



## Colony complexity affects microplastic loads in *Pocillopora* corals

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### ABSTRACT

Microplastic (MP) pollution poses a significant threat to marine ecosystems. Coral reefs, often located near land-based sources of these pollutants, act as potential sinks due to their complex three-dimensional structures. While the interactions between reef-building corals and MPs have been increasingly investigated, the role of coral structural complexity in MP accumulation remains poorly understood. This study investigated the influence of coral structural complexity on MP trapping efficiency under natural conditions, specifically aiming to: I) quantify and characterize MPs trapped by *Pocillopora* corals, II) compare MP distribution across coral compartments (surface, tissue, and skeleton), and III) assess the relationship between seven metrics of coral complexity (i.e., S/V ratio, fractal dimension, compactness, convexity, sphericity, packing, and rugosity) and MP loads. Six *Pocillopora* sp. colonies, comprising 36 fragments, were sampled from a reef in Kāne'ohe Bay, Hawai'i. MPs were extracted from the coral surface, tissue, and skeleton for quantification and characterization using microscopy and FTIR spectroscopy. Coral complexity was assessed using photogrammetry and 3D scanning. MPs were found at an average of  $0.029 \pm 0.079$  particles per g coral, mostly at the coral surface (61%). Compact, thick-branched coral morphologies showed higher MP accumulation, likely due to increased formation of stagnant water regions and reduced turbulence. Our results demonstrate that coral complexity plays a significant role in MP deposition under natural conditions, with potential implications for coral health and the transfer of MPs to other reef sinks. This highlights the importance of considering coral morphological complexity when evaluating the risk of MP pollution.

### 1. Introduction

Microplastic (MP) pollution (i.e., plastic particles <5 mm) is widespread, raising growing concern about its diverse impacts on marine life (Avio et al., 2017; GESAMP, 2015; Wright et al., 2013). Coral reefs are particularly susceptible, also due to their proximity to the source of pollution, often located along the coastlines (Huang et al., 2021). Coral reefs have been identified as potential sinks for MPs (de Smit et al., 2021; Jandang et al., 2024; Reichert et al., 2021) and reef-building corals with their complex 3D structure have been shown to effectively trap and deposit particles (Yen et al., 2024), similar to other marine environments, such as mangroves, the seafloor, or the deep sea (Näkki et al., 2019; Woodall et al., 2014; Zamprogno et al., 2021).

MPs can be found in three main compartments of corals: attached to the outside surface, within the coral tissue, or embedded in the calcium

carbonate skeleton (Martin et al., 2019; Reichert et al., 2022). These different locations reflect the various ways corals interact with and process these particles. Initially, MPs are passively trapped by corals through particle interception, settling on branches or within the coral structure (Mendrik et al., 2024; Yen et al., 2024). Once MPs encounter the coral surface, they can get caught by the coral polyps or the mucus layer (Martin et al., 2019; Reichert et al., 2018). Upon contact with a particle, the coral elicits a behavioral response that determines the fate of the particle. In healthy corals, polyps typically recognize non-food particles, like MPs, within minutes and actively reject them (Allen et al., 2017; Reichert et al., 2024a). This rejection process can occur either at the polyp level via the tentacles or through cleaning mechanisms, such as mucus shedding (Rades et al., 2022; Reichert et al., 2018). Consequently, a substantial number of MPs are trapped on the coral surface (Corona et al., 2020; Martin et al., 2019). Despite these mostly

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effective rejection mechanisms, some MPs are occasionally mistaken for food and ingested, ending up within the coral tissue (Hall et al., 2015; Reichert et al., 2024a, 2022). Here, most ingested particles are recognized as non-food within minutes to hours and are subsequently egested. However, MPs can also become embedded in the coral skeleton. This often occurs when particles accumulate in areas where the rejection or cleaning mechanisms of the coral are ineffective, either due to localized hydrodynamics or compromised coral health (Hierl et al., 2021; Reichert et al., 2022). Additionally, a small fraction (<5 %) of ingested particles may remain stuck within the coral tissue and eventually become incorporated into the growing skeleton (Reichert et al., 2024a).

The structural complexity of a coral colony plays a central role in how it interacts with its environment, influencing water flow, feeding, and sediment deposition (Swierts and Vermeij, 2016; van Woesik et al., 2012). This complexity also plays a crucial role in how corals interact with MPs. At the largest scale, the density of coral colonies within a reef (often referred to as canopy density) can significantly affect MP retention. Studies have shown that denser reefs, characterized by higher structural complexity, tend to trap more MPs (Mendrik et al., 2024). This increased trapping potential can have important implications for the entire reef ecosystem, potentially exposing a greater number of reef organisms to MP pollution. Moving to a smaller scale, the branching patterns of individual coral colonies also influence MP retention. Complex branching corals, with their intricate network of branches, create complex flow profiles around and within the colony, increasing the likelihood of particles interception (Chang et al., 2009; Sebens et al., 1997; Yen et al., 2024). These complex branching structures can create areas of flow convergence, particularly at branch junctions, where particles tend to accumulate (Duckworth et al., 2017). Relatedly, the overall compactness of a coral colony influences MP trapping. Compact branching colonies have been found to trap more MPs and facilitate their deposition closer to the colony compared to more open, less compact morphologies (Yen et al., 2024). This difference is likely due to variations in flow dynamics around colonies with different shapes. Finally, at even smaller scales, features like polyp size and surface roughness can also play a role, although their influence on MP trapping appears less pronounced. While small-polyp corals tend to accumulate more MPs (Jandang et al., 2024), large-polyp corals ingest drastically higher numbers of particles per polyp (Reichert et al., 2024a). Similarly, although surface roughness can alter near-surface flow, studies comparing live, dead, and waxed coral surfaces suggest that its direct impact on overall MP trapping is relatively low (Yen et al., 2024). However, measuring surface roughness is still relevant as it may interact with other complexity levels, and provide a more comprehensive understanding of the surface characteristics of the corals.

*Pocillopora* corals, known for their variable branching patterns, offer an ideal system to study the link between colony morphology and MP trapping (Yen et al., 2024). Their high phenotypic plasticity, enabling them to adapt their colony form to environmental conditions like wave exposure and light availability (Johnston et al., 2018; Todd, 2008; Veron, 2000), suggests that MP trapping efficiencies may also vary considerably within this genus. This morphological plasticity is particularly relevant given the frequent interaction of *Pocillopora* spp. with and high risk from MPs (Reichert et al., 2024a). These interactions can lead to negative physiological impacts, such as reduced growth and altered photosynthesis (Reichert et al., 2024b, 2019; Tirpitz et al., 2025). The combination of high phenotypic plasticity, documented MP susceptibility, and well-characterized negative physiological effects make *Pocillopora* spp. a particularly relevant study organism for investigating the complex relationships between coral morphology and MP interactions.

While we have first-hand laboratory evidence connecting the relationship between coral colony complexity and MP trapping efficiency, these dynamics remain poorly understood under naturally occurring MP exposure scenarios. Yet, research under natural conditions is crucial, as it allows for studying the combined effects of variable MP characteristics

(e.g., size, shape, polymer type, or biofilms) and fluctuating hydrodynamics under natural feeding behaviors of the corals. Therefore, the goal of our study is to investigate the influence of coral structural complexity on MP trapping efficiency in *Pocillopora* corals under natural exposure conditions in the reef. Specifically, we aim I) to quantify and characterize MPs trapped by *Pocillopora* corals, II) to compare the distribution of MPs across the different compartments of the corals (surface, tissue, and skeleton), and III) to assess the relationship between coral complexity (measured as surface-to-volume ratio, fractal dimension, and rugosity at the colony and fragment level) and MP loads in the corals.

Our results will provide crucial insights into the relationships between structural complexity and MP trapping efficiency under natural conditions, incorporating environmental variabilities under natural long-term exposure conditions. This will help identify whether corals with certain structural complexities are at higher risk from MP pollution, which is crucial for understanding the long-term ecological risks of this pollutant in coral reef ecosystems.

## 2. Material and methods

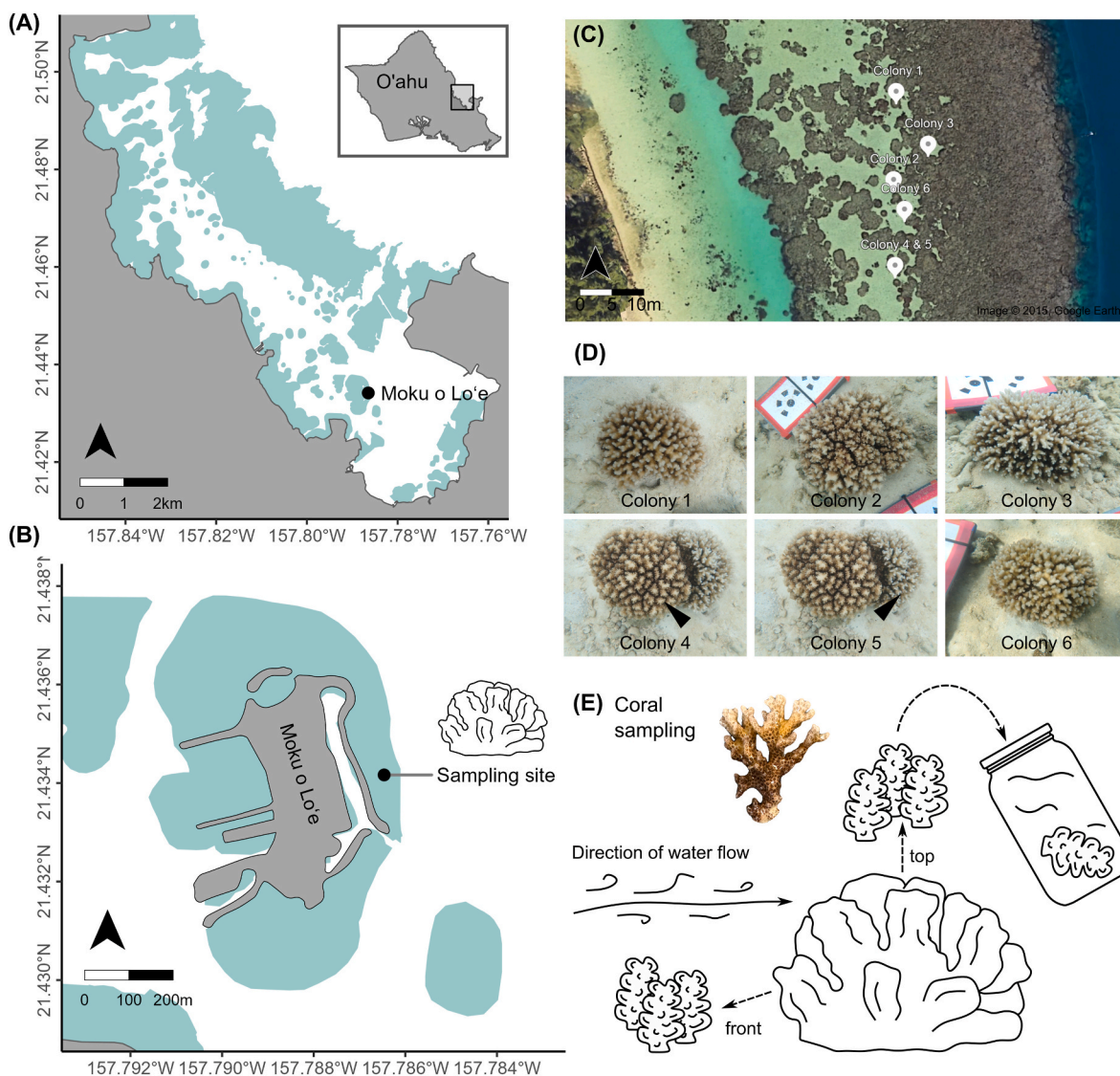
### 2.1. Coral sampling and documentation

MP loads were determined in six coral colonies of the reef-building coral *Pocillopora* sp. The sampled colonies likely belong to the species *Pocillopora* cf. *acuta*, which is the dominant species making up ~96 % of *Pocillopora* spp. in Kāneʻohe Bay (Johnston et al., 2018). As species identification of *Pocillopora* spp. based on morphology is difficult and has not been confirmed genetically in our samples, we here refer to the genus. The colonies were sampled between November 14–24th 2023 from the point reef off Moku o Loʻe, Kāneʻohe Bay, Hawaiʻi, US (Fig. 1A and B), with one colony sampled per day (Permit: SAP, 2024–45). Samples were taken from the reef within 25 m of lateral extent, expecting similar wave and microplastic exposure conditions (Fig. 1C). Six solitary colonies of ~20 cm diameter, surrounded by sandy bottom and growing at distances >1 m to adjacent coral reef structures, of different structural complexity were selected to be sampled (Fig. 1D). To control for potential site impacts, two fused colonies (4 and 5) growing at the same location but exhibiting strongly different morphologies have been included in the dataset. Underwater photos of colonies were collected for Structure from Motion (SfM, details see below) to assess their structural complexity. Then three samples were taken with a bone cutter from front positions (facing the direction of the current) and three from top positions in the middle of the colony (Fig. 1E). Each sample was directly transferred to a 1-L glass jar, filled with ambient water and closed underwater. An additional water sample of 1 L was taken per colony to assess potential environmental microplastic loads.

### 2.2. Extraction of MPs

MPs were extracted from three compartments of the coral: 1) particles trapped in the coral mucus and adhering to the outside surface, i.e., surface, 2) particles embedded in the coral tissue, i.e., tissue, and 3) particles deposited in the calcium carbonate skeleton, i.e., skeleton. To extract MPs from each compartment, the modified protocol described by Reichert et al. (2022) was followed (Fig. S1).

To remove and collect the particles from the surface and mucus, coral fragments were picked up with tweezers and shaken vigorously in the sampling jar, before being removed for further processing. The remaining sampling water, containing particles that adhered to the coral, was vacuum-filtered onto 25 µm filters (Whatman Cellulose filters, Grade 4) and the beaker was rinsed with Type I water from a Milli-Q water purification system (final filtration 0.22 µm) to remove and collect any remaining particles. Following this, coral fragments were weighed (Ohaus Pioneer, precision 0.01 g) and documented using 3D scanning (HandySCAN 3D with VX elements, Creaform, Canada, for details see below). After the documentation, fragments were rinsed thoroughly



**Fig. 1. Study location and sampling of coral colonies.** (A) Map of Kane'ohe Bay, O'ahu, Hawai'i, showing the (B) study location at the point reef at Moku o Lo'e. Light green areas show the presence of reefs. (C) Coral colonies were sampled from the eastern side of the reef at Moku o Lo'e, within ~25 m. Map data: Google Earth, 2015. (D) The six *Pocillopora* sp. colonies sampled showed different levels of structural complexity. (E) Six fragments were sampled *in situ* from each coral colony, three at the front, facing the flow direction at the time of sampling and three at the top in the middle of the colony. Sampled fragments were transferred underwater to 1-L glass jars. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

with filtered water to remove particles, which might have been introduced as contamination during the measurement procedure and transferred to a glass beaker (600 mL) for further processing. To determine particle loads in the coral tissue, the fragment was covered in filtered 7.5 % NaClO (up&up disinfecting Bleach, KIK International LLC, Canada; ~20 mL per g coral sample) and dissolved overnight (18 h). Then, the remaining skeleton samples were taken out of the solution after being gently shaken to remove any remaining residues around the sample and transferred to another glass beaker (600 mL). The NaClO solution containing particles from the coral tissue was filtered as described above. To determine particle loads in the coral skeleton, the fragment was dissolved in filtered 5 % HCl (20 mL per g coral sample) for 4 h and the resulting solution containing particles from the coral skeleton was filtered as described above.

### 2.3. Quality assurance and quality control

The microplastic extraction was performed according to current standards to minimize and control for MP contamination (Prata et al.,

2021; Kutralam-Muniasamy et al., 2023; Wesch et al., 2017). Coral samples were collected in 1-L glass jars, previously rinsed with filtered water and covered with metal lids. 1 L of water sample was taken with each colony to assess potential environmental MP contamination. All lab equipment was rinsed with filtered water and covered in aluminum foil between procedural steps to avoid (cross-)contamination. Only glass and metal materials were used, avoiding plastic materials. Cotton lab coats were worn during laboratory activities. All working solutions were filtered prior to use (Whatman Cellulose filters, Grade 2). Quality control blanks were collected during all processing steps to check for airborne contamination in the laboratory. For this, a clean filter was placed in proximity to the workspace during the filtering, documentation, and visual sorting. Additional procedural control samples were collected for each compartment without coral samples added to check for contamination of the procedures, equipment, or solutions.

### 2.4. Microplastic identification and polymer determination

Filters were screened for visual identification of particles under a

stereomicroscope (SMZ-168, W10X/23×5 magnification, Motic, Hong Kong). Putative plastic items ( $\geq 50 \mu\text{m}$ ) were categorized by shape (fragment, fiber, film, pellet, foam), color, and size. Four size classes were defined:  $<0.1 \text{ mm}$ ,  $0.1\text{--}0.5 \text{ mm}$ ,  $0.5\text{--}1 \text{ mm}$ , and  $1\text{--}5 \text{ mm}$ . The polymeric composition of all extracted particles was assessed using a Thermo Nicolet iS50 FTIR spectrometer, coupled with a Continuum IR microscope (Thermo Fisher Scientific, USA). The spectral range was set at  $4000\text{--}650 \text{ cm}^{-1}$ , at the spectral resolution of  $8 \text{ cm}^{-1}$ , and 40 scans were accumulated for each spectrum. The spectra obtained were then analyzed using the Omnic Picta software and compared to open-access polymer spectral libraries (i.e., FLOPP and FLOPP-e, De Frond et al., 2021). Match values lower than 70 % were not accepted.

### 2.5. Structure from Motion to document coral colonies

3D models of coral colonies were reconstructed using Structure from Motion (SfM). 200–500 pictures were taken from all angles around the colony before sampling (Olympus Tough, OMDS, Japan). All colonies were documented, except for the fused colonies 4 and 5, from which colony growth form could not be determined individually. Images were processed with Agisoft Metashape Professional (version 2.1.1., 2024, Agisoft LLC, Russia). Photos were aligned (accuracy: high) and the resulting model was scaled, using reference markers placed in proximity of the colony during documentation. Error reduction was performed through gradual selection (reconstruction uncertainty: 30 %, projection accuracy: 10 %, and reprojection error: level 0.35). A dense cloud was built with high quality and mild depth filtering, from which a mesh was constructed. The model was exported and processed in VXEelements (Creaform, Canada) to clean the mesh and remove the reef structures around the colony. Models were transformed to be oriented correctly and exported as .ply (Polygon File Format), a common 3D mesh file type, for further analysis.

### 2.6. 3D scanning to document coral fragments

Coral fragments were documented with 3D scanning (HandySCAN 3D with VX elements, Creaform, Canada). For this, the fragments were placed on a rotation plate and documented in two scans from opposite sides. The two resulting meshes (resolution =  $0.5 \text{ mm}$ ) were merged and cleaned to remove artifacts and fill holes. Models were oriented and exported as .ply for further analysis.

### 2.7. Determination of complexity values of coral colonies and fragments

3D models of colonies and fragments were analyzed to extract quantitative shape parameters that describe different aspects of coral morphology in terms of size (i.e., colony diameter, surface area, and volume) and complexity (i.e., surface-to-volume ratio, compactness, convexity, sphericity, packing, rugosity, and fractal dimension). Surface-to-volume ratio (S/V ratio) compares the surface area of the coral to its volume, with higher values indicating more exposed surface area relative to the volume. Compactness compares the cubed surface area of the coral to its squared volume, with lower values indicating denser, bulkier shapes. Convexity compares the volume of the coral to the volume of its convex hull, with higher values indicating less concave shapes. Sphericity describes the roundness of a coral, with higher values indicating more spherical forms. Packing describes how efficiently the surface area of the coral fills its convex hull, with lower values indicating more voids or exposed surfaces. Rugosity measures the surface area of the coral in comparison to its planar area, with higher values indicating more intricate, uneven surfaces with rougher structures. Fractal dimension quantifies the complexity of the coral surface in terms of self-similarity, combining information from different spatial scales into one measure, with lower values indicating simpler shapes.

Surface area and volume were determined using Meshlab (v1.3.4beta, Visual Computing Lab, Italy) and S/V ratio and

compactness ( $S^3/V^2$  ratio, Bribiesca, 2008) were calculated from them. Convexity, sphericity, packing, and rugosity were determined using the Habtools package (Schiettekatte et al., 2025). Fractal dimension (via Minkowski–Bouligand dimension) was calculated using the fractal dimension toolbox (Reichert et al., 2017). Colony diameter was measured in Meshlab, at the widest horizontal distance of the colony.

### 2.8. Data analysis

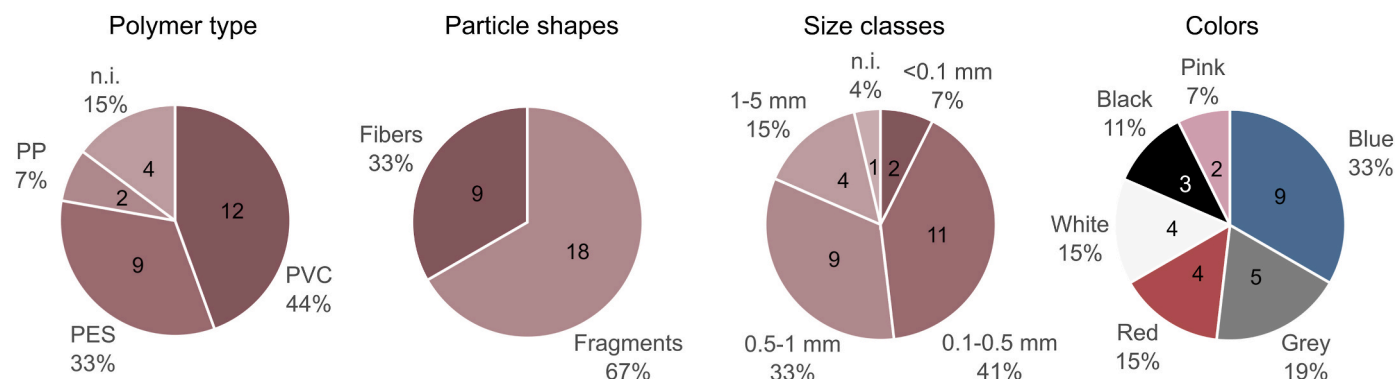
All data processing and analyses were performed in the R statistical environment (v. 4.3.1; R Core Team, 2023). Microplastic loads were standardized to surface area, derived from 3D scanning and wet weight of the individual fragments, and are expressed as particles per  $\text{cm}^2$  surface area and particles per g, respectively. Mean values are given with standard deviation (SD). Differences between the total numbers of particles, particles per g wet weight, and particles per  $\text{cm}^2$  surface area in the different compartments of the coral fragments ( $n = 36$  fragments analyzed) were derived from Wilcoxon rank-sum tests followed by holm-adjustment for multiple testing, with statistical significances defined as  $p \leq 0.05$ . Differences between total numbers of particles, particles per g wet weight, and particles per  $\text{cm}^2$  surface area at the different positions of the coral colony were also derived from Wilcoxon rank-sum tests. Differences in fragment complexity (i.e., S/V ratio, fractal dimension, and rugosity of coral fragments) between fragments with and without MPs in the different compartments (i.e., surface, tissue, skeleton) were analyzed accordingly. Correlations between mean microplastic particle densities per colony in the different compartments (i.e., surface, tissue, skeleton) and complexity metrics (i.e., S/V ratio, fractal dimension, compactness, convexity, sphericity, packing, and rugosity) of the coral colony and the mean complexity of the coral fragments per colony were derived from linear models. The relationship between size parameters of the coral colony and sampled fragments (colony diameter, colony surface area, fragment surface area, fragment volume, and fragment weight) and the microplastic particle densities (particles per  $\text{cm}^2$ ) were analyzed accordingly. To explore the relationship between coral complexity, size, and microplastic loads, a principal component analysis (PCA) was conducted on scaled variables using the `prcomp()` function. Given the limited underlying data, this analysis aimed to provide an overview of potential associations, but no further analysis was performed.

## 3. Results

### 3.1. Characterization of isolated particles

MPs were present in 5 out of the 6 sampled coral colonies (83 %) and 15 out of 36 of the sampled coral fragments (42 %). No MPs were found in the water sampled around the corals. Only cotton fibers were detected in the blanks, hence samples were not blank-corrected for contamination. In the 108 coral samples analyzed, we found 27 MP particles. On average, we found  $0.029 \pm 0.079$  particles per g in the coral fragments studied, corresponding to  $0.007 \pm 0.020$  particles per  $\text{cm}^2$  surface area. The highest density was observed in colony 1 with  $0.062 \pm 0.134$  particles per g and  $0.016 \pm 0.008$  particles per  $\text{cm}^2$ , the lowest values in colony 3, where no particles were found (Fig. S2). Most polymers found were polyvinyl chloride (PVC, 44 %), followed by polyester (PES, 33 %) and polypropylene (PP, 7 %) (Fig. 2). The majority of particles were fragments (67 %), followed by fibers (33 %). Most particles were found in the two lowest size classes from 0.1 to 1 mm, with fragments measuring on average  $0.48 \pm 0.44 \text{ mm}$  and fibers  $1.13 \pm 0.66 \text{ mm}$ .

Most particles adhered to the surface of the coral colonies (61 %, 16 particles in total), corresponding to  $0.013 \pm 0.026$  particles per  $\text{cm}^2$  (Fig. 3A and B, Wilcoxon rank-sum test,  $p = 0.04$ , Table S1). Fewer MPs were found in the coral tissue (30 %, 8 particles in total), corresponding to  $0.006 \pm 0.02$  particles per  $\text{cm}^2$ , and the skeleton (9 %, 3 particles in total), corresponding to  $0.003 \pm 0.010$  particles per  $\text{cm}^2$ . Larger



**Fig. 2. Characteristics of MP particles found in *Pocillopora* sp.** The pie charts illustrate the distribution of polymer types, particle shapes (i.e., fibers and fragments), size classes (i.e., <0.1 mm, 0.1–0.5 mm, 0.5–1 mm, and 1–5 mm), and colors. Chart labels indicate the absolute number of particles in each category. Values are given for all particles analyzed ( $n = 27$ ), including those not identified (n.i.). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

particles (1–5 mm) were mainly found attached to the coral surface, but only once in the tissue and not in the skeleton. While the number of particles was comparable between the front and top at the surface and inside the tissue of the corals, the deposition of particles in the coral skeleton only occurred at the front of the colonies (Fig. 3C, Fig. S3, Table S2).

### 3.2. Effects of coral complexity on MP attachment and deposition

Colony and fragment complexity were correlated with particle densities (Fig. 4, Table S3). Specifically, lower fractal dimensions, lower compactness values (indicating more bulky corals), and higher sphericity of the coral colonies were associated with higher particle densities adhering to the surface and inside the tissue (Linear model,  $p < 0.05$ , Fig. 4A). Additionally, higher convexity and lower packing of the coral colony were associated with higher particle densities in the tissue (Linear model,  $p < 0.05$ , Fig. 4A). Lower rugosity of the coral fragments was associated with higher particle densities (Linear model,  $p < 0.05$ , Fig. 4B). The complexity of coral fragments with or without MPs did not differ significantly (Wilcoxon tests,  $p > 0.05$ , Fig. S5). The size of the coral colonies had little effect on the densities of the particles found within them (Fig. S4, Table S4). Only in the skeleton, lower densities of particles were found in corals with larger surface areas of the fragments (Linear model,  $p = 0.036$ ). A PCA was conducted to explore the relationships between complexity and size parameters and microplastic loads, and to reduce the dimensionality of the dataset (Fig. 5). The first two principal components (PCs) explained 52 % and 36 % of the total variance, respectively, cumulatively accounting for 88 % of the variability in the data. The eigenvalues for PC1 and PC2 were 3.38 and 2.80, respectively. The PCA revealed that some colony complexity parameters had a moderately positive (rugosity and packing) and negative (fractal dimension and compactness) association with microplastic loads. Fragment complexity parameters, overall, exhibited a weaker association with microplastic loads compared to colony complexity. Size parameters showed a very weak or negligible association with microplastic loads.

## 4. Discussion

This study is one of the first to explore how the structural complexity of corals affects MP attachment and deposition in a natural setting. Our analysis revealed that MP loads are omnipresent but low in the *Pocillopora* sp. corals studied in Kāneʻohe Bay, Hawaiʻi. Most particles were found adhering to the coral surface, less in the coral tissue and skeleton. Overall, structural complexity was correlated with particle densities and less complex corals accumulated more particles.

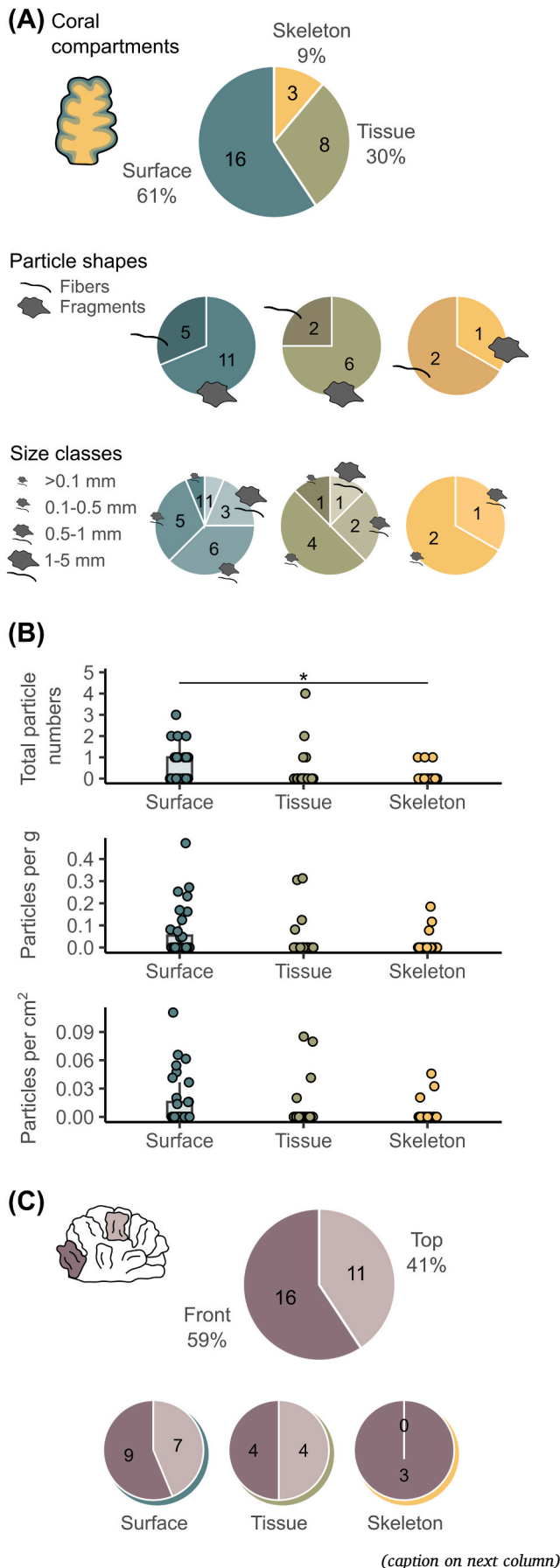
### 4.1. Properties of particles found in corals

MPs were present in five out of six coral colonies sampled, underlining the pervasiveness of this pollutant. Overall, MP loads in these coral fragments averaged  $0.029 \pm 0.079$  particles  $g^{-1}$ , substantially lower than previous *in situ* findings. Compared to other studies on *Pocillopora* spp. (Maldives:  $2.8 \pm 0.9$  particles per g, Raguso et al., 2022; Gulf of Thailand:  $2.28 \pm 0.12$  particles per g, Jandang et al., 2024; South China Sea: 0.48 particles per g, Ding et al., 2019), MP loads in Kāneʻohe Bay corals were 1–2 orders of magnitude lower. The lower MP abundance in corals likely reflects the 1–2 orders of magnitude lower MP concentrations in Kāneʻohe Bay waters ( $0.0061$ – $0.0810$  particles per  $m^3$ , Axworthy et al., 2024) compared to other reefs like the Maldives ( $0.02$ – $0.48$  particles per  $m^3$ , Saliu et al., 2018), South China Sea ( $0.148$ – $0.842$  particles per  $m^3$ , Wang et al., 2019), or Gulf of Thailand ( $0.02$ – $42.46$  particles per  $m^3$ , Nakano et al., 2024). The shallow, low-flow environment at Moku o Loʻe likely reduced coral-MP interactions. Besides, coral polymer types likely mirrored those in the water column, as corals show limited polymer selectivity (Allen et al., 2017; Reichert et al., 2024a).

The most common coral polymers were PVC, followed by PES and PP, consistent with findings in coral reef waters (Huang et al., 2021) and recently in the surface waters of the study location (Axworthy et al., 2024). The prevalence of PVC and PES may relate to their higher density and sinking, potentially increasing their availability to corals, though water column MP data around corals is lacking. MPs associated with corals were two-thirds fragments and one-third fibers, similar to findings in the Gulf of Thailand (~75 % fragments, ~24 % fibers, Jandang et al., 2024). In contrast, fibers are often more prevalent in water, comprising over 88 % of particles in Kāneʻohe Bay, Hawaiʻi (Axworthy et al., 2024; Huang et al., 2021). These findings suggest that fragments are more likely to be associated with corals than fibers, possibly due to their resemblance to natural food and higher ingestion likelihood compared to elongated fibers. Most particles were 0.1–1 mm (fragments:  $0.48 \pm 0.44$  mm; fibers:  $1.13 \pm 0.66$  mm), fitting the natural food size range of corals and supporting the assumption of ingestion due to confusion with food particles (Houlbrèque and Ferrier-Pagès, 2009).

### 4.2. MP loads in different compartments

Most particles adhered to the surface of the coral colonies, where they were presumably trapped in the mucus or caught by the tentacles or mesenteric filaments. Given no additional particles in surrounding water samples, we are confident our results represent particles associated with the coral colonies, and ambient water contamination was negligible. Adhesion of MP to corals is essential in transferring MP to other sinks like sediments (Lim et al., 2020; Martin et al., 2019; Yen



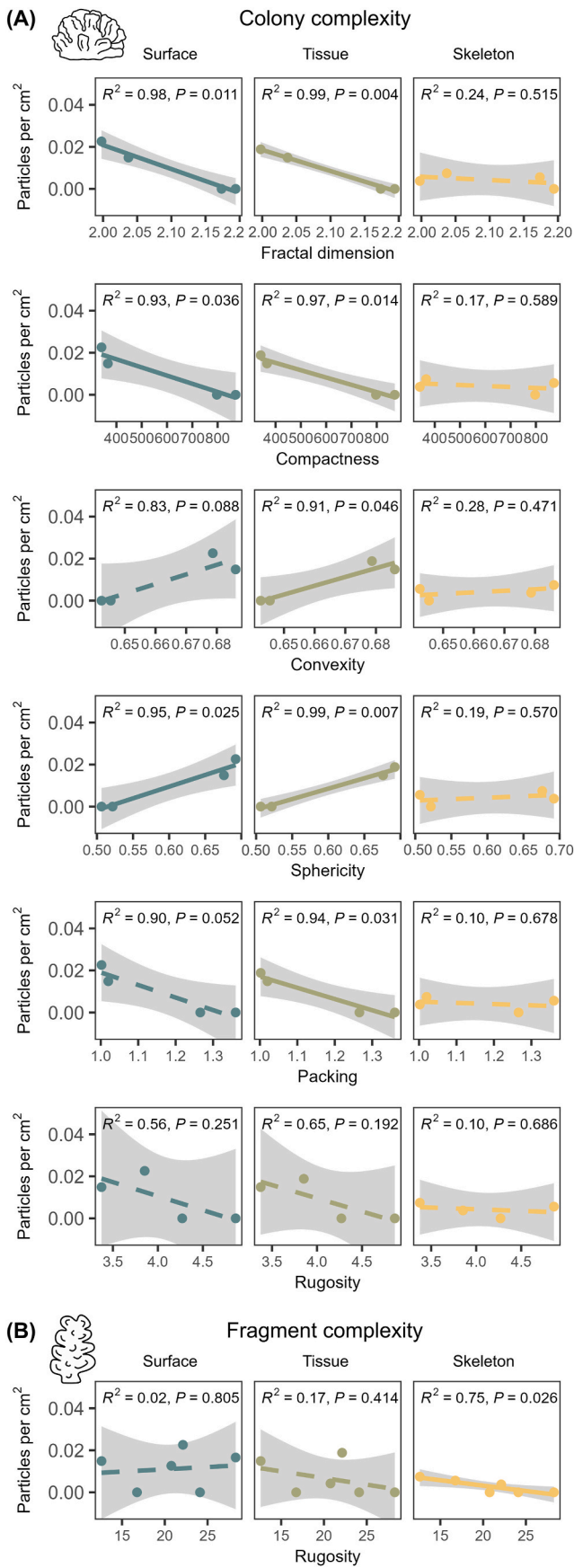
**Fig. 3. MP particles in the different compartments of the coral fragments.** A) The distribution of particles across the different compartments of the coral fragments (i.e., outside surface, tissue, and skeleton) are displayed as pie charts. Chart labels indicate the absolute number of particles in each category. The distributions of particle types (i.e., fibers and fragments) and size classes (i.e., <0.1 mm, 0.1–0.5 mm, 0.5–1 mm, and 1–5 mm) within the different compartments of the coral fragments are displayed accordingly. (B) Total numbers of particles, particles per g wet weight, and particles per cm<sup>2</sup> surface area in the different compartments of the coral fragments (n = 36 fragments analyzed). Data are displayed as raw data points next to violin plots overlaid with box-and-whisker plots. The violin plots illustrate the distribution and density of the data, while the box-and-whisker plots provide summary statistics: lines indicate medians, boxes indicate the first and third quartile, and whiskers indicate ±1.5 IQR. Asterisks indicate levels of statistical significance, derived from Wilcoxon rank-sum tests followed by holm-adjustment for multiple testing: \*p ≤ 0.05. (C) Pie charts showing the distribution of particles at different positions within the coral colony, overall and within the different compartments of the coral fragments (i.e., outside surface, tissue, and skeleton). Chart labels indicate the absolute number of particles in each category.

et al., 2024). Recent studies have shown that adhesion is an important driver of MP accumulation in reefs (Jandang et al., 2024; Kim et al., 2024; Martin et al., 2019), thus corroborating the idea of coral reefs as a sink for MPs (Reichert et al., 2022; Soares et al., 2023).

Fewer MPs were detected in coral tissue, suggesting infrequent ingestion and more frequent rejection as non-food, aligning with laboratory studies showing ~7 % ingestion of adhering particles in *Pocillopora* spp. (Allen et al., 2017; Reichert et al., 2024a). Even fewer particles were found in the coral skeleton, which can be either ingested particles that occasionally get stuck inside the gastric cavity or particles that were overgrown in areas where rejection and cleaning mechanisms are not effective, e.g., due to water flow (Hierl et al., 2021; Reichert et al., 2018). Skeleton particles found only in flow-facing fragments support the assumption that they were trapped from the water, as trapping likely occurs at the front of the coral colony. Laboratory feeding experiments support this, showing most ingested particles are egested within hours (Allen et al., 2017; Reichert et al., 2024a). Our results suggest size-selective ingestion, as larger particles (1–5 mm) were mostly surface-attached, not in tissue or skeleton. This suggests that although coral colonies structurally trap more larger than smaller particles (Yen et al., 2024), they mainly ingest particles within their natural food size range (Houlbrèque and Ferrier-Pagès, 2009). This is supported by the observation that the likelihood of MP ingestion increases significantly when the size of the particle is small in relation to the calyx size of the coral (Hankins et al., 2022). However, our size limits owing to the visual observation at stereomicroscope might bias observations, likely underestimating actual MP loads, especially smaller particles (≤50 μm) in coral tissue and skeleton.

#### 4.3. Effects of complexity on MPs deposition

Our results show that more compact *Pocillopora* sp. corals accumulated more particles. These findings from natural settings are in accordance with those from laboratory experiments (Yen et al., 2024). More compact *Pocillopora* colonies reduce water flow and increase the trapping efficiency of corals (Chang et al., 2014; Reidenbach et al., 2006; Yen et al., 2024) due to flow patterns around and within coral colonies (Hench and Rosman, 2013; Lowe et al., 2005). Water flowing through the coral colony slows down in the shear layer surrounding the coral, and stagnant regions form between the branches. Laboratory evidence shows that MPs get trapped in the stagnant regions of *Pocillopora* sp. colonies (Yen et al., 2024). Compact colonies create larger, persistent stagnant regions, thus trapping more MP particles (Kaandorp et al., 2003; Yen et al., 2024). Additionally, more compact colonies create larger shear layers with reduced flow, further facilitating surface particle trapping (Lowe et al., 2005; Yen et al., 2024). Our study identifies aspects of coral morphology promoting particle adherence. Lower



(caption on next column)

**Fig. 4. MP particle densities in relation to complexity metrics in the different compartments of the coral.** Mean MP particle densities per colony in the different compartments (i.e., surface, tissue, skeleton) are plotted against complexity metrics, which correlated significantly with MP loads (i.e., fractal dimension, compactness, convexity, sphericity, packing, and rugosity) of (A) the coral colony (n = 4 because large scale complexity of fused colonies 4 and 5 was not documented) and (B) the mean complexity of the coral fragments per colony (n = 6 because individual fragments were documented in all colonies). Data points represent observed values, while lines depict linear models with 95 % confidence intervals (grey shading). Coefficients of correlation ( $R^2$ ) and significance values ( $P$ ), derived from linear models, are provided with solid lines indicating statistically significant relationships ( $p < 0.05$ ).

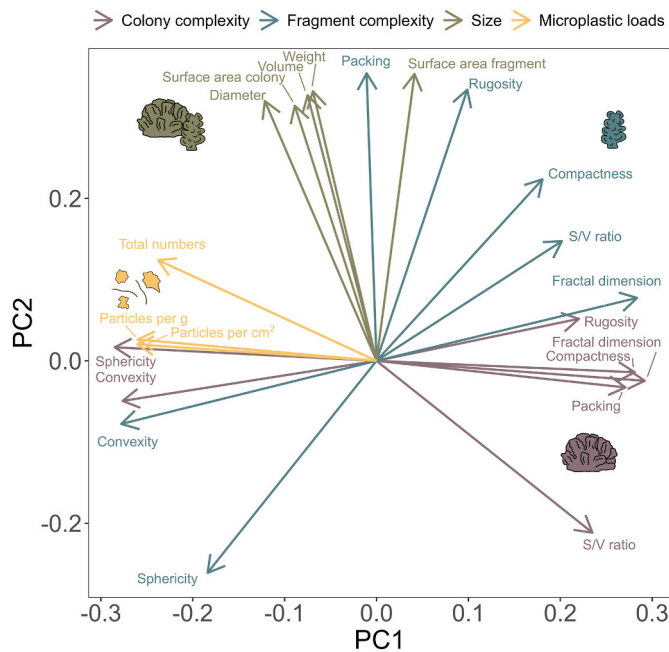
fractal dimension, associated with higher MP loads, indicates simpler, bulkier shapes with fewer intricate branches and more massive branches. This lower complexity likely results in less turbulent, low-speed flow promoting particle accumulation. The lower compactness values, indicating more bulky shapes, associated with higher particle trapping suggest a) a denser, more compact colony morphology. Such shapes might create larger shear layers, reducing water flow around the colony and facilitating particle trapping. Further, the higher convexity associated with higher MP loads indicates solid, rounded shapes such as b) thicker and denser branches. Similarly, higher sphericity suggests a lack of surface complexity, such as fewer fine, intricate branches. Both might lower turbulence and increase particle retention. Additionally, the lower packing associated with higher MP loads indicates c) decreased gaps between the branches of the colony, likely creating more persistent stagnant regions for particle settling. These correlations were consistently found, although not always significant, on the surface and in the tissue, supporting these inferences. In the coral skeleton, these correlations were not detected. There, lower rugosity of the coral fragments was associated with higher MP loads. This might indicate that d) smoother surfaces of coral fragments are more likely to create a more laminar and streamlined flow over their surfaces, promoting particle deposition due to fewer resuspending eddies. However, previous laboratory assessments comparing coral skeletal surfaces with the same surfaces smoothed by wax did not find any differences in the trapping behavior (Yen et al., 2024), suggesting that the spatial complexity at the colony or fragment level is more relevant than the surface structure. At larger scales, however, reef rugosity seems to have a different effect. MPs in coral tissues of *Montastraea cavernosa* and *Orbicella faveolata* increased with reef rugosity (Hankins et al., 2024).

In our study, coral colony size had little effect on particle densities, likely due to the comparable colony dimensions. The only correlation was found in the skeleton, where smaller surface area fragments had more particles, likely due to associated lower rugosity.

However, the number of MPs attached to and deposited in coral tissues and skeletons can be influenced by several environmental factors, like MP concentrations or flow conditions. The shallow, low-flow reef site studied exhibited similar flow across sampling sites; therefore, we believe that flow and light had only a minimal effect on MP availability. Similarly, growth form was unlikely influenced by flow or light, supported by finding different growth forms at the same location (colonies 4 and 5). Thus, shape differences are likely genetic, making this site well-suited for studying MP trapping and deposition independent of environmental parameters.

#### 4.4. Limitations and recommendations for future applications

Although this study encompassed a high number of samples (n = 108), given the low number of particles detected (n = 27), the correlations are only indicative. Future studies are needed to confirm these results using larger sample sizes or in higher-polluted areas. Although the impacts of MPs on corals are commonly species-specific, *Pocillopora* spp. have been found to respond very similarly to MPs. However, we cannot exclude species- or colony-specific effects in the sampled



**Fig. 5.** Principal Component Analysis (PCA) biplot showing the relationship between size and complexity parameters of the coral colony and fragments and microplastic loads. Colors indicate the different categories of parameters. Vector directions and lengths indicate the contribution of each parameter to the principal components. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

*Pocillopora* sp. complex. We did not identify specimens to the species level, as morphological identification of *Pocillopora* spp. in Hawai'i is unreliable without genetic analyses. The sampled colonies likely belong to the species *Pocillopora* cf. *acuta*, which represents ~96 % of the *Pocillopora* species in Kāne'ohe Bay (Johnston et al., 2018).

The lack of standardized analytical procedures (e.g., solutions, units) hinders comparisons across MP studies in coral reefs. Harmonized guidelines are needed for better comparisons and robust impact assessments. Here, we standardized MP loads to coral surface area, which revealed the best correlations (Table S3). We recommend this standardization whenever possible, as this unit is relevant to the coral organism (i.e., the living coral tissue) and allows for better comparison with monitoring parameters, such as coral cover or growth rates. While surface area standardization aids ecological interpretation, we also found consistent results with weight-based standardization (Table S3). However, weight measurements are easily accessible, especially in resource-limited settings, and can therefore provide valuable information for broader monitoring.

Given the limited data, further investigations are needed to understand the role of coral colony complexity in MP deposition. Studies should investigate species-specific patterns and encompass a broader geographical range, including more polluted reefs.

#### 4.5. Implications for coral reefs

Our study showed that despite the overall low MP levels in Kāne'ohe Bay, Hawai'i, corals clearly face MP pollution. Constant exposure can have physiological impacts, like reduced growth, changes in photosynthesis, and energy reserves (López et al., 2025; Reichert et al., 2019; Tang et al., 2018; Tirpitz et al., 2025). Also, constant contact might have chemical impacts as MPs can transfer harmful chemicals (e.g., phthalates, persistent organic pollutants, Saliu et al., 2019). However, low exposure levels likely limit strong impacts on coral physiology or skeletal integrity. Furthermore, our results confirm that corals act as sinks

for MPs in coral reefs, and adhesion appears to be an important process for catching particles from the water column and transporting them to the sediments (Jandang et al., 2024; Martin et al., 2019; Reichert et al., 2022). The finding that lower complexity corals accumulate more particles has implications for reefs. Corals with lower complexity might act as MP sinks. For *Pocillopora* sp. this could mean high-flow environments with massive growth forms are important MP sinks and more susceptible to exposure impacts. Overall reef complexity might also affect MP retention, as more complex reefs accumulate more particles (Hankins et al., 2024; Mendrik et al., 2024). In the light of the low overall MP concentrations at our study location, the observed patterns and subsequent effects might be even stronger in locations with higher pollution, in reefs closer to anthropogenic pressure, in proximity to urban centers, and under higher intensity of human activities. These findings highlight the importance of considering structural complexity when assessing the risk from MP pollution, which is crucial for understanding the long-term ecological risks of this pollutant in coral reef ecosystems.

#### CRediT authorship contribution statement

**Jessica Reichert:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joshua S. Madin:** Writing – review & editing, Resources. **Martina Pierdomenico:** Writing – review & editing, Resources. **Daniel Schar:** Writing – review & editing, Resources. **Silvia Morgana:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

#### Use of generative AI

During the preparation of this work, Gemini, a large language model from Google AI, was used to improve the language of the manuscript. The authors thoroughly reviewed all content and take full responsibility for the content of the published article.

#### Declaration of competing interest

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

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2025.126480>.

#### Data availability

Data and scripts are available at [https://github.com/JessiReichert/MP\\_complexity](https://github.com/JessiReichert/MP_complexity).

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