertebrates.

### Table 2. Comparison of microplastic (MP) concentration between different reef platforms.

| Location                              | Habitat                | MP size fraction investigated | Average MP concentration /kg /m² | References   |
|---------------------------------------|------------------------|------------------------------|----------------------------------|--------------|
| **Beach**                             |                        |                              |                                  |              |
| Semak Daun, Indonesia                 | Atoll island           | 125 µm to 5 mm               | 99 –                             | This study   |
| Panggang, Indonesia                   | Atoll island           | 125 µm to 5 mm               | 20 –                             | This study   |
| Faavu Atoll, Maldives                 | Atoll island           | 1 to 5 mm                    | – 4 to 36                        | Saliu et al. (2018) |
| Faavu Atoll, Maldives                 | Atoll island           | 150 µm to 1 mm*              | 156 –                            | Saliu et al. (2018) |
| **Subtidal environments**             |                        |                              |                                  |              |
| Semak Daun, Indonesia                 | Atoll                  | 125 µm to 5 mm               | 40 –                             | This study   |
| Panggang, Indonesia                   | Atoll                  | 125 µm to 5 mm               | 85 –                             | This study   |
| Lombok, Indonesia                     | Fringing reef          | <5 mm                        | 48 –                             | Cordova et al. (2018) |
| Nansha Island, South China Sea        | Atoll                  | <5 mm                        | 73 –                             | Zhang et al. (2019) |
| Weizhou Island, South China Sea       | Fringing reef          | <5 mm                        | 75 –                             | Zhang et al. (2019) |
| Sanya LHT, South China Sea            | Fringing reef          | <5 mm                        | 168 –                            | Zhang et al. (2019) |
| Xisha Island, South China Sea         | Atoll                  | <5 mm                        | 260 –                            | Zhang et al. (2019) |
| Hong Kong, South China Sea            | Fringing reef          | 0.3 to 5.0 mm                | 189 –                            | Cheang et al. (2018) |

*Saliu et al. (2018) also analyzed the abundance of microplastics <150 µm. Only the abundance of the 150 µm to 1 mm size fraction reported by Saliu et al. (2018) is considered here for a better comparison.*
Fragments of diatoms were observed on microplastic fibres from the sand apron of Semak Daun (Fig. 8). Biofouling experiments from the Baltic Sea show that diatom fragments were abundant on microplastics after an incubation period of only six weeks (Kaiser et al., 2017) and diatoms are also known to be among the first colonizers of seagrass blades (Corlett & Jones, 2007). Colonization by diatoms and general biofouling seems to be a relatively rapid process that allows even buoyant microplastics to settle to the seafloor.

Another process that is specific to reef environments is the trapping of floating and suspended sediment grains by coral mucus (Wild et al., 2004). Mucus is a gel-like substance released by corals. It is used as a defence mechanism under stressed conditions, for example to prevent desiccation during air exposure (Wild et al., 2004), but also to facilitate heterotrophic feeding (Lewis & Price, 1976). Mucus is known to accumulate into floats that drift from the reef towards the lagoon before they sink to the seafloor. This process effectively traps suspended sediments, which could include even the buoyant microplastic fraction.

Other polymers, that are slightly less dense compared to seawater, are thought to be transported similarly to clay minerals (Zalasiewicz et al., 2016) and could be easily winnowed.

Fig. 8. Scanning electron microscopy (SEM) images of synthetic fibres. (A) Fibre from the sand apron of Semak Daun (Sample M16). (B) Fibre from the intertidal beach of Semak Daun (Sample M19). (C) Biofouling of fibre from the sand apron of Panggang (Sample M01). (D) Biofouling of fibre from the sand apron of Semak Daun (Sample M18). A SEM energy dispersive X-ray spectrometer (SEM-EDX) confirms that the organic fragments in (C) and (D) are composed of silica. The fragments are interpreted to be derived from diatom tests, based on morphology and elemental composition.
from higher energy depositional environments. Plots of microplastic abundance versus grain size of bulk sediment (Fig. 7) show a high variability but generally indicate that the highest microplastic concentrations are limited to sediments with a mean grain size of $<100\ \mu m$ and a fine fraction content of $>50\%$. These fine-grained sediments occur exclusively in the lagoon, indicating that the lagoon acts as a sink for microplastics once it has accumulated in a low-energy environment. The assumption that microplastics are subject to similar transport and accumulation processes as fine-grained siliciclastics is supported by the fact that increased values of siliciclastics and microplastics only occur in samples with $>50\%$ fine fraction (Fig. 9). There is no local source for siliciclastic phases on the reef platforms in the study area. Clay minerals (smectite) and fine-grained quartz are thought to be derived from neighbouring larger islands, such as Sumatra. Subsequently, they are transported into the study area by oceanic currents (Utami et al., 2021). In the reef platforms they are concentrated below the local wave base, indicated by bulk fine fraction contents of $>50\%$ (Utami et al., 2021). A similar hydrodynamic control has been shown before for microplastic distribution in siliciclastic sediments in the lagoon of Venice (Vianello et al., 2013). Besides proximity to sources of plastic input, hydrodynamics seems to be an important control for microplastic accumulation.

It is surprising that high concentrations of low-density microplastics have been observed in the high energy environments of the reef crest and sand apron (Fig. 4) where carbonate sediments are characterized by coarse grain sizes and are lacking clay minerals (Fig. 7). It is well-known that seagrass baffles currents (Corlett & Jones, 2007). Utami et al. (2018) demonstrated that the mean grain size of sediments on the sand apron of Panggang is reduced within dense seagrass meadows. Huang et al. (2020) showed that intertidal seagrass beds act as a trap for microplastics, with a two-fold to three-fold enrichment in sediments from seagrass beds compared to barren areas. The comparison of microplastic concentrations on the sand apron of Semak Daun shows no significant difference between the areas within and outside seagrass meadows (independent samples Mann-Whitney $U$ test, $P = 0.55$). However, this point should be studied with a larger dataset to evaluate the effect of subtidal seagrass beds on microplastics trapping conclusively.

The entrainment and resuspension of the microplastic particles might be hindered by armouring and interlocking effects (sensu Kench & McLean, 1996). Bed armouring shields finer particles below coarse particles, limiting the capacity of currents for entrainment and transport (Reed et al., 1999). This effect might be amplified by the shape of microplastic fibres. The entanglement of fibres with carbonate grains might contribute to an interlocking effect by

![Graph](image.png)

**Fig. 9.** A plot of microplastics and siliciclastic mineral concentrations with fine fraction ($<125\ \mu m$) content in the bulk sample. The highest concentrations of microplastic and siliciclastic minerals are found in sediment with $>50\%$ fine fraction content, indicating similar transport behaviour. Mineralogy and associated bulk grain sizes are from Utami et al. (2021).
which particles are tightly held by their neighbours. This process might even create compound grains (Fig. 10), consisting of mixed microplastic/carbonate particles with a density close to carbonate and a very irregular shape. The irregular shape and porous nature of reef sands might facilitate these entanglements, compared to more rounded and smoother siliciclastic grains. Another type of microplastic/carbonate compound grains was observed in beach sediments of Panggang (Fig. 10). Blue microplastic seems to partially cover carbonate grains. The colour of the microplastics closely resembles the blue colour of local fishing boats (Fig. 3), which are regularly painted at the beach. The grains are therefore interpreted to result from the contact of carbonate sand grains with fresh boat paint. Biofouling, armouring, interlocking and the creation of compound grains will all contribute to the sinking and accumulation of microplastics in relatively high energy environments such as the beach, sand apron and reef crest. An alternative pathway for the incorporation of microplastics into carbonate grains in reefs would be the in vivo trapping within intraskeletal pores of the coral skeleton or the inclusion within the coral skeleton itself. Both processes have been described for suspended siliciclastic sediments (Barnard et al., 1974; Risk & Edinger, 2011) and seem to be common for corals living in turbid water (Cortés & Risk, 1985). The same might apply to microplastics that are overgrown by coral tissue or ingested and retained by coral polyps. Microplastics within corals (tissue and/or skeleton) have been

Fig. 10. Entanglement of fibres and adhesion of paint creates compound grains. The higher density of these grains compared to pure microplastics facilitates their accumulation on the seafloor. (A) Entanglement of fibre with carbonate sand grains (sample M20, intertidal beach, Semak Daun). (B) Entanglement of fibre with carbonate sand grains (sample M29, intertidal beach, Panggang). (C) Microplastics, interpreted as remnants of paint droplets, wrapped around a sand grain (sample M29, intertidal beach, Panggang). (D) Microplastics, interpreted as remnants of paint droplets, attached to the surface of sand grains (sample M28, intertidal beach, Panggang).
observed from the South China Sea (Ding et al., 2019) and the Belize Barrier Reef (Oldenburg et al., 2021) but not in the study area.

Reef sediments as a permanent sink for microplastics

Due to their widespread occurrence, microplastics are regarded as a good practical indicator of Anthropocene strata (Zalasiewicz et al., 2016). However, the authors cautioned that shelf sediments might be depleted in microplastics due to the effect of currents transporting plastic offshore into deeper water. There is a shortage of studies investigating the depth distribution of microplastics in shallow subtidal sediments and a complete lack of data for reef systems. This study indicates that microplastics are not only common in sediments close to the seafloor (0 to 3.5 cm) but also in sediments between 3.5 cm and 7.0 cm depth.

The mixing depth is defined as the vertical thickness of a layer of active sediment exchange, below which lies an immobile bed (Sherman et al., 1993). Besides hydrodynamic mechanisms, sediment mixing depth is influenced by bioturbation. Jackson et al. (2005) found that bioturbation is responsible for an increased mixing depth in estuarine beaches. An experimental study by Nåkki et al. (2017) revealed that bioturbation can distribute microplastics within the uppermost 5 cm of the sediment column in just three weeks. Martin et al. (2017) found that microplastics are ubiquitous in superficial sediment of the Irish continental shelf but limited to a depth of less than 4 cm, inferring significant exposure of filter and deposit feeders. Bioturbation is pervasive on the sand apron of reef platforms in Kepulauan Seribu (Fig. 11) which could explain the presence of microplastics in a depth >3.5 cm.

Hydrodynamic transport of sediment grains on the sand apron of reef systems is an understudied topic. However, measurements on the sand apron of the high-energy reef of One Tree Island (Great Barrier Reef), indicate a mixing depth of <2.5 cm under modal conditions (Vila-Concejo et al., 2014). Microplastics in the interval below 3.5 cm, therefore, are unlikely to be remobilized under modal weather conditions. However, it is typically assumed that erosion and deposition on reef platforms are strongly influenced by high-energy events such as storms. This is especially true for reefs between 7° and 25° north and south of the equator, that are affected by tropical cyclones (Scoffin, 1993). In contrast, the reef platforms of Kepulauan Seribu belong to the equatorial carbonate system (Park et al., 2010; Utami et al., 2021) and are mainly influenced by the monsoonal wind system (Umbgrove, 1947). Beach sediments of sand keys in Kepulauan Seribu are subject to erosion by the seasonally reversing monsoonal winds (Poerbandono, 2016). Microplastics in beach sediments might be resuspended, likely resulting in a lower preservation potential of microplastic accumulations. However, analysis of wind strength over a 30 year interval for
Kepulauan Seribu indicated maximum offshore significant wave heights of <0.4 m (Poerbandono, 2016), which is much less compared to the average offshore significant wave height of 1.15 m at One Tree Island (Hopley et al., 2007). High energy events are not likely to cause resuspension of microplastics from subtidal environments, which are considered to be a permanent sink. Martin et al. (2019) observed that the concentration of floating microplastics in the Red Sea is unusually low. Those authors attributed this to the adhesion of microplastics to corals in the abundant reefs of the Red Sea. This study suggests that burial of microplastics in reef sediments might be an alternative or additional mechanism to explain the relatively low concentrations in the Red Sea.

**Microplastics and reef health**

The bioavailability of microplastics in sediment allows biological interactions with deposit and detritus feeding organisms with uncertain consequences for the health of the organisms (Wright et al., 2013). Sea cucumbers (Holothuroidea) are major bioturbators of sediments in tropical reef environments (Uthicke, 1999). Sea cucumbers have been documented to ingest microplastics in feeding experiments (Graham & Thompson, 2009) and on reef islands just south of the present study area, close to Jakarta Bay (Sayogo et al., 2020). Grazing organisms common to reef systems like sea urchins (Tripneustes gratilla) and gastropods (Cyprea tigris) are also known to accumulate microplastic from the environment (Tahir et al., 2020). Filter-feeders such as the giant clam Tridacna maxima were shown experimentally to actively take up microplastics from seawater (Arossa et al., 2019). These examples demonstrate that the complete reef ecosystem is affected by microplastic pollution, but the health effect of microplastic ingestion by reef organisms is still under-studied (Sweet et al., 2019). However, several studies were dedicated to the impact of microplastic exposure on reef corals.

Scleractinian corals are known to ingest microplastics that they confuse with natural prey (Hall et al., 2015; Allen et al., 2017; Reichert et al., 2019) and microplastics adhere passively on the surface of reef corals (Ding et al., 2019; Martin et al., 2019). Only a relatively small fraction of the ingested microplastics are retained by the corals, which use similar rejection mechanisms for microplastics as for other sedimentary grains (Stafford-Smith & Ormond, 1992; Reichert et al., 2018). However, egestion of microplastics and other rejection mechanisms are thought to be energetically costly (Reichert et al., 2019). Most laboratory experiments show that exposure to microplastics has several negative impacts on coral health, such as bleaching, tissue necrosis, or impairment of the immune system (Reichert et al., 2018; Tang et al., 2018; Syakti et al., 2019). Plastic debris can also be the carrier of pathogens or chemical contaminants (Saliu et al., 2019; Feng et al., 2020), increasing the probability of coral disease by 4 to 89% (Lamb et al., 2018). No effect on calcification rates was observed for 28 days under laboratory conditions (Lancót et al., 2020), but a species-specific reduction of growth rates was shown for chronic exposure to microplastics over a period of six months (Reichert et al., 2019). However, most laboratory studies use a very high concentration of microplastics that may not be ecologically relevant (Lenz et al., 2016). Microplastic concentrations of <100 particles/kg observed for the current study area indicate that concentrations used in laboratory experiments likely are artificially high. Hence results from high exposure studies must be interpreted with caution and ideally should be compared to field studies.

Phthalic acid esters or phthalates, a common group of plastic additives, were found in the tissue of 95% coral samples from an atoll in the Maldivian archipelago (Saliu et al., 2019; Montano et al., 2020). This was the first indication that microplastics might transfer plastic additives into reef corals within their natural environment (Saliu et al., 2019; Montano et al., 2020). It is noteworthy that, in the present study, phthalates were detected on the surface of two microplastic particles, making the contaminants bioavailable to corals after ingestion. The widespread presence of microplastics in all facies zones and water depths is in line with the finding of Montano et al. (2020), who noticed no significant differences in phthalate concentrations in coral tissue from different water depths. In Kepulauan Seribu, parts of the reef are exposed subaerially during low tide. This would allow direct exposure to microplastics floating on the sea surface. Moreover, the data of this study show that appreciable amounts of microplastics are sinking to the seafloor in all facies zones, including the reef crest (Fig. 4). Here microplastic particles could adhere to the coral tissue or be resuspended, increasing the potential exposure time that corals are subjected to. The effect of long-time exposure of corals to
Microplastics is still poorly understood since most experiments used relatively short times of exposure. It is therefore highly recommended that future experimental studies should be ecologically relevant, especially with respect to microplastic concentrations and exposure time (Lartaud et al., 2020). Microplastics concentration at the reef crest of Panggang is even significantly higher compared to the beach. This could indicate that the risk to microplastics exposure for coral reefs is hitherto underestimated, since most sediment studies are limited to the beach environment (Imhof et al., 2017; Saliu et al., 2018). Globally coral reefs are suffering from anthropogenic stressors. Microplastics in the coral reef environment deserve careful consideration, since microplastics pose an additional threat to corals and their ability as framework builders in reef systems.

CONCLUSIONS

Microplastics are present as a sedimentary component in two reef platforms from the island chain of Kepulauan Seribu, about 30 km north of the Greater Jakarta Area. One of the reef platforms, Panggang, hosts a densely populated island. A small unpopulated island on the reef platform of Semak Daun is intensively used for unregulated tourist camping. The microplastic contamination in both reef systems is related to marine and local, coastal anthropogenic factors. The abundance of microplastics in sediment is controlled to some extent by the proximity to the source area of larger plastic debris.

Processes of microplastics transport and accumulation are thought to be comparable to fine siliciclastic grains in the reef system. Microplastics are partly winnowed from high-energy environments of the reef system and accumulate in low-energy environments, such as the lagoons. This emphasizes that hydrodynamic controls are important for microplastics distribution.

However, microplastic contamination was also found in high-energy environments, such as the beach, the sand apron and the reef crest. One of the mechanisms that allows buoyant microplastics to sink to the seafloor is density modification through biofouling. In the sand apron, bed armouring and interlocking effects could entrain and resuspended microplastics by shielding finer particles below coarse particles. This effect might be amplified by the shape of microplastic fibres. The entanglement of fibres with carbonate grains also contributes to an interlocking effect by which particles are tightly held by their neighbours. Furthermore, entanglement might create compound grains, consisting of mixed microplastic/carbonate particles with a density close to carbonate and a very irregular shape. These processes principally can operate in different sedimentary environments but might be promoted by the irregular shape and porous nature of bioclastic carbonate grains. A process, which is specific to reef environments, is the trapping of sedimentary grains and potentially microplastics by the mucus produced by corals.

Microplastics are not only present in the surface layer (0 to 3.5 cm), but also at a depth between 3.5 cm and 7.0 cm. Transport of microplastics to deeper sediment layers likely is controlled by bioturbation, which is pervasive on the reef platforms of Kepulauan Seribu. Microplastics below a depth of 3.5 cm are unlikely to be remobilized from subtidal sediments under modal weather conditions. Subtidal environments are therefore considered to be a permanent sink for microplastics in equatorial reef systems that are not affected by high energy events, such as tropical cyclones. For this reason, microplastics in subtidal reef environments from the equatorial zone can be a good practical indicator of Anthropocene strata. The influence of storm events on the accumulation of microplastics needs further investigation.

The reef crest in the study area is partially exposed subaerially during low tide, allowing direct contact to microplastics floating on the sea surface. Microplastics are also abundant in surface sediments of all reef environments, including the reef crest. Resuspension can lead to the repeated exposure to microplastic, which is energetically costly for corals. Phthalates, a common plastic additive, was detected on the surface of microplastic particles in the study area. This demonstrates that contaminants associated with microplastics could become bioavailable to corals after ingestion. Microplastics in coral reef environments therefore deserve careful consideration, since microplastics pose an additional threat to corals and their ability as framework builders in reef systems.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Tables S1 and S2.

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