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Microplastic pollution in the water column and benthic sediment of the San Pedro Bay, California, USA

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ABSTRACT

The concentration, character, and distribution of microplastics in coastal marine environments remain poorly understood, with most research focusing on the abundance of microplastics at the sea surface. To address this gap, we conducted one of the first comprehensive assessments of microplastic distribution through the marine water column and benthic sediment during the wet and dry season in the coastal waters of the San Pedro Bay Southern California, USA. Microplastic concentrations in the water column did not vary significantly across season but were significantly higher in nearshore environments and at the surface of the water column. Sediment samples contained significantly more microplastics in the wet season and in offshore environments. Black particles were the most dominant color, while fibers were the most abundant morphology, accounting for over 50% of both water column and sediment microplastics. Polyethylene and polypropylene were identified as the most abundant polymers in the water column regardless of morphology type. Tire and road wear particles were found through the study domain. Average microplastic concentrations in the San Pedro Bay were estimated to be $8.65 \times 10^5 \pm 7.60 \times 10^5$ particles/km^2 and 3.19 ± 2.96 particles/m^3. This study highlights the complexity of microplastic concentration, character, and distribution in marine environments and demonstrates that surface only sampling strategies significantly underestimate microplastic concentrations. Our findings underscore the need for continued and expanded research into microplastic distribution and transport dynamics across the marine environment to aid in understanding, managing, and mitigating plastic pollution in coastal marine systems.

1. Introduction

The widespread distribution and persistence of microplastics, defined as plastic particles between 1 um and 5 mm in size (Thompson et al., 2004; Arthur et al., 2009; Moore, 2008; Andrady, 2011), pose a substantial risk to marine life because of their small size, varying morphologies, and toxicity (Ageel et al., 2022; Coffin et al., 2022; Sharma et al., 2022). These concerns have motivated investigations into the fate, transport, and concentration of microplastics in the marine environment (van Sebille et al., 2015; Lebreton et al., 2017; Isobe et al., 2021; Eriksen et al., 2023). Recent studies estimate that approximately 250 kilotons of plastic are floating on the ocean surface (Kaandorp et al., 2023) with 24.4–170 trillion pieces of microplastics in the world's upper oceans (Isobe et al., 2021; Eriksen et al., 2023). However, mechanistic, traceable, and analytical modeling approaches (Koelmans et al., 2017) indicate that the global inventory of plastic in the ocean is at least an order of magnitude lower than the estimated influx of plastic pollution (Cózar et al., 2015; Weiss et al., 2021; Isobe and Iwasaki, 2022). Several factors may account for this discrepancy including large uncertainty in global estimates and the wide variation in microplastic morphology, size, and polymer types, which affect their transport behavior (Liu et al., 2020). Assessment of the fate and transport of these "missing plastics" is lacking

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because of the difficulty in determining the amount of plastic that is removed from the ocean surface and distributed through the water column and sediment (Isobe and Iwasaki, 2022) but is crucial to understand in order to assess the nature and significance of the impacts of plastic pollution in the ocean (Cózar et al., 2015).

In an attempt to quantify the presence of microplastics in the marine environment, numerous observational studies have been conducted, however they have predominantly focused on the surface layer of the water column (i.e., the upper 5 m) (Doyle et al., 2011; Cózar et al., 2015; Eriksen et al., 2014) due in part to time, cost and equipment constraints. Consequently, our understanding of microplastic distribution with depth remains limited (Liu et al., 2020). Although a few studies have examined microplastic distribution beyond the surface layer (Chevalier et al., 2023), their scope has been restricted to midwater ranges (i.e., 10's of meters) (Desforges et al., 2014; Reisser et al., 2015; Kooi et al., 2016). Additionally, investigations into temporal (Janakiram et al., 2023) and spatial variations across study areas (Kanhai, 2019; Kwon et al., 2020; Wang et al., 2020; Ikenoue et al., 2023) have not concurrently analyzed the microplastic distribution throughout the water column. Furthermore, microplastic characteristics, ocean currents, seasonal variability inputs such as fluvial fluxes, spatial heterogeneity in the nearshore and offshore environments that affect microplastic transport dynamics, concentration and distribution are not always taken into consideration (Koelmans et al., 2017; Wang et al., 2020; Isobe et al., 2021; Evans and Ruf, 2022).

To begin to address these needs we conducted an ambient assessment of microplastic concentration in the coastal waters of the San Pedro Shelf in Southern California, USA. The objective of our study was to determine the concentration, character, and distribution of microplastics throughout the water column and surficial bottom sediment and determine how microplastics varied temporally (wet versus dry season), laterally (nearshore versus offshore environment), and vertically (through the water column at the surface, midwater, bottom and sediment). This research contributes to the existing body of literature that has examined microplastics at the ocean surface layer but its novelty lies in the fact that we further explore the effect that depth, season, and distance from the shore have on microplastic concentration, character and distribution.

2. Materials and methods

2.1. Study region

Microplastics monitoring was conducted in the coastal waters of Southern California, USA, on the San Pedro Shelf. The San Pedro Shelf is situated within the Southern California Bight, an open embayment 94,000 km^2 in size (Sutula et al., 2021) extending from Point Conception to Baja California. The San Pedro Shelf is a relatively shallow, gentle sloping seabed that is approximately 40 km wide, 100 km long and extends to a maximum depth of ~900 m (Hickey, 1992). It is comprised of a sediment covered sea floor, low relief rock outcrops, and boulders. This near coastal environment experiences complex ocean currents including the California Current comprising of water masses originating from the subarctic Pacific and the California undercurrent composed of water masses originating from the eastern tropical North Pacific (Kessouri et al., 2021). These currents converge in the Southern California Bight interacting with local coastal topography and the atmosphere resulting in circulation that varies on interannual, seasonal, and intra-seasonal time scales (Kessouri et al., 2021). The Mediterranean climate of the region is characterized by hot dry summers with average temperatures ranging from 20 to 24 °C and mild wet winters with temperatures ranging from 8 to 14 °C and average annual precipitation ranging from 635-1524 mm (Kauffman, 2003). The San Pedro Bay receives discharge from the Los Angeles and San Gabriel Rivers, which together contribute ~70% of the freshwater flow to the bight (Sutula et al., 2021). The Southern California Bight boasts rich marine diversity and provides several important ecosystems services including climate regulation, recreation, and fisheries but is under threat because it is adjacent to one of the most heavily urbanized areas in North America and is susceptible to overfishing, negative impacts from port and maritime activities, climate change, invasive species, and pollution, including plastic marine debris.

2.2. Sample collection

2.2.1. Net sample collection

Sampling in San Pedro Bay was conducted at three nearshore and four offshore locations. Offshore locations (MSPB_SP3, OSPB_SP4, HSB_H2, HS_H3) were greater than 3000 m from the shore (Fig. 1). The distance from the shore to the nearest sampling site (SG_SP2) was 1079 m while the distance to the furthest site (HS_H3) was 14,536 m (Table s1). Sampling took place at each site once in the wet season (March 2021) and once in the dry season (September 2021) (Table s1). At each site, during each season, samples in the water column were collected at three depths: the surface, midwater at 7–10 m below the surface, and near the bottom (20 cm above the ocean floor). The depth of the sites at which the bottom samples were taken ranged from 8.6 m at the shallowest site (LA_SP1) to 352 m at the deepest site (HS_H3) (Table s1). Surface samples were collected using a manta trawl with a rectangular opening (width · depth: 0.9 m · 0.15 m), with a 3.5 m long, 333 μm mesh net. For concentration calculation purposes it was assumed that only half the net was submerged at the surface. Midwater samples were collected using paired bongo nets with circular 0.61 m diameter intakes and a 3 m long, 333 μm mesh net. The contents from both nets were combined to create one bongo sample. Near bottom samples were collected using an epibenthic sled with a rectangular (0.28 m · 0.30 m) intake positioned 20 cm above the ocean floor and a 1 m long, 333 μm mesh net (Fig. 1). The opening of each of the sample nets faced the direction of flow. A General Oceanics flowmeter was mounted to the net openings of all sampling devices during deployment and the counts at the start and end of the trawl were recorded to calculate the volume of water that passed through the net. Trawls were conducted over 1 km long transects at each site. The Bongo and Manta nets were trawled along the transect in unison followed by the epibenthic sled once the vessel returned to the start position of the transect. On the completion of the sample collection, the nets were brought back on board and the outside of each net was thoroughly rinsed using pumped ocean water to move the sample through the net and into the cod ends (the removable portion of a net system, located at the posterior of the net and designed for sample collection). The cod ends from each of the sampling devices were removed after sample collection at each site and stored in separate Ziplock bags, kept cool and transferred to the laboratory where they remained in a cold room until they were processed. New cod ends were attached to the sampling device at every sampling location.

2.2.2. Sediment sample collection

At each site during the seasonal sampling event, seabed sediment was collected using a stainless steel Van Veen grab at the start location of each transect (Table s1). Upon reaching the seabed a small ~0.1 m^2 sample of surface sediment was collected. Once the sample was back on the vessel, sediment was scooped using a stainless-steel trowel and stored in four 1 L glass jars at each site. The sample was stored until further processing.

2.3. Sample processing

2.3.1. Net samples processing

For microplastic extraction and analysis at the laboratory, the contents of the cod ends were rinsed using microfiltered deionized water into a 250 μm stainless steel sieve. The sample was then transferred into a beaker and underwent a Fenton's reagent wet peroxide oxidation (WPO) digestion to remove organic material present. This digestion

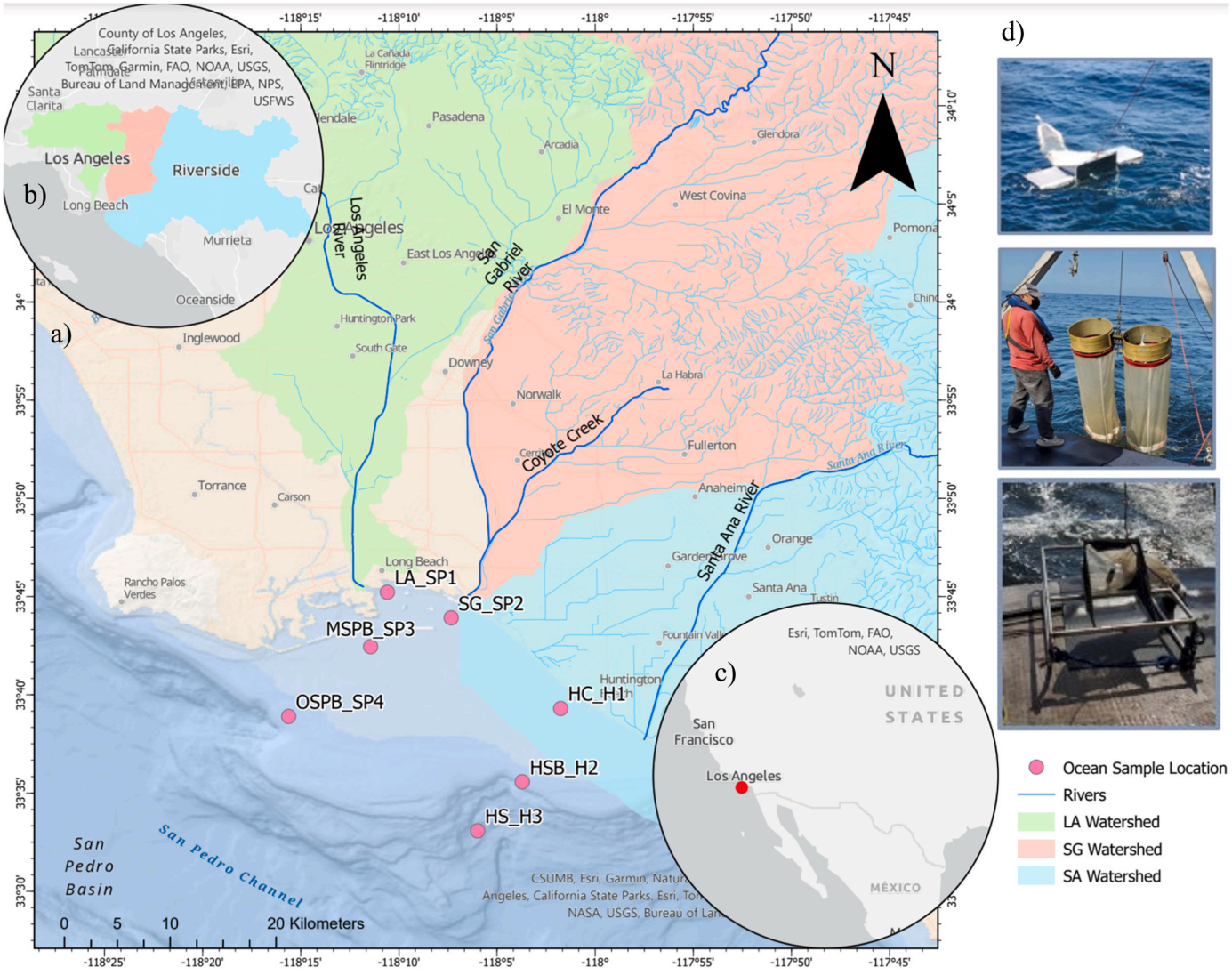

Fig. 1. Site map showing a) sampling locations. Sites LA_SP1, SG_SP2 and HC_H1 are the nearshore sites at the outlets of the Los Angeles, San Gabriel, and Santa Ana Rivers respectively. Samples at each of these locations were collected once in the wet and dry season. b) watershed of the Los Angeles, San Gabriel and Santa Ana Rivers. c) San Pedro Shelf in relation to the Southern California coast. The pictures d) indicate the sampling device used at each site to collect samples of microplastics through the water column, at the surface (manta), midwater (Bongo) and bottom (epibenthic sled).

method was modified from the method described in the NOAA technical memorandum for laboratory methods for the analysis of microplastics in the marine environment (Masura et al., 2015). Once the digestion was complete, the sample was stored in glass jars with lids until further analysis.

2.3.2. Sediment sample processing

The sediment was decanted from the 1 L glass jars and homogenized. A 1 cm^3 volume of sample was removed and subjected to dry bulk density analysis. Following this, a 1000 g subsample (to ensure limits of quantification and detection were met) of wet sediment collected at each site was processed for microplastic extraction. The subsample was passed through a sieve stack (250 μm, 500 μm, 1 mm) and the sediment collected on each sieve was transferred to separate glass beakers. The samples then underwent a Fenton's reagent wet peroxide oxidation (WPO) digestion (Masura et al., 2015). On completion of the digestion, all the samples from each beaker were rinsed through the sieve stack, the contents of each sieve were transferred into separate glass jars with lids, until further analysis.

2.4. Microplastic analysis

Preliminary identification of microplastics from net and sediment samples were conducted using a dissecting microscope (8–35·magnification, Leica EZ4 W Stereozoom Microscope). Any suspected microplastic particles from the samples were extracted using fine tipped forceps and adhered to glass microscope slides using double sided sticky tape. Images were taken of each particle using the microscope's built-in camera and its associated software. Each particle was characterized in terms of color and morphology visually, and size including length, width and area using Image J software (n = 7509) (Rueden et al., 2017). Microplastic morphological classification was determined on the basis of previously established criteria used in an interlaboratory study to inform methods to quantify and characterize microplastics (De Frond et al., 2022): spheres (round, regular shaped particles usually engineered at this size class), fragments (irregularly shaped pieces of plastic), film (planar and flexible irregular shaped plastics), fibers (fiber or filaments between 0.3 and 1 dtex according to the textile industry (Song et al., 2015), foams (often spherical and pliable) (Cowger et al., 2020) or tire and road wear particles (TRWP), (black irregularly shaped particles that are rubber-like to the touch, usually elongated and have

encrustations on their surface) (Mattsson et al., 2023) (Figure s1). TRWP were identified initially by morphological characteristics including texture, shape and color. Additionally, a subset (n = 5) of suspected TRWP from the sediment samples and another subset (n = 10) from the ocean water column samples comprising of a mix of black particles and suspected TRWP were analyzed with pyrolysis gas chromatography mass spectrometry (py GC-MS) for verification. Each sample (between 0.1 and 0.5 mg) underwent a single shot (flash) pyrolysis at 650 °C in helium with a flow of 0.1 ml-min through a long ultra-alloy column (Frontier UA5: 30 m × 250 μm x 0.25 μm). MS analysis was performed in scanning ion mode (28–600 m/z at 2.6 scans sec-1). This analysis was completed on the Frontier Laboratories EGA/PY-3030 with autoshot sampling carousel affixed to an Agilent 8890 GC/5977 MSD. The National Institute of Standards and Technology (NIST) mass spectral library was used for peak compound identification. All the suspected TRWP from the sediment and water column samples were confirmed to be TRWP and the suspected black plastic were correctly extracted and identified as microplastics.

2.5. Chemical identification

To estimate the proportion of morphologically identified particles that were plastic, a random selection of at least 30 particles per sample, encompassing all morphological types except TRWP, were further analyzed using micro-Fourier Transform Infrared Spectroscopy (μFTIR) (n(total) = 7509 n(subset) = 861). Particles were analyzed on a Thermo Scientific Nicolet™ iN™10 MX FTIR microscope with OMNIC™ Picta™ software. Particle spectra were collected using the reflectance collection mode, with a spectral resolution of 8 cm^{-1} and a spectral range of 675 cm^{-1} to 4000 cm^{-1}. Chemical identification was performed using raw spectra which were processed and analyzed in Open Specy (Cowger et al., 2021). All confirmed spectral matches met a correlation threshold of 0.7 or higher in the latest version of Open Specy, which accommodates batch uploads of spectra and therefore faster processing and output. Because of this, the same pre-processing steps were applied to all spectra, which included the flattening of the CO^2 peak which results from lab atmospheric conditions between the 2200 cm^{-1} and 2400 cm^{-1} wavenumbers. A smoothing polynomial of 3 was selected to enhance the signal to noise ratio for better matches and a baseline correction of 8 was selected which shifts the baseline of all non-peak regions to zero absorbance to improve the fit of the spectra. Most spectra were collected in absorbance but for spectra that were collected in transmittance, the intensity adjustment was selected to transform the spectra to absorbance units followed by the other pre-processing steps (https://openanalysis.org/openspecy/) (Cowger et al., 2021). The final microplastics count for each sample was adjusted by multiplying the visual microscopy count by the proportion of particles subjected to FTIR spectroscopy that were confirmed to be plastics.

2.6. Data analysis

Microplastic concentrations were calculated at the sample level. Particles preliminarily identified as microplastics by visual microscopy were included in further analysis if they corresponded to the size range (333–5000 μm) defined by our sampling net mesh and the maximum size of microplastics. The final microplastics count after the FTIR adjustment was used to calculate concentration. The concentration of microplastics in each sample (water column: particles/m^3; sediment: particles/kg dry weight) was calculated. For water column samples, the sample volume (m^3) was determined by dividing the flow meter reading by the calibration constant to obtain the linear distance (m) of water traveling into the net and multiply by the area of the net opening (m^2). Sediment sample dry mass was calculated by multiplying the wet weight by the wet to dry mass ratio obtained through dry bulk density analysis.

Microplastic concentrations and the distribution of microplastic characteristics (color, morphology, size, and polymer type) were aggregated by season (temporal), offshore position [nearshore/offshore] (Lateral), and sample depth [surface, midwater, bottom] (for water column samples) for hypothesis testing. Microplastic concentration, morphology-specific concentration (fiber, non-fiber [fragment, foams, films and spheres], and TRWP) (Figure s1) and polymer density concentrations were visualized using ggplot2 (Wickham et al., 2016). The polymer types and associated density were grouped as positively buoyant (<0.8–1 g/cm^3), neutrally buoyant (1–1.3 g/cm^3), and negatively buoyant (1.3->1.6 g/cm^3) and the concentration within each group for each sample was determined (water column: Table s4, Sediment: Table s5). Subsequently, concentration data in each case were log-transformed and tested pairwise for differences in the mean. For the lateral and temporal comparison states, if the assumption of normality and equality of variance was met, a two-sample *t*-test was conducted to determine significant differences in mean concentration. If these assumptions were not met a non-parametric Mann-Whitney *U* test was performed. Significant differences in concentration across the water column depth were investigated using a Kruskal Wallis Test, the non-parametric alternative to the one-way analysis of variance (ANOVA) (Kruskal and Wallis, 1952) followed by the Dunn Post Hoc Test. Particle length (measurement along the longest axis) was used to create cumulative particle size distribution curves for each of the comparison states for water column and sediment samples. The Kolmogorov-Smirnov (K-S) test was used to compare the cumulative distributions of each comparison (Stephens, 1992).

Finally, the results from this study were compared to other studies conducted in the Pacific Ocean using net samples through average surface area and volumetric microplastic concentration. To determine the volumetric concentration for the entire study area, the surface, midwater and epibenthos sample from all sites was summed and then an average was determined taking each sites total concentration in both the wet and dry season into consideration.

2.7. Quality assurance/quality control and detection thresholds

Several QA/QC practices were employed during sample collection and analysis to limit contamination, ensure reliability and comparability of data, and facilitate the calculation of minimum detection thresholds for microplastics in our samples. Sample storage containers and lab equipment used were either glass or stainless steel whenever possible. All equipment was cleaned using lab-grade detergent and natural materials (e.g., natural sponges) and triple rinsed with microfiltered deionized water before use. During sample extraction and identification in the laboratory, all personnel wore cotton lab coats and nitrile powder free examination gloves to prevent external contamination of the samples. Samples remained covered with aluminum foil when not in use. High efficiency particulate air (HEPA) filters were placed in the lab and all stock solutions were filtered through a 1 μm glass microfiber filter before use.

In the field, a clean cod end was used for each sample collection. To limit contamination between sample sites, the sample nets were rinsed on the outside with ocean water pumped through the vessel after use at each site without the cod end attached. After this cleaning step, the net was rinsed again, and a sample of this rinsing water was collected in 1L amber glass jars as an equipment blank. Cleaning the net thoroughly between sites was difficult and these equipment blanks were more an indication of sample smearing between sites than a true sample blank. Nevertheless, these samples were treated as blanks and even though many particles were found in them initially, more than 90% of these particles were smaller than the 333 μm size threshold (net aperture size) and were excluded from the blank correction analysis. A beaker of water was left open next to the researcher to investigate background contamination from the lab environment. Both the equipment and background contamination blank samples were then visualized under the dissecting microscope and any suspected microplastics were extracted and placed on double sided sticky tape. The blank particles

were characterized in terms of color, morphology and size.

The minimum detectable amount (MDA) was then calculated using both the equipment and background laboratory processing blanks following the process outlined by (Lao and Wong, 2023). MDA_A was calculated for both the lab and field blank as:

$$MDA_A = N_b + 3 + 3.29 \times SD_b \times \sqrt{1 + \frac{1}{n}} \quad \text{Equation 1}$$

where N_b is the average number of blank particles and SD_b the standard deviation of blank particles (Equation (1)). The number of particles identified in the samples exceeded the minimum detectable amount calculated, no further blank adjustment was performed (Table s6).

3. Results

3.1. Microplastic concentrations

Microplastics concentrations ranging between 0.03 and 8.71 particles/m^3 were found in the San Pedro Bay water column (Fig. 2). In the dry season, higher microplastic concentrations were found in the water column at almost every site (Figs. 2 and 3) and overall (mean = 1.29 particles/m^3) compared to the wet season (0.90 particles/m^3) (Fig. 3), but the difference was not significant (Table s2). The highest microplastic concentrations were observed in nearshore environments (sites LA_SP1, SG_SP2 and HC_H1) (Fig. 2) (mean concentration = 1.78 particles/m^3, Fig. 3, Table s2), located near the outfalls of the Los Angeles, San Gabriel, and Santa Ana Rivers respectively, which were significantly different ($p = 0.01$) than the microplastic concentrations offshore (mean concentration = 0.55 particles/m^3) (Fig. 3, Table s2). A decrease in microplastic concentrations from nearshore to offshore sites was also observed, except at the site furthest offshore (HS_H3), just off the San Pedro Shelf (Fig. 2). Mean microplastic concentrations were significantly higher at the surface ($p = 0.02$, 2.06 particles/m^3) (Fig. 2) than the rest of the water column including the midwater (0.53 particles/m^3), and epibenthos (0.75 particles/m^3) (Fig. 3, Table s2).

3.1.1. Microplastic concentration in benthic sediment

Microplastic concentrations in the sediment of the San Pedro Shelf ranged from 500 to 3000 particles/kg dry weight (Fig. 2). Microplastic concentrations in sediment did not differ significantly by season ($p = 0.72$, Table s3). Higher microplastic concentrations were found in the nearshore environment in the wet season while higher concentrations were observed at the offshore sites during the dry season (Fig. 3). Overall, microplastic concentrations in sediment was higher in the nearshore (1102 particles/kg) than the offshore environment (416 particles/kg), but the difference was not significant ($p = 0.18$) (Fig. 3, Table s3).

3.2. Microplastic characteristics across the sampling area

3.2.1. Microplastic morphology investigation in the San Pedro Shelf

In the water column, black was the most dominant microplastic particle color across all sample sites and levels of organization (Fig. 4). Fibers were the most abundant morphology across all sites, which accounted for about 50% of water column microplastics, followed by fragments and then TRWP (Fig. 4). Fiber concentrations did not differ significantly between seasons, with distance offshore or with depth (Table s2). Proportionally, fibers were greater in the dry season, offshore, and in the bottom water samples (Fig. 4). The concentrations of non-fiber morphologies (fragment, foam, films) were significantly higher in the nearshore environment and in the surface waters (films, foams, and spheres: Table s7) as compared to the rest of the water column (Table s2). Even though there were no significant differences in concentrations, TRWPs were proportionally more abundant in the midwater column, in the wet season, and at the nearshore sites (Fig. 4). This could be attributed to runoff events in the wet season that carry TRWP to the nearshore marine environment where vertical mixing, which dominates during this time (Kessouri et al., 2021) may have

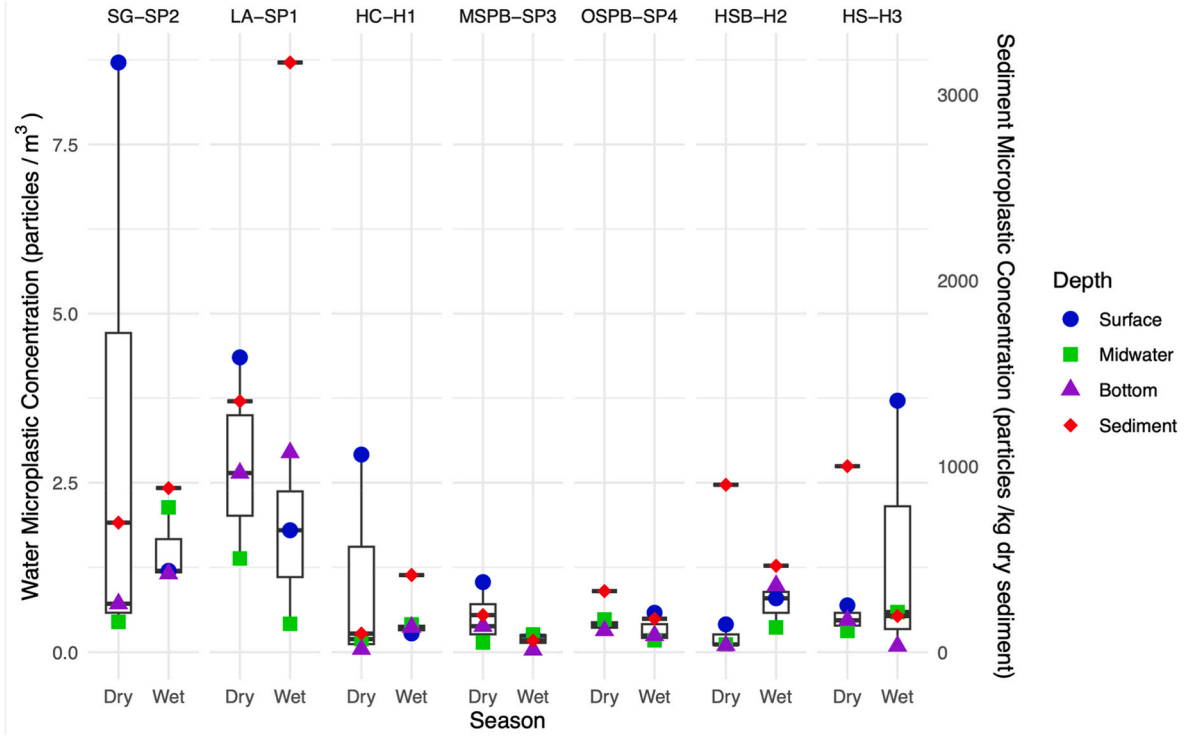

Fig. 2. Microplastic concentration (particles/m^3) in water column samples and sediment samples (particles/kg dry sediment) at each site in the wet and dry season. Shapes represent microplastic concentration at the various water column positions through the water column and sediment. Sample sites are ordered from closest to the shore (left) to the site furthest away from the shore (right).

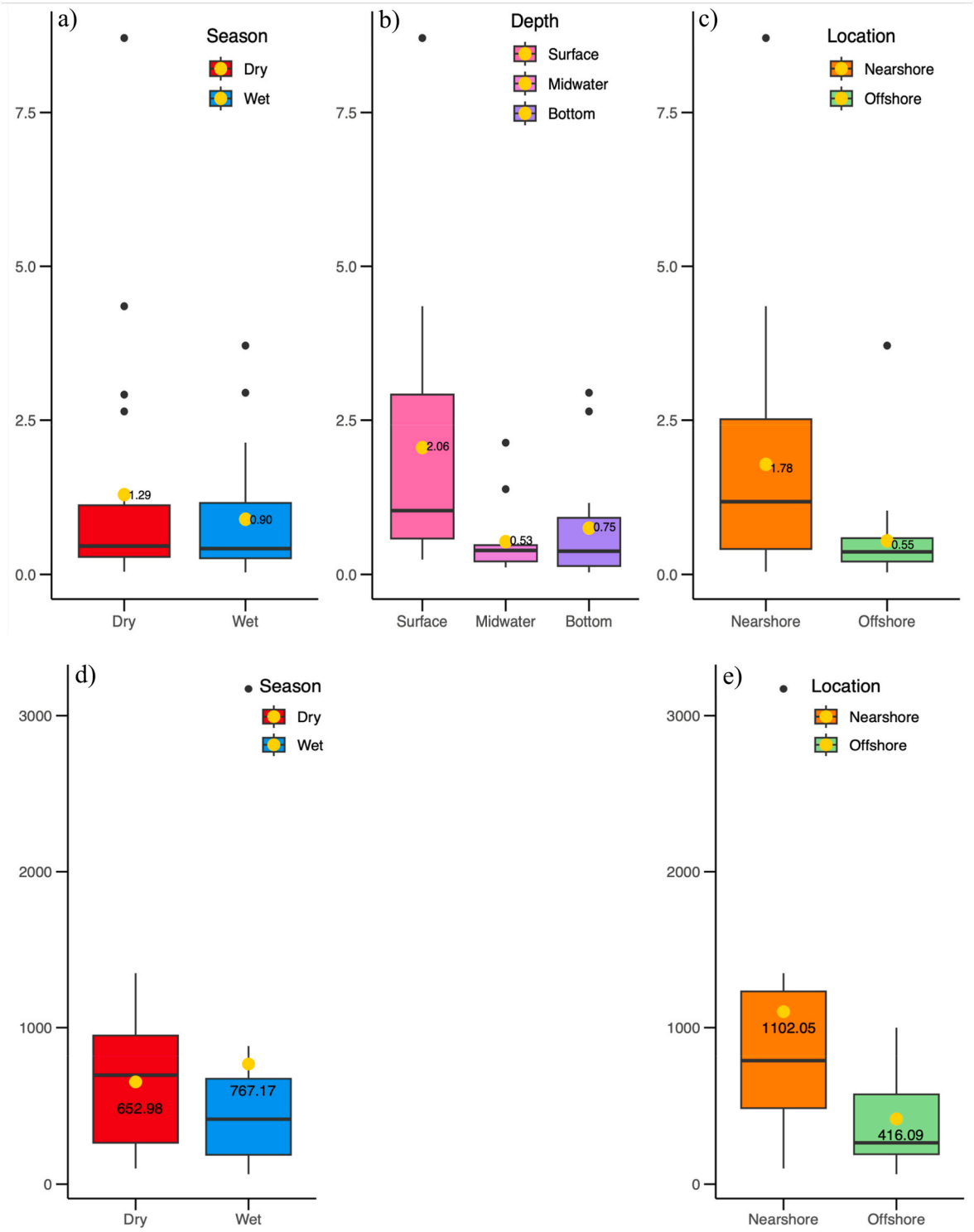

Fig. 3. Concentration boxplots for water column samples across the comparison states for water column samples by (a) season (Wet, Dry), b) water column position (Surface, Midwater, Bottom), and c) location (Nearshore, Offshore) and sediment samples by d) season and e) location. Black dots represent outliers of individual samples, thick black lines represent median concentration, and yellow labelled dots indicate and report the mean concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

supported their suspension in the midwater column.

Fibers were also the most dominant morphology type (60%) in all the sediment samples, followed by TRWP (20%), and fragments (10%) (Fig. 5). As with the water column samples, black was the most common microplastic particle color followed by gray, blue and clear (Fig. 5). Large proportions of fibers in sediment, the ultimate sink for microplastics in the ocean (Bergmann et al., 2017; Zobkov et al., 2020) have been previously attributed to wastewater treatment outfalls in the ocean (Desforges et al., 2014; Wang et al., 2020).

3.2.2. *Microplastic polymer investigation in the San Pedro Shelf*

More than 70% of all particles analyzed with FTIR were positively identified as plastic (Figure s2). Polyethylene and polypropylene were the most common polymer types found in water column samples

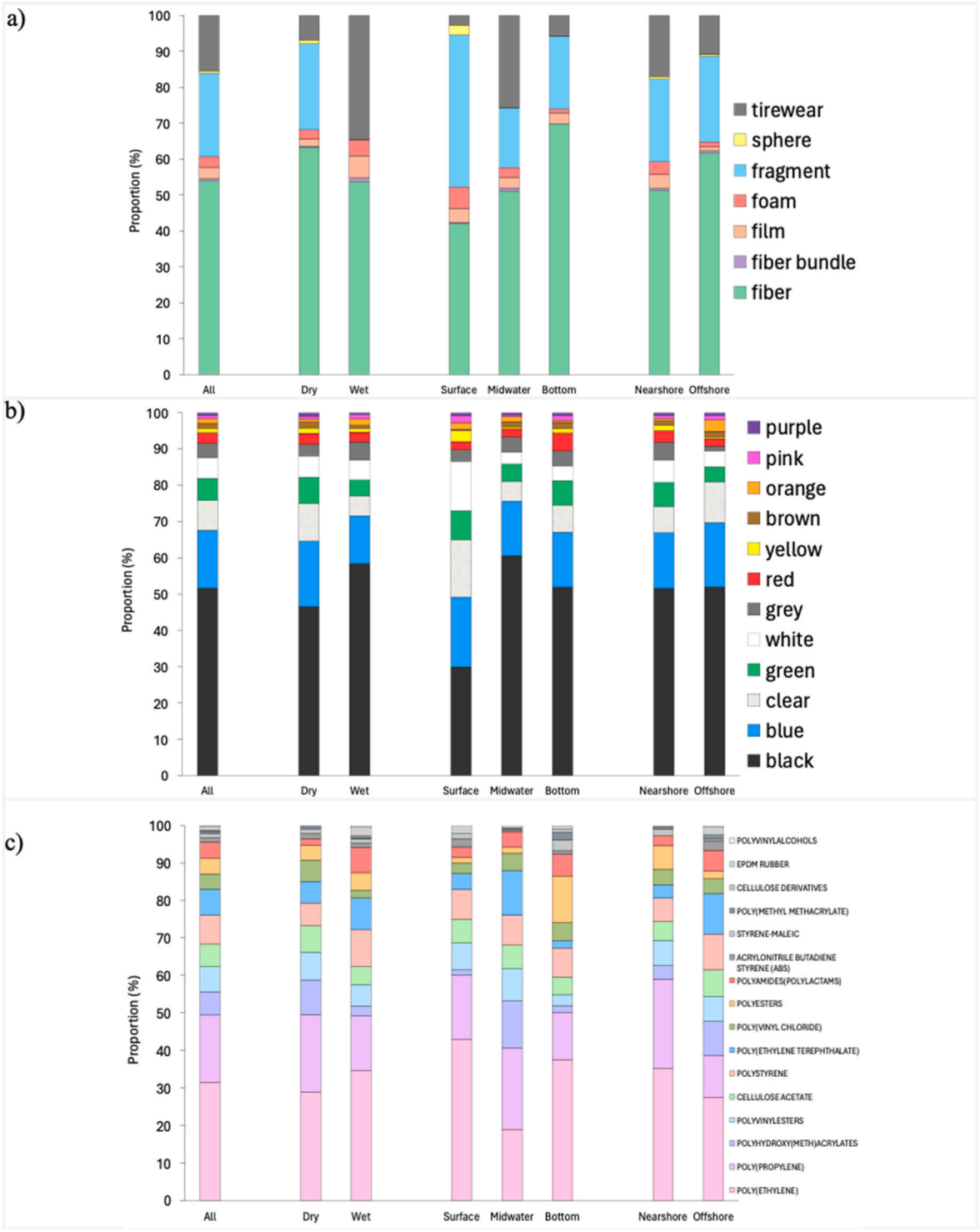

Fig. 4. Microplastic composition of water column samples in terms of a) morphology, b) color, and c) polymer type aggregated across the entire study (All), and by season (Dry, Wet), water column position (Surface, Midwater, Bottom), and distance from shore (Nearshore, Offshore). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 4). A similar distribution of polymer types was found in the water column samples between the wet and dry season especially for the most abundant polymers (Table s2). However, there was a significant difference in neutrally buoyant ($p = 0.04$) and negatively buoyant polymers ($p = 0.04$) in the wet and dry season in the water column with higher concentrations of neutrally buoyant particles in the wet season and higher concentrations of negatively buoyant polymers found in the dry season (Table s2). We also found that there was a significantly higher concentrations of positively, negatively and neutrally buoyant particles at the surface than through the rest of the water column (Table s2) iterating the effect that polymer characteristics such as density have on their distribution through the water column. In the sediment, polyether, polyethylene and polymethyl macrylates were proportionally greater than the other polymer types (Fig. 5). There were significantly more positively and neutrally buoyant polymers in the nearshore as compared to the offshore environment and significantly more neutrally buoyant

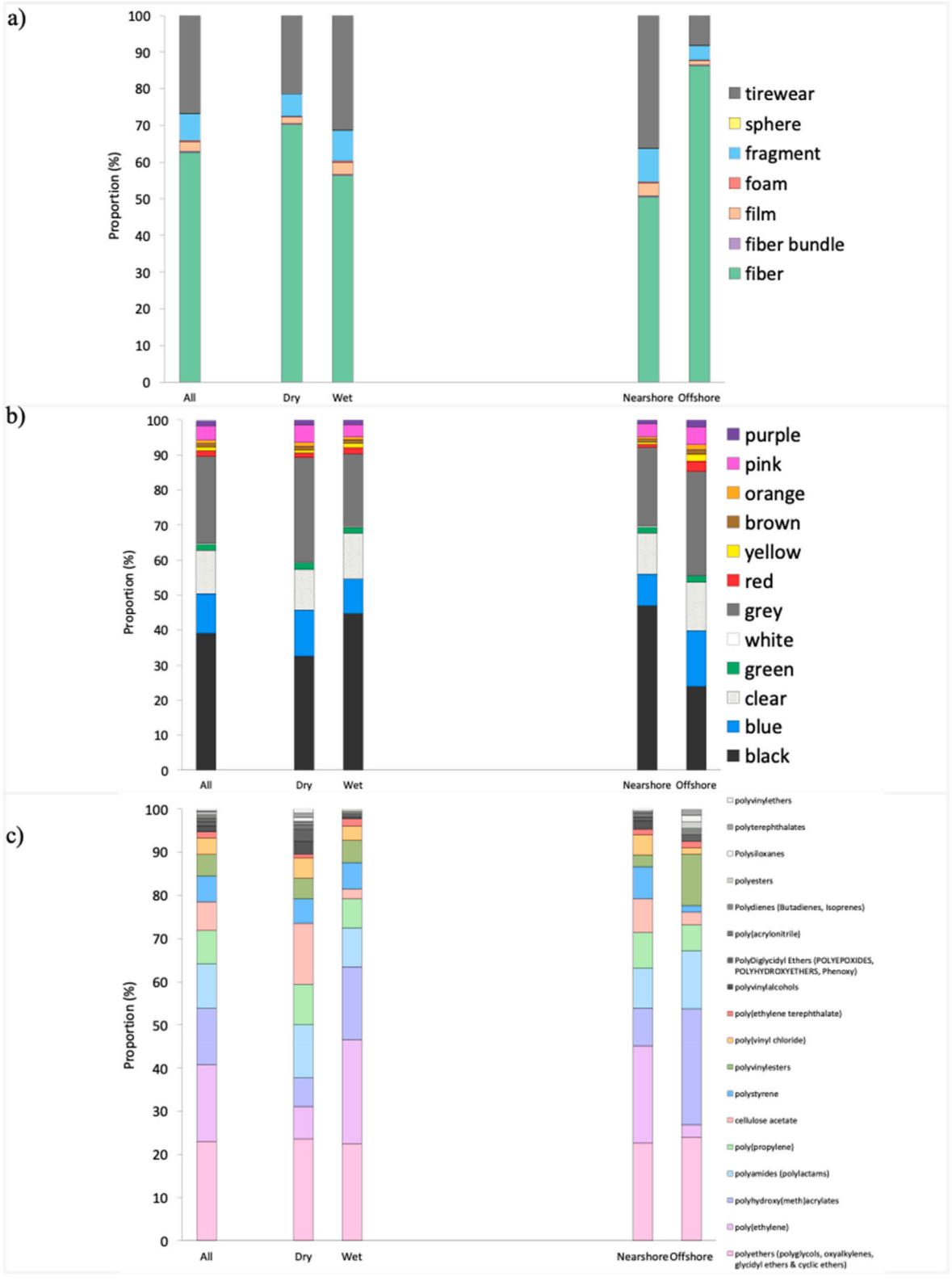

Fig. 5. Microplastic composition of sediment samples in terms of a) morphology, b) color, and c) polymer type aggregated across the entire study (All), by season (Dry, Wet), and distance from shore (Nearshore, Offshore). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

polymers in the wet as compared to the dry season in the sediment samples (Table s3).

3.2.3. Microplastic particle size distribution

Microplastic particles in the water column ($p = 2.2 \times 10^{-16}$) (Table s2), and benthic sediment ($p = 1.73 \times 10^{-6}$) (Table s3) were significantly larger in the dry season as compared to the wet season

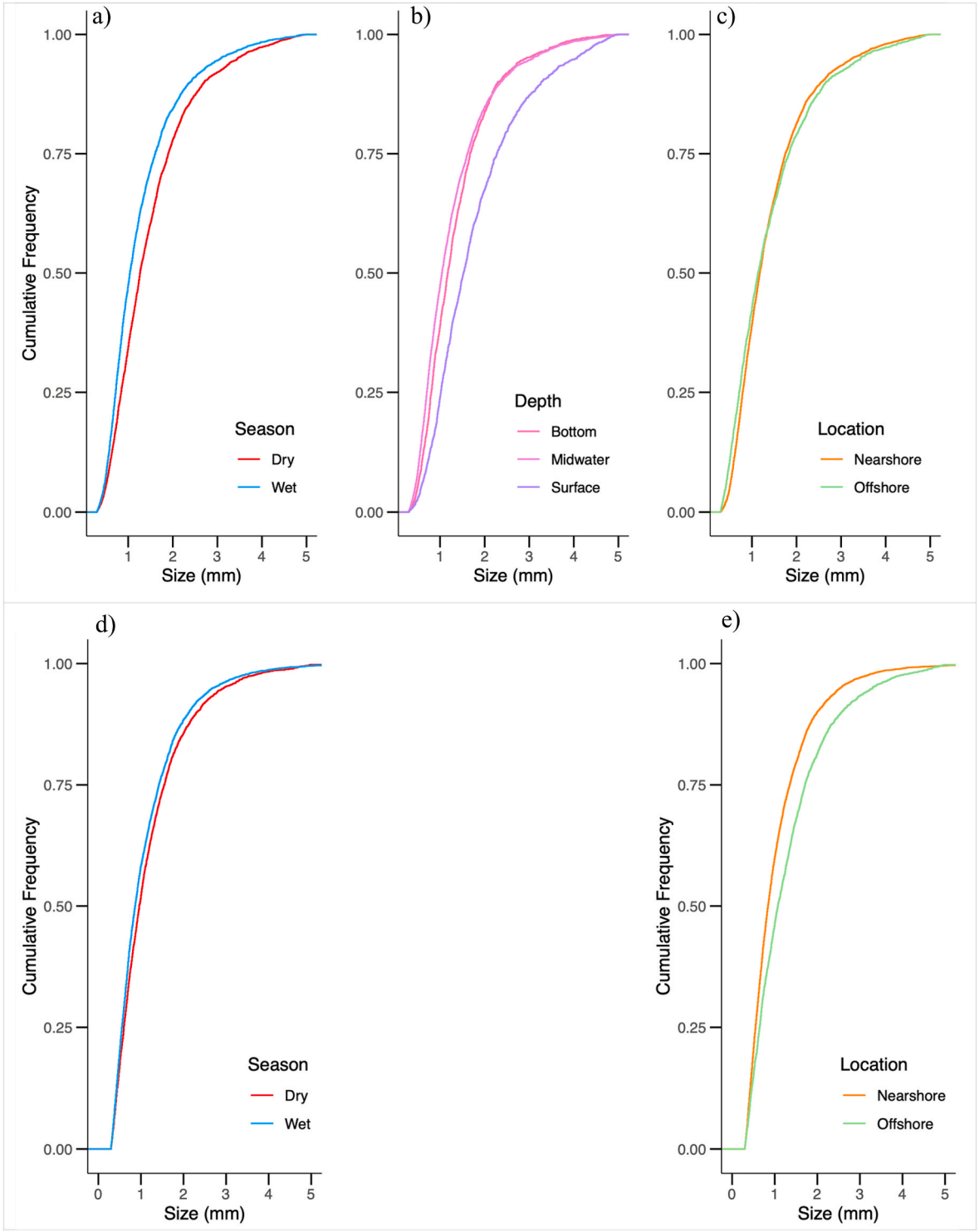

Fig. 6. Microplastic size cumulative frequency distribution for water column samples by a) season (Wet, Dry), b) water column position (Surface, Midwater, Bottom), and c) location (Nearshore, Offshore), and for sediment samples by d) season and e) location.

(Fig. 6). There was no significant difference in the size of microplastics in the nearshore versus offshore environment for the water column (Table s2). In the sediment samples however, microplastics were significantly larger in offshore locations ($p = 1.73 \times 10^{-6}$) (Fig. 6, Table s3). In both the water column and sediment samples, 80% of the particles were less than 2.5 mm in size (Fig. 6). More than 95% in the water column and sediment samples where secondary microplastics. Larger microplastics were present at the surface as compared to the rest of the water column ($p = 2.2 \times 10^{-16}$) (Table s2) (Fig. 6).

3.3. Comparison to other microplastic studies in the Pacific Ocean

Comparison of studies of microplastics in the Pacific Ocean were done selecting studies that sampled using manta nets of the same mesh size used in the present study (333 μm). The average areal concentration of microplastic in the surface water of San Pedro Bay ($8.64 \times 10^5 \pm 7.60$

$\times 10^5$ particles/km^2) is the highest reported to date, albeit similar to concentrations in San Francisco Bay (7×10^5 particles/km^2; Sutton et al., 2016). Lower values were reported in the North Pacific Central Gyre (3.34×10^5 particles/km^2; Moore et al., 2001), the North Pacific Ocean (1.05×10^5 particles/km^2; Eriksen et al., 2014)), the North Pacific Subtropical Gyre (3.31×10^4 particles/km^2; Law et al., 2014) and the South Pacific Subtropical Gyre (2.69×10^4 particles/km^2; Eriksen et al., 2013). The average volumetric concentration of microplastics found in this study was 3.19 ± 2.96 particles/m^3 comparable to (Lattin et al., 2004), who also sampled at multiple depths through the water column and found 3.29 particles/m^3. Surface volumetric concentration of this study was 2.06 ± 2.41 particles/m^3, which is higher than the concentrations observed in the Northeast Pacific Ocean (0.004 particles/m^3 (Doyle et al., 2011); and the Mid North Pacific Ocean (0.51 particles/m^3; (Pan et al., 2022) (Table 1).

4. Discussion

4.1. Seasonal differences in water column microplastic concentrations

Microplastics concentrations were greater but not significantly different in the dry season as compared to the wet season. In the study by (Baini et al., 2018) in the Mediterranean Sea it was found that seasonality also did not affect microplastic concentration significantly. Further the study by (Cheung and Not, 2023) in Hong Kong showed that even with wet season concentrations 5x greater than the dry season, the difference was insignificant. In contrast, the study by (Lattin et al., 2004) investigating neustonic microplastic concentration in the Santa Monica Bay found an 18-fold increase in microplastic concentration before and after a storm event. The study by (Cheung and Not, 2023) in addition to wet and dry season microplastic concentration investigations also investigated the change in microplastic concentrations before and after storm and typhoon events which showed concentration increases by 11–36 times (Cheung and Not, 2023). These dramatic increases in microplastic concentration after rainfall events are likely attributed to elevated supply of terrestrial microplastics transported by urban storm runoff (Browne et al., 2011; Doyle et al., 2011; Desforges et al., 2014; Chen et al., 2021a,b). This trend may not have been observed in this study because even though sampling took place in the wet season in March 2021, the actual sampling event did not occur immediately after a rainfall event as was the case with (Lattin et al., 2004) or extreme weather events like with (Cheung and Not, 2023).

4.2. Microplastics in nearshore and offshore waters

Significantly higher microplastic concentrations were observed in the nearshore compared to offshore environments of this study and have been observed in multiple other studies as well (Pedrotti et al., 2016; Desforges et al., 2014; Wang et al., 2020; Amenábar et al., 2023). This could be attributed to land based anthropogenic activity contributing to elevated concentrations of microplastics in the nearshore environment (Chen et al., 2021a,b). In addition, the co-location of this study with the outfalls of the Los Angeles, San Gabriel and Santa Ana River and the fact that rivers are a conduit of plastic pollution to the marine environment (van Emmerik et al., 2023; Meijer et al., 2021) likely contributed to the significantly higher microplastic concentrations in the nearshore environment.

The pattern of decreasing concentration with increasing distance from the shore observed in this study has not been consistently found in other regions. For example (Baini et al., 2018), found higher concentrations of microplastics further from the shore in the waters of the Northwestern Mediterranean Sea, while (Goldstein et al., 2013) observed higher concentrations further offshore in sampling locations close to the convergence zone of the North Pacific Sub Tropical Gyre. Choy et al. (2019) also found that samples contained higher microplastic concentrations offshore in Monterey Bay, California. The increase in concentration at the site furthest of shore (HS_H3) in this study could be attributed to the seasonally dependent wind forcing and upwelling currents characteristic of the greater California Current (Ryan et al., 2009; Kessouri et al., 2021), which can result in the entrainment of plastic debris to offshore locations (Doyle et al., 2011). In addition, topography is one of the greatest drivers of circulation currents inside the San Pedro Bay (Kessouri et al., 2021), Therefore, the location of this site just off the shelf and the associated currents could be responsible for the observed increase in microplastic concentration. A more intensive monitoring program coupled with transport modeling investigations would be required to further elucidate the causes of microplastics concentration distributions throughout San Pedro Bay.

4.3. Distribution of water column microplastics with depth

There were significantly higher microplastic concentrations at the surface than the rest of the water column. Most research at present only focuses on microplastic at the sea surface and those that have conducted subsurface sampling have focused mostly on the midwater column (Doyle et al., 2011; Cózar et al., 2015; Eriksen et al., 2013; Chevalier et al., 2023). Studies that have conducted subsurface sampling found higher microplastic concentrations at the surface as well (Goldstein et al., 2013; Choy et al., 2019). However, floating microplastics may not remain near the surface as they are subjected to photodegradation (Andrady, 2011), wind mixing (Kooi et al., 2016; Sebille et al., 2020; Reisser et al., 2015), waves (Sebille et al., 2020), and biofouling (Goldstein et al., 2013), which can cause these particles to sink and/or be mixed deeper into the water column (Kooi et al., 2017; Liu et al.,

Table 1
Water column microplastic concentrations found in the Pacific Ocean.

Author	Date	Location	Manta		Manta Bongo	Manta Bongo Epibenthic
			Concentration (particles/km^2)	Concentration (particles/m^3)	Concentration (particles/m^3)	Concentration (particles/m^3)
Moore et al.,	2001	North Pacific Central Gyre	334,271			
Eriksen et al.,	2013	South Pacific Sub Tropical Gyre	26,898			
Sutton et al.,	2016	San Francisco bay	700,000			
Mu et al.,	2019	North West Pacific Ocean	90,000			
Isobe et al.,	2015	North Pacific Ocean	105,100			
Pan et al.,	2022	Mid North Pacific Ocean		0.51		
Doyle	2011	NorthEast Pacific Ocean		0.004		
Goldstein et al.	2013	Eastern Pacific			0.448	
Lattin et al.,	2004	Santa Monica Bay				3.92
This Study			**864,796 ± 760,312**	**2.06 ± 2.41**	**2.53 ± 2.39**	**3.19 ± 2.96**

2020). During the summer, ocean stratification is stronger off the Californian coast while seasonal mixing resulting in dilution is more predominant in winter, further transporting particles through the water column due to higher turbulence (Doyle et al., 2011; Chevalier et al., 2023) needs to be taken into consideration when designing sampling plans.

The selective loss of particles from the surface to the rest of the water column (Eriksen et al., 2013; Reisser et al., 2015; Kooi et al., 2016) is affected by size, polymer density (Lenaker et al., 2019; Chevalier et al., 2023) and in turn the rise and settling velocity of particles (Kooi et al., 2016). It is sometimes believed that deeper water column sampling is likely to be unnecessary when determining microplastic concentrations in the marine environment because of this exponential decrease between the surface and the midwater (Reisser et al., 2015; Baini et al., 2018). Even though a sharp decline in microplastic concentration from the surface (2.06 particles/m^3) to midwater samples (0.53 particles/m^3) was observed in our study, we also found an increase in concentration of microplastics in the bottom water samples (0.75 particles/m^3) as compared to the midwater (Fig. 3). Furthermore, given the massive volume of water in the subsurface versus surface domain (depth of 9 m at the shallowest to 350 m at the deepest), our study suggests that most of the microplastics (likely >99%) in the waters of San Pedro Bay are found in the subsurface. Therefore, these findings indicate that in order to accurately determine microplastic concentrations in the marine environment it is as important to consider concentrations throughout the water column (Lefebvre et al., 2019), especially under conditions where increased wind and vertical mixing may entrain buoyant particles below the surface and potentially contribute to the suspension of negatively buoyant particles (Goldstein et al., 2013).

4.4. Microplastic morphology and polymer type

The high proportional abundance of microplastic fibers found in water column and sediment samples in this study is in agreement with the findings of many other ocean microplastic monitoring studies in the Midwest Pacific Ocean (Wang et al., 2020), the Northwestern Mediterranean Sea (Lefebvre et al., 2019), and the Northeast Pacific Ocean and Coastal British Columbia (Desforges et al., 2014). Microplastic fibers can originate from a number of sources including wastewater treatment outfalls (Wang et al., 2020) textiles, cigarette filters, and personal care products such as wipes. Textiles shed fibers throughout their life cycle from production to washing and drying and even after disposal (Athey and Erdle, 2022) resulting in their abundance in the environment, but further research is required to elucidate their dominant emission and transport pathways to and through the environment (Zhang et al., 2022).

polyethylene and polypropylene were the most abundant polymers in the water column of this study. Overall, polyethylene and polypropylene are the most abundantly manufactured polymers (Erni-Cassola et al., 2019; Geyer, 2020) accounting for about 74% of global plastic production in 2015 (Erni-Cassola et al., 2019). These polymers are most abundant in the marine environment globally (Baini et al., 2018; Eriksen et al., 2014) because of their extensive use in single use plastics such as plastic bags, bottle caps and containers (Desforges et al., 2014). The abundance of polyethylene and polypropylene microplastics may also be enriched at the sea surface due to their low density (Erni-Cassola et al., 2019). It is important to note that while cellulose acetate is anthropogenic, other cellulose derivatives may occur naturally. However, these were minimal in the sample (<1%).

Studies such as Liu et al. (2020), Erni-Cassola et al. (2019); Schwarz et al. (2019), Ferreira and Lôbo-Hajdu (2023) also identified polyethylene and polypropylene as the most abundant polymer types in marine environments. In contrast, other studies such as that of Lefebvre et al. (2019) identified polyethylene terephthalate followed by polyamide as most abundant. These differences in polymer types across studies indicate the potential dependence of polymer distribution on the source of microplastics to the ocean, transport pathways, sampling location, and sampling method in determining the most dominant polymer type (Erni-Cassola et al., 2019). In addition, it is important to note that the morphological characteristics of fibers such as their large aspect ratio often makes it difficult to collect spectral signatures and identify their polymer types, which could bias the results. Scanning of the entire field of view instead of point and shoot method for fibers could be beneficial for better spectral collection. Apart from material density, the presence of certain polymers through and across the water column are also affected by wave driven turbulent mixing, particle morphology, and size (Cózar et al., 2015; Erni-Cassola et al., 2019; Rowlands et al., 2023).

In the sediment polymers identified were not necessarily negatively buoyant indicating that other factors such as wind driven mixing and biofouling affect the rising and settling of the particles influencing their distribution through the water column (Li et al., 2023; Rowlands et al., 2023). Therefore, Sampling microplastics exclusively at the sea surface does not account for seasonal effects on ocean currents and rainfall/runoff relationships and thus may result in an underestimation of the concentration of higher density polymers.

4.5. Microplastic size distribution

In this study significantly larger microplastics were found in the dry as compared to the wet season. In contrast (Chen et al., 2021a,b), observed the opposite trend with larger particles found in the wet season along the coast of Taiwan, which could be attributed to the increased influx of microplastics from closer land-based sources in the wet season. The size variations of microplastics found in this study could be influenced by seasonal differences in the particle size distribution of primary riverine sources and increased hydrodynamic activity during the winter which may influence the rate of weathering of plastic particles (Rizzo et al., 2021), combined with ocean mixing which may result in increased fragmentation and movement of these weathered particles over longer distances (Martin et al., 2019; Doyle et al., 2011). Most of the microplastics were less than 2.5 mm in size and were classified as secondary microplastics both of which indicate the dominance of these microplastics produced through fragmentation/weathering from larger plastic material sources (Doyle et al., 2011; Baini et al., 2018). However, further investigation of microplastic source, weathering, and transport dynamics will be required to elucidate these controls on microplastic size distributions in coastal marine systems.

Smaller positively buoyant particles found through the water column are more susceptible to downward transport due to their lower rising velocities (Reisser et al., 2015; Baini et al., 2018) and it has been found that microplastic size exponentially decreases with depth (Liu et al., 2020). Smaller particles have a higher surface area to volume ratio and experience more rapid changes to their specific densities through biofouling, surface adsorption, and flocculation, which can increase sinking rates (Kaiser et al., 2017; Reisser et al., 2015; Ryan et al., 2009; Isobe et al., 2014; Liu et al., 2020) regardless of polymer type and density (Kaiser et al., 2017).

4.6. Limitations of microplastic sampling in the near coastal marine environment

Field-based sampling is challenging, particularly in dynamic environments such as the near coastal marine zone. Time, logistical, technology and monetary challenges can be prohibitive for studies that target multiple locations, seasons, and water depths. However, high variability of microplastic concentrations across and through the water column will make future changes in microplastic concentrations difficult to detect without substantial sampling effort (Goldstein et al., 2013). In terms of sampling devices, net based sampling implicitly introduces bias based on net mesh size, obtaining sufficient volumes for analysis because of net clogging and the inability to retain fibers and smaller

microplastics (Razeghi et al., 2021). Further, the inverse power law relationship of increasing microplastic concentration with decreasing size (Kooi and Koelmans, 2019; Gilfillan, 2009) is not always observed because of the sampling apparatus used, human error and limitations and differences in size classes of microplastics analyzed. For example, Di Mauro et al. (2017) compared microplastic concentrations in bulk water samples collected using Niskin bottles and net samples in the Northern Gulf of Mexico and found a two factor increase in microplastic concentrations from net samples to bulk water samples because of the exponentially higher concentrations of microplastics at smaller size ranges.

The diversity in characteristics such as size, shape, color, and polymer of these microplastic particles can provide insights into sources, weathering, and fragmentation processes, but also complicate comparing and understanding how microplastics behave in different scenarios related to ocean circulation, temporal and spatial dynamics, and water column distribution (Pan et al., 2022). Comparison with other studies is often complicated by a lack of reporting on sampling and laboratory methodologies and microplastic particle sizes, as well as differences in reported concentration units. Some studies report concentration on an areal basis (e.g. particles/km^2) while others use volumetric measures (e.g. particles/m^3); converting between these units can increase error and uncertainty or even be completely stymied by insufficient metadata (Di Mauro et al., 2017).

5. Conclusion

Our findings underscore the importance of a robust sampling regime to consider geography, distance from potential plastic sources, temporal variation and changes in coastal ocean currents. These factors can affect microplastic concentration, character, and distribution laterally and through the water column. The fact that microplastics were observed through the entire water column and in benthic sediment emphasizes the need to expand marine monitoring activities beyond the surface of the water column in order to accurately estimate the concentration of microplastics in the marine environment. The size of microplastics was also significantly larger at the surface than the rest of the water column. Based on the results of this study, we conclude that monitoring programs focused solely on the water surface risk grossly underestimating microplastics in the marine environment.

CRediT authorship contribution statement

Samiksha Singh: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrew B. Gray:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Clare Murphy-Hagan:** Writing – review & editing, Software, Methodology, Data curation. **Hannah Hapich:** Writing – review & editing, Software, Methodology, Data curation. **Win Cowger:** Writing – review & editing, Software, Resources, Methodology, Conceptualization. **John Perna:** Writing – review & editing, Methodology, Data curation. **Thai Le:** Methodology, Data curation. **Hinako Nogi:** Methodology, Data curation. **Bani Badwal:** Methodology, Data curation. **Karen McLaughlin:** Methodology, Conceptualization. **Fayçal Kessouri:** Writing – review & editing, Methodology, Conceptualization. **Charles Moore:** Resources, Investigation. **Gwen Lattin:** Resources, Investigation. **Leah M. Thornton Hampton:** Writing – review & editing. **Charles S. Wong:** Writing – review & editing. **Martha Sutula:** Writing – review & editing, Resources, Project administration, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.120866.

Data availability

https://github.com/SamikshaSingh2506/OceanMP

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