

Possible sink of missing ocean plastic: Accumulation patterns in reef-building corals in the Gulf of Thailand

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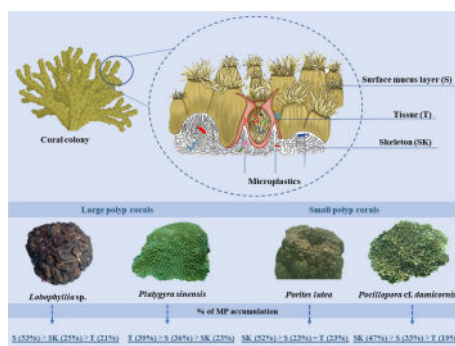
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HIGHLIGHTS

- Microplastic (MP) accumulation was analyzed in four coral species.
- MPs were present in all parts (mucus layer, tissue, and skeleton) of each species.
- *Pocillopora cf. damicornis* exhibited the highest MP accumulation.
- Large-polyp corals exhibited significant variation in polymer types across different parts.

GRAPHICAL ABSTRACT



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ABSTRACT

Individual coral polyps contain three distinct components—the surface mucus layer, tissue, and skeleton; each component may exhibit varying extent of microplastic (MP) accumulation and serve as a short- or long-term repository for these pollutants. However, the literature on MP accumulation in wild corals, particularly with respect to the different components, is limited. In this study, we investigated the adhesion and accumulation of MPs in four coral species, including both large (*Lobophyllia* sp. and *Platygyra sinensis*) and small (*Pocillopora* cf. *damicornis* and *Porites lutea*) polyp corals collected from Si Chang Island in the upper Gulf of Thailand. The results revealed that MP accumulation varied significantly among the four coral species and their components. Specifically, *P. cf. damicornis* exhibited the highest degree of accumulation (2.28 ± 0.34 particles g^{-1} w.w.) [Tukey's honestly significant difference (HSD) test, $p < 0.05$], particularly in their skeleton (52.63 %) and with a notable presence of high-density MPs (Fisher's extract test, $p < 0.05$). The most common MP morphotype was fragment, accounting for 75.29 % of the total MPs found in the coral. Notably, the majority of MPs were black, white, or blue, accounting for 36.20 %, 15.52 %, and 11.49 % of the samples, respectively. The predominant size range of MP particles was 101–200 μ m. Nylon, polyacetylene, and polyethylene terephthalate (PET) were the prevalent polymer types, accounting for 20.11 %, 14.37 %, and 9.77 % of the identified samples, respectively. In the large

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polyp corals, while MP shapes, colors, and sizes exhibited consistent patterns, remarkable differences were noted in the polymer types across the three components. The findings of this study improve the understanding of MP accumulation and its fate in coral reef ecosystems, underscoring the need for further investigation into MP-accumulation patterns in reef-building corals worldwide.

1. Introduction

The extensive utilization of plastics and insufficient waste management practices have resulted in the massive dispersion of plastics throughout the marine environment (Lebreton et al., 2017). The annual influx of plastics into the marine environment is estimated to be 4.8–12.7 million tons (Jambeck et al., 2015; Avio et al., 2017). Plastic debris can be classified into various size categories, ranging from macroplastics (≥ 1000 mm) to mesoplastics (≥ 25 mm) and microplastics (MPs; ≤ 5 mm) (GESAMP, 2019). Notably, the MPs derived from primary and secondary sources pose a major risk worldwide due to their widespread distribution, persistence, and potential impact on the environment and biota (Rochman et al., 2015; Alfaro-Núñez et al., 2021).

Coral reefs are ecosystems with profound biological and economic significance globally, serving as crucial habitats for diverse marine species and supporting the livelihoods of coastal communities (Moberg and Folke, 1999; Blackall et al., 2015; UNEP, 2018). Plastic pollution, particularly that related to MPs, poses a major risk to such ecologically sensitive habitats (Pantos, 2022). In general, corals interact with MPs through ingestion and egestion (Hankins et al., 2018; Reichert et al., 2018) via several potential pathways—1) adhesion on coral surface, wherein MPs may adhere to the coral surface layer through active ingestion and passive filtration; 2) accumulation in coral tissue, wherein MPs transported to the gastrovascular cavity may get stuck in the digestive system of the organism, causing irritation and abrasion and potentially leading to tissue overgrowth; 3) deposition in the skeleton, wherein MPs accumulated in coral tissue may be integrated into the skeleton of the organism during the calcification process (Hall et al., 2015; Reichert et al., 2022; Hierl et al., 2021). However, the evidence regarding the potential impact of MPs on corals remains controversial. While Rades et al. (2024) and Mouchi et al. (2019) reported no negative impact when corals were exposed to realistic concentrations of MPs over a long period, other studies demonstrated species-specific responses that could affect the mucus production, photosynthetic efficiency, and growth rates of corals (Allen et al., 2017; Reichert et al., 2019; Mendrik et al., 2021). These species-specific responses may induce major changes in coral community composition and the associated biodiversity within coral reef ecosystems (Reichert et al., 2019; Soares et al., 2020).

The estimated number of plastic particles in suspension within the global oceans is believed to exceed 170 trillion (Eriksen et al., 2023), with only 24 trillion particles (6.8 %) observed as plastics floating on the ocean surface (Law, 2017; Isobe et al., 2021). Controversies persist regarding the disposition of the residual quantity of floating MPs in the ocean, especially with respect to small-sized MPs (1–1000 μm) (Song et al., 2014; Gigault et al., 2018; Zhao et al., 2022). In this sense, biological processes significantly influence MP lifecycle, encompassing the movement, transformation, and fate of MPs through complex ecological and biogeochemical interactions (i.e., ingestion, egestion, and biofouling) (Kooi et al., 2017; Amjad et al., 2023); this approach may enhance the understanding of missing ocean MPs.

The accumulation of MPs in marine organisms can be temporary and/or permanent, depending on several factors, such as the physiology, feeding behavior, and mechanisms of foreign-body removal (Law, 2017; Reichert et al., 2022). For example, fish can eliminate ingested materials, including MPs, after feeding through various physiological processes (regurgitation and egestion with fecal materials) (Roch et al., 2020; Solomando et al., 2020). In this context, fish may be regarded as a transient reservoir (short cycle) of MPs as it temporarily removes MPs from the environment and subsequently releases them (Setälä et al.,

2014; Roch et al., 2020). Allen et al. (2017) documented that corals exhibit a nearly ten-fold ingestion frequency for MP particles compared to that for suspended sediments. Given their distinctive feeding behaviors and growth patterns, corals can interact with MP particles in two ways—temporarily (through adhesion to the surface mucus layer) and permanently (through accumulation within the skeletal structures) (Martin et al., 2019; Corona et al., 2020; Reichert et al., 2022).

Notably, MPs can accumulate within various coral parts, such as the mucus layer, tissue, and skeleton; however, the literature does not present an effective method for the complete extraction of MPs from each of these components. Ding et al. (2019) employed density-separation techniques to isolate MPs and quantify their abundance across an entire tissue section (mucus layer + tissue). However, this method does not allow for the quantification of MPs adhered temporarily to the mucus layer. Furthermore, previous studies utilized high-concentration acids for MP extraction from coral skeletons, potentially resulting in MP-particle damage, thereby skewing the estimation of MP quantities in coral samples by either underestimating or overestimating their presence (Enders et al., 2017; Ding et al., 2019; Lim et al., 2022; Adedapo et al., 2024).

Despite the focus on MP pollution in reef-building corals, little is known about the capacity of corals for the temporary or permanent uptake of MPs from reef ecosystems, especially within the context of Southeast Asian countries, which are among the top 10 marine-plastic polluters worldwide. In this study, we investigated the adhesion and accumulation of MPs in four coral species that are native to Si Chang Island in the upper Gulf of Thailand. The corals analyzed included large polyp corals—*Lobophyllia* sp. and *Platygyra sinensis* (>9300 and 3500 – 6500 μm ; Levy et al., 2006)—and small polyp corals—*Pocillopora* cf. *damicornis* and *Porites lutea* (~ 1000 μm ; Christiansen et al., 2009; Pacherres et al., 2013). Notably, these coral species are widely distributed across coral reefs worldwide. Owing to their ecological importance and diverse physiological and feeding behaviors, they are valuable for studying the interactions between corals and MPs. In addition, we refined the methodology for MP extraction, enabling investigations across distinct coral parts (surface mucus layer, tissue, and skeleton). The outcomes of this study provide crucial information regarding the interactions between corals and MPs while highlighting their capacity to sequester MP particles from the surrounding environment.

2. Materials and methods

2.1. Study area

For this study, we selected a site on the Tham Phung coast, Si Chang Island, in the eastern part of the upper Gulf of Thailand ($13^{\circ}08.545' \text{N}$, $100^{\circ}45.590' \text{E}$) (Fig. 1). Si Chang, a small island well known as a prominent tourist attraction, is situated within a region of economic significance in Thailand. In addition, this area is considered a pivotal industrial center and is strategically positioned in proximity to the Eastern Seaboard industrial estates [the Eastern Economic Corridor (EEC)]. Several anthropological activities, including recreational activities and land pollution, affect the water quality and marine species diversity in this region. The Tham Phung coast is located to the west of the island and has more open-water circulation than the east side. This area contains multiple small reef flats bounded by a narrow fringing reef, with a predominant distribution in shallow waters.

2.2. Coral sample collection

Coral samples were collected during the wet season (August 22 and 29, 2022). The following four coral genera were considered in this study: *Lobophyllia* sp. and *Platygyra sinensis* (large polyps) and *Pocillopora* cf. *damicornis* and *Porites lutea* (small polyps). These corals are generally found in shallow reefs (at depths of 5–8 m). Each colony was photographed for subsequent analysis. Coral fragments ranging from 2.5 to 5 cm in size were carefully obtained from the colonies using a diving knife for cutting branching-form corals and a hammer and chisel for extracting mound-form corals. The project and sample collections were conducted under the permit of the Plant Genetic Conservation Project, under the Royal Initiative of Her Royal Highness Princess Maha Chakri Sirindhorn, and the Royal Thai Navy. In total, 27 coral samples were collected, including 6 samples of *Lobophyllia* sp., 7 of *P. sinensis*, *P. cf. damicornis*, and *P. lutea*. All samples were collected at the same depth (approximately 6 m) under conditions of strong current exposure. The samples were wrapped individually in an aluminum foil after being collected, placed in an ice-box container, and then transported to the laboratory; the samples were stored at $-20\text{ }^{\circ}\text{C}$ until analysis. Biological measurements, including determination of wet weight and number of coral polyps, were conducted. A fragment of each coral specimen was photographed using an Olympus Tough TG-6 camera (Olympus Corporation, Japan) prior to MP isolation and pre-treatment.

2.3. Sample processing

To extract MPs from the coral, each coral fragment was placed in a 100–250-mL glass beaker (depending on the fragment size). We employed an extraction process tailored to the potential presence of MPs in each coral component, including the surface mucus layer, inner layer

tissue, and skeleton (Fig. 2).

2.3.1. Surface mucus layer

A saturated NaI solution (1.83 g cm^{-3}) was prepared by mixing 100 mL Milli-Q water and 184 g NaI in a beaker; the solution was filtered before use (see Section 2.5). Each sample was immersed in a beaker containing the saturated NaI solution, covered with an aluminum foil, and then ultrasonicated for 5 min at room temperature (to detach the MPs). The coral fragments were then gently rinsed with Milli-Q water, and the rinsed water was collected in the same beaker containing the solution. The NaI solution containing the MPs and other organic residues was added to 1–2 mL of 30 % H_2O_2 and left overnight for digestion. The remaining coral fragments were transferred to a new clean beaker to extract the inner tissue layer with MP contamination.

2.3.2. Inner tissue layer

The tissue of the coral fragment was dissolved by submerging the fragment in a 10 % KOH solution at $50\text{ }^{\circ}\text{C}$ for 24 h for *P. cf. damicornis* and *P. lutea* and 48 h for *Lobophyllia* sp. and *P. sinensis* in an incubator. After digestion, the coral skeleton was rinsed carefully with Milli-Q water until it was thoroughly cleaned. The remaining coral skeleton was transferred to a new clean beaker for MP extraction.

2.3.3. Skeleton

The skeletons were dissolved by submerging the sample in a 15 % HCl solution at room temperature; *P. cf. damicornis* required approximately 10–15 min, *P. sinensis* required 20–30 min, and *P. lutea* and *Lobophyllia* sp. required 30–60 min for complete dissolution.

After MP extraction, each solution (NaI + H_2O_2 , 10 % KOH, and 15 % HCl) containing the potential MP particles was vacuum-filtered through a polytetrafluoroethylene (PTFE) filter paper (diameter = 47 mm, pore

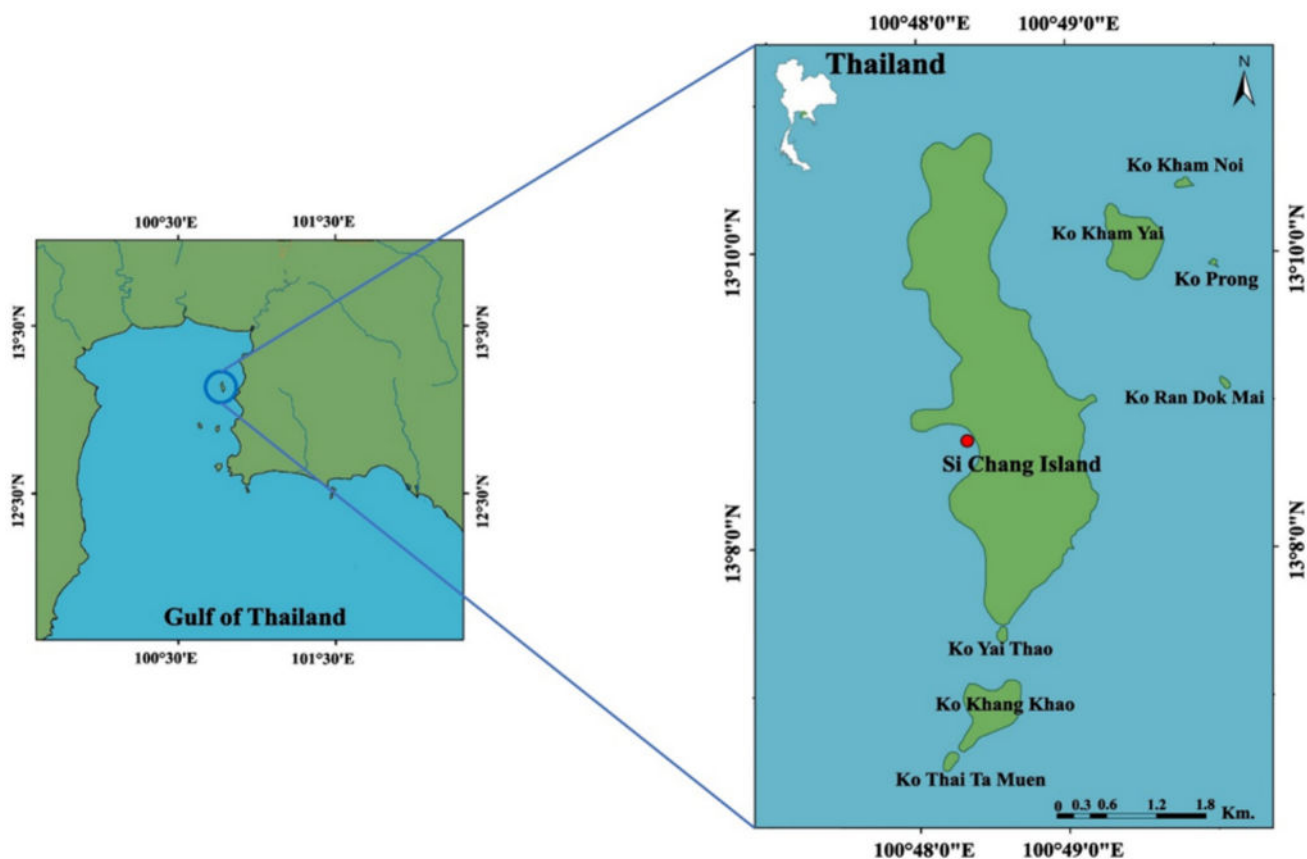


Fig. 1. Location map of the study site in the Tham Phung coastal region on Si Chang Island in the upper Gulf of Thailand. The red point indicates the sampling location.

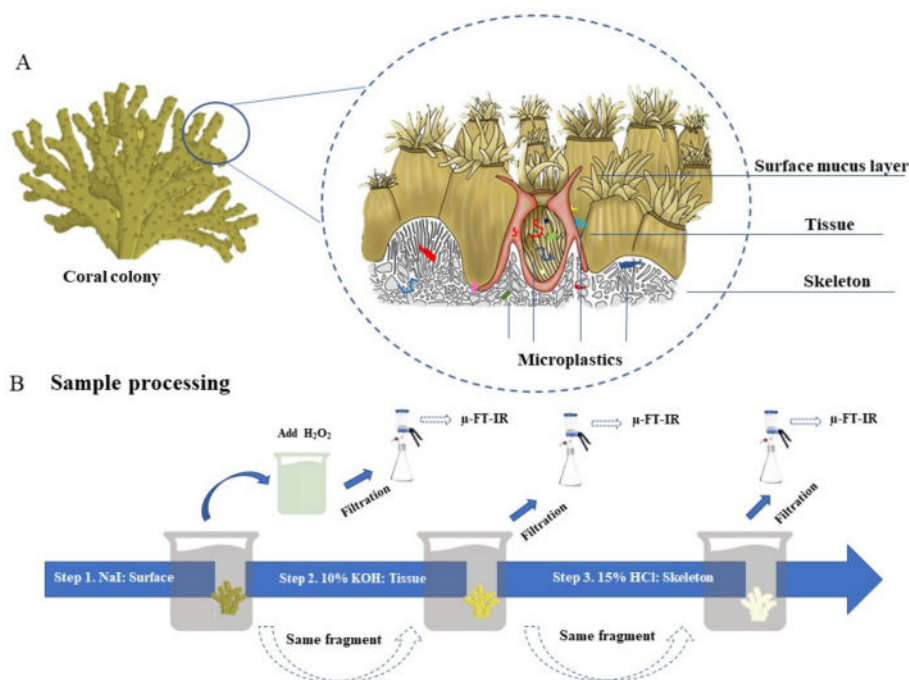


Fig. 2. (A) Schematic diagram depicting the potential incorporation of microplastics (MPs) in corals and (B) MP sample process employed for the mucus layer, tissue, and skeleton of the coral samples.

size = 5 μm ; Omnipore TM membrane) in a glass filtration unit equipped with a vacuum pump to obtain the MPs attached to the surface mucus layer, tissue, and skeleton. The PTFE filters were carefully transferred to 60-mm glass Petri dishes and stored at room temperature for further analysis.

2.4. MP sorting and polymer analysis using Fourier transform infrared (FT-IR) spectroscopy

We thoroughly examined the suspected MP particles across the entire surface area of the filter paper using a stereomicroscope (Olympus BX51, Japan). Upon identifying a suspected particle, we marked its location and recorded the count. Each suspected particle was measured and photographed using the stereomicroscope at 10–40 \times magnification; additionally, we used an image analysis system USB camera (Shodensha DN3V-500, Japan) and the Measure Pro light software. The particles were classified by type based on their shape (e.g., fibers, fragments, and films). In addition, the lengths of all the particles (in the longest dimension, Feret diameter) were measured. All suspected MPs were picked with fine tweezers and placed on a clean PTFE filter paper, held on a custom-made circular stainless steel support, for imaging, measurement, and Fourier transform infrared (FT-IR) analysis. The PTFE paper with the suspected MP particles was gently transferred to the FT-IR system (Shimadzu AIM-9000 Automated Infrared Microscope, Japan) for polymer-type identification. Each particle was identified using micro-FT-IR ($\mu\text{FT-IR}$) in the transmission mode. The $\mu\text{FT-IR}$ spectrum was scanned (32 scans/sample) within the range of 1300–4000 cm^{-1} at a resolution of 4 cm^{-1} . The obtained spectra were compared with those in a database from the Shimadzu libraries to verify the polymer type (Table S1). The plastic polymer spectra that depicted a match of $\geq 70\%$ with the reference spectra were accepted and classified as MP polymers.

2.5. Quality assurance and control

To eliminate potential contamination, specialized lab coats and latex gloves were worn during the processing and analytical procedures. The glassware, tools, and filtration units were washed using an ultrasonic

cleaner at room temperature for 3 min and rinsed thoroughly using 0.2- μm filtered Milli-Q water. The glassware was dried and sealed with an aluminum foil before use. Plastic containers and materials were avoided wherever possible. Before use, all the chemicals/reagents used in the experiments were filtered through a GF/C (diameter 47 mm; pore size 1.2 μm) glass microfibre filter (Whatman, UK). The work surfaces were cleaned with ethanol before sample preparation. All processes, including sample preparation and filtration, were performed in a clean bench laminar flow unit (Haier HBC-1300v, Haier, China) to reduce airborne contamination. A procedural blank was prepared using the same chemical reagents (NaI + H_2O_2 , 10% KOH, and 15% HCl), and the same procedural steps were followed for each coral sample. The blanks ($n = 9$) and filtered samples on filter papers were placed in 60-mm Petri dishes for visual inspection. The contamination blanks were counted and reported after MP identification (three particles). Additionally, positive controls were prepared in triplicate using 100 fluorescent orange polystyrene microspheres of 45–53 μm (Cospheric, Lot Ref#:051123, LLC, USA).

2.6. Statistical analysis

The abundance of MPs in each coral species was quantified as particles per gram (particles g^{-1}) of the wet weight (w.w.), which was reported as mean \pm standard error. The normality of data was confirmed using the Shapiro–Wilk test. The differences in MP abundance among the four coral genera and the differences in MP sizes across the three parts in each sample genera were analyzed using a one-way analysis of variance (ANOVA). For the significant results ($p < 0.05$), post-hoc comparisons were conducted using the Kruskal–Wallis or Tukey's honestly significant difference (HSD) tests to identify specific differences between the groups. Additionally, Fisher's Exact tests were employed to compare particle shapes, colors, and polymer types and the densities of all MPs (low-density MPs: $< 1 \text{ g cm}^{-3}$, high-density MPs: $> 1.12 \text{ g cm}^{-3}$) across the three components. All statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) 16.0 for Windows and R software (version 3.6.3; R Core Team, 2020).

3. Results

3.1. Quality assurance and quality control

Despite the implementation of numerous measures employed in this study to mitigate blank contamination, complete contaminant elimination could not be achieved. In this study, MP contamination in the blanks ranged from 0 to 3 particles per sample. A total of 2 particles were collected from the step involving the use of NaI and H₂O₂ solutions and 1 particle from the step involving the use of a 15 % HCl solution. Notably, no MP contamination was detected in the step involving the use of a 10 % KOH solution. The morphology of the particles in the blanks comprised a black fiber, a transparent film, and green fragments with an average size of $151.66 \pm 58.07 \mu\text{m}$. Chemical identification of the particles in the blanks revealed the presence of polyester (PES), polypropylene (PP), and very low-density polyethylene (VLDPE). As transparent PP film and green VLDPE fragments were not detected in any sample, we proceeded to deduct one black PES fiber from the samples in which these polymer types were present. For the positive control, the average recovery rate for pellets from the procedures involving NaI + H₂O₂, 10 % KOH, and 15 % HCl solutions were 70.91 %, 79.91 %, and 72.69 %, respectively (Table S2).

3.2. Abundance of MPs in the coral samples

In this study, MPs were detected in all the 27 coral samples. In total, 395 particles suspected to be MPs were sorted from the 27 coral fragments. Following $\mu\text{FT-IR}$ correction, we concluded that 174 plastic particles, or 44.05 % of the total number of suspected MPs, were extracted from the reef-building corals. The number of particles was higher in small-polyp corals, with *P. cf. damicornis* and *P. lutea* comprising 2.28 ± 0.12 and 1.58 ± 0.25 particles g^{-1} w.w., respectively. The large-polyp corals *Lobophyllia* sp. and *P. sinensis* displayed less number of particles, at 0.70 ± 0.12 and 1.12 ± 0.25 particles g^{-1} w.w., respectively (Table S3).

3.3. Abundance of MPs in the surface mucus layer, tissue, and skeleton of the sampled corals

We quantified MPs across various components of the structures, including the surface mucus layers, tissues, and skeletons, of the four reef-building coral species. Overall, the proportions of MPs that adhered to the surface mucus layer and deposited on the coral skeleton were comparable, accounting for 37 % and 38 % of the total number of MPs, respectively; the MPs that were accumulated in the tissue accounted for 25 % of the total number of MPs (Fig. 3A). However, the degree of MP

accumulation varied among the coral species and components. In *Lobophyllia* sp., 53.19 % of the total MPs were found in the surface mucus layer. In *P. sinensis*, 39.47 % of the total MPs were located in the tissue. In *P. cf. damicornis* and *P. lutea*, 52.63 % and 47.06 % of the total MPs were detected in the skeleton, respectively (Fig. 3B). Notably, only *P. cf. damicornis* exhibited a significant difference in MP accumulation, with the highest proportion being noted in the skeleton (Tukey's HSD test, $p < 0.05$).

3.4. Characteristics of MPs accumulated in the coral samples

The general characteristics of the MPs identified in this study are shown in Figs. 4 and S1. All the four coral species exhibited similar distributions with respect to color and shape (ANOVA, $p > 0.05$). Fragment morphotypes were the most abundant MPs across all the species, accounting for 75.29 % of the total number of MPs detected in the samples, followed by fibers (24.14 %). The film morphotypes were rare, accounting for only 0.57 % the total number of MPs detected in the samples (Fig. 5A). Notably, only one film was identified in *P. lutea* (Fig. 5A). With respect to the color, black MPs were the most abundant (36.20 %), followed by white (15.52 %), blue (11.49 %), greenish-brown (9.19 %), red (4.60 %), and other colored (22.99 %) MPs (Fig. 5B). The most common size range of MP particles was 101–200 μm (Fig. 5C). However, the mean size of MPs in *P. lutea* was approximately 418.1 μm larger than that of the MPs observed in other corals. In total, 21 polymer types of MPs were identified (shown in Table S4), with nylon, polyacetylene, polyethylene terephthalate (PET) and polyurethane (PU) being the most common types in all the coral species, accounting for 20.11 %, 14.37 %, 9.77 %, and 8.62 % of the total number of MPs, respectively (Fig. 5D). We noted a clear predominance of high-density polymers in all the coral samples (61 %) (Fig. 6A), specifically in *P. cf. damicornis* (Tukey's HSD test, $p < 0.05$) (Fig. 6B).

3.5. Characteristics of MPs detected in the surface mucus layer, tissue, and skeleton of the coral samples

The general characteristics of the MPs identified in each coral component are shown in Figs. 7 and S2. All four coral species exhibited similar patterns with respect to the shape and color of MPs detected in individual coral components, with no significant differences (Fisher's Exact, $p > 0.05$). The fragment-type particles were the most common type of MPs across all the coral parts; film-type MPs were detected only on the surface mucus layer of *P. lutea* (Fig. 7A). Black, white, and blue were the most prevalent colors across almost all coral species and components (Fig. 7B). With respect to particle size, the size of MPs primarily ranged between 101 and 200 μm in individual coral

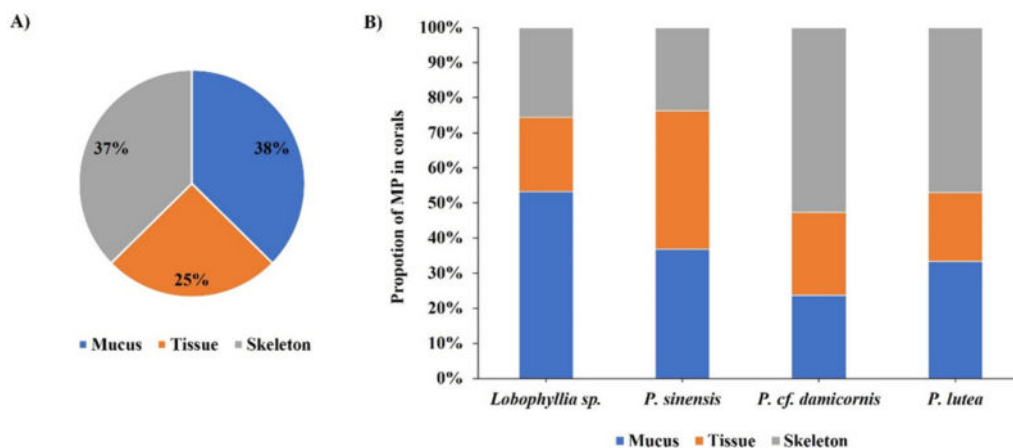


Fig. 3. Proportion of microplastics (MPs) obtained from the mucus, tissue, and skeleton parts for A) all the four coral species and B) each individually species.

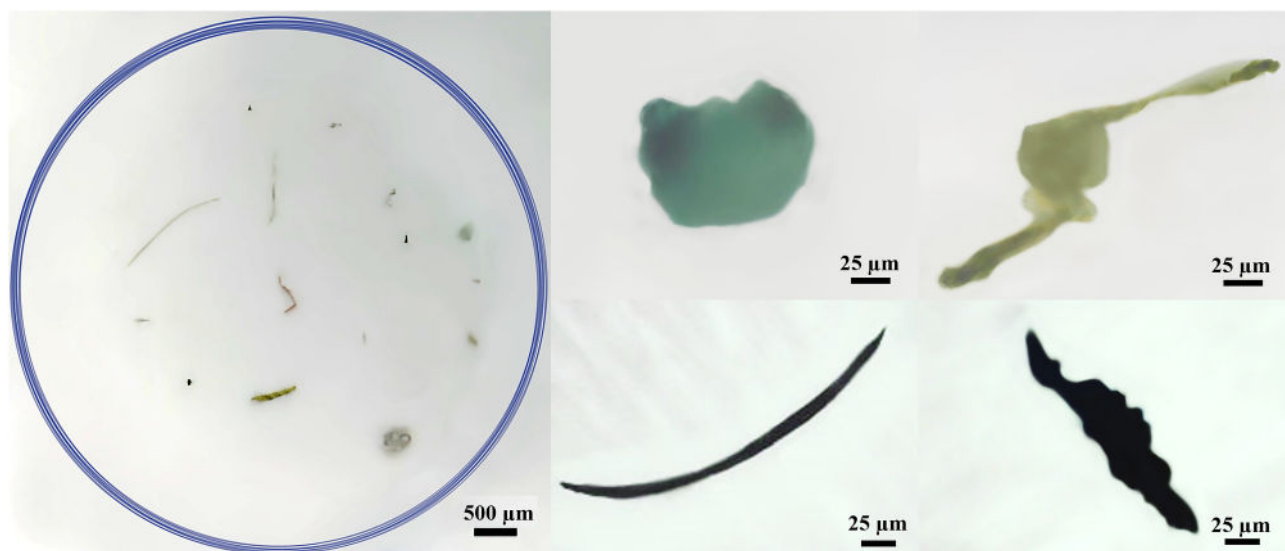


Fig. 4. Characteristics of the microplastics (MPs) identified in the coral samples.

components in all species. *Lobophyllia* sp. exhibited variation in MP sizes across its components, with larger particles found in the skeleton compared to the surface mucus layer (Fig. 7C). However, no significant differences in MP size distribution were observed among the three components across all coral species. Notably, the majority of MP particles that exceeded the average size of polyps were detected in the skeleton of *P. lutea* (Fig. S3), although without statistical significance.

The primary polymer types detected in the surface mucus layer and tissue were predominantly nylon, accounting for 27.69 % and 18.18 % of the total number of MPs, respectively. In the skeleton, nylon and polyethylene (PE) were the most abundant types of MPs, each accounting for 13.84 % of the total number of MPs. The skeleton component exhibited the highest diversity in polymer types, depicting 18 different types, followed by the tissue component (15 types) and surface mucus layer (11 types). Furthermore, the composition of polymer types significantly varied across different components within the large-polyp corals (Fisher's Exact, $p < 0.05$). For instance, in *Lobophyllia* sp. and *P. sinensis*, a high proportion of nylon was found in the surface mucus layer, whereas the skeleton component contained the lowest proportion. Polypropylene (PP) was not detected in the surface mucus layer of *Lobophyllia* sp.; however, it was detected in the skeleton. In *P. sinensis*, PP was only detected in the tissue (Fig. 7D). Notably, *Lobophyllia* sp. and *P. sinensis* did not show any significant differences in the polymer density across the three components; however, *P. cf. damicornis* and *P. lutea* exhibited distinct patterns of polymer density accumulation. Specifically, *P. cf. damicornis* samples exhibited a significantly high abundance of high-density MPs in their skeletons, whereas *P. lutea* samples exhibited an abundance of low-density MPs in their skeletons (Fisher's Exact, $p < 0.05$) (Fig. S4).

4. Discussion

4.1. Presence of MPs in reef-building corals and the factors influencing MP accumulation

We analyzed the accumulation of MPs in reef-building corals in the upper Gulf of Thailand. This study serves as a compelling and reinforcing evidence for highlighting the issue of MP contamination in marine ecosystems, particularly within coral reefs. The accumulation of MP particles within corals can occur through active ingestion and passive adhesion (Corona et al., 2020). However, diverse coral species and different geographical locations may exhibit distinct responses to this form of pollution (Chapron et al., 2018; Mouchi et al., 2019). Small-

polyp corals exhibited the highest MP abundance, with the number of MPs detected within corals at this location increasing approximately 4.8-fold (2.28 ± 0.34 particles g^{-1} w.w.) and 2.8-fold (1.58 ± 0.25 particles g^{-1} w.w.) compared to the levels observed in the *Pocillopora* and *Porites* corals in the South China Sea (0.48 and 0.55 particles g^{-1} w.w.), respectively (Ding et al., 2019). Conversely, the MPs in these two coral genera were comparable to those observed in the sea around the Maldives (Raguso et al., 2022); however, comparative studies on large-polyp corals (*Lobophyllia* and *Platygyra*) are lacking (Table 1). Notably, the lack of standardized procedures hinders the comparison of findings across different studies on MPs within the context of corals. Thus, establishing harmonized guidelines based on global insights is crucial for promoting studies on MP accumulation in coral reefs. Currently, there is no universally accepted protocol for assessing MP accumulation in corals, and variations in measurement units (particle count per gram, polyp, or surface area) further complicate such comparisons. While using the coral surface area as a unit facilitates global comparisons with other monitoring parameters (e.g., coral coverage, and growth rate), these conventional methods are destructive and do not allow the collection of MPs from each coral component. Thus, developing advanced techniques for measuring the surface areas of corals while facilitating MP extraction from each component is necessary for conducting detailed studies.

In general, the quantity of MPs accumulated in corals can be influenced by several ambient factors, including local MP concentrations, regional geography, and ocean currents (Hankins et al., 2018; Borges-Ramírez et al., 2020; Mendrik et al., 2021; Tang et al., 2021). With respect to the substantial contribution of Southeast Asian countries to ocean plastic pollution, our study revealed considerable accumulation of MPs in coral samples. Furthermore, our results are consistent with the observations of Nakano et al. (2024), who revealed a significant increase in MP abundance (21.78 particles m^{-3}) in seawater samples obtained from Si Chang Island, with reference to the average MP abundance noted in all coral species (1.42 particles g^{-1}). The interplay of precipitation, wind patterns, and ocean currents considerably influences MP abundance in corals by increasing the exposure of corals to elevated MP concentrations (Cheung and Not, 2023; Nakano et al., 2024). Additionally, since the reef site was situated near a large rock formation, it experienced strong water movements due to constant wave action. Such hydrodynamic regimes generally increase the water flow rate over the reef, potentially enhancing the interactions between corals and MP particles (Reichert et al., 2024).

In the present study, small-polyp corals (*P. cf. damicornis* and *P. lutea*)

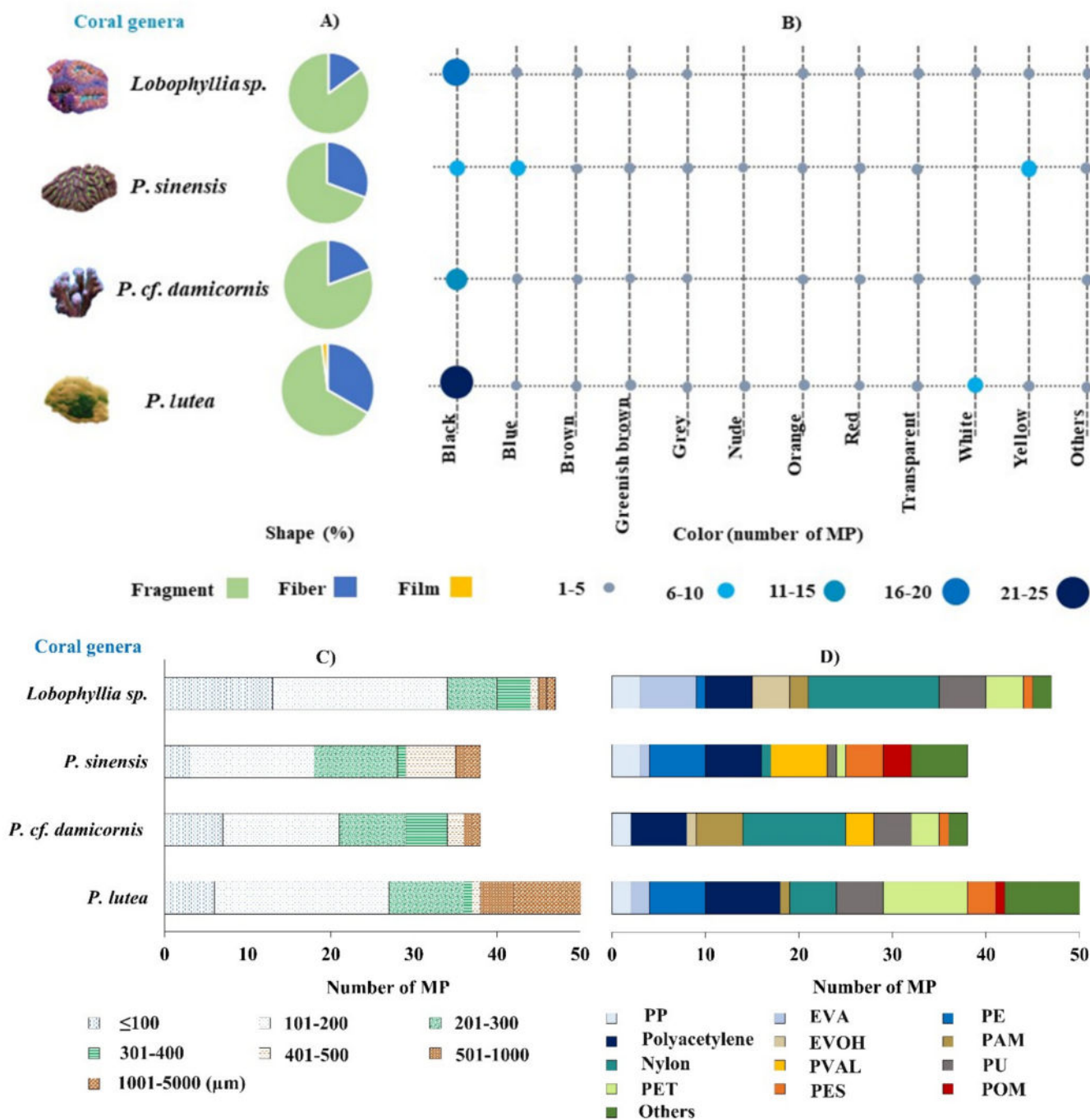


Fig. 5. Composition profiles of microplastics (MPs) in the four coral species with respect to (A) shape, (B) color, (C) size (μm), and (D) polymer type. Abbreviations: PP (polypropylene), EVA (ethylene-vinyl acetate), PE (polyethylene), EVOH (ethylene vinyl alcohol), PAM (polyacrylamide), PVAL (polyvinyl alcohol), PU (polyurethane), PET (polyethylene terephthalate), PES (polyester), POM (polyoxymethylene).

demonstrated a higher degree of MP accumulation (particles g^{-1}) than the large-polyp corals. This discrepancy may be attributed to the differences in the physiological and environmental adaptability among the four coral species as well as the different ambient factors (Mouchi et al., 2019; Reichert et al., 2019). The accumulation of MPs in corals is influenced by the particle-rejection ability of the corals, including the processes used by the organisms to remove foreign particles and self-clean (Allen et al., 2017). Small-polyp corals, such as *Acropora* and *Pocillopora*, are reportedly more effective at sediment removal than massive corals (Duckworth et al., 2017; Reichert et al., 2018). However, the difference in the physical and chemical properties of natural particles and MPs may elicit varying responses from different corals. In some

cases, corals prefer to ingest MPs instead of natural prey, possibly due to the release of phagostimulants by MPs and/or biotic factors (i.e., biofilms) that may mimic preys (Allen et al., 2017; Rotjan et al., 2019; Reichert et al., 2024). After conducting a feeding experiment, Reichert et al. (2024) revealed that *Pocillopora* spp. had the highest number of MP particles on coral colonies, suggesting the occurrence of species-specific responses to such stressors. Additionally, small branching corals, with their numerous inclined and angular surfaces, tend to accumulate more particles than the other coral forms (Duckworth et al., 2017; Reichert et al., 2018). This may be the reason for the higher MP accumulation rate in *Pocillopora* observed in this study.

Although massive corals are characterized by a smaller surface area,

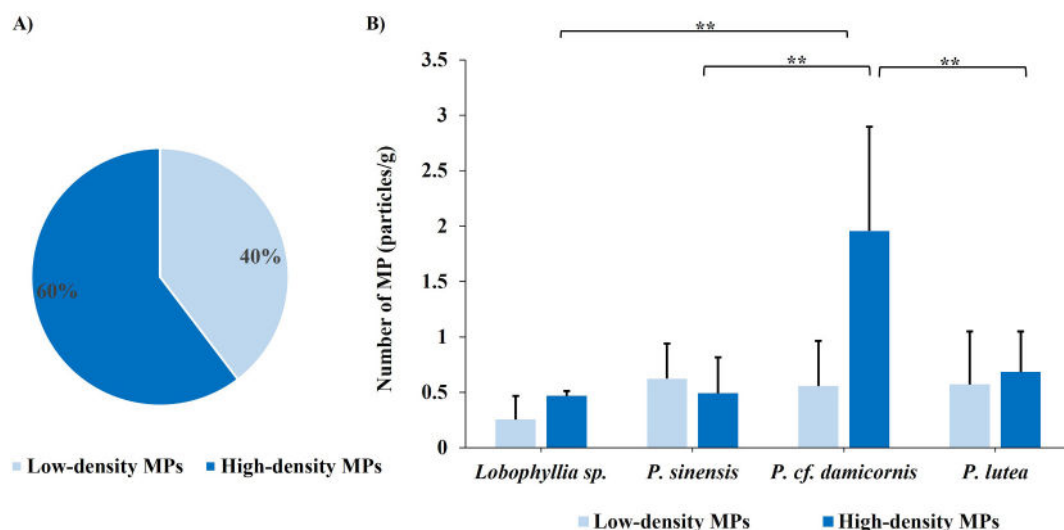


Fig. 6. Proportion of low- and high-density microplastics (MPs) with respect to (A) all the coral species and (B) individual species.

which may result in the accumulation of fewer food and MP particles, *P. lutea* demonstrated a high capacity for mucus production (Mahmoud and Kalendar, 2016; Bessell-Browne et al., 2017). While mucus production is considered a self-cleaning mechanism, it is also an efficient method for trapping MPs from the surrounding environment, potentially enhancing the accumulation of MPs within coral colonies (Bessell-Browne et al., 2017), along with suspended sediments (Coffroth, 1990). Although larger-polyp corals, such as *Galaxea*, demonstrate significantly higher tolerance to MPs than small-polyp corals (Tang et al., 2021), this tolerance may not necessarily correspond to increased MP accumulation. Overall, small-polyp corals may manifest increased susceptibility to deleterious effects if the retention of MP impedes their ability to access vital food resources (Hankins et al., 2018). This study suggests that *Pocillopora* and *Porites* present valuable avenues for examining the repercussions of MP pollution owing to their widespread distribution (Aronson, 2001) and sensitivity to the impacts of anthropogenic stressors (Bergman et al., 2021).

4.2. Characteristics of MPs detected in the coral samples

The contamination of synthetic fibers in marine ecosystems has been extensively documented (Cesa et al., 2017; Suaria et al., 2020). However, our study revealed a notable prevalence of MP fragments among all the examined coral specimens (Fig. 5A), contrasting with the results of previous studies that analyzed coral samples obtained from the Maldives and the South China Sea, wherein the prevalent MPs identified were films and fibers (Ding et al., 2019; Lim et al., 2022; Raguso et al., 2022). Note that the identification of MP fragments suggests secondary sources, possibly the breakdown of larger plastic items discarded in the environment. The predominance of fragments is generally consistent with MPs sampled by surface net towing conducted in the uppermost layer of seawater (Nakano et al., 2024; Fig. 5A). Additionally, in previous studies, small fragments were detected in zooplankton sampled by surface net towing (Alfonso et al., 2024). The meticulous survey and analysis protocol adopted in this study could be considered essential for uncovering the MP contamination in marine ecosystems. However, the primary morphology of MPs may exhibit temporal fluctuations in the marine environment due to seasonal variations (Li et al., 2023); this factor must be considered in future studies.

In this study, black was the predominant MP color (Fig. 5B); however, the reason for the color predominance was not conclusive. The MPs sampled through surface net towing in the same area predominantly consisted of non-pigmented particles (white and blue in color), while black fragments accounted for <10 % of the total number of MPs

detected in the samples (Nakano et al., 2024; Fig. 5B). Although the average detection rate of black particles tends to be lower than that for other colors (Huang and Xu, 2022), previous studies reported the prevalence of black particles in benthic organisms such as crabs and shrimp (Gurjar et al., 2021; Zhang et al., 2021). However, in general, blue fibers predominate in several studies on marine environments; they could be derived from fishing nets and ropes (Wright et al., 2021; Barboza et al., 2023). The color may influence the likelihood of ingestion or be mistaken as prey, particularly if the color resembles that of the sought-after prey species commonly consumed by fishes and crustaceans (Ory et al., 2017; Horie et al., 2024). However, corals cannot selectively take up black particles from various colored suspended particles in the ambient seawater. Therefore, their predominance may be explained by other factors such as polymer density and plastic sources. In fact, most black MPs are high-density polymers (65.40 %), which may explain their predominance at the marine bottom compared to that on the water surface (Nakano et al., 2024).

The predominant size range of MPs ingested by the coral samples considered in this study was 101–200 μm (Fig. 5C), consistent with the findings of Raguso et al. (2022). However, this observation contrasts with the results of several previous studies that reported the ingestion of large-sized MPs by corals (Lei et al., 2021; Zhou et al., 2022). The larger sizes reported in these studies often corresponded to fibers, which typically have large average lengths and dimensions (Lim et al., 2022; Liu et al., 2022). Additionally, the $\mu\text{FT-IR}$ detection technique used in this study facilitated the examination of smaller MP particles. However, while larger microfibers could be readily observed, smaller fragments may have been overlooked due to observer bias (Lusher et al., 2020). The environmental context of our study site may have influenced the observed size distribution of ingested MPs. Alfonso et al. (2024) and Nakano et al. (2024) identified a dominance of MP fragments in the seawater and zooplankton that surrounded the sampled corals. This environmental profile may explain the dominance of smaller fragment-shaped MPs in the coral samples, as these particles were more readily available for ingestion through both active and passive feeding mechanisms. Despite the general expectation that corals predominantly ingest particles smaller than their polyp size (i.e., calyx) (Hankins et al., 2022), our study revealed larger MP fibers in *P. lutea*. The ingestion of larger fibers may be due to the inherent flexibility of the MPs. Unlike rigid particles, MP fibers can bend and deform, facilitating ingestion by corals, even when the fibers exceed the diameter of the polyp. This flexibility may increase the likelihood of ingestion, as suggested by previous studies (Desforges et al., 2015; Hankins et al., 2018).

The presence of nylon and PET polymers suggested a source from

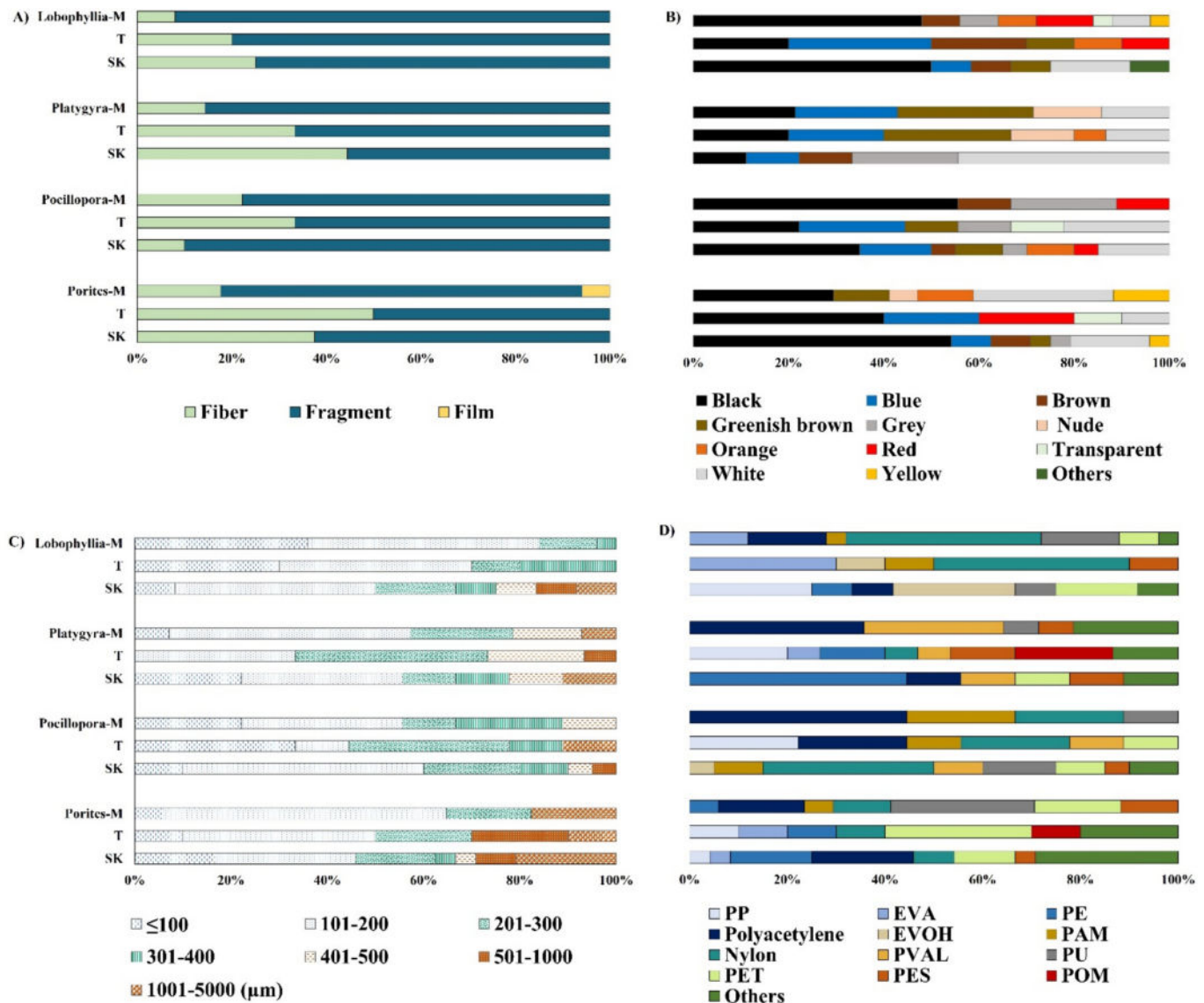


Fig. 7. Composition profiles of microplastics (MPs) in the four coral species considered in this study with respect to each component: (A) shape, (B) color, (C) size (μm), and (D) polymer type. Abbreviations: PP (polypropylene), EVA (ethylene-vinyl acetate), PE (polyethylene), EVOH (ethylene vinyl alcohol), PAM (polyacrylamide), PVAL (polyvinyl alcohol), PU (polyurethane), PET (polyethylene terephthalate), PES (polyester), POM (polyoxymethylene). M = Surface mucous layer, T = Tissue, and SK=Skeleton.

polymer ropes of fishing gear, potentially fragmented to form MPs that were released into the benthic environment in shallow waters (Welden and Cowie, 2017; Syversen et al., 2022). In fact, visual surveys of our study site revealed several abandoned fishing gears that covered the coral colonies along a 100-m line transect (Fig. S5). Considering the loss of fishing gear estimated worldwide by the Food and Agriculture Organization (FAO, 2018) and the studies that monitored the degradation of commonly used polymer ropes, we conclude that the release of MP particles into benthic environments from fishing gear could be substantial (Syversen et al., 2022). In addition to ocean-based plastics from fishing gear, land-based heavy plastics, such as ethylene vinyl alcohol (EVOH) (1.1–1.2 g cm⁻³), used for food packaging, and polyacetylene (1.2 g cm⁻³), used in electronic devices such as battery of cell phones, were detected in the corals. The findings related to land-based heavy plastics suggest a possible pathway from coasts to coastal waters along the seafloor, although an in-depth examination is needed to uncover whether this bedload transport of heavy MPs is important for a variety of MPs (Morales-Caselles et al., 2021).

One of the findings of our study was the predominance of MPs with

densities higher than the density of seawater (Fig. 6). As corals reside on the seafloor, they tend to engage with high-density polymers that sink to the seafloor. In this study, the sum of PE and PP MPs with densities lighter than seawater accounted for over 70 % of the MPs detected in the uppermost layer of the seawater (Nakano et al., 2024) and in zooplanktons (Alfonso et al., 2024). However, our findings also revealed fragmented MPs with densities lower than the density of seawater, suggesting that low-density MPs may also infiltrate benthic environments through settling processes after undergoing biofouling and/or integration into organic matter (Cole et al., 2016) to be subsequently ingested by benthic organisms. The less buoyant polymers predominant in the corals suggested MP pathways other than the pathway from the surface layer and zooplankton to benthic corals. The predominance of MP fragments lighter than seawater (PP and PE) in the uppermost layer of the sea (Nakano et al., 2024) and zooplankton (Alfonso et al., 2024) also reinforced the probability of the abovementioned pathway (in the vertical direction). However, these PP and PE particles accounted for 10 % or less of the total MPs detected in the samples; therefore, the vertical pathway via biological processes was likely to be non-dominant in the

Table 1
Summary of microplastic studies in wild reef-building corals around the world.

Country and name of coral reef	Coral genus	Number of MP	Extraction method	FT-IR technique	Shape	Size (μm)	Polymer type	Reference
Maldives, Magoodhoo island	<i>Pocillopora</i>	$2.8 \pm 0.9^*$	30 % $\text{H}_2\text{O}_2 \rightarrow \text{ZnCl}$ (whole fragment)	ATR- $\mu\text{FT-IR}$	Film	25–150	PE & PP	Raguso et al. (2022)
	<i>Porites</i>	1.5						
	<i>Pavona</i>	1.2 ± 0.7						
Taiwan, Liuqiu Island	<i>Acropora</i>	$0.77 \pm 0.47^*$	$\text{NaCl} + \text{H}_2\text{O}_2 \rightarrow 37\% \text{HCl}$ (tissue and skeleton separated)	ATR- $\mu\text{FT-IR}$	Fiber	1000–2000, and 2000–3000	Rayon & PES	Lim et al. (2022)
	<i>Galaxea</i>	0.95 ± 0.66						
	<i>Pocillopora</i>	0.36 ± 0.16						
China, Xisha Island	<i>Pocillopora</i>	0.48 *	$\text{NaCl} + \text{H}_2\text{O}_2 \rightarrow 37\% \text{HCl}$ (tissue and skeleton separated)	ATR- $\mu\text{FT-IR}$	Fiber	20–330 and 1000–5000	PET	Ding et al. (2019) ^a
	<i>Porites</i>	0.55						
Thailand, Si Chang Island	<i>Lobophyllia</i>	$0.70 \pm 0.12^*$	$\text{NaI} + \text{H}_2\text{O}_2 \rightarrow 10\% \text{KOH} \rightarrow 15\% \text{HCl}$ (mucus, tissue and skeleton separated)	Transmission- $\mu\text{FT-IR}$	Fragment	101–200	Nylon & Polyacetylene	This study
	<i>Platygyra</i>	1.12 ± 0.25						
	<i>Pocillopora</i>	2.28 ± 0.34						
	<i>Porites</i>	1.58 ± 0.25						
USA, Rhode Island	<i>Astrangia</i>	$112 \pm 5.01^{**}$	0.9 % HCl (whole fragment)	ATR-FT-IR	Fiber	N/A	PA	Rotjan et al. (2019)
China, Hainan Island	<i>Acropora</i>	$0.27 \pm 0.26^{**}$	1.0 % HCl \rightarrow 10 % NaOH (whole fragment)	μRaman spectrometer	Fiber	<500, 500–1000 and 1000–2000	PET	Lei et al. (2021)
	<i>Galaxea</i>	2.32 ± 0.86						
China, Hainan Island	<i>Galaxea</i>	$5.89 \pm 5.15^{**}$	KOH (whole fragment)	$\mu\text{FT-IR}$	Fiber	1–500 and 201–1000	CP & PET	Tang et al. (2021)
	<i>Pocillopora</i>	3.68 ± 3.94						
Jepara coastal, Indonesia	<i>Acropora</i>	0.012 **	30 % $\text{H}_2\text{O}_2 \rightarrow \text{NaCl}$ (whole fragment)	N/A	Fiber	<1000	N/A	Sabdono et al. (2022)
	<i>Galaxea</i>	0.009						
	<i>Montipora</i>	0.011						
	<i>Porites</i>	0.01						
China, Xisha Island	<i>Galaxea</i>	$1.2 \pm 0.6^{***}$	KOH (whole fragment)	ATR diamond- $\mu\text{FT-IR}$	Fiber	0–500, 501–1000 and 1001–2000	CP & PET	Zhou et al. (2022)
	<i>Pocillopora</i>	0.9 ± 0.5						
	<i>Porites</i>	2.5 ± 1.6						

Abbreviations: PE (polyethylene), PP (polypropylene), PET (polyethylene terephthalate), PA (polyamide), CP (cellophane).

The asterisk represents a unit of microplastic in coral * particles g^{-1} , ** particles polyp^{-1} , *** particles cm^{-2} .

^a Denotes that the study was carried out across multiple coral species ($n = 1\text{--}2/\text{species}$) but only included those species that were similar to those selected in this study.

study area.

4.3. Species-specific patterns of MP accumulation in different coral parts (mucus, tissue, and skeleton)

This study revealed notable patterns in the distribution of MPs and their characteristics across four coral species and three parts of individual corals. Although no significant differences were noted in the shape, color, and size of MPs among the species, the findings suggest that species-specific factors could influence the distribution of polymer types within individual coral parts of large-polyp corals. Previous studies reported a correlation between the shapes and colors of MPs in coral tissues and skeletons, in agreement with the results of our study (Ding et al., 2019; Lim et al., 2022). However, the results revealed a predominance of fragment-shaped MPs, contrasting with earlier reports that identified fiber shapes and green and red colors as being more common in all coral parts (Ding et al., 2019; Lim et al., 2022). The widespread presence of MP fragments across the three coral parts suggests their prevalence in the environment, possibly due to the degradation of larger plastic items (Nakano et al., 2024). The consistent appearances of specific MP colors across species and components likely reflect the composition of MP contamination in the local coral-reef habitats (Ding et al., 2019; Lim et al., 2022). Additionally, the absence of selective trapping of MPs by corals with respect to their color or shape, along with factors such as water currents and the proximity of the corals to pollution sources, may contribute to the uniform distribution of MPs in coral reefs (Hall et al., 2015; Lei et al., 2021). To better understand the impact of local MP accumulation on corals, future studies must include water and sediment sampling around coral habitats.

In this study, the majority of coral samples ingested particles smaller

than their polyp sizes. However, large polyp corals tended to accumulate larger MPs owing to their extended tentacles and more substantial mouthparts, which enabled them to capture a broader range of particle sizes (Houlbrèque and Ferrier-Pagès, 2009; Hall et al., 2015). *Lobophyllia* sp. exhibited a tendency to accumulate larger particles within their skeletons; these particles were smaller than the size of their calyx (Hankins et al., 2022). Conversely, small-polyp corals, such as *Pocillopora*, avoid ingesting larger MPs (Yen et al., 2024). However, in this study, *P. lutea* accumulated MPs larger than their polyp size, a behavior that may be attributed to their ability to produce a substantial amount of mucus, likely facilitating the trapping and subsequent tissue-overgrowth around larger particles (Reichert et al., 2018).

The variation in polymer types among the three coral parts highlights the complex interactions between coral species and MPs. In this study, large-polyp corals exhibited significant differences in polymer types across their components. Their large polyps and highly rugose surfaces likely enhanced their ability to trap a diverse range of polymers (Martin et al., 2019). Additionally, the distinct physical and chemical properties of mucus produced by these corals may have enabled them to selectively trap certain particles, further influencing the diversity of polymers across the three parts (Jatkar et al., 2010; Bhagwat et al., 2024). Overall, the corals with smaller polyps, which often rely on passive feeding, exhibited a uniform distribution of particles, likely due to less selective ingestion and removal processes (Fabricius and Metzner, 2004; Houlbrèque and Ferrier-Pagès, 2009). To conserve energy, these corals may not be selective when ingesting or removing foreign particles (Corona et al., 2020), which could explain the consistent distribution of MPs across their individual parts. Furthermore, the corals with shallow corallites, such as *P. cf. damicornis* and *P. lutea*, may allow MPs to settle more evenly across their surfaces, resulting in quicker ingestion and

accumulation.

Our study revealed that *Lobophyllia* and *Platygyra* did not accumulate nylon particles in their skeletons despite this polymer being predominantly found in the surface mucus layers and tissues of all coral species examined in this study. The presence or absence of specific polymer MPs in coral components may be influenced by various factors, including species-specific response, water flow dynamics, and exposure to different plastic-pollution profiles (Reichert et al., 2018; Mendrik et al., 2021; Wijayanti et al., 2024). The distribution of polymer types across coral species and their individual parts is likely more complex, especially in natural conditions.

Coral mucus, which is continuously produced, shed, and replaced, interacts with the surrounding environment by trapping particles and pollutants from the water column (Brown and Bythell, 2005; Huettel et al., 2006). This mucus acts as a dynamic barrier, capturing particles and reflecting the contaminants that were exposed to the organism (Wild et al., 2004). Coral skeletons, which grow slowly, have the ability to incorporate particles, such as MPs, during the process of calcification; this process allows them to preserve a record of past environmental conditions and pollution events (Reichert et al., 2018; Mendrik et al., 2021). Consequently, a wide variety of polymer types was detected within the skeleton (Fig. 7D). The presence of nylon primarily in the surface mucus and tissue suggests recent plastic pollution, while polymers found in coral skeletons may provide insights into historical records of pollution. In this study, the *P. cf. damicornis* (~30 cm in diameter) colony was estimated to be approximately six years old, while the *Lobophyllia* sp. (~30 cm), *P. sinensis* (~30 cm), and *P. lutea* (~40 cm) colonies were estimated to be around 16, 16, and 30 years old, respectively, based on the growth rates and colony sizes (Zamani et al., 2016; Tortolero-Langarica et al., 2017; Shlesinger and van Woessik, 2021; Arafat et al., 2022). Notably, *P. cf. damicornis*, the youngest coral, exhibited a high proportion of nylon (a high-density MP) in its skeleton; furthermore, we noted the presence of nylon in most mucus and tissue layers across all the coral species. Therefore, the coral age could also significantly influence the accumulation of MP polymers in their skeletons, reflecting a “legacy of pollution.” This suggests that younger corals may have been more exposed to recent nylon pollution, while older corals may have accumulated different profiles of MPs over time with the evolution in the pollution landscape (Reichert et al., 2018; Roberts et al., 2024).

Previous studies reported the accumulation of high-density MPs in coral samples (Ding et al., 2019; Lei et al., 2021; Tang et al., 2021; Lim et al., 2022). Our findings align with those of Lim et al. (2022), depicting that corals predominantly accumulate high-density MPs across their individual parts. It is plausible that corals may exhibit different compositions of low- and high-density MPs across their components, as each component may represent a different period of MP-pollution exposure (Reichert et al., 2018; Roberts et al., 2024; Wijayanti et al., 2024). However, the mechanisms underlying the selective removal of high-density polymers and the apparent preference for low-density MP accumulation in *P. lutea* remain unclear.

This study highlights the potential influence of coral morphology and age on the accumulation of MP polymers. Given the limited studies on this topic, further investigations are crucial for an in-depth analysis of MP accumulation in corals. Such studies could enhance our understanding of MP-accumulation pattern in reef-building corals and offer valuable insights into the history and impact of plastic pollution in marine environments.

4.4. Corals as a sink for MPs: Presence in the mucus layer, tissue, and skeleton

In this study, we observed that the adhesion and deposition of MPs occurred almost equivalently between surface mucus layer and skeleton (Fig. 3A). However, the extent of MP accumulation varied by part, depending on the coral species (Fig. 3B). Large-polyp corals exhibited a

higher prevalence of MP particles adherence to the surface mucus layer, whereas small-polyp corals, *P. cf. damicornis*, exhibited a higher extent of the accumulation of MPs within their skeletons. The varying rate of mucus secretion (Richman et al., 1975; Jatkar et al., 2010) may influence the number of MPs that adhere to this surface layer. *Platygyra* reportedly produces a greater quantity of thicker mucus than *P. lutea* (Mahmoud and Kalendar, 2016), potentially enhancing its ability to trap more MPs on its outer layer. Mucus production in corals is a physiological response to various stressors; its serves as a primary defense mechanism against sedimentation and alien particles (Shnit-Orland and Kushmaro, 2009; Bessell-Browne et al., 2017).

MP adherence to the surface mucus was considered to be responsible for the sinking of MPs from the water column (Martin et al., 2019). However, not all adhered particles are ingested by corals; thus, some MPs are likely to be removed by seawater flow around the coral colony (Yen et al., 2024). Despite the ability of the corals to expel a substantial portion of ingested MPs, approximately only 8 % of the ingested MP particles can be retained after 24 h (Allen et al., 2017). Nonetheless, coral species, at least those investigated in the present study, are capable of trapping MPs for a long time, as the majority of MPs (62.64 %) were detected in both the tissue and skeleton (Fig. 3). Once MPs are retained in corals for 24 h or more, it becomes difficult to remove them. This is because alien particles tend to be situated deeper within the mesenteric tissues, potentially leading to the long-term deposition of MPs in coral tissues and skeletons (Murdock, 1978; Goldberg, 2002; Hall et al., 2015).

Although corals generally possess self-cleaning mechanisms, the morpho-physiology of corals may play a crucial role in the uptake and accumulation of MP particles. For instance, in this study, the *P. cf. damicornis* samples exhibited a significantly high degree of MP accumulation in their skeletons (Fig. 3B), potentially due to their fast growth, high prey-capture abilities, and high feeding rates (Kuanui et al., 2016; Saper et al., 2023). These traits may lead to the inadvertent consumption of a considerable number of MPs from their surroundings. Additionally, *Pocillopora* is a finely branching coral; this morphology creates areas where particles tend to accumulate, particularly at the junctions of branches, making their removal from the coral colony difficult (Duckworth et al., 2017). Moreover, there should be an increased concern for other branching corals that possess scale-like radial corallites, such as *Acropora* spp., as these structures provide a larger area of steeply angled branches where MP particles can attach (Duckworth et al., 2017; Yen et al., 2024). In general, MPs transferred to marine organisms are trapped for a short time until they are returned to the marine food chain (Yuan et al., 2022; Tuuri and Leterme, 2023). However, in particular, the MPs deposited in skeletons are likely to be preserved on a millennium timescale, even if the corals die. Thus, given the extensive presence of coral reefs worldwide, corals can accumulate a considerable number of MPs, thereby acting as a sink for ocean plastics. This highlights the possibility that corals can reveal the answer to missing ocean plastics.

Notably, this study has a few limitations. We could not collect coral samples from different sites with varying degrees of anthropogenic influence. This limitation may affect the generalizability of our findings regarding MP accumulation patterns. Future studies should aim to include samples from a range of environments with different levels of anthropogenic impact to offer a comprehensive understanding of MP accumulation patterns in reef-building corals.

5. Conclusion

In this study, we investigated MP contamination in various coral species with respect to their surface mucus layers, tissues, and skeletons. The branching small-polyp coral *P. cf. damicornis* exhibited significant accumulation of MPs (particles g^{-1} w.w.). Additionally, this coral species exhibited a high rate of MP accumulation in its skeleton, whereas large-polyp corals, such as *Lobophyllia* sp., showed high amounts of MPs

that adhered to their surfaces. Notably, once the MPs adhere to the mucus layer, there is a high chance that these MPs will translocate to the tissue and eventually permanently sink into the coral skeleton. This evidence suggests that corals could account for the missing plastics in the ocean, as they are likely to preserve MPs on a millennial timescale, even after the corals die. Moreover, MP contamination can act as a stressor, further contributing to the shifts in the coral-reef community assemblages and affecting their resilience. Therefore, conducting extensive and systematic studies across a diverse array of coral species, geographic locations, and varying degrees of anthropogenic influence is imperative to accurately evaluate the impact of MPs on coral ecosystems. Moreover, developing standardized methods for studying MP accumulation in corals is crucial for the generation of comparable data.

CRedit authorship contribution statement

Suppakarn Jandang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **María Belén Alfonso:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition. **Haruka Nakano:** Writing – review & editing, Writing – original draft, Investigation. **Nopphawit Phinchan:** Investigation, Data curation. **Udomsak Darumas:** Formal analysis, Investigation, Methodology. **Voranop Viyakarn:** Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Suchana Chavanich:** Project administration, Resources, Writing – original draft, Writing – review & editing. **Atsuhiko Isobe:** Funding acquisition, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced 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 to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176210>.

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