

Research Article

Microplastic Contamination in Water and Sediment and Occurrence in the Ascidian *Polycarpa aurata* at Malalayang Beach, Manado, Indonesia

Gabriel Suripatty¹, Neviaty Putri Zamani^{2,4*}, Sebastian C. A. Ferse^{3,5,6}, Muhammad Reza Cordova⁷ and Beginer Subhan²

¹PhD Student, Marine Science Study Program, Department of Marine Science and Technology, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, Indonesia

²Department of Marine Science and Technology, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, Indonesia

³Faculty of Fisheries and Marine Sciences, IPB University, Bogor, Indonesia

⁴Center for Transdisciplinary and Sustainability Sciences, IPB University, Bogor, Indonesia

⁵Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany

⁶Marine Ecology Department, Faculty of Biology and Chemistry (FB2), University of Bremen, Bremen, Germany

⁷Research Center for Oceanology, National Research, and Innovation Agency, North Jakarta, Indonesia



ARTICLE INFO

Received: July 07, 2026
Accepted: August 31, 2026
Published: Sept 09, 2026
Available online: Oct 04, 2026

*) Corresponding author:
E-mail: neviaty@apps.ipb.ac.id

Keywords:

Microplastic
Polycarpa aurata
Coral reef
Marine pollution
Biomonitoring



This is an open access article under the CC BY-NC-SA license (<https://creativecommons.org/licenses/by-nc-sa/4.0/>)

Abstract

Marine plastic debris increasingly threatens coral reefs, yet the potential of tropical reef-dwelling filter feeders as microplastic biomonitors remains untested in the Coral Triangle, the global center of marine biodiversity. This study aimed to describe the benthic cover condition, identify microplastic characteristics and abundance in surface water and sediment, quantify microplastic occurrence within the body of the ascidian *P. aurata*, and compare microplastic abundance and composition among compartments and between stations. Sampling was conducted at two stations selected to differ in proximity to a river mouth, hereafter referred to as Near-River and Far-River, at Malalayang Beach, North Sulawesi, Indonesia. At each station, five replicate samples of surface water, five replicate samples of sediment and three *P. aurata* specimens were collected (total n = 10, 10, and 6, respectively). Benthic cover was assessed by underwater photo transect, while microplastics were extracted by wet peroxide oxidation, density separation, and alkaline digestion, then characterized by stereomicroscopy and ATR-FTIR and compared using independent t-tests, Bray-Curtis similarity, and Sorensen indices. Hard coral cover was poor near the river (8.6%) and fair (26.5%) far from the river. Microplastic abundance reached 838 and 790 n m⁻³ in water, 390 and 118 n kg⁻¹ in sediment, and 11.17 and 7.50 n ind⁻¹ in *P. aurata* at the Near-River and Far-River stations, respectively; only sediment differed significantly. Fibers dominated all compartments (76 to 97%), and synthetic elastomers and polyester were the main polymers. Microplastic was consistently found in *P. aurata*, with composition similar to that found in the ambient environment. Microplastic contamination at Malalayang was recorded across all three compartments. *P. aurata* consistently contained microplastics, positioning it as a candidate biomonitor requiring broader validation. Broader multi-station, multi-season validation with larger samples is recommended.

Cite this as: Suripatty, G., Zamani, N. P., Ferse, S. C. A., Cordova, M. R., & Subhan, B. (2026). Microplastic Contamination in Water and Sediment and Occurrence in the Ascidian *Polycarpa aurata* at Malalayang Beach, Manado, Indonesia. *Jurnal Ilmiah Perikanan dan Kelautan*, 18(3):863-886.<https://doi.org/10.20473/jipk.v18i3.93431>

1. Introduction

Marine plastic debris has become a growing global crisis that threatens marine life, ecosystems, and human health (Jambeck et al., 2015; Khanjani et al., 2023; Mamun et al., 2023; Prata et al., 2020). Approximately 80% of marine litter is plastic; global plastic waste has reached around 369 million tons, of which roughly 11 million tons enter the ocean each year, and about 90% originates from land-based sources that reach the sea mainly through rivers and surface runoff (Galgani et al., 2015; Jambeck et al., 2015; Meijer et al., 2021). Once in the ocean, plastics gradually fragment through ultraviolet radiation, hydrolysis, and mechanical abrasion into microplastics, particles smaller than 5 mm (Andrady, 2011; Thompson et al., 2004). When ingested, these particles can induce oxidative stress and impair the digestion, reproduction, and immune function of marine organisms (Chen et al., 2025; Kim et al., 2022; Soliman et al., 2023). Coral reef ecosystems, among the most biodiverse and economically valuable habitats on the planet, are increasingly exposed to this contamination; plastic contact has been reported to raise the likelihood of coral disease from 4% to 89%, with billions of plastic items estimated to be entangled across Asia-Pacific reefs (Lamb et al., 2018; Woodhead et al., 2019). Documenting the extent and behavior of microplastics within reef ecosystems is therefore an urgent prerequisite for their protection.

Studies of microplastic contamination in coral reef ecosystems have expanded rapidly, reporting particle accumulation across surface water, sediment, and reef-associated biota (Bian et al., 2024; Cordova et al., 2018; Lim et al., 2024). In Indonesian reef waters, contamination has been documented in reef sediment and invertebrates in the Thousand Islands and around northern Sulawesi, where fiber-dominated microplastics were recorded in bay sediment, the water column, and bivalves (Imanuel et al., 2022; Kawung et al., 2022; Sulistiowati et al., 2023). These works establish that microplastics are pervasive in tropical reef environments, yet most focus on abiotic matrices or commercially harvested taxa rather than on common resident organisms that could serve as standardized monitoring tools.

Ascidians are sessile filter feeders that capture suspended particles non-selectively and have been proposed as sensitive bioindicators of marine pollution (Rosner and Rinkevich, 2024). They accumulate heavy metals and potentially toxic elements in proportion to ambient levels (Metri, 2019; Tzafri-

ri-Milo et al., 2019), and several species retain microplastics and phthalate plasticizers far more efficiently than co-occurring bivalves (Bonello et al., 2018; Vered et al., 2019). Research on ascidian–microplastic interactions, however, remains concentrated on a few temperate species such as *Ciona robusta* and is dominated by the Mediterranean region, which also hosts exceptionally high ascidian diversity (Messinetti et al., 2018; Shenkar and Swalla, 2011).

Despite this progress, the potential of tropical, reef-dwelling filter feeders as microplastic biomonitors remains largely unexplored, and no such assessment exists for the Coral Triangle, the global center of marine biodiversity. Northern Sulawesi lies within this region and supports more than 600 coral species and 2,600 reef fish species, yet rising anthropogenic activity increasingly loads its coastal waters with land-derived litter (Allen and Erdmann, 2012; Kittinger et al., 2015; Veron et al., 2009). The ascidian *P. aurata* is abundant and widely distributed across reef ecosystems of Wallacea and Sulawesi (Wainwright et al., 2020) and has recently been validated as a passive biomonitor of polymetallic and potentially toxic elements in Indonesian reef waters (Saputri et al., 2026; Turicchia et al., 2025), yet its capacity to record microplastic exposure has not been tested. This study provides a multi-compartment assessment, spanning surface water, sediment, and *P. aurata* soft tissue, of microplastic contamination in a Coral Triangle reef. The novelty lies in this multi-compartment dataset, and the concurrent use of *P. aurata* is treated as a preliminary test of its suitability as a biomonitor. The findings offer baseline contamination data to support reef management and highlight *P. aurata* as a candidate species for future microplastic biomonitoring, pending further validation across broader spatial and temporal scales.

This study aimed to (1) describe the benthic cover condition; (2) identify the characteristics (shape, color, size, and polymer) and abundance of microplastics in the abiotic compartments (surface water and sediment); (3) quantify microplastic occurrence within the soft tissue (excluding tunic) of the ascidian *P. aurata*; and (4) compare microplastic abundance and composition among compartments and between stations, and descriptively contextualize these findings alongside the local benthic cover conditions. The study further examined whether the observed microplastic contamination pattern is consistent with land-derived input entering the reef through river runoff and provides an initial evaluation of *P. aurata* as a potential biomonitor of microplastic exposure in coral reef ecosystems.

2. Materials and Methods

2.1 Materials

2.1.1 Laboratory analysis

The chemical reagents used were potassium hydroxide (KOH), hydrogen peroxide (H₂O₂, 30%), zinc chloride (ZnCl₂), and ethanol (90%), all of analytical grade (Merck, Germany). A ZnCl₂ solution was prepared to a density of 1.7 g mL⁻¹ for density separation. Supporting materials included cellulose-nitrate membrane filters (0.45 µm pore size, 47 mm diameter; Whatman, UK), glass-fiber membrane filters (GF/C, 1.2 µm pore size, 50 mm diameter; Whatman, UK), parafilm, aluminum foil, and double-distilled water (DDW).

2.1.2 Field sampling

Field sampling and analysis used an action camera (Osmo Action 4, DJI, China), a 58 × 44 cm quadrat frame, a 50 m roll meter, a global positioning system unit, a 70 µm plankton net, stainless-steel buckets and scoops, and aluminum-foil bags for sample storage. Benthic images were analyzed with Coral Point Count with Excel extensions (CPCe) software (Kohler and Gill, 2006). Microplastic particles were observed under a stereomicroscope (SZ61, Olympus, Japan), and polymer identification was performed using an attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectrometer (Cary 630, Agilent Technologies, USA).

2.1.3 Ethical approval

This study did not require ethical approval because it did not involve experimental vertebrate animals; the study organism, the ascidian *P. aurata*, is a non-protected marine invertebrate.

2.2 Methods

2.2.1 Study area

The study was conducted from November 2025 to April 2026 at Malalayang Beach, Manado, North Sulawesi, Indonesia. Two stations were established, differing in proximity to a river mouth: a Near-River station adjacent to river runoff (124°47'32"E, 1°27'40"N) and a Far-River station distant from the mouth of Malalayang River (124°47'53"E, 1°27'41"N). The two stations were separated by approximately 700 m (Figure 1). At each station, a 50 m line transect was established parallel to the shoreline at a depth of approximately 6 m, serving as the basis for both benthic cover assessment and microplastic sample collection.

Benthic cover, surface water, sediment, and the ascidian *P. aurata* were sampled at each station, with five replicates taken for the water and sediment compartments and three specimens of *P. aurata* collected per station.

2.2.2 Benthic cover assessment

Benthic community data were collected using the Underwater Photo Transect (UPT) method at a depth of approximately 6 m (English *et al.*, 1997; Giyanto *et al.*, 2014). A 50 m transect line was laid parallel to the shoreline, and images were captured at 1 m intervals alternating to the left and right of the transect line, yielding 50 frames per station (Giyanto *et al.*, 2014). The images were processed in CPCe, in which 30 random points were overlaid on each frame to estimate percentage cover via point-counting (Kohler and Gill, 2006). The percentage cover of each category per frame was calculated using Equation 1, and the resulting values from the 50 frames per station were averaged to obtain the mean percentage cover for each category at the station level. The standard error (SE) of the mean percentage cover was calculated from the variation among the 50 frames within each station. Comparisons of benthic cover among stations were presented descriptively:

$$\% \text{ Cover} = (\text{Number of points per category}) / (\text{Total number of random points}) \times 100\% \dots\dots\dots(i)$$

Benthic components were classified into hard coral (HC), soft coral (SC), dead coral (DC), dead coral with algae (DCA), sponge (SP), fleshy seaweed (FS), other biota (OT), rubble (R), sand (S), and silt (Si). Reef health status was assigned from live hard coral cover into four categories, namely poor (0-24.9%), fair (25-49.9%), good (50-74.9%), and excellent (>75%) (Madduppa and Zamani, 2011). Hard-coral growth forms were further identified as *Acropora* and non-*Acropora* (English *et al.*, 1997). The *Acropora* group consisted of branching (ACB), digitate (ACD), and encrusting (ACE) forms, whereas the non-*Acropora* group comprised branching (CB), encrusting (CE), foliose (CF), massive (CM), mushroom (CMR), and submassive (CS) forms.

2.2.3 Microplastic sampling

Surface water and sediment were sampled along the same transect used for benthic cover assessment, divided into five consecutive 10 m segments (0-10 m, 10-20 m, 20-30 m, 30-40 m, and 40-50 m). One water sample and one sediment sample were collected haphazardly within each segment, yielding five replicates per compartment per station. Surface water was

sampled at a depth of 0-30 cm below the surface by filtering 50 L through a 70 μm plankton net, establishing a minimum operational size limit of 70 μm for water samples. The net was rinsed so that all retained particles were transferred into 250 mL glass bottles, which were sealed, labeled, stored in a cool box with ice packs during transport, and refrigerated until analysis (Kılıç et al., 2024). Sediment was collected by SCUBA diving, in which approximately 400 g was taken from the 0–5 cm surface layer using a stainless-steel scoop, stored in aluminum-foil bags, and kept cold until analysis (Cordova, 2021; Cordova et al., 2018). Specimens of *P. aurata* (5-7 cm) were collected with forceps at the same stations, preserved in 90% ethanol, and stored in a cool box with ice packs until further analysis (Turicchia et al., 2025; Vered et al., 2019).

by stirring thoroughly with a contamination-free stainless-steel spoon in a glass container, and a 200 g portion was oven-dried (50°C, 48 h) and sieved (4.75 mm). A 100 g subsample was then mixed with 250 mL of ZnCl_2 (1.7 g mL^{-1}) and left to settle for 24 h. The supernatant was filtered, the sediment was re-washed with ZnCl_2 to recover residual particles, and the collected filters were then digested by WPO following the same procedure as for water (Masura et al., 2015; Sulistiowati, et al., 2023). For *P. aurata*, the soft tissue (excluding the tunic) was cut into small pieces and placed in a 200 mL container. The soft tissue was digested in 10% KOH at 50°C for 24 h until the solution became clear with no soft tissue residue, and was then filtered onto a 1.2 μm glass-fiber filter (Rojas-Luna et al., 2025; Turicchia et al., 2025; Vered et al., 2019).

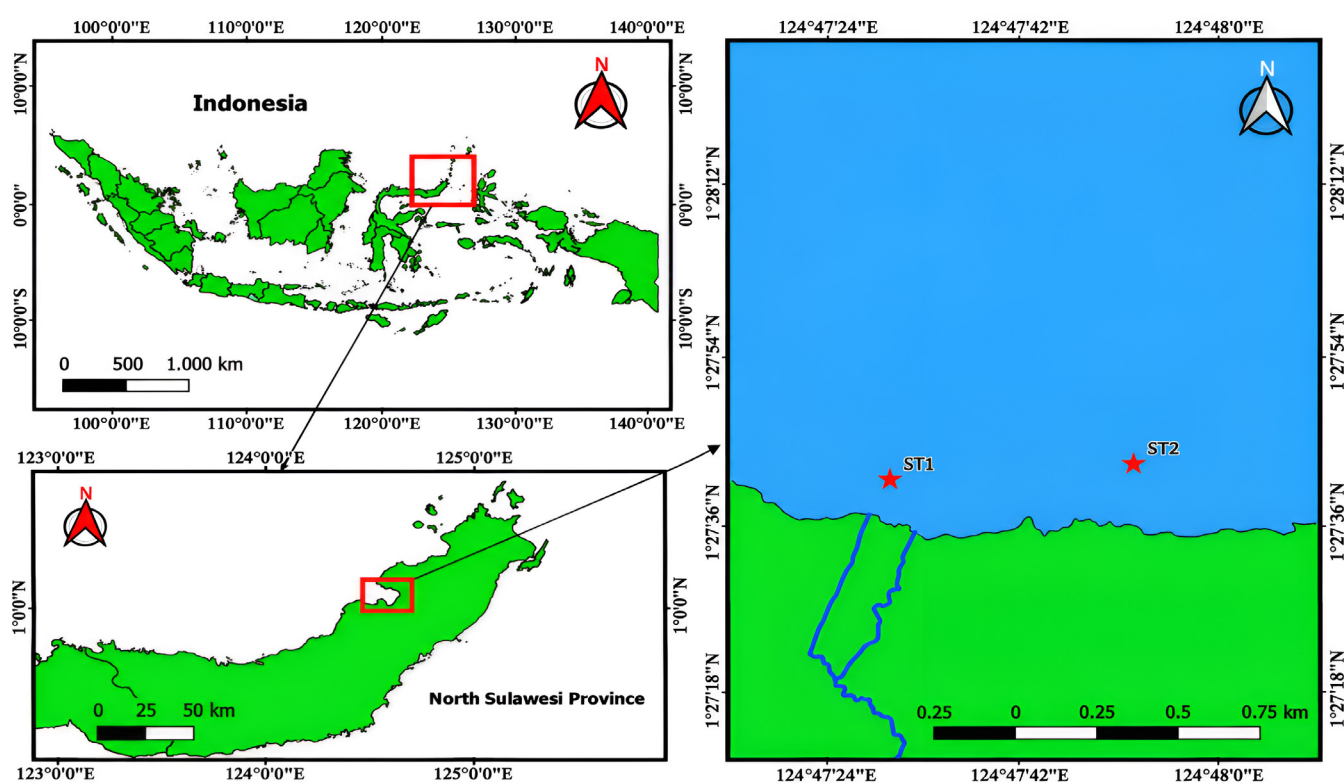


Figure 1. Map of the study area showing the two sampling stations (Near-River and Far-River) in the coral reef ecosystem of Malalayang Beach, Manado City, North Sulawesi, Indonesia.

2.2.4 Microplastic extraction

For surface water, the sample was first filtered through a vacuum pump onto a 0.45 μm cellulose-nitrate filter. The filter was then placed in a screw-cap tube, and 25 mL of 30% H_2O_2 was added for wet peroxide oxidation (WPO) to degrade organic matter. The mixture was left for 24 h until the solution became clear and was then re-filtered onto a new 0.45 μm cellulose-nitrate filter, with the previous filter rinsed to ensure that all particles were transferred (Cordova, 2021; Hidalgo-Ruz et al., 2012; Masura et al., 2015). For sediment, 400 g of wet sediment was well-mixed

All final filters were sealed and air-dried before observation.

2.2.5 Microplastic identification

Identification was carried out in three stages, namely visual observation, confirmation of the plastic nature of the particles, and polymer identification. Particles were first observed under the stereomicroscope (SZ61, Olympus, Japan) and identified as microplastics based on color uniformity, the absence of cellular structures, and unsegmented morphology (Hidalgo-Ruz et al., 2012; Nor and Obbard, 2014).

Suspected particles were then confirmed using the hot-needle test, in which particles that melted or curled were retained and non-responsive particles were discarded (De Witte *et al.*, 2014). Each confirmed particle was then classified into standard categories for shape (fiber, fragment, film, foam and pellets), color, and size class (<200, 200-500, 500-1000, and 1000-5000 μm), with its longest dimension measured (Wang *et al.*, 2020). Polymer types were determined by ATR-FTIR (Cary 630, Agilent Technologies, USA) over 4000–650 cm^{-1} , and the recorded spectra were matched against a reference polymer spectral library to yield a spectral hit quality index indicating similarity to the reference library. A polymer was assigned when the hit quality index reached at least 70% (Jung *et al.*, 2018; Woodall *et al.*, 2014). Polymer identification was attempted on all confirmed particles; however, only a subset could be successfully retrieved and analyzed by ATR-FTIR.

2.2.6 Quality assurance and quality control

Measures were taken to minimize contamination at every handling and analysis step (Munno *et al.*, 2023). Plastic tools were replaced with stainless-steel or glass equivalents, all reagents were pre-filtered, sample containers were covered with aluminum foil, and work surfaces were cleaned before use. Analyses were run in batches (water, sediment, and *P. aurata*), each accompanied by an air blank of DDW opened during sample handling. Blank filters were processed identically to the samples, and the number, shape, and color of blank particles were recorded and used to correct sample abundances.

2.3 Analysis Data

Microplastic abundance was expressed as number of particles per cubic meter (n m^{-3}) for water, particles per kilogram dry weight ($\text{n kg}^{-1} \text{DW}$) for sediment, and particles per individual (n ind^{-1}) for *P. aurata*, and was reported as mean $\pm$ standard deviation, whereas benthic cover was reported as mean $\pm$ standard error. All tests were performed at a 95% confidence level ($\alpha = 0.05$). Data normality was assessed using the Shapiro–Wilk test: both stations met the assumption for water (Near-River $p=0.363$; Far-River $p=0.111$) and sediment (Near-River $p=0.593$; Far-River $p=0.967$), while for *P. aurata* the Near-River group met the assumption ($p=0.298$) but the Far-River group showed a significant deviation ($p<0.001$); given the very small sample size ($n=3$ per station), the Shapiro–Wilk test has limited power at this scale, and the independent two-sample t-test was retained on the grounds that it is generally robust to moderate deviations from normality with small, balanced sam-

ples. Homogeneity of variance was assessed using Levene's test, and variances were homogeneous for water ($p=0.513$), sediment ($p=0.085$), and *P. aurata* ($p=0.759$). Differences in microplastic abundance between the Near-River and Far-River stations were tested separately for each compartment using an independent two-sample t-test. As each station was represented by a single sampling location, the resulting comparisons should be interpreted as differences between these two specific stations rather than as a generalized test of river-proximity effects. Particle counts per replicate were standardized to relative composition (%) to account for differences in total particle abundance among samples, and the compositional similarity of particle shape was quantified using the Bray-Curtis index (Bray and Curtis, 1957) calculated at the replicate level; differences in shape composition were tested using PERMANOVA and ANOSIM (999 permutations, Bray-Curtis dissimilarity) (Anderson, 2001; Clarke, 1993), comparing among compartments and between stations. Polymer identification was performed on a non-randomly selected subset of confirmed particles (69 of 767), representing the maximum number that could be successfully retrieved and analyzed by ATR-FTIR (Cary 630, Agilent Technologies, USA). Because polymer counts were pooled across replicates and stations within each matrix, only a single composite value was available per compartment ($n=3$ units total: water, sediment, ascidian), precluding replication-based significance testing; polymer composition was therefore analyzed descriptively using the Sorensen index (presence/absence of polymer types between compartment pairs), without formal significance testing (Dice, 1945; Sørensen *et al.*, 1948). Mean hard coral cover and mean microplastic abundances per compartment were available only at the “station” level ($n=2$) and relationships could therefore not be tested statistically; values of coral cover are reported descriptively alongside the microplastic results, without implying a tested relationship.

3. Results and Discussion

3.1 Results

3.1.1 Coral reef condition

Benthic cover at both stations comprised ten components, namely hard coral (HC), soft coral (SC), dead coral (DC), dead coral with algae (DCA), sponge (SP), fleshy seaweed (FS), other biota (OT), rubble (R), sand (S), and silt (Si) (Figure 2). Hard coral cover was $8.6 \pm 1.8\%$ at the Near-River station and $26.5 \pm 2.8\%$ at the Far-River station, corresponding to poor and fair reef health status, respectively. Dead coral with algae was the largest component at both stations,

reaching $29.9 \pm 2.6\%$ at Near-River and $33.1 \pm 2.3\%$ at Far-River, whereas recent dead coral remained low at $1.1 \pm 0.5\%$ and $1.2 \pm 0.6\%$. Fleishy seaweed cover was higher at Near-River ($24.9 \pm 2.3\%$) than at Far-River ($14.3 \pm 1.7\%$) (Figure 3a), and sponge cover was likewise higher at Near-River ($9.7 \pm 1.4\%$) than at Far-River ($3.9 \pm 0.9\%$). Among the abiotic components, sand was more abundant at Near-River ($22.3 \pm 2.4\%$) than at Far-River ($5.7 \pm 1.1\%$) (Figure 3b), whereas rubble was higher at Far-River ($10.1 \pm 2.7\%$) than at Near-River ($1.5 \pm 0.5\%$). Soft coral, other biota, and silt each accounted for less than 4% at both stations.

Hard coral growth forms comprised nine lifeforms distributed across the *Acropora* and non-*Acropora* groups (Figure 4). The *Acropora* group was absent at the Near-River station but present at the Far-River station, where it reached a total cover of 7.3% and was dominated by branching *Acropora* ($5.9 \pm 2.3\%$) (Figure 3c). Massive coral was the dominant growth form at both stations, with higher cover at Far-River ($10.1 \pm 1.7\%$) than at Near-River ($4.2 \pm 1\%$) (Figure 3d). The remaining non-*Acropora* lifeforms occurred at low cover at both stations, with detailed values presented in Figure 4.

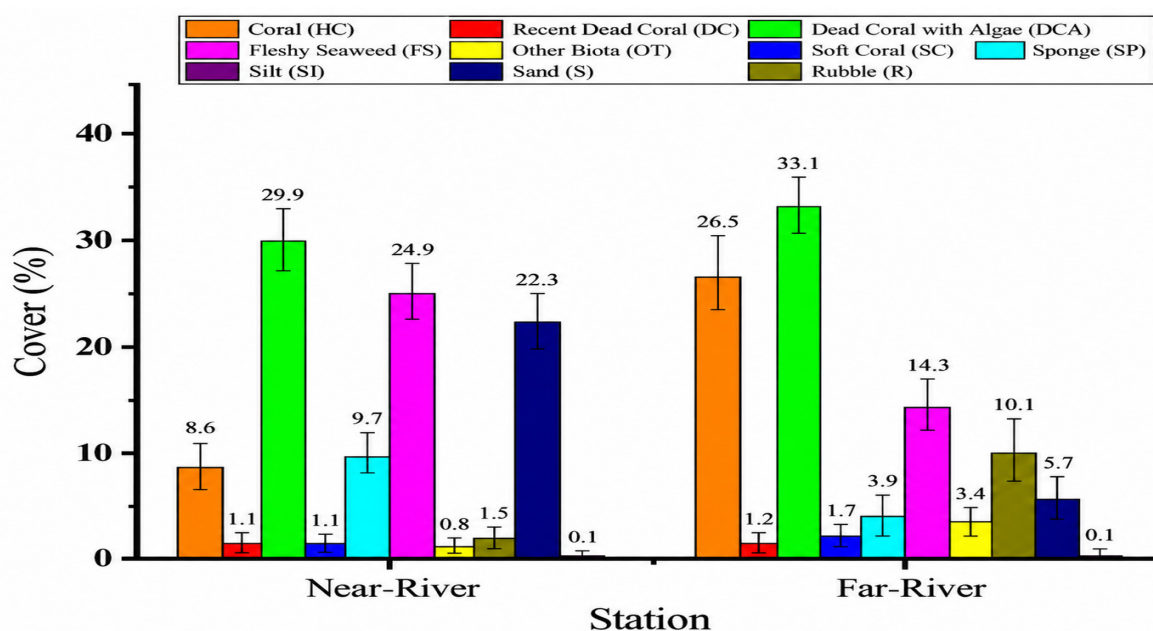


Figure 2. Percentage cover (mean $\pm$ SE) of benthic community components at the Near-River and Far-River stations, Malalayang Beach. Error bars represent SE calculated from variation among the 50 photo frames within each station.

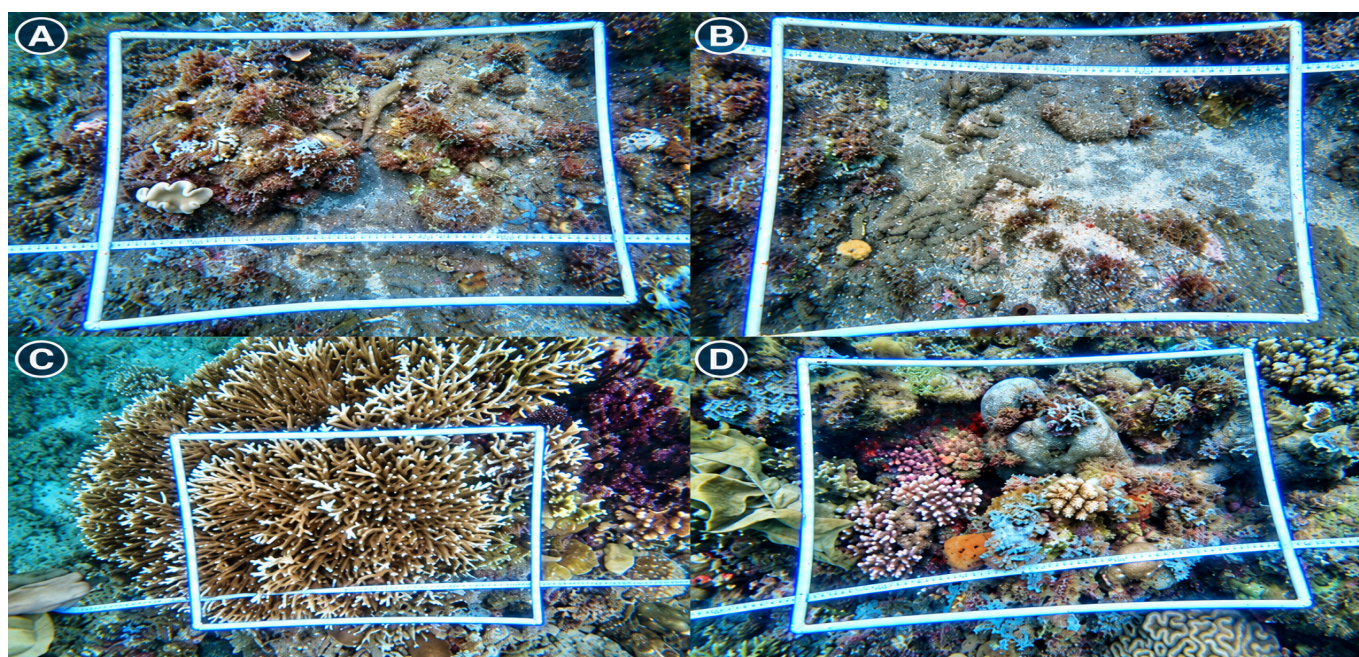


Figure 3. Representative benthic cover at the study sites. (a) Near-River station illustrating high algal cover on dead coral. (b) Near-River station illustrating sandy substrate. (c) Far-River station illustrating *Acropora* branching forms. (d) Far-River station illustrating another non-*Acropora* forms.

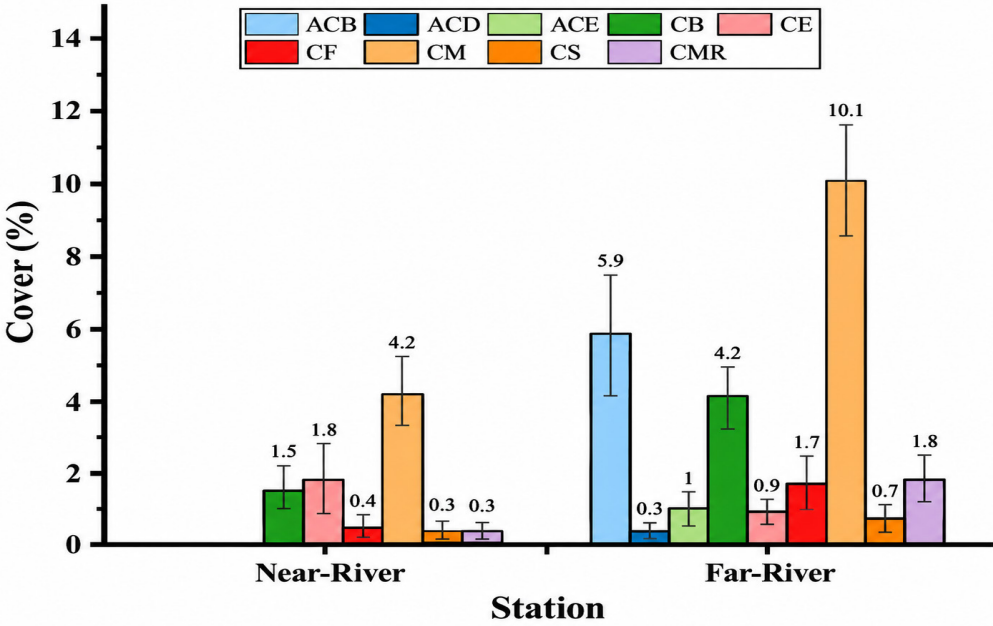


Figure 4. Relative cover (%; mean $\pm$ SE) of hard-coral growth forms at the Near-River and Far-River stations, Malalayang Beach. Acropora forms: ACB, branching; ACD, digitate; ACE, encrusting. Non-Acropora forms: CB, branching; CE, encrusting; CF, foliose; CM, massive; CMR, mushroom; CS, submassive. Error bars represent SE calculated from variation among the 50 photo frames within each station.

3.1.2 Microplastic abundance

All abundance values reported here were corrected against procedural blanks, which averaged 2.10 particles per water sample, 2.20 particles per sediment sample, and 1.17 particles per *P. aurata* sample. Microplastic abundance in surface water was 838 ± 191 n m⁻³ at the Near-River station and 790 ± 317 n m⁻³ at the Far-River station, and the difference between stations was not significant (t-test, $t = 0.29$, $df = 8$, $p = 0.78$, Cohen's $d = 0.18$) (Figure 5).

In the sediment, abundance was 390 ± 74 n kg⁻¹ DW at the Near-River station and 118 ± 32 n kg⁻¹ DW at the Far-River station, and this difference was significant (t-test, $t = 7.59$, $df = 8$, $p < 0.0001$, Cohen's $d = 4.77$). The microplastic contamination in the soft tissue of *P. aurata* was 11.17 ± 3.21 n ind⁻¹ at the Near-River station and 7.50 ± 2.31 n ind⁻¹ at the Far-River station, and this difference was not significant (t-test, $t = 1.61$, $df = 4$, $p = 0.18$, Cohen's $d = 1.31$).

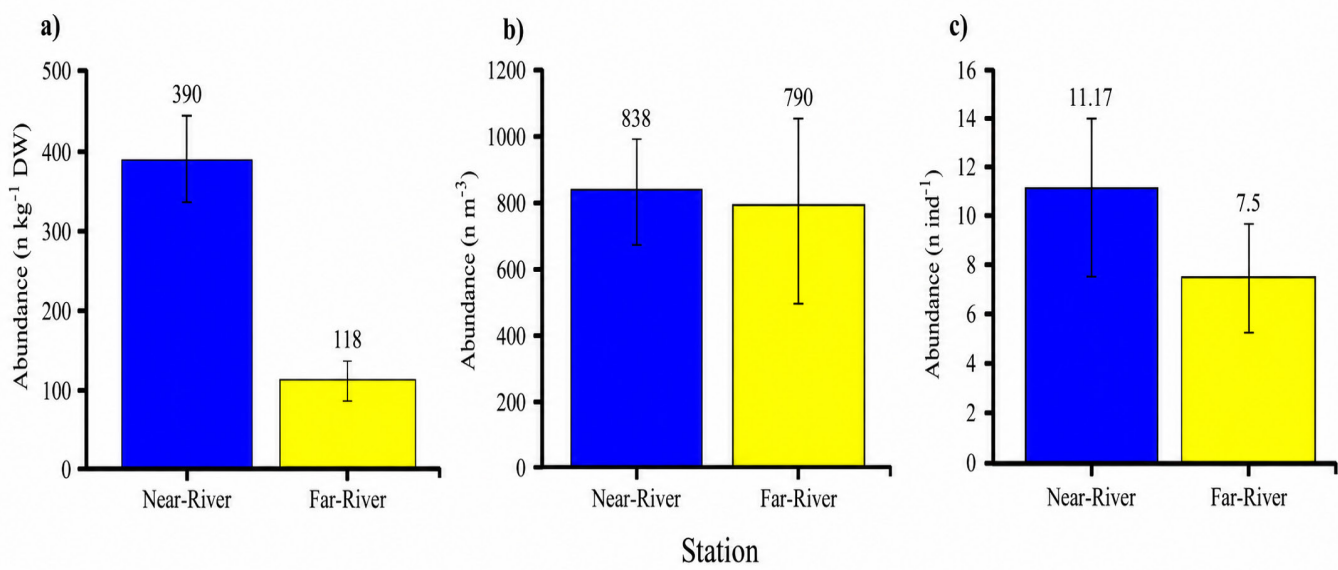


Figure 5. Microplastic abundance (mean $\pm$ standard deviation) at the Near-River and Far-River stations in (a) sediment: 390 ± 74 vs 118 ± 32 n kg⁻¹ dry weight; (b) surface water: 838 ± 191 vs 790 ± 317 n m⁻³; and (c) the ascidian *P. aurata*: 11.17 ± 3.21 vs 7.50 ± 2.31 n ind⁻¹.

Microplastic abundance was therefore comparable between stations in the surface water and in *P. aurata*, but markedly higher in the sediment at the Near-River station. However, the lack of statistical significance should not be interpreted as absolute equivalence between the two stations, given the small sample size. A compiled overview of microplastic contamination across global coral reef environments is presented in Figure 6.

largest size class (class D, 1000-5000 μm) held the highest single proportion, at around 30 to 36%, most particles were smaller than 1000 μm , as the cumulative proportion of classes A to C reached about 64 to 70%. The smallest class (class A, <200 μm) was the least frequent. Among the matrices, the mean particle size was larger in *P. aurata* (1085.6 μm) and sediment (996.3 μm) than in surface water (826.0 μm).

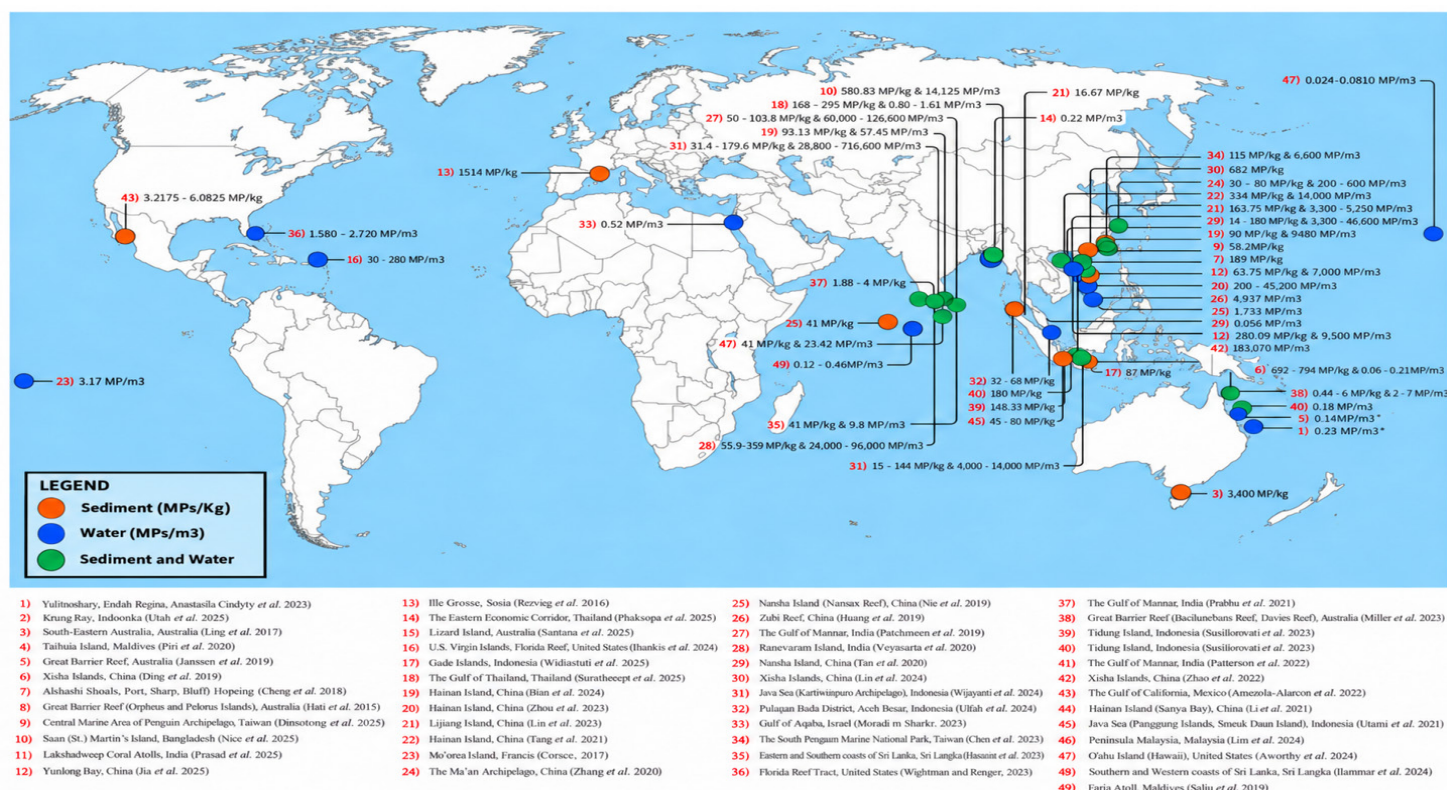


Figure 6. Global distribution of reported microplastic abundance in coral reef ecosystems compiled from published studies.

3.1.3 Microplastic characteristics

Three microplastic shapes were identified across all matrices, namely fiber, fragment, and film, whereas foam and pellet were not found. Representative particles of each shape are shown in Figure 7. Fiber was the dominant shape in every matrix, generally ranging from about 76 to 97%, followed by fragment. Film was the least common shape, accounting for less than 7%, and was absent from *P. aurata* at both stations and from sediment at the Far-River station. The proportion of fiber increased from surface water to sediment and was highest in *P. aurata* (Figure 8).

Particle size ranged from 14.9 to 4751.1 μm across all matrices, with an overall mean of 908.6 $\mu\text{m} \pm 837.35 \mu\text{m}$ (Figure 9). The minimum recorded size of 14.9 μm was found in the sediment compartment, consistent with their finer filter pore limits (0.45 μm for sediment and 1.2 μm for *P. aurata*, respectively), whereas all particles recovered from surface water exceeded the 70 μm mesh limit. Although the

Nine color categories were recorded (Figure 10). Blue was the dominant color overall, at around 31 to 36%, and was the most abundant color in surface water and sediment at both stations. Transparent and red formed the next most common group, followed by black, whereas the remaining colors each accounted for less than 5%. In *P. aurata*, black was the dominant color, at around 40 to 46%.

Of the 767 confirmed particles, 69 (9%) were successfully recovered and assigned a polymer type, comprising 7% of the particles in surface water, 9.1% in sediment, and 22.2% in *P. aurata* (Figure 11). The five most abundant polymers overall were ethylene-propylene rubber (EPM, 17.4%), polyester (PES, 15.9%), ethylene propylene diene monomer rubber (EPDM, 10.1%), chlorobutyl rubber (CIIR, 8.7%), and polytetrafluoroethylene (PTFE, 8.7%). Among the matrices, EPM and PES were the main polymers in sediment, whereas PES was the largest component in *P. aurata*, followed by EPDM, EPM, and polypropylene (PP).

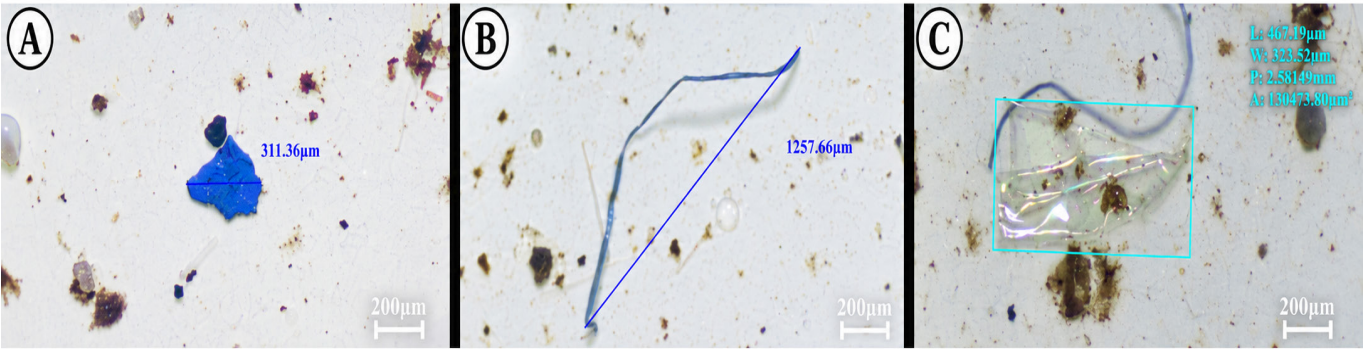


Figure 7. Representative photomicrographs of microplastic morphotypes recovered from Malalayang Beach: (a) fragment, (b) fiber, and (c) film.

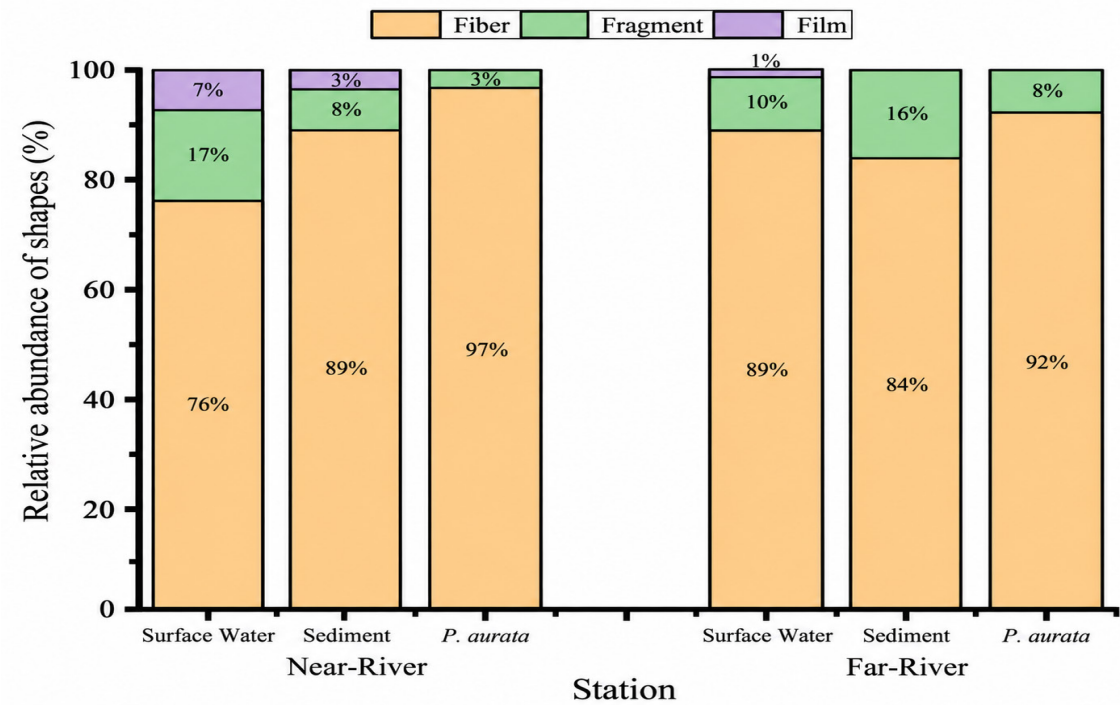


Figure 8. Relative abundance (%) of microplastic shapes (fiber, fragment, and film) in surface water, sediment, and the ascidian *P. aurata* at the Near-River and Far-River stations, Malalayang Beach.

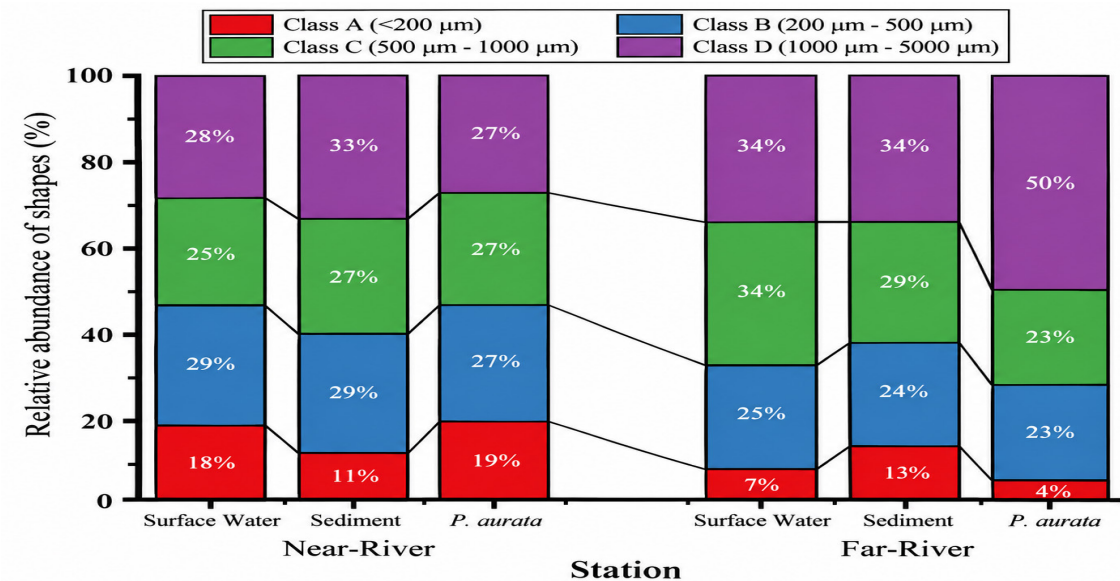


Figure 9. Relative abundance (%) of microplastic size classes (<200, 200–500, 500–1000, and 1000–5000 µm) in surface water, sediment, and the ascidian *P. aurata* at the Near-River and Far-River stations, Malalayang Beach.

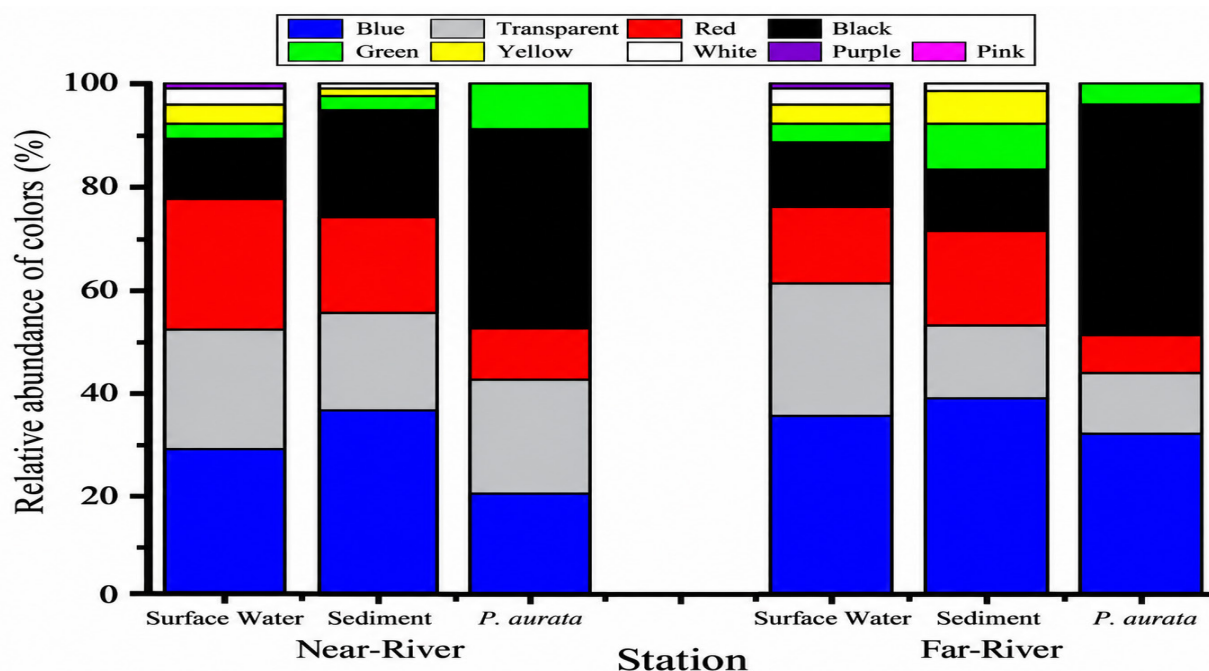


Figure 10. Relative abundance (%) of microplastic colors (blue, transparent, red, black, green, yellow, white, purple, and pink) in surface water, sediment, and the ascidian *P. aurata* at the Near-River and Far-River stations, Malalayang Beach.

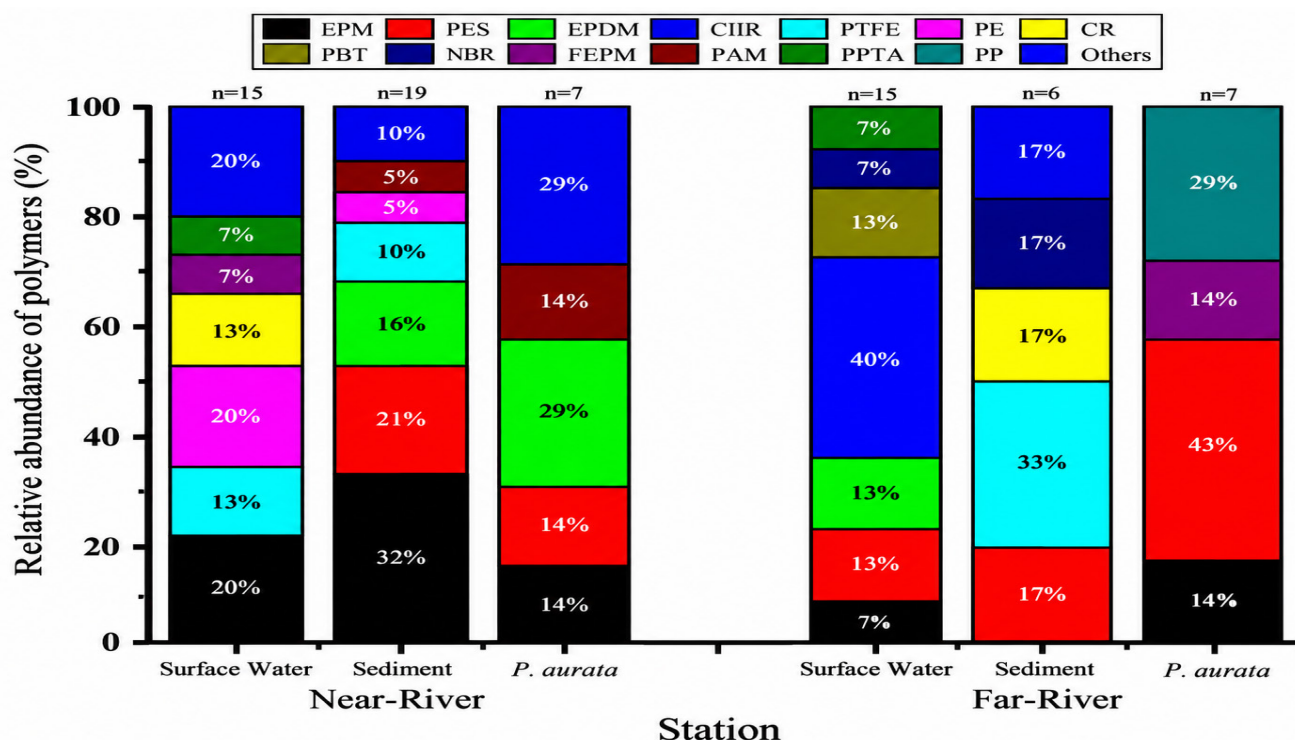


Figure 11. Relative abundance (%) of microplastic polymer types in surface water, sediment, and the ascidian *P. aurata* at the Near-River and Far-River stations, Malalayang Beach. Polymers detected in at least two particles are shown individually; the remaining rare polymers detected as single particles (PET, PU, FKM, EAA, SBR, EVOH, NR, and PAK) are grouped as “Others”. Sample sizes (n) are shown above each bar. EPM, ethylene-propylene rubber; PES, polyester; EPDM, ethylene-propylene-diene monomer rubber; CIIR, chlorobutyl rubber; PTFE, polytetrafluoroethylene; PE, polyethylene; CR, polychloroprene; PBT, polybutylene terephthalate; NBR, nitrile butadiene rubber; FEPM, tetrafluoroethylene-propylene rubber; PAM, polyacrylamide; PPTA, para-aramid; PP, polypropylene; PET, polyethylene terephthalate; PU, polyurethane; FKM, fluoroelastomer; EAA, ethylene-acrylic acid copolymer; SBR, styrene-butadiene rubber; EVOH, ethylene vinyl alcohol copolymer; NR, natural rubber; PAK, polyacrylate.

3.1.4 Compositional similarity among compartments

The compositional similarity of microplastic shapes (fiber, fragment, and film) was compared among the three compartments (surface water, sediment, and *P. aurata*) and between the two stations using Bray-Curtis dissimilarity. Multivariate analyses revealed no significant differences in shape composition among the compartments (PERMANOVA: pseudo-F = 2.54, $p = 0.089$; ANOSIM: $R = 0.058$, $p = 0.159$). Similarly, no significant differences were observed between the Near-River and Far-River stations when all compartments were pooled (PERMANOVA: pseudo-F = 1.06, $p = 0.330$; ANOSIM: $R = -0.013$, $p = 0.523$). Further tests evaluating the spatial differences within each compartment separately also yielded non-significant results for surface water ($p = 0.125$), sediment ($p = 0.165$), and *P. aurata* ($p = 1.0$). These statistics demonstrate that the morphological composition, which was heavily dominated by fibers (76–97%), remained strictly uniform across the reef environment regardless of the matrix or proximity to the river. For polymer composition, the proportion of shared polymer types was about 56% between surface water and sediment, 42% between sediment and *P. aurata*, and 36% between surface water and *P. aurata*.

3.2 Discussion

3.2.1 Coral reef condition and land-based pressure

Hard coral cover classified the Near-River station as poor and the Far-River station as fair, a contrast that is consistent with differences in proximity to the river mouth, although other site-specific factors cannot be excluded. The Near-River station, which receives direct river runoff, supported lower coral cover and a benthic community dominated by macroalgae, dead coral with algae, and sand, whereas the Far-River station retained higher coral cover and branching *Acropora*. Terrestrial runoff delivers sediment and dissolved nutrients that remain among the most widespread drivers of nearshore reef degradation, acting through smothering, light reduction, and the inhibition of coral recruitment (Bhuyan *et al.*, 2025; Rogers and Ramos-Scharrón, 2022). The benthic coverage at the Near-River station aligns with literature describing the combined effects of sedimentation and nutrient enrichment rather than a single stressor (Arias-González *et al.*, 2017; Liu *et al.*, 2015; Sura *et al.*, 2021).

Macroalgae and dead coral with algae dominated the Near-River station, a benthic configuration characteristic of nutrient-enriched reefs. Under ele-

vated nutrients, fleshy macroalgae gain a competitive advantage over hard coral, overgrow and shade coral tissue, and inhibit the settlement and survival of coral recruits, reinforcing a shift toward an algae-dominated state (Adam *et al.*, 2021; Gallagher *et al.*, 2026). The higher proportion of sand at this station reduces light availability and lowers recruitment success, whereas the greater rubble cover at the Far-River station may reflect natural fragmentation of its more abundant branching coral, as well as potential physical disturbances such as anchoring or destructive fishing (Bhuyan *et al.*, 2025; Kenyon *et al.*, 2023).

Coral morphology also differed between the two stations. Massive growth forms dominated both stations and were the only substantial coral component at the Near-River station, whereas *Acropora* was absent there but present at the Far-River station, which was surveyed at the same 6 m depth contour. This distribution is consistent with morphology-specific tolerance to turbidity and sedimentation, in which massive corals such as *Porites* better reject sediment and sustain heterotrophic feeding under low light, while complex branching forms such as *Acropora* are more susceptible to smothering and reduced recruitment (Bessell-Browne *et al.*, 2017; Erfemeijer *et al.*, 2012; Zweifler *et al.*, 2024). The prevalence of massive corals at the Near-River may reflect a community shift toward sediment-tolerant taxa, a pattern that has also been noted in some other runoff-influenced reefs (Browne *et al.*, 2019; Hongo and Yamano, 2013).

3.2.2 Morphological and polymer characteristics of microplastics

The morphology of the recovered particles offers the first indication of their likely origin. Statistical analyses indicated no statistically significant difference in shape composition across the entire reef environment, with fiber proportion increasing from surface water through sediment to *P. aurata* soft tissue. Fragments were consistently subordinate and film remained a minor component, and neither foam nor pellet was detected. A fiber-dominated assemblage of this kind is widely interpreted as a signature of secondary microplastics produced by the shedding of synthetic textiles during domestic laundering and by the abrasion of ropes, nets, and lines used in fishing and small-boat activity (Browne *et al.*, 2011; Napper and Thompson, 2016). The subordinate fragment fraction is consistent with a secondary origin from the progressive breakdown of larger, rigid plastic items such as bottles, caps, and household containers, which embrittle and microcrack under combined ultraviolet,

thermal, and mechanical weathering (Andrady, 2011; Lin et al., 2024a). The minor film component most plausibly derives from the fragmentation of thin, flexible plastics, single-use carrier bags and packaging wrap, whose photo- and mechanochemical degradation yields sheet-like particles in coastal waters and sediments; its low contribution is consistent with the limited packaging-derived input also inferred from the absence of foam (Kalogerakis et al., 2017; Kuroda et al., 2024). The absence of pellets, which are typical of industrial feedstock, together with the absence of foam, which is characteristic of expanded polystyrene packaging, indicates that primary and packaging-derived inputs were minor at Malalayang (James et al., 2026).

Blue was the dominant color in surface water and sediment, followed by transparent and red, whereas *P. aurata* body was dominated by black particles. A predominance of blue fibers in water and biota has been documented across diverse environmental compartments and is commonly attributed to the widespread use of blue dyes in denim and synthetic fishing gear (De Haan et al., 2026). Comparable color profiles, in which blue, transparent and black fibers are the most frequently recorded, have been reported for commercially important fish from the Adriatic Sea, a recognized marine-litter accumulation area (Santonicola et al., 2025). The substantial transparent fraction is consistent with a mixture of unpigmented fibers and particles that have lost color through photodegradation and prolonged environmental weathering (De Haan et al., 2026; Zhao et al., 2022). The shift toward black particles in *P. aurata*, despite blue being dominant in the surrounding water and sediment, indicates that color composition does not transfer directly between compartments, and the underlying mechanism remains unclear from the present data (Harel et al., 2024; Mattsson et al., 2023).

Particle size reinforced the depositional behavior inferred from the morphological data. Recovered particles ranged from 14.9 to 4751.1 μm , and although the coarsest size class held the highest single proportion, most particles fell below 1000 μm . This distribution is partly a corollary of the fiber-dominated assemblage described above, as fibers are elongated and generally register a greater maximum dimension than the more compact fragment and film particles. Mean size increased from surface water through sediment to *P. aurata* inner body. The compartments differed in their operational lower-size limits, with water constrained by the 70 μm collection mesh while sediment and tissue were processed with finer laboratory filters. This difference likely contributed to the observed size gradient, alongside any prefer-

ential settling of larger particles in the benthic compartments. Documenting the size distribution is analytically important because particle size is a widely recognized determinant of microplastic bioavailability in aquatic environments, influencing the range of organisms able to ingest particles and their subsequent environmental behavior (Browne et al., 2008; Enyoh et al., 2020; Nawaz et al., 2025).

The polymer composition offers plausible clues about the contributing sources. Synthetic elastomers were prominent among the typed particles, with ethylene-propylene rubber, ethylene-propylene-diene monomer rubber, and chlorobutyl rubber together forming a substantial share that is characteristic of tire and road-wear particles and of general rubber goods, pointing to vehicular traffic, road runoff, and harbor and boating infrastructure as contributors (Boucher and Friot, 2017; Kole et al., 2017). Although synthetic elastomers like EPM possess a specific gravity lower than seawater (e.g., $\sim 0.85\text{--}0.90\text{ g/cm}^3$) and should theoretically float, their high abundance in the sediment matrix is a widely documented phenomenon. This deposition is driven by rapid environmental modification; specifically, colonization by marine biofilms (Kaiser et al., 2017; Kooi et al., 2017) and heteroaggregation with denser suspended mineral particulates characteristic of river runoff (Michels et al., 2018; Summers et al., 2024). These interactions increase the effective density of the microplastics, overcoming their natural buoyancy and facilitating vertical deposition into the reef sediment. Polyester, the leading polymer in *P. aurata* inner body, is a mainstay of synthetic textiles plausibly linked to domestic wastewater as a fiber source (Vassilenko et al., 2021), while polypropylene reflects widely used packaging and consumer products (Khoironi et al., 2020). Considered together with the fiber-dominated morphology and the blue and black color profile, the polymer spectrum suggests a potential contribution from the mixed land use of a peri-urban coastal setting, in which domestic effluent, road runoff, and small-scale fisheries operate as the principal contributors (Boucher and Friot, 2017; Kumar et al., 2025; Yona et al., 2019). Only about one-tenth of confirmed particles could be assigned to a polymer type, from a non-randomly selected subset, so this polymer-based source inference is best regarded as indicative.

Collectively, characterizing these morphotypes, namely shape, color, size, and polymer composition, is essential rather than merely descriptive, because each attribute governs the bioavailability of microplastics and the way aquatic organisms encounter, ingest, and respond to them. Color influences selective uptake by visually feeding species;

for example, the planktivorous Amberstripe scad (*Decapterus muroadsi*) preferentially ingested blue microplastics resembling its copepod prey in the clear waters around Rapa Nui (Ory *et al.*, 2017). Size determines ingestibility, as shown in four Atlantic reef-building corals whose active ingestion depended on the interaction between microplastic size and polyp calyx size, with larger-calyx species taking up larger particles while the smallest particles offered were rejected by all species (Hankins *et al.*, 2022). Shape modulates retention and injury: fibers accumulated in the zebrafish gut far more than fragments or beads and produced the most severe intestinal toxicity, including mucosal damage, increased permeability, and inflammation (Qiao *et al.*, 2019). Polymer identity further shapes the biological response, as polyethylene microparticles of 10 to 40 μm induced oxidative stress and gut-microbiome dysbiosis in larval zebrafish, effects attributable to the chemical nature of the polymer rather than to physical blockage alone (Kurchaba *et al.*, 2020). Read together, these findings indicate that the fiber-dominated, predominantly blue and black, sub-millimeter, polyester- and rubber-rich assemblage characterized here combines several of the attributes most consistently linked to ingestion and sublethal stress in aquatic biota, underscoring why detailed morphotype and polymer characterization is integral to interpreting the ecological significance of microplastic contamination at Malalayang.

3.2.3 Microplastic distribution in the water and sediment

Sediment showed the strongest contrast between the two sampled stations. Microplastic abundance in the sediment was significantly higher at the Near-River station than at the Far-River station, whereas surface water was statistically similar between the two stations. The divergence follows from the contrasting behavior of the two matrices. Surface water is continuously mixed by tides and waves; consequently, it is plausible that buoyant and low-density particles are redistributed and any spatial signal from the source is rapidly homogenized. Sediment, in contrast, acts as a longer-term sink in which denser and biofouled particles settle and accumulate, which can preserve the imprint of proximity to land-based sources (Soares *et al.*, 2023; Summers *et al.*, 2024). The higher sediment load near the river is consistent with the role of rivers as a dominant pathway transferring land-based microplastics to the coastal zone (Lebreton *et al.*, 2017; Meijer *et al.*, 2021).

Sediment microplastic abundance at Mala-

layang was higher than at several less-impacted or well-flushed reefs. The Near-River value exceeded those reported for the Java Sea (15–144 n kg^{-1}) (Wijayanti *et al.*, 2024), Aceh waters, Indonesia (32–68 n kg^{-1}) (Ulfah *et al.*, 2024), and the Gulf of Mannar (1.88–4 n kg^{-1}) (Pradhap *et al.*, 2023). It was of a similar magnitude to reefs under moderate land influence, including Hainan Island, China (91–378 n kg^{-1}) (Bian *et al.*, 2024), Naifaru in the Maldives (about 291 n kg^{-1}) (Patti *et al.*, 2020), and Tidung Island north of Jakarta (60–340 n kg^{-1}) (Sulistiowati *et al.*, 2023). It was lower than reefs under intense anthropogenic loading, such as the marine parks of the Gulf of California (3,217–6,802 n kg^{-1}) (Arreola-Alarcón *et al.*, 2022), Gede Island, Indonesia (847 n kg^{-1}) (Widiaratih *et al.*, 2025), and the Xisha Islands, China (about 682 n kg^{-1}) (Lin *et al.*, 2024b).

Surface water abundance at Malalayang was lower than at heavily loaded reef waters, including Sanya Bay, China (18,370 n m^{-3}) (Lei *et al.*, 2021), the Gulf of Mannar (60,000–126,600 n m^{-3}) (Patterson *et al.*, 2020), and the Xisha Islands, China (200–45,200 n m^{-3}) (Ding *et al.*, 2019). It was higher than at more remote reefs, such as those off Sri Lanka (about 9.8 n m^{-3}) (Hansani *et al.*, 2023) and the Lakshadweep atolls, India (about 57 n m^{-3}) (Praved *et al.*, 2025). The comparison places Malalayang among reef waters influenced by land-based input but well below the most heavily urbanized reef systems. The absence of a station difference in surface water abundance of microplastics, despite the clear sediment differences, suggests that the water column may redistribute particles faster than a spatial signal can develop, whereas the sediment integrates and stores the land-derived input over time.

The station contrast at Malalayang is consistent with reef and estuarine systems that show declining microplastic abundance away from land-based sources. A similar pattern was reported for the Gulf of Thailand, where a nearshore reef site accumulated more microplastics than an offshore site (Sutthacheep *et al.*, 2025), and for Sanya Bay, China, where spatial differences in seawater were attributed to river discharge and intensive human activity (Lei *et al.*, 2021). Estuarine gradients reinforce the same mechanism, with abundance decreasing sharply from inner, source-proximal waters toward the open coast (Cheung *et al.*, 2016; Osorio *et al.*, 2021). A contrasting outcome, however, was reported for the Kepulauan Seribu reefs in the Java Sea, where a submarine channel diverted land-derived material away from the reefs so that local inputs, rather than mainland proximity, governed contamination (Utami *et al.*,

2021). The comparison suggests that the sediment contrast observed at Malalayang is not necessarily a general feature of reefs, but may depend on site-specific conditions and local hydrodynamics that were not directly measured in this study.

3.2.4 *P. aurata* as a potential microplastic biomonitor

P. aurata accumulated microplastics at both stations, with a higher mean at the Near-River station than at the Far-River station, although the difference was not statistically significant. This pattern paralleled that of surface water, which likewise showed no significant difference between stations, whereas sediment differed significantly. The correspondence between particles in the ascidian and the water column is consistent with the biology of ascidians, which feed by filtering suspended particles from the surrounding water through a mucous net and capture them with low selectivity (Petersen and Svane, 2002; Rosner and Rinkevich, 2024). Once captured by the ascidian's non-selective branchial filter, microplastics enter the digestive tract. Studies on model ascidians, such as *Ciona intestinalis*, have demonstrated that fine microplastics can subsequently translocate across the gut epithelium and enter the hemocoelic cavity. Within the circulatory system, these particles are phagocytized by circulating hemocytes (immune cells) as a physiological defense mechanism, which inadvertently facilitates their systemic transport from the digestive system into surrounding internal tissues (Messinetti *et al.*, 2019). As a sessile filter feeder drawing particles from the overlying water, *P. aurata* would be expected to reflect the water-column signal, and the parallel absence of a station difference in both water and tissue supports this interpretation.

Microplastic contamination in the soft tissue of *P. aurata* at Malalayang (7.50-11.17 n ind⁻¹) was roughly an order of magnitude higher than values reported for solitary ascidians in a tropical bay in Brazil (0.72 n ind⁻¹ for *Styela plicata*) (Sorrentino *et al.*, 2025), and along the Brazilian coast (1.21 n ind⁻¹ for *Phallusia nigra*) (Silva *et al.*, 2025). Ingestion has also been recorded in ascidians from environments with minimal human activity, such as *Cnemidocarpa verrucosa* in Antarctica (Gonzalez-Pineda *et al.*, 2025), indicating that ascidian microplastic uptake occurs across a wide range of settings. The higher per-individual values at Malalayang are consistent with the elevated land-based input documented for this reef, although differences in extraction method and organism body size limit direct numerical comparison across studies.

These findings position *P. aurata* as a candidate species warranting formal biomonitor validation for microplastic contamination in reef ecosystems. The species is abundant and broadly distributed across the reefs of Wallacea and Sulawesi (Wainwright *et al.*, 2020) and has already been validated as a passive biomonitor of polymetallic and potentially toxic elements in Indonesian reef waters (Saputri *et al.*, 2026; Turicchia *et al.*, 2025). Its consistent uptake of microplastics at both stations extends this established monitoring role from dissolved and particulate metals to anthropogenic microparticles, indicating that a single, widely available reef organism can integrate multiple classes of contaminant exposure. As an initial field demonstration, the present results establish the ecological plausibility of this application and provide a preliminary baseline motivating future multi-site validation of *P. aurata* as a tool for reef microplastic surveillance.

3.2.5 Microplastic transfer and its link to coral reef condition

The compositional relationships among compartments trace the pathways by which microplastics move through the reef. Based on shape composition, no statistically significant difference was detected among compartments. The universal dominance of fibers across water, sediment, and ascidian inner body indicates that the heavy environmental loading of fibers outweighs any subtle preferential retention mechanisms at this scale. For polymer composition, descriptive indices suggest that the ascidian shares a moderate overlap in particle types with both the seabed and the water column, while surface water and sediment shared the highest similarity. Though the limited polymer dataset precludes formal statistical comparison, this pattern aligns with the literature suggesting that *P. aurata* as a filter-feeder organism may draw on a particle pool compositionally similar to the ambient environment (Ding *et al.*, 2021).

Beyond accumulating particles, filter feeders such as ascidians can potentially accelerate their transfer. By capturing suspended microplastics and repackaging them into denser faecal material, filter feeders are widely reported in the literature to enhance downward flux and couple the pelagic and benthic compartments, which could reinforce the sediment as the ultimate reservoir (Harel *et al.*, 2024; Jacobi *et al.*, 2018; Rosner and Rinkevich, 2024). *P. aurata* may hypothetically occupy a dual position, serving both as an organism that integrates water-column exposure and as a potential conduit that channels microplastics into the benthos and into reef food webs through trophic transfer.

The ecological relevance of the compositional patterns becomes apparent when placed alongside the condition of the two stations sampled. The Near-River station, with a low hard coral cover (poor status), was accompanied by the highest sediment microplastic abundance recorded in this study, while the Far-River station, with a higher coral cover (fair status), was accompanied by a lower sediment microplastic abundance. This pattern cannot be read as following only one direction, since the relationship between reef condition and microplastic concentration reported in the wider literature is shaped by several interacting factors rather than reef condition alone (Soares *et al.*, 2023; Sutthacheep *et al.*, 2025). Structurally complex and healthier reef habitats can themselves enhance microplastic retention, since three-dimensional coral framework reduces seafloor turbulent kinetic energy and bottom shear stress, favoring the deposition of small and high-density particles regardless of reef health status (Soares *et al.*, 2023). Spatial differences in reef-associated microplastic abundance have also been attributed to hydrodynamic regimes, where monsoon-driven current reversal and localized upwelling or downwelling control particle retention and export independently of coral condition (Sutthacheep *et al.*, 2025). At the catchment scale, land use and population density have been found to influence microplastic type more strongly than microplastic concentration, with concentration instead more closely related to sediment properties and hydrologic condition (He *et al.*, 2020). Taken together, these findings suggest that the magnitude and proximity of land-based input, together with the local hydrodynamic setting, are plausible explanatory factors for the microplastic concentration pattern observed in reef-associated compartments at Malalayang, alongside the structural or ecological condition of the reef itself.

4. Conclusion

Microplastics were detected in all three compartments examined at the Malalayang reef: surface water, sediment, and the ascidian *P. aurata*. Fibers dominated the visually classified particles. Sediment microplastic abundance differed significantly between stations, while water and *P. aurata* did not differ significantly between stations. *P. aurata* consistently contained microplastics, indicating an uptake from its environment. The station with higher sediment microplastic abundance also had lower hard-coral cover. This co-occurrence does not establish a causal relationship and would require targeted testing to confirm it. Multi-station, multi-season studies with larger organism sample sizes and replicated river-distance gradients are recommended to further evaluate

P. aurata's suitability as a monitoring tool in Coral Triangle reef systems.

Acknowledgement

The authors would like to express their sincere gratitude to the Master to Doctoral Programs for outstanding graduates scholarship program for providing the financial and academic support to the first author, which made this research possible.

Authors' Contributions

All authors have contributed to the final manuscript. The contribution of each author is as follows: GS conducted the sampling, performed the analysis, managed the software, and contributed to writing, reviewing, and editing the manuscript. NPZ devised the conceptualization, designed the methodology, and contributed to writing, reviewing, and editing. BS contributed to writing, reviewing, and editing the manuscript. SCAF contributed to reviewing and editing the manuscript. MRC contributed to writing, reviewing, and editing the manuscript. All authors discussed the results and approved the final manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

Declaration of Artificial Intelligence (AI)

The author(s) acknowledge the use of ClaudeAI for language refinement in preparing this manuscript. All AI-generated content was rigorously reviewed, edited, and validated to ensure accuracy and originality. Full responsibility for the manuscript's final content rests with the author(s).

Funding Information

This research was fully supported by the Directorate General of Research and Development of the Ministry of Higher Education, Science, and Technology in accordance with the 2025 Research Budget Implementation Contract Number: 006/C3/DT.05.00/PL/2025.

References

- Adam, T. C., Burkepile, D. E., Holbrook, S. J., Carpenter, R. C., Claudet, J., Loiseau, C., Thiault, L., Brooks, A. J., Washburn, L., & Schmitt, R. J. (2021). Landscape-scale patterns of nutrient enrichment in a coral reef ecosystem: Implica-

- tions for coral to algae phase shifts. *Ecological Applications: A Publication of the Ecological Society of America*, 31(1):1-9.
- Allen, G. R., & Erdmann, M. V. (2012). Reef fishes of the East Indies. Tropical reef research.
- Anderson, M. J. (2001). A new method for non-parametric multivariate analysis of variance. *Austral Ecology*, 26(1):32-46.
- Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, 62(8):1596-1605.
- Arias-González, J. E., Fung, T., Seymour, R. M., Garza-Pérez, J. R., Acosta-González, G., Bozec, Y. M., & Johnson, C. R. (2017). A coral-algal phase shift in Mesoamerica not driven by changes in herbivorous fish abundance. *PLoS ONE*, 12(4):1-7.
- Arreola-Alarcón, I. M., Reyes-Bonilla, H., Sakthi, J. S., Rodríguez-González, F., & Jonathan, M. P. (2022). Seasonal tendencies of microplastics around coral reefs in selected marine protected national parks of gulf of California, Mexico. *Marine Pollution Bulletin*, 175(2):1-12.
- Axworthy, J. B., Lasdin, K. S., & Padilla-Gamiño, J. L. (2024). Low incidence of microplastics in coral reefs of Kāneʻohe Bay, Hawaiʻi, USA. *Marine Pollution Bulletin*, 208(11):1-13.
- Bessell-Browne, P., Negri, A. P., Fisher, R., Clode, P. L., Duckworth, A., & Jones, R. (2017). Impacts of turbidity on corals: The relative importance of light limitation and suspended sediments. *Marine Pollution Bulletin*, 117(1-2):161-170.
- Bhuyan, M. S., Jenzri, M., & Adikari, D. (2025). Impacts of sedimentation on coral health and reef ecosystems: A comprehensive review. *Marine Pollution Bulletin*, 221(12):1-12.
- Bian, W., Zeng, Y., Li, Y., Na, G., Mu, J., Lv, S., & Liu, M. (2024). Microplastic pollution in tropical coral reef ecosystems from the coastal South China Sea and their impacts on corals in situ. *Journal of Hazardous Materials*, 480(20):1-12.
- Bonello, G., Varrella, P., & Pane, L. (2018). First evaluation of microplastic content in benthic filter-feeders of the Gulf of La Spezia (Ligurian Sea). *Journal of Aquatic Food Product Technology*, 27(3):284-291.
- Boucher, J., & Friot, D. (2017). Primary microplastics in the oceans: A global evaluation of sources. IUCN: Global Marine and Polar Programme.
- Bray, J. R., & Curtis, J. T. (1957). An ordination of the upland forest communities of Southern Wisconsin. *Ecological Monographs*, 27(4):325-349.
- Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: Sources and sinks. *Environmental Science and Technology*, 45(21):9175-9179.
- Browne, M. A., Dissanayake, A., Galloway, T. S., Lowe, D. M., & Thompson, R. C. (2008). Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environmental Science and Technology*, 42(13):5026-5031.
- Browne, N. K., Braoun, C., McIlwain, J., Nagarajan, R., & Zinke, J. (2019). Borneo coral reefs subject to high sediment loads show evidence of resilience to various environmental stressors. *PeerJ*, 7(1):1-33.
- Carbery, M., Herb, F., Reynes, J., Pham, C. K., Fong, W. K., & Lehner, R. (2022). How small is the big problem? Small microplastics <300 µm abundant in marine surface waters of the Great Barrier Reef Marine Park. *Marine Pollution Bulletin*, 184(11):1-10.
- Cheang, C. C., Ma, Y., & Fok, L. (2018). Occurrence and composition of microplastics in the seabed sediments of the coral communities in proximity of a metropolitan area. *International Journal of Environmental Research and Public Health*, 15(10):22-70.
- Chen, C. F., Ju, Y. R., Chen, C. W., Albarico, F. P. J. B., Lim, Y. C., Ke, C., Cheng, Y. R., & Dong, C. Di. (2023). Microplastics in coral reef sediments underestimated? They may hide in biominerals. *Science of the Total Environment*, 899(52):1-9.
- Chen, L., Tu, Z., Zhong, Z., Wei, S., Hu, M., & Wang, Y. (2025). Differential effects of polyvinyl chloride microplastics and kaolin particles on gut immunity of mussels at environmental concentrations. *Journal of Hazardous Materials*, 484(4):1-14.
- Cheung, P. K., Cheung, L. T. O., & Fok, L. (2016). Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. *Science of the Total Environment*, 562(20):658-665.

- Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology*, 18(1):117-143.
- Connors, E. J. (2017). Distribution and biological implications of plastic pollution on the fringing reef of Mo'orea, French Polynesia. *PeerJ*, 2017(8):1-14.
- Cordova, M. R. (2021). Guidelines for microplastic sampling, analysis, and identification in coastal and marine ecosystems. Bogor: IPB Press.
- Cordova, M. R., Hadi, T. A., & Prayudha, B. (2018). Occurrence and abundance of microplastics in coral reef sediment: A case study in Sekotong, Lombok-Indonesia. *Advances in Environmental Sciences Bioflux*, 10(1):23-29.
- De Haan, W. P., Martí, E., Sanchez-Vidal, A., Ivar Do Sul, J. A., & Frias, J. P. G. L. (2026). Fashion fades, microplastics are eternal: A critical systematic literature review to assess microplastic fibre colours in environmental samples. *Environmental Research Letters*, 21(7):1-17.
- De Witte, B., Devriese, L., Bekaert, K., Hoffman, S., Vandermeersch, G., Cooreman, K., & Robbens, J. (2014). Quality assessment of the blue mussel (*Mytilus edulis*): Comparison between commercial and wild types. *Marine Pollution Bulletin*, 85(1):146-155.
- Dice, L. R. (1945). Measures of the amount of ecologic association between species. *Ecology*, 26(3):297-302.
- Dimaongon, N. G., Araña, K. N. D., Chen, C. W., Chen, C. F., Dong, C. Di, & Huang, C. E. (2025). Revealing the hidden environmental risks: A two-step sequential extraction of mobile and immobile (mineral-bound) microplastics in coral reef sediments. *Environmental Research*, 286(30):1-11.
- Ding, J., Jiang, F., Li, J., Wang, Z., Sun, C., Wang, Z., Fu, L., Ding, N. X., and He, C. (2019). Microplastics in the coral reef systems from Xisha Islands of South China Sea. *Environmental Science & Technology*, 53(14):8036-8046.
- Ding, J., Sun, C., He, C., Li, J., Ju, P., and Li, F. (2021). Microplastics in four bivalve species and basis for using bivalves as bioindicators of microplastic pollution. *Science of the Total Environment*, 782(35):1-10.
- English, S. A., Wilkinson, C. R., & Baker, V.J. (1997). Survey manual for tropical marine resources (2nd ed.). Australian Institute of Marine Science.
- Enyoh, C. E., Shafea, L., Verla, A. W., Verla, E. N., Qingyue, W., Chowdhury, T., & Paredes, M. (2020). Microplastics exposure routes and toxicity studies to ecosystems: An overview. *Environmental Analysis, Health and Toxicology*, 35(1):1-10.
- Erfteemeijer, P. L. A., Riegl, B., Hoeksema, B. W., & Todd, P. A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine Pollution Bulletin*, 64(9):1737-1765.
- Galgani, F., Hanke, G., & Maes, T. (2015). Global distribution, composition and abundance of marine litter. In M. Bergmann, L. Gutow, M. Klages (Eds.), *Marine anthropogenic litter*. (pp. 29-56). Springer.
- Gallagher, J. P., Schmitt, R. J., Burkepile, D. E., & Holbrook, S. J. (2026). Nutrient enrichment strengthens feedbacks that promote and stabilize coral-to-macroalgae regime shifts on tropical reefs. *Ecosphere*, 17(5):1-16.
- Giyanto, G., Manuputty, A. E. W., Abrar, M., Sirinoringo, R. M., Suharti, S. R., Wibowo, K., Ineuya, A., Cappenberg, H. A. W., Sihalo, H. F., Tuti, Y., & Zulfianita, D. (2014). Coral reef health monitoring guide. In COREMAP CTI LIPI. PT. Sarana Komunikasi Utama.
- Gonzalez-Pineda, M., Avila, C., Lacerot, G., Lozoya, J. P., Mello, F. T. D., Faccio, R., Pignanelli, F., & Salvadó, H. (2025). Experimental ingestion of microplastics in three common Antarctic benthic species. *Marine Environmental Research*, 204(2):1-7.
- Hall, N. M., Berry, K. L. E., Rintoul, L., & Hoo-genboom, M. O. (2015). Microplastic ingestion by scleractinian corals. *Marine Biology*, 162(3):725-732.
- Hamman, M., Schyff, V. V., Yive, R. N. S. C. K., Iordachescu, L., Simon-Sánchez, L., & Bouwman, H. (2024). Microplastics in coral from three Mascarene Islands, Western Indian Ocean. *Marine Pollution Bulletin*, 208(11):1-15.
- Hankins, C., Lasseigne, D., Davis, S. M., Edwards, K., & Paul, J. S. (2024). Coral reef attributes associated with microplastic exposure. *Coral Reefs*, 44(1):193-207.
- Hankins, C., Raimondo, S., & Lasseigne, D. (2022). Microplastic ingestion by coral as a function of the interaction between calyx and micro-

- plastic size. *Science of the Total Environment*, 810(14):1-8.
- Hansani, K. U. D. N., Thilakarathne, E. P. D. N., Koongolla, J. B., Gunathilaka, W. G. I. T., Perera, B. G. D. O., Weerasingha, W. M. P. U., & Egodaunya, K. P. U. T. (2023). Contamination of microplastics in tropical coral reef ecosystems of Sri Lanka. *Marine Pollution Bulletin*, 194(9):1-12.
- Harel, E., Zucker, I., & Shenkar, N. (2024). Effects of biological filtration by ascidians on microplastic composition in the water column. *Chemosphere*, 367(22):1-10.
- He, B., Wijesiri, B., Ayoko, G. A., Egodawatta, P., Rintoul, L., & Goonetilleke, A. (2020). Influential factors on microplastics occurrence in river sediments. *Science of the Total Environment*, 738(43):1-8.
- Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science and Technology*, 46(6):3060-3075.
- Hongo, C., & Yamano, H. (2013). Species-specific responses of corals to bleaching events on anthropogenically turbid reefs on Okinawa Island, Japan, over a 15-year period (1995-2009). *PLoS ONE*, 8(4):1-9.
- Huang, Y., Yan, M., Xu, K., Nie, H., Gong, H., & Wang, J. (2019). Distribution characteristics of microplastics in Zhubi reef from South China Sea. *Environmental Pollution*, 255(15):1-8.
- Imanuel, T., Pelle, W. E., W Schadu, J. N., H Paulus, J. J., C Rumampuk, N. D., & Sangari, J. R. (2022). The form and distribution of microplastic in sediment and water columns of Manado Bay, North Sulawesi. *Jurnal Ilmiah PLATAX*, 10(2):336-343.
- Jacobi, Y., Yahel, G., & Shenkar, N. (2018). Efficient filtration of micron and submicron particles by ascidians from oligotrophic waters. *Limnology and Oceanography*, 63(1):S267-S279.
- Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, 347(6223):768-771.
- James, K., Gopinath, V., Vasant, K., & Devipriya, S. P. (2026). Marine microplastics: Environmental fate, trophic transfer and implications for ecosystem and human health. *Estuarine, Coastal and Shelf Science*, 340(1):1-11.
- Jensen, L. H., Motti, C. A., Garm, A. L., Tonin, H., & Kroon, F. J. (2019). Sources, distribution and fate of microfibres on the Great Barrier Reef, Australia. *Scientific Reports*, 9(1):1-15.
- Jeyasanta, K. I., Patterson, J., Grimsditch, G., & Edward, J. K. P. (2020). Occurrence and characteristics of microplastics in the coral reef, sea grass and near shore habitats of Rameswaram Island, India. *Marine Pollution Bulletin*, 160(11):1-16.
- Jia, C., Chen, M., Xu, Q., & Gao, F. (2025). Pollution characteristics of microplastics in the wild tropical sea cucumber *Holothuria atra* (Echinodermata: Holothuroidea) and its habitat at different seasons. *Marine Environmental Research*, 210(8):1-9.
- Jung, M. R., Horgen, F. D., Orski, S. V., Rodriguez, C., V., Beers, K. L., Balazs, G. H., Jones, T. T., Work, T. M., Brignac, K. C., Royer, S. J., Hyrenbach, K. D., Jensen, B. A., & Lynch, J. M. (2018). Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. *Marine Pollution Bulletin*, 127(2):704-716.
- Kaiser, D., Kowalski, N., & Waniek, J. J. (2017). Effects of biofouling on the sinking behavior of microplastics. *Environmental Research Letters*, 12(12):1-11.
- Kalogerakis, N., Karkanorachaki, K., Kalogerakis, G. C., Triantafyllidi, E. I., Gotsis, A. D., Partinevelos, P., & Fava, F. (2017). Microplastics generation: Onset of fragmentation of polyethylene films in marine environment mesocosms. *Frontiers in Marine Science*, 4(3):1-15.
- Kawung, N. R., Adnyana, I. W. S., & Hendrawan, I. G. (2022). Analysis of microplastic abundance in Bivalves in the waters of Tuminting and Malayang, Manado City. *Ecotrophic: Jurnal Ilmu Lingkungan (Journal of Environmental Science)*, 16(2):220-231.
- Kenyon, T. M., Mumby, P. J., Callaghan, D. P., Baldock, T. E., & Doropoulos, C. (2023). Coral rubble dynamics in the Anthropocene and implications for reef recovery. *Limnology and Oceanography*, 68(12):2955-2969.

- Khanjani, M. H., Sharifinia, M., & Mohammadi, A. R. (2023). The impact of microplastics on bivalve mollusks: A bibliometric and scientific review. *Marine Pollution Bulletin*, 194(9):1-23.
- Khoironi, A., Hadiyanto, H., Anggoro, S., & Sudarno, S. (2020). Evaluation of polypropylene plastic degradation and microplastic identification in sediments at Tambak Lorok coastal area, Semarang, Indonesia. *Marine Pollution Bulletin*, 151(2):1-10.
- Kılıç, E., Yücel, N., Bengil, F., Bengil, E. G. T., & Şahutoğlu, S. M. (2024). Microplastic pollution levels in the surface water and sediment of Orontes basin: Urgent risk for endangered species. *Marine Pollution Bulletin*, 208(11):1-10.
- Kim, K., Yoon, H., Choi, J. S., Jung, Y. J., & Park, J. W. (2022). Chronic effects of nano and microplastics on reproduction and development of marine copepod *Tigriopus japonicus*. *Ecotoxicology and Environmental Safety*, 243(15):1-8.
- Kittinger, J. N., Teneva, L. T., Koike, H., Stamoulis, K. A., Kittinger, D. S., Oleson, K. L. L., Conklin, E., Gomes, M., Wilcox, B., & Friedlander, A. M. (2015). From reef to table: Social and ecological factors affecting coral reef fisheries, artisanal seafood supply chains, and seafood security. *PLoS ONE*, 10(8):1-24.
- Kohler, K. E., & Gill, S. M. (2006). Coral point count with excel extensions (CPCe): A visual basic program for the determination of coral and substrate coverage using random point count methodology. *Computers & Geosciences*, 32(9):1259-1269.
- Kole, P. J., Löhr, A. J., Belleghem, F. G. A. J. V., & Ragas, A. M. J. (2017). Wear and tear of tyres: A stealthy source of microplastics in the environment. *International Journal of Environmental Research and Public Health*, 14(10):1-31.
- Kooi, M., Nes, E. H. V., Scheffer, M., & Koelmans, A. A. (2017). Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. *Environmental Science and Technology*, 51(14):7963-7971.
- Kumar, A., Soratur, A., Kumar, S., Kiruba-Sankar, R., Jha, D. K., & Maran, B. A. V. (2025). Drivers of microplastic pollution in soil sediments at fish landing centers in Sri Vijaya Puram (Port Blair), South Andaman Island. *PeerJ*, 13(1):1-30.
- Kurchaba, N., Cassone, B. J., Northam, C., Ardelli, B. F., & LeMoine, C. M. R. (2020). Effects of MP polyethylene microparticles on microbiome and inflammatory response of larval zebrafish. *toxics*, 8(3):1-15.
- Kuroda, M., Isobe, A., Uchida, K., Tokai, T., Kitakado, T., Yoshitake, M., Miyamoto, Y., Mukai, T., Imai, K., Shimizu, K., Yagi, M., Mituhashi, T., & Habano, A. (2024). Abundance and potential sources of floating polystyrene foam macro- and microplastics around Japan. *Science of the Total Environment*, 925(21):1-12.
- Lamb, J. B., Willis, B. L., Fiorenza, E. A., Couch, C. S., Howard, R., Rader, D. N., True, J. D., Kelly, L. A., Ahmad, A., Jompa, J., & Harvell, C. D. (2018). Plastic waste associated with disease on coral reefs. *Science*, 359(6374):460-462.
- Lebreton, L. C. M., Zwet, J. V. D., Damsteeg, J. W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, 8(1):1-10.
- Lei, X., Cheng, H., Luo, Y., Zhang, Y., Jiang, L., Sun, Y., Zhou, G., & Huang, H. (2021). Abundance and characteristics of microplastics in seawater and corals from reef region of Sanya Bay, China. *Frontiers in Marine Science*, 8(1):1-10.
- Lim, K. P., Sun, C., Yusoff, S., Ding, J., Loh, K. H., Li, J., & Lim, P. E. (2024). Abundance of microplastics and its ecological risk assessment in coral reef regions of Peninsular Malaysia. *Marine Pollution Bulletin*, 209(1):1-13.
- Lim, Y. C., Chen, C. W., Cheng, Y. R., Chen, C. F., & Dong, C. D. (2022). Impacts of microplastics on scleractinian corals nearshore Liuqu Island southwestern Taiwan. *Environmental Pollution*, 306(16):1-9.
- Lin, H. T., Schneider, F., Aziz, M. A., Wong, K. Y., Arunachalam, K. D., Praveena, S. M., Sethupathi, S., Chong, W. C., Nafisyah, A. L., Parthasarathy, P., Chelliapan, S., & Kunz, A. (2024a). Microplastics in Asian rivers: Geographical distribution, most detected types, and inconsistency in methodologies. *Environmental Pollution*, 349(11):1-14.
- Lin, J., Zhao, Y. M., Zhan, Z. G., Zheng, J. Y., Zhou, Q. Z., Peng, J., Li, Y., Xiao, X., & Wang, J. H. (2024b). Microplastics in remote coral reef environments of the Xisha Islands in the

- South China Sea: Source, accumulation and potential risk. *Journal of Hazardous Materials*, 469(9):1-12.
- Ling, S. D., Sinclair, M., Levi, C. J., Reeves, S. E., & Edgar, G. J. (2017). Ubiquity of microplastics in coastal seafloor sediments. *Marine Pollution Bulletin*, 121(1-2):104-110.
- Liu, P. J., Hsin, M. C., Huang, Y. H., Fan, T. Y., Meng, P. J., Lu, C. C., and Lin, H. J. (2015). Nutrient enrichment coupled with sedimentation favors sea anemones over corals. *PLoS ONE*, 10(4):1-14.
- Madduppa, H., & Zamani, N. P. (2011). A Standard criteria for assessing the health of coral reefs: Implication for management and conservation. *Journal of Indonesia Coral Reefs*, 1(2):137-146.
- Mamun, A. Al, Prasetya, T. A. E., Dewi, I. R., & Ahmad, M. (2023). Microplastics in human food chains: Food becoming a threat to health safety. *Science of the Total Environment*, 858(8):1-17.
- Masura, J., Baker, J. E., Foster, G. D. Gregory D., Arthur, C., & Herring, C. (2015). Laboratory methods for the analysis of microplastics in the marine environment: Recommendations for quantifying synthetic particles in waters and sediments.
- Mattsson, K., Lima, J. A. D., Wilkinson, T., Järnskog, I., Ekstrand, E., Sköld, Y. A., Gustafsson, M., & Hassellöv, M. (2023). Tyre and road wear particles from source to sea. *Microplastics and Nanoplastics*, 3(1):1-11.
- Meijer, L. J. J., Emmerik, T. V., Ent, R. V. E., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science Advances*, 7(18):1-13.
- Messinetti, S., Mercurio, S., Parolini, M., Sugni, M., & Pennati, R. (2018). Effects of polystyrene microplastics on early stages of two marine invertebrates with different feeding strategies. *Environmental Pollution*, 237(6):1080-1087.
- Messinetti, S., Mercurio, S., Parolini, M., Sugni, M., & Pennati, R. (2019). Ingested microscopic plastics translocate from the gut cavity of juveniles of the ascidian *Ciona intestinalis*. *The European Zoological Journal*, 86(1):189-195.
- Metri, R. (2019). The ascidian *Microcosmus exasperatus* as bioindicator for the evaluation of water quality in estuaries. *International Journal of Advanced Research*, 7(8):174-185.
- Michels, J., Stippkugel, A., Lenz, M., Wirtz, K., & Engel, A. (2018). Rapid aggregation of biofilm-covered microplastics with marine biogenic particles. *Proceedings of the Royal Society B: Biological Sciences*, 285(1885):1-9.
- Miller, M. E., Motti, C. A., Hamann, M., & Kroon, F. J. (2023). Assessment of microplastic bioconcentration, bioaccumulation and biomagnification in a simple coral reef food web. *Science of the Total Environment*, 858(8):1-12.
- Munno, K., Lusher, A. L., Minor, E. C., Gray, A., Ho, K., Hankett, J., T Lee, C. F., Primpke, S., McNeish, R. E., Wong, C. S., & Rochman, C. (2023). Patterns of microparticles in blank samples: A study to inform best practices for microplastic analysis. *Chemosphere*, 333(26):1-8.
- Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin*, 112(1-2):39-45.
- Nawaz, F., Islam, Z. U., Ghorri, S. A., Bahadur, A., Ullah, H., Ahmad, M., & Ullah, G. U. (2025). Microplastic and nanoplastic pollution: Assessing translocation, impact, and mitigation strategies in marine ecosystems. *Water Environment Research*, 97(2):1-8.
- Nice, M. S., Chakraborty, T. K., Kharel, G., Netema, B. N., Islam, K. R., Chowdhury, P., Debnath, P. C., Rahman, M. S., Rayhan, M. A., Zaman, S., & Ghosh, G. C. (2025). Physicochemical characterization, ecological risk assessment and spatial distribution of microplastics in Bangladesh's largest coral reef systems. *Physics and Chemistry of the Earth, Parts A/B/C*, 141(6):1-19.
- Nie, H., Wang, J., Xu, K., Huang, Y., & Yan, M. (2019). Microplastic pollution in water and fish samples around Nanxun Reef in Nansha Islands, South China Sea. *Science of the Total Environment*, 696(54):1-7.
- Nor, N. H. M., & Obbard, J. P. (2014). Microplastics in Singapore's coastal mangrove ecosystems. *Marine Pollution Bulletin*, 79(1-2):278-283.
- Ory, N. C., Sobral, P., Ferreira, J. L., & Thiel, M. (2017). Amberstripe scad *Decapterus muroadsi* (Carangidae) fish ingest blue microplas-

- tics resembling their copepod prey along the coast of Rapa Nui (Easter Island) in the South Pacific subtropical gyre. *Science of the Total Environment*, 586(11):430-437.
- Osorio, E. D., Tanchuling, M. A. N., & Diola, M. B. L. D. (2021). Microplastics occurrence in surface waters and sediments in five river mouths of Manila Bay. *Frontiers in Environmental Science*, 9(1):1-7.
- Patterson, J., Jeyasanta, K. I., Laju, R. L., Booth, A. M., Sathish, N., & Edward, J. K. P. (2022). Microplastic in the coral reef environments of the Gulf of Mannar, India - Characteristics, distributions, sources and ecological risks. *Environmental Pollution*, 298(8):1-14.
- Patterson, J., Jeyasanta, K. I., Sathish, N., Edward, J. K. P., & Booth, A. M. (2020). Microplastic and heavy metal distributions in an Indian coral reef ecosystem. *Science of the Total Environment*, 744(47):1-15.
- Patti, T. B., Fobert, E. K., Reeves, S. E., & Silva, K. B. D. (2020). Spatial distribution of microplastics around an inhabited coral island in the Maldives, Indian Ocean. *Science of the Total Environment*, 748(51):1-10.
- Petersen, J. K., & Svane, I. (2002). Filtration rate in seven Scandinavian ascidians: Implications of the morphology of the gill sac. *Marine Biology*, 140(2):397-402.
- Phaksopa, J., Worachananant, S., Thamrongnawasawat, T., Tanapivattanukul, K., Kumnuandao, S., Chamcha-em, T., Khamrueang, A., & Chaimongkol, T. (2025). Microplastic pollution and risk assessment around coral reefs of the Eastern Part, Thailand. *Environmental Science and Pollution Research International*, 32(20):12441-12454.
- Pradhap, D., Gandhi, K. S., Radhakrishnan, K., Magesh, N. S., Godson, P. S., Krishnakumar, S., & Saravanan, P. (2023). Distribution and characterization of microplastic from reef associated surface sediments of Vembar group of Islands, Gulf of Mannar, India. *Total Environment Research Themes*, 5(1):1-13.
- Prata, J. C., Costa, J. P. D., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Science of the Total Environment*, 702(5):1-9.
- Praved, P. H., Sreeraj, P., Neethu, K. V., Nandan, S. B., Ravindran, S., & Marigoudar, S. R. (2025). Unraveling the invisible threat of microplastics to Lakshadweep coral atolls, Indian Ocean: Multifaceted ecological risk and pollution profiling. *Journal of Hazardous Materials*, 498(17):1-20.
- Qiao, R., Deng, Y., Zhang, S., Wolosker, M. B., Zhu, Q., Ren, H., & Zhang, Y. (2019). Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish. *Chemosphere*, 236(22):1-12.
- Reuning, L., Hildebrandt, L., Kersting, D. K., & Pröfrock, D. (2025). High levels of microplastics and microrubber pollution in a remote, protected Mediterranean *Cladocora caespitosa* coral bed. *Marine Pollution Bulletin*, 217(8):1-14.
- Rogers, C. S., & Ramos-Scharrón, C. E. (2022). Assessing effects of sediment delivery to coral reefs: A Caribbean watershed perspective. *Frontiers in Marine Science*, 8(1):1-23.
- Rojas-Luna, R. A., Rueda-Reyes, P. A., García-Alzate, C. A., García-Alzate, R., Trilleras, J., Medina-Calderon, J. H., Santos-Martínez, A., Pineda, J. E. M., Sierra, C. A., & Arana, V. A. (2025). Widespread microplastic ingestion in Colombian Caribbean marine fish: Trophic influence, spatial-temporal trends, and polymer composition. *Marine Pollution Bulletin*, 221(12):1-10.
- Rosner, A., & Rinkevich, B. (2024). Harnessing ascidians as model organisms for environmental risk assessment. *Environments*, 11(11):1-28.
- Saliu, F., Montano, S., Leoni, B., Lasagni, M., & Galli, P. (2019). Microplastics as a threat to coral reef environments: Detection of phthalate esters in neuston and scleractinian corals from the Faafu Atoll, Maldives. *Marine Pollution Bulletin*, 142(5):234-241.
- Santana, M. F. M., Tonin, H., Vamvounis, G., Herwerden, L. V., Motti, C. A., & Kroon, F. J. (2025). Predicting microplastic dynamics in coral reefs: Presence, distribution, and bio-availability through field data and numerical simulation analysis. *Environmental Science and Pollution Research*, 32(15):9655-9675.
- Santonicola, S., Volgare, M., Olivieri, F., Cocca, M., & Colavita, G. (2025). Natural and regenerated cellulosic microfibers dominate anthropogenic particles ingested by commercial fish species from the Adriatic Sea. *Foods*, 14(7):1-12.
- Saputri, M., Yusnaini, Y., Zainuri, M., Widowati, I.,

- Asriyana, A., Muarriif, S., Brault-Favrou, M., Churlaud, C., Guyot, T., Radenac, G., Fichet, D., & Helene, T. (2026). First baseline study on polymetallic passive biomonitoring of *Polycarpa aurata* in coral reef ecosystems in Southeast Sulawesi, Indonesia. *Regional Studies in Marine Science*, 93(1):1-14.
- Shenkar, N., & Swalla, B. J. (2011). Global diversity of Ascidiacea. *PLoS ONE*, 6(6):1-12.
- Silva, P. C. A., Almeida, M. P. D., Sorrentino, R. D., & Skinner, L. F. (2025). Baseline survey of microplastics in *Phallusia nigra* (Ascidiacea) in different sites along the Brazilian Coast, Central, and Southwest Atlantic. *Ocean and Coastal Research*, 73(1):1-13.
- Soares, M. O., Rizzo, L., Neto, A. R. X., Barros, Y., Filho, J. E. M., Giarrizzo, T., & Rabelo, E. F. (2023). Do coral reefs act as sinks for microplastics? *Environmental Pollution*, 337(24):1-10.
- Soliman, H. A. M., Salaah, S. M., Hamed, M., & Sayed, A. E. D. H. (2023). Toxicity of co-exposure of microplastics and lead in African catfish (*Clarias gariepinus*). *Frontiers in Veterinary Science*, 10(2):1-10.
- Sorensen, T. (1948). A method of establishing groups of equal amplitude in plant sociology based on similarity of species content and its application to analyses of the vegetation on Danish commons. *Biologiske Skrifter/Kongelige Danske Videnskabernes Selskab*, 5:1-34.
- Sorrentino, R., Silva, P. C. A. D., Ramos, B. D. S., & Skinner, L. F. (2025). Detection of microplastic contamination in shallow marine habitats using solitary ascidians: Influence of morphology and habitat in a Tropical Bay, SW Atlantic. *Water, Air, and Soil Pollution*, 236(15):1-13.
- Sulistiowati, Zamani, N. P., Bengen, D. G., & Cordova, M. R. (2023a). Microplastic contamination around coral reefs diving spot in Tidung Island, Kepulauan Seribu, Jakarta. *Carpathian Journal of Earth and Environmental Sciences*, 18(2):333-341.
- Sulistiowati, Zamani, N. P., Bengen, D. G., Lim, C. L., & Cordova, M. R. (2023b). Characteristic of microplastic on coral reef sediment and sea urchin (*Diadema* sp.) in Tidung Island, Jakarta Bay, Indonesia. *ILMU KELAUTAN: Indonesian Journal of Marine Sciences*, 28(4):289-300.
- Summers, E., Du, J., Park, K., Wharton, M., & Kaiser, K. (2024). Importance of the water-sediment bed interactions in simulating microplastic particles in an estuarine system. *Frontiers in Marine Science*, 11:1-17.
- Sura, S. A., Bell, A., Kunes, K. L., Turba, R., Songer, R., & Fong, P. (2021). Responses of two common coral reef macroalgae to nutrient addition, sediment addition, and mechanical damage. *Journal of Experimental Marine Biology and Ecology*, 536(3):1-8.
- Sutthacheep, M., Chamchoy, C., Suebpala, W., Wongnutpranont, A., Jungrak, L., Aunkhongthong, W., Pengsakun, S., Klinthong, W., Jowantha, M., Sangsawang, L., & Yeemin, T. (2025). Assessment of microplastic pollution in corals, seawater, and marine sediments in the Gulf of Thailand. *Frontiers in Marine Science*, 12(1):1-17.
- Tan, F., Yang, H., Xu, X., Fang, Z., Xu, H., Shi, Q., Zhang, X., Wang, G., Lin, L., Zhou, S., Huang, L., & Li, H. (2020). Microplastic pollution around remote uninhabited coral reefs of Nansha Islands, South China Sea. *Science of the Total Environment*, 725(28):1-9.
- Tang, J., Wu, Z., Wan, L., Cai, W., Chen, S., Wang, X., Luo, J., Zhou, Z., Zhao, J., & Lin, S. (2021). Differential enrichment and physiological impacts of ingested microplastics in scleractinian corals in situ. *Journal of Hazardous Materials*, 404(5):1-11.
- Thompson, R. C., Olson, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., & Russell, A. E. (2004). Lost at sea: Where is all the Plastic? *Science*, 304(5672):1-8.
- Turicchia, E., Ercadi, R., Tamburini, M., Badocco, D., Zampa, G., Gasparini, F., Ballarin, L., Guerra, R., Lasut, M. T., Makapedua, D. M., Mamua-ja, J., Schadu, J. N. W., Tumbol, R. A., Pastore, P., & Ponti, M. (2025). *Polycarpa aurata* as biomonitor to assess potential toxic elements across the Coral Triangle. *Coral Reefs*, 45(2):211-229.
- Tzafriri-Milo, R., Benaltabet, T., Torfstein, A., & Shenkar, N. (2019). The potential use of invasive ascidians for biomonitoring heavy metal pollution. *Frontiers in Marine Science*, 6(1):1-17.
- Ulfah, M., Juliani, R., Agustina, S., Purnawan, S., Malayana, I., Muliari, Miswari, N., Yusrizal, & Irfannur. (2025). The abundance of microplas-

tics in coral reef ecosystems in the waters of Krueng Raya, Aceh Besar. *BIO Web of Conferences*, 156(1):1-10.

- Ulfah, M., Ziliwu, I. N., Agustina, S., Octavina, C., Khairunnisa, & Yucharoen, M. (2024). Microplastic accumulation in coral reef ecosystems at Peukan Bada District, Aceh Besar. *Ecological Engineering & Environmental Technology*, 25(6):291-300.
- Utami, D. A., Reuning, L., Konechnaya, O., & Schwarzbauer, J. (2021). Microplastics as a sedimentary component in reef systems: A case study from the Java Sea. *Sedimentology*, 68(6):2270-2292.
- Vassilenko, E., Watkins, M., Chastain, S., Mertens, J., Posacka, A. M., Patankar, S., & Ross, P. S. (2021). Domestic laundry and microfiber pollution: Exploring fiber shedding from consumer apparel textiles. *PLoS ONE*, 16(7):1-17.
- Vered, G., Kaplan, A., Avisar, D., & Shenkar, N. (2019). Using solitary ascidians to assess microplastic and phthalate plasticizers pollution among marine biota: A case study of the Eastern Mediterranean and Red Sea. *Marine Pollution Bulletin*, 138(1):618-625.
- Vered, G., & Shenkar, N. (2023). Plastic pollution in a coral reef climate refuge: Occurrence of anthropogenic debris, microplastics, and plasticizers in the Gulf of Aqaba. *Science of the Total Environment*, 905(58):1-8.
- Veron, J. E. N., Devantier, L. M., Turak, E., Green, A. L., Kininmonth, S., Stafford-Smith, M., & Peterson, N. (2009). Delineating the coral triangle. *Galaxea, Journal of Coral Reef Studies*, 11(2):91-100.
- Wainwright, B. J., Arlyza, I. S., & Karl, S. A. (2020). Population genetic structure in the coral reef associated ascidian, *Polycarpa aurata*, throughout Wallacea, Indonesia. *Regional Studies in Marine Science*, 39(7):1-8.
- Wang, T., Hu, M., Song, L., Yu, J., Liu, R., Wang, S., Wang, Z., Sokolova, I. M., Huang, W., & Wang, Y. (2020). Coastal zone use influences the spatial distribution of microplastics in Hangzhou Bay, China. *Environmental Pollution*, 266(14):1-9.
- Widiaratih, R., Sulhana, B. L. A., Putranto, A. B., Maslukah, L., Ismanto, A., Ayuningrum, D., Hadibarata, T., & Satya, E. D. (2025). The correlation between microplastics characteristics and sediment grain size to microplastics accumulation in coral reef sediment in Gede Island, Rembang, Indonesia. *Journal of Ecological Engineering*, 26(3):200-212.
- Wightman, E., & Renegar, D. A. (2023). The microscopic threat with a macroscopic impact: Microplastics along the southeast Florida reef tract. *Marine Pollution Bulletin*, 191(6):1-10.
- Wijayanti, D. P., Indrayanti, E., Haryanti, D., Sibero, M. T., Widyarizia, M. E., Az Zahra, A. Q., & Bachtiar, M. (2024). Characteristic and histological evidence of microplastic in scleractinian corals of Java Sea. *Egyptian Journal of Aquatic Research*, 50(1):95-102.
- Woodall, L. C., Sanchez-Vidal, A., Canals, M., Paterson, G. L. J., Coppock, R., Sleight, V., Calafat, A., Rogers, A. D., Narayanaswamy, B. E., & Thompson, R. C. (2014). The deep sea is a major sink for microplastic debris. *Royal Society Open Science*, 1(4):1-8.
- Woodhead, A. J., Hicks, C. C., Norström, A. V., Williams, G. J., & Graham, N. A. J. (2019). Coral reef ecosystem services in the Anthropocene. *Functional Ecology*, 33(6):1023-1034.
- Yona, D., Sari, S. H. J., Iranawati, F., Bachri, S., & Ayuningtyas, W. C. (2019). Microplastics in the surface sediments from the eastern waters of Java Sea, Indonesia. *F1000Research*, 8(1):1-14.
- Zhang, D., Cui, Y., Zhou, H., Jin, C., Yu, X., Xu, Y., Li, Y., & Zhang, C. (2020). Microplastic pollution in water, sediment, and fish from artificial reefs around the Ma'an Archipelago, Shengsi, China. *Science of the Total Environment*, 703(5):1-9.
- Zhao, X., Wang, J., Leung, K. M. Y., & Wu, F. (2022). Color: An important but overlooked factor for plastic photoaging and microplastic formation. *Environmental Science & Technology*, 56(13):9161-9163.
- Zhou, Z., Tang, J., Cao, X., Wu, C., Cai, W., & Lin, S. (2023). High heterotrophic plasticity of massive coral *Porites pukoensis* contributes to its tolerance to bioaccumulated microplastics. *Environmental Science & Technology*, 57(8):3391-3401.
- Zhou, Z., Wan, L., Cai, W., Tang, J., Wu, Z., & Zhang, K. (2022). Species-specific microplastic enrichment characteristics of scleractinian corals from reef environment: Insights from an in-situ study at the Xisha Islands. *Science of the Total Environment*, 815(4):1-9.

Zweifler, A., Browne, N. K., Levy, O., Hovey, R., & O’Leary, M. (2024). *Acropora tenuis* energy

acquisition along a natural turbidity gradient. *Frontiers in Marine Science*, 11(1):1-15.