A Year-long Field Study of Buried Plastics Reveals Underestimation of Plastic Pollution on Hawaiian Beaches

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Abstract

Global models estimate that two-thirds of floating ocean plastic has accumulated in coastal areas since the 1950s, with Hawai‘i's windward shores particularly vulnerable due to their proximity to the North Pacific Garbage Patch. Our quarterly surveys revealed that 91% of recovered plastic particles were buried below the surface (deeper than 2 cm), with most particles being small fragments (93%) ranging from 5.4 to 7.9 mm. This study offers new insights into subsurface plastic pollution, exposing a previously hidden vertical distribution. We observed significant variations in plastic abundance across depths, beaches, and sampling periods, along with a positive correlation between particle size and sand grain size. Additionally, through reconciliation science, we critically reflect on the cultural impacts of our research, emphasizing the importance of aligning plastic pollution studies with local community values and environmental stewardship.

1. Introduction

Plastic pollution has become one of the most pressing environmental challenges globally (Calil, J *et al.*, 2021). Since the onset of synthetic polymer production in the 1950s, global models of plastic pollution predict that approximately two-thirds of the plastic mass released into the ocean has either stranded or settled around the world's shorelines (Kaandorp *et al.*, 2023; Lebreton *et al.*, 2019; Onink *et al.*, 2021). Furthermore, plastic debris transported by ocean currents and wind can travel vast distances across the world's ocean far away from its source, eventually converging in one of the five subtropical gyres, where it persists as "legacy plastics." The accumulation of floating plastic debris in these gyres is commonly referred to as "Garbage Patches" (Eriksen *et al.*, 2014; Lebreton *et al.*, 2018; Maximenko *et al.*, 2012; van Sebille *et al.*, 2020). Shorelines near these Garbage Patches, particularly those of islands that are exposed to the large current systems that form the gyres, are particularly susceptible to receive "legacy plastics" pollution (Barnes *et al.*, 2018; Pham *et al.*, 2023). While large-scale models are valuable in identifying high accumulation areas, they often lack the resolution needed to fully describe the temporal and spatial variations in plastic accumulation as well as the state of plastics (e.g. size, shape, type, degradation level) in these regions (Critchell *et al.*, 2015; Critchell & Lambrechts, 2016; Hardesty *et al.*, 2017; Melvin *et al.*, 2021). This limitation hinders our ability to develop effective mitigation strategies tailored to the specific challenges these areas face.

Hawaiʻi is heavily impacted by plastic pollution due to its proximity to the North Pacific Subtropical Gyre, where the high concentration of floating plastic debris is known as the North Pacific Garbage Patch, NPGP, (Berg *et al.*, 2024; Carson *et al.*, 2013; Kaandorp *et al.*, 2023; Lebreton *et al.*, 2018). Beaches on the windward (east) side of the islands, which are exposed to the trade winds and are aligned with the NPGP, receive a significant amount of weathered marine debris that has traveled across the Pacific Ocean (Brignac *et al*., 2019; Berg *et al*., 2024; Carson *et al*., 2013). This has been confirmed by studies showing that a significant number of identifiable items on Hawaiian beaches originate from non-local sources, as evidenced by foreign labels, and the severely degraded, biofouled surfaces suggesting long-term exposure to the marine environment (Brignac *et al*., 2019; Carson *et al*., 2013; Connors *et al*., 2024). Although numerous studies and field surveys have investigated the state and abundance of plastic debris on Hawaiian beaches, these studies have focused on the beach surface layers, and to our knowledge, there are no reports investigating the distribution of plastic particles deeper than 10 cm in the sand columns of Hawaiian beaches (Agustin *et al*., 2015; Berg *et al*., 2024; Blickley *et al*., 2016; Brignac *et al*., 2019; Carson *et al*., 2011, 2013; Cooper & Corcoran, 2010; McDermid & McMullen, 2004; Ribic *et al*., 2012; Young & Elliott, 2016).

The handful of studies that have investigated buried plastic—in beaches in Brazil, in the Indian Ocean, and on the Azores—have highlighted significant quantities in the deeper sediment layers (Fauziah *et al*., 2015; Kusui & Noda, 2003; Lavers *et al*., 2019; Pham *et al*., 2023; Taniguchi *et al*., 2016). For instance, Pham *et al*., (2023) revealed that buried plastic in sand column cores (10.1-100 cm) from sandy beaches across the Azorean archipelagos accounted for 84% of the total abundance of plastic particles found in the sampled sand-core, with concentrations varying across the horizontal stretch of the beach, with the highest concentration at the backshore of the beach (comprising the berm and foredune). Another study by, Lavers *et al*., (2019) on the Cocos Islands (Australia) revealed that between 10-70 times more debris items per m^2 are buried compared to items visible on the surface of beaches. Moreover, plastic particles were discovered down to 2 m depth on a sandy beach in Brazil (Taniguchi *et al*., 2016; Turra *et al*., 2014). These findings highlight that limiting surveys to plastic particles on the beach surface could underestimate the total abundance of plastic pollution in littoral environments.

Considering that the quantity and type of plastic found on beach surfaces are often used to get a proxy for the extent of ocean plastic pollution levels, with oceanic insular areas being particularly valuable for monitoring global pollution trends (Barnes *et al*., 2018; Pham *et al*., 2023; Serra-Gonçalves *et al*., 2019), including the subsurface concentration would provide a more comprehensive assessment of the state of ocean plastic pollution. Furthermore, repeated measures of beach plastic, with appropriate frequencies, could reflect changes in the abundance of debris at sea (Ryan *et al*., 2009). As noted by Pham *et al.* (2023), tracking buried plastic particles over time may provide a more accurate representation of total plastic abundance on beaches and serve as a more stable indicator of ocean plastic pollution, as these buried plastics are less susceptible to disturbance from e.g. wind and beach clean-ups. Thus, a better understanding of the quantity of plastic particles in the deeper layer of the sand column could be useful in assessing ocean plastic pollution and the effectiveness of upstream mitigation efforts, especially in zones which are predicted to receiving significant amount of the "legacy plastics."

In this study, we investigate the distribution and concentration of plastic debris within the sand columns of beaches on the windward side of Oʻahu. Through quarterly surveys of plastic debris (> 0.5 mm) across different depths (up to 1 m) in 60 x 60 cm quadrats, conducted from November 2022 to February 2024, we aim to assess changes in observed plastic abundance in the sand column. By examining plastic concentrations at various depths and beaches, we also provide first insights into the total abundance and distribution of plastic on beaches of Hawaiʻi.

This data can refine our understanding of beach plastics on the shores of Hawai‘i and contribute to more comprehensive monitoring of broader trends of plastic pollution in the Pacific Ocean.

This study also includes an initially unplanned but transformative collaboration with a Kanaka ‘Ōiwi (Native Hawaiian) leader, Kimeona Kāne, Chairperson of the Waimānalo Neighborhood Board and cultural practitioner, which began in the later stages of the research. This collaboration led to critical realizations about the potential harm our research methods might have caused, such as disinterring ancestral burial remains, and prompted a reflection on how our scientific approach failed to address important cultural considerations. We draw from and seek to extend Liboiron *et al.*'s (2021) concept of reconciliation science, which calls for integrating such reflections into the scientific process. As Liboiron *et al.* argue, these reflections should be named in scientific works, “*Rather than dividing these reflections into a separate ‘opinion’ piece or social science paper...*” In line with this approach, we provide a critical reflection on our research methods and findings through the lens of this collaboration, aiming to prevent further harm by highlighting our missteps. These insights are discussed in the Results and Discussion sections.

1. Methods

1.1. Study area

The field sampling for this study was conducted on O‘ahu which is one of the eight main islands of the Hawaiian archipelago in the North Pacific Ocean and is the third largest and most populated island in Hawai‘i (Fletcher *et al*., 2012). O‘ahu has approximately 107 km of sandy beach that is separated into four regions: north, east, south, and west (Fletcher *et al*., 2012). The three beach sites used for this study; Kahuku (21°42'09.0"N 157°57'36.0"W), Kokololio (21°37'41.2"N 157°55'15.6"W), and Waimānalo (21°20'06.0"N 157°41'45.6"W), are all located on the east side of O‘ahu (as shown in Fig. 1), also known as the windward side due to the predominant easterly trade winds that consistently hit O‘ahu's eastern coast and expose the shoreline to short-period trade wind waves year-round. In addition to trade wind waves the windward coast is also affected by large refracted North Pacific swells during winter (Fletcher *et al*., 2012). Shallow fringing reefs protect much of East O‘ahu's shoreline from the full energy of large waves. However, beaches behind these protective reefs are typically low-lying and narrow, prone to inundation during large waves and storms. Furthermore, Hawai‘i is in a micro-tidal zone with a tidal range of about 1 m but large winter swells can cause variations in beach width by up to two-thirds (Fletcher *et al*., 2012).

The combination of the east side of O‘ahu facing and being near the North Pacific Subtropical Convergence Zone, where debris accumulates to form the NPGP, and the influence of northeast and easterly trade winds, brings significant amounts of plastic debris to the shores on the windward side of O‘ahu (Cooper & Corcoran, 2010; Kubota, 1994). Studies comparing the leeward and windward sides of O‘ahu also suggest that the windward side is more prone to accumulate plastic originating from the open ocean (Brignac *et al*., 2019). The beaches were selected due to their locations on the windward of O‘ahu, and their varying beach characteristics and plastic accumulation patterns, with Kahuku known for accumulating the largest amounts of plastics at the surface (Brignac *et al*., 2019; Young & Elliott, 2016). A summary of the key characteristics of Kahuku, Kokololio, and Waimānalo, including their positions, dimensions, and sand size as classified by the Wentworth scale (Wentworth, 1922), and notable features, is provided in Table 1.

Table 1: Key characteristics of the three studied beaches; Kahuku, Kokololio, and Waimānalo, including their geographical position, approximate beach length, subaerial width, sand grain

size (classified by the Wentworth scale; Wentworth, 1922), and any notable environmental or physical features relevant to the study.

Beach	Position	Length (m)	Width (m)	Sand size (Wenworth)	Notable Features
Kahuku	North East	~600	5-15	Coarse	Located in James Campbell National Wildlife Refuge (low human presence). Exposed to strong winter North Pacific swells. Dynamic shoreline changes.
Kokololio	East	~650	10-30	Coarse to Medium	Situated in a bay. Affected by trade wind waves year-round and large refracted North Pacific swells during winter.
Waimānalo	South East	~6,500	20-40	Medium to very fine	Largest of the three beaches, located in a bay. Exposed to easterly trade winds and winter swells.

1.2. Beach plastic sampling

All sites considered in this study were sampled every three months over 15 months, starting in November 2022, with subsequent samplings in February 2023, May 2023, August 2023, November 2023, and February 2024. Sampling was conducted using triplicate quadrats (60 x 60 cm) placed 10 m apart (measuring from the middle of the quadrats) and parallel to the shoreline along the drift line (the berm). The drift line was defined as the line of debris accumulation above the high tide line (as shown in Fig. S1 in the SI). All three quadrats were sampled on the same day, resulting in three separate sampling days per beach (with 1-7 days between the sampling days, most of which were conducted during weekends to allow more volunteers to join). The exact locations of the quadrats were marked by their distance from the vegetation line and documented with photographs. The quadrats were positioned 5-10 m from the locations of the previous quadrats from the preceding sampling campaign three months prior, using the previous location information. The distance varied to avoid disturbing local wildlife (e.g., monk seals) and beachgoers. The same quadrat was never resampled during the field surveys. All sets of quadrats were sampled within the same sections of the beaches, within an approximately 20-50 m range, to maintain consistency and avoid significant variations across different beach areas.

The quadrats used were four-sided hollow boxes with dimensions of 60 x 60 cm and a width of 20 cm and were made on Oʻahu by Pac Pro Hawaiʻi (https://www.ppg-hi.com/) using 16-gauge galvanized steel with welded corners. Inside the metal frame, markings at 2 cm and 10 cm were added as guides for collecting different sand layers (see Fig. S6 for the metal frame in the SI).

The sand of the surface layer was collected within the metal box frame down to the 2 cm marking and added to a 5-gallon bucket (22.7 L), which had a marking of 7.2 L (corresponding to the volume of sand from 60 x 60 x 2 cm), serving as a secondary guideline for the quantity of sand needed to be collected. The collected sand in the bucket was weighed, and the temperature and moisture content of the sand were measured using a liquid-in-glass thermometer and a high-frequency moisture meter DML300L by MeterTo. The mass of the dry sand was then calculated by subtracting the mass attributed to moisture from the total mass of the sand of each layer. The sand was then transferred to the top bin of the Buoyancy Separation Device (BSD) developed on Oʻahu by Seed.World (https://www.seed.world/). The BSD is a wheelbarrow equipped with a top bin (see Fig. S8 in the SI) and two battery-powered hoses that circulate ocean water from the main body of the wheelbarrow (under the top bin) to the top bin. The water from the hoses is used to stir the sand and to separate the buoyant debris from the sand. By positioning the BSD at a tilted angle, the floating debris moves towards the lower end of the wheelbarrow and is collected in a 250-µm mesh bag, while the heavier cleaned sand remains in the top bin. Once the sand had been stirred until no more floating debris was observed, the clean sand was returned to the beach. This method facilitated the effective in-field separation of sand and floating debris, allowing only the removal of floating debris. After removing the first 2 cm of sand, the quadrat content of the next 10 cm of sand was exhumed to a depth of 12 cm, representing the 2-12 cm layer. This sand was collected into two 5-gallon buckets with markings at 18 L each to guide the collection of the next 10 cm layer of sand, totaling 36 L (volume of 60 x 60 x 10 cm). The floating debris was collected as described above. The process was repeated, collecting buried floating debris in subsequent 10 cm increments down to a depth of 1 m. Buoyant debris from each depth layer was collected into separate mesh bags, resulting in 11 mesh bags per quadrat. Efforts were made to avoid collecting too much natural debris. On the occasional encounters with small marine animals (e.g., crabs) within the sand column were returned to the beach if found in the quadrats.

Overall, 594 samples were collected (11 depth layers, 6 sampling time sets, 3 beaches, and 3 quadrats per beach). After each quadrat was sampled and the plastic removed, the 'clean' sand was replaced to restore the area. A detailed field survey method, with step-by-step pictures, are provided in the SI.

1.3. Plastic sampling processing

The mesh bags with the floating debris collected per stratified layer were air-dried for at least a week after collection. The content for each dried mesh bag was weighed to the nearest 0.001 g (Mettler-Toledo, AE 240-S Dual Range Balance) and then spread out on a mat. The plastic debris was manually separated from the natural debris and the total amount of plastic particles collected per sample was weighed to the nearest 0.001 g. The plastic debris was then laid out on a blue background sheet alongside a reference coin of 37 mm diameter and were photographed with a resolution of at least 10 pixels in diameter. The image was processed using the Segmentation Model developed by The Ocean Cleanup, where the model workflow is described by Royer *et al*., 2024. This model classifies each plastic particle into four classes (hard fragment, pellet, line, and foam), into 12 colors (black, white, blue, green, red, orange, salmon, yellow, lightblue, lightgreen, indigo, turquoise, and lightgray), and measures the size of the particles (minimum and maximum length).

The plastic counts (*n*) provided by the Segmentation Model processing and the mass (in kg) of the measured dry weight (DW) of the sand were used to calculate the concentration (n . kg^{-1} DW) of plastics in the sand column sampled at the three beach sites. The total counts of plastic particles per stratified layer and the concentration (n . dm^{-3}) of plastic particles in terms of the volume of sand are provided in S9 and S10, respectively, in the SI.

1.4. Polymer identification

Attenuated Total Reflectance/Fourier Transform Infrared spectroscopy (ATR/FTIR) was used to determine the bulk polymer identity of sampled plastic particles collected during field surveys. If the sample size exceeded 60 particles, a random selection of 60 particles was subjected to polymer ID analysis. The spectra were recorded between 4000 cm^{-1} and 550 cm^{-1} with a resolution of 4 cm^{-1} and 16 scans on a Nicolet iS5 FTIR spectrometer equipped with a KBr beam splitter and a diamond laminate iD5 ATR module. The main peaks in the spectra were identified, using the OMNIC$^{\mathrm{TM}}$ Spectra Software, to determine the functional groups present and establish the polymer identity, following the method described by (Jung *et al*., 2018). For samples requiring further verification or those that could not be identified manually, spectral libraries within the OMNIC^{TM} Spectra Software were consulted, provided the search score was ≥ 0.90 (on a scale from 0 to 1). Samples that remained unidentified after these steps were labeled as UnI (UnIdentified).

1.5. Data analysis

To determine whether plastic counts (the dependent variable) differed among the fixed effects - beach sites, months, and depth - while accounting for quadrats as a random effect, a generalized linear mixed-effects model (GLMM) was employed following similar approach to that employed by Pham *et al*., 2023. The GLMM accommodates both fixed effects, which were 'Beach', 'Month', and 'Depth', and random effects, specifically 'Quadrat' in our case. It should be noted that the number of Months used in our model were six to represent the six field surveys. The random effect for quadrats allows for variability between sampling units to be accounted for, acknowledging that each quadrat might have inherent differences affecting plastic counts. The model was fitted using a negative binomial distribution to address overdispersion in the count data. The 'lme4' package (using R software) was used for fitting the linear and GLMM models. To assess the significance of the fixed effects, an ANOVA was conducted using Wald Chi-square (χ^2) tests using the 'car' package (using R software). This analysis tested the influence of each fixed effect on the dependent variable, 'Counts'. Specifically, the categories tested were 'Beach', 'Month', and 'Depth'. The ANOVA provided a statistical assessment of how plastic counts varied across these categories. All data processing and graphical representations were performed using R software version 2024.04.2.

1.6. Sand grain size

To measure the sand grain size at each beach, we used the Citizen Science tool 'SandSnap' (https://sandsnap-erdcchl.hub.arcgis.com/), a web-based application designed to collect sand grain information from a wide range of locations worldwide. Users take a photo of the sand with a U.S. coin in the frame and upload the image for automated sand grain analysis. The application calculates nine gradation metrics (D_{10}, D_{16}, D_{25}, D_{50}, D_{65}, D_{75}, D_{84}, D_{90}, and mean), and the results are added to the SandSnap database, which can be viewed on the data viewer at https://sandsnap-erdcchl.hub.arcgis.com/ (McFall *et al*., 2024). For our study, we used a U.S. quarter for the SandSnap processing and used the value D_{50} which is the commonly used data point to represent sand grain size. The D_{50} value, or the median grain diameter, represents the size at which 50% of the grains in a sediment sample are smaller and 50% are larger. SandSnap has reported a 22% error in D_{50} values (McFall *et al*., 2024). Pictures were taken for each depth layer along the sand column in 1-2 quadrats, and this was conducted during the last two field campaigns (November 2023 and February 2024). Our data entries are summarized in the table S1 in the SI. SandSnap provided an easy and convenient method to collect many data points without the need to extract sand from beaches.

1.7. Permits

The beach site at Kahuku was located just outside the James Campbell National Wildlife Refuge, requiring a permit for access. This permit was secured through the James Campbell National Wildlife Refuge prior to the commencement of fieldwork and remained valid for the duration of the study. No additional permits were necessary for plastic removal activities on the beach, as confirmed by the Department of Land and Natural Resources (DLNR) and the Division of Aquatic Resources (DAR), provided that only plastic was removed.

1.8. Analysis of Methods for Reconciliation Science

In our effort to align with reconciliation science as conceptualized by Liboiron *et al.* (2021), we critically analyzed our methods through collaboration with cultural practitioner

Kimeona Kāne. Reconciliation science, as described by Liboiron *et al.*, (and how we interpret it), emerges from the recognition that scientific research often perpetuates colonial frameworks and extractive practices that often overlook or undermine local cultural practices and culture-ecological interconnections. Liboiron *et al.* advocates for embedding reflections of research relations within the scientific study and reporting, rather than relegating them to separate afterthought pieces. This encouragement, together with our collaboration with Kimeona Kāne provided guidance for how we reflected on our work in Hawaiʻi, especially after realizing that our initial methods failed to adequately consider the cultural and ecological implications for the local Hawaiian community.

2. Results & Discussion

2.1. Plastic concentration in the sand column

From the 594 samples collected at Kahuku, Kokololio, and Waimānalo during the six field campaigns, a total of 77,033 plastic particles were recovered across all three beaches. Each plastic sample was photographed, and the images were processed through the Segmentation Model (Royer *et al*., 2024) which provided detailed information on the plastic particle count for each sample, along with additional data such as particle lengths, colors, and classifications. An example of the output image from the Segmentation Model is shown in Fig. 3.

Plastic particles were found at depths down to 1 m across all three beaches, and the sand column sampling revealed that the majority (91%) of the total abundance of sampled plastic particles were located below the surface, ranging from 2 to 102 cm deep. Specifically, at Kahuku, 75% of the plastic particles recovered were buried; at Kokololio, 91%; and at Waimānalo, 92% of the total plastic particles were found below the surface layer. This higher abundance of plastics in the deeper layers aligns with findings from studies investigating the distribution of plastics below the sand surface. This higher abundance of plastic particles in the deeper layers is consistent with the findings of the handful of studies that have investigated buried plastics on sandy beaches (Pham *et al*., 2023; Lavers *et al*., 2019; Taniguchi *et al*., 2016; Turra *et al*., 2014). These findings suggest that solely examining surface layers may significantly underestimate the total abundance of plastic pollution on beaches. For example, in our study, the surface layer contains only 8-25% of the total plastic particles, depending on the beach.

Furthermore, using the plastic particle counts for each sample, we investigated the concentration of plastic particles per dry weight of sand along the sand column as shown in Fig. 4. While the highest concentration of plastic particles is generally found at the surface, the sand column analysis at Kokololio and Waimānalo revealed notable exceptions. Several deeper layers, specifically at depths of 52-62 cm, 62-72 cm, and 72-82 cm, showed significantly higher concentrations of plastic particles, which are particularly apparent during the February 2024 sampling at Waimānalo and the February 2023 sampling at Kokololio, with some layered samples revealing over 2000 particles at these depths. To date, it remains unclear how plastics become buried at such depths (2-102 cm). Whereas the observed plastic abundance within the 1-meter sand column during May 2023 and August 2023 was relatively low across all three beaches. To further investigate the observed variations in plastic abundance, we conducted statistical analyses to identify significant factors contributing to these changes, as detailed below.

To investigate whether factors such as depth within the sand column significantly affect plastic particle counts, we fitted a GLMM with a negative binomial distribution to account for overdispersion. The fixed effects in the model included ‘Beach’, ‘Month’, and ‘Depth’, while

‘Quadrat’ was treated as a random effect. Results from the GLMM summary revealed that the variance for quadrat (random effect) was low (variance = 0.03, Std. Dev. = 0.17), indicating minimal variability between quadrats in plastic counts and that the variation in plastic counts is likely driven by the fixed effects rather than quadrat-level differences. ANOVA was conducted to test the influence of each fixed effect; ‘Beach’, ‘Month’, and ‘Depth’, on the dependent variable, ‘Counts’. The results showed that all three factors - Beach, Month, and Depth - significantly contributed to the variation in plastic particle counts, as summarized in Table 2.

Table 2. Analysis of deviance with χ^2 of fixed categorical variables: depth (n = 11), beach (n = 3), and Month (n = 6) in GLMM negative binomial of plastic counts.

Variable	χ^2	Df	*p*
Beach	267.751	2	< 0.001
Month	120.985	5	< 0.001
Depth	56.155	10	< 0.001

In line with ANOVA results, and as observed in Fig. 4 the beach has a significant impact on the observed plastic concentration in the sand column. Significantly fewer plastic particles were consistently recovered at Kahuku compared to Kokololio and Waimānalo. For instance, Kahuku had a total of 4,269 particles recovered across all field surveys. In contrast, Kokololio had nearly ten times as many particles, with a total abundance of 41,840 plastic particles, and Waimānalo had about seven times more than Kahuku, with a total of 30,924 particles. Interestingly, Kahuku and the neighboring beach Kahuku are commonly known to be the most polluted beaches on Oʻahu (Brignac *et al.*, 2019; Young & Elliott, 2016), more so than Waimānalo and Kokololio. These findings highlight that a beach with high surface pollution may not necessarily correspond to high pollution levels in the sand column.

Additionally, we observed significant fluctuations in the number of plastic particles at all three beaches when sampling during different months (Fig. 4). To better visualize these temporal trends, we plotted the total abundance of buried plastics (2-102 cm) and surface plastics (0-2 cm) against the survey months (Fig. 5). As shown in Fig. 5, a decrease in the total abundance of plastic particles (in logarithmic scale) was observed in the 1 meter sand column at all three beaches from February 2023 to May 2023, followed by an increase from August 2023 to November 2023, and another rise into February 2024, (with the exception for Kahuku in February 2024).

The quarterly surveys revealed variations in the observed abundance of plastic particles within the sand column down to 1 meter from the surface. Higher abundances were typically observed during winter months and lower abundances during summer months across all three beaches. The variation in observed plastic concentrations across different sampling months may be attributed to processes such as fresh sand deposition, erosion, or the plastic being washed away. Our ongoing research effort focuses on sediment erosion, accretion, and deposition at these sites to better understand whether the burial of plastics in the sand column are driven by beach erosion, deposition dynamics, and other environmental factors. This work will help clarify the processes affecting the observed plastic concentrations in the deeper beach sediment layers.

2.2. Plastic Sizes

The size distribution of the recovered plastic particles was measured using the Segmentation Model. This approach allows for a more continuous distribution of particle sizes compared to traditional size ranges (Royer *et al*., 2024). By rounding up the maximum length computed by the Segmentation Model to 0.1 mm, we investigated the distribution of particle lengths by calculating the mean max length (mean length = m, in mm) of the particles (counts per sample = n) at each depth and beach, as illustrated in the box plots in Fig. 6. To avoid skewedness of results the lines were removed and the results with lines (representing 3% of all particles sampled) are also shown in Fig. S14 in the SI. The average particle lengths per layer in the sand column were measured to be in the range of 5.9-7.5 mm at Kahuku, 6.6-7.6 mm at Kokololio, and 5.5-6.6 mm at Waimānalo. The sizes of the plastic particles did not exhibit a clear trend with increasing depth in the sand column.

During the field surveys, we observed that the sand grain size also varied among the three beaches, with Waimānalo having the finest sand. To investigate any possible correlation between the sand grain size and the mean length of the plastic particles, we measured the grain size using SandSnap (McFall *et al.*, 2023) during the last two field survey campaigns (November 2023 and February 2024). The output files retrieved from SandSnap are available in Table S1 in the SI. Using SandSnap D_{50} values, we determined the sand composition at each beach according to the Wentworth scale: Kahuku has coarse sand (larger D_{50} values), Kokololio has medium to coarse sand (medium D_{50} values), and Waimānalo has medium to fine sand (smaller D_{50} values) (Wentworth, 1922). For each depth in the sand column, we measured the D_{50} value of the sand grain size and correlated it with the mean maximum length of the plastic particles at that depth through a linear regression model. Fig. 7 illustrates a potential positive correlation ($m = 1.79$, $R^2 = 0.18$, with a p-value of 5.36×10^{-5} from Wald test) in that as sand grain size increases, the mean particle length tends to increase as well. As highlighted in the colored circles, Waimānalo (blue), with its finer sand, generally contained smaller plastic particles. Kokololio (green), with coarser sand than Waimānalo but finer than Kahuku (red), contained plastic particles that were slightly larger than those at Waimānalo but smaller than those at Kahuku. The plastic particle sizes at Kahuku exhibited greater variability compared to

Kokololio and Waimānalo, however in general slightly larger plastic particles were found in the sand columns at Kahuku.

It could be assumed that finer sands, such as Waimānalo, tend to retain smaller plastic particles, while coarser sands, like those at Kahuku and Kokololio, are less effective at retaining these smaller particles. This relationship could suggest that beach sediment characteristics influence how plastics are retained and distributed within the sand column. This is in line with Rodrigues *et al*. (2024) which showed that grain size was an important factor explaining microplastic concentration on sandy beaches across the Azores archipelagos. This differential retention capacity could explain why Kahuku, with a larger sand grain size, shows subsurface plastic particle abundance. Nonetheless, the linear regression analysis revealed that sand grain size accounts only for 18% of the variance in mean particle length, indicating that other factors also contribute to variations in particle length.

Furthermore, the sand grain sizes at different beaches are also results of different beach characteristics; for example, coarser sand grain sizes, such as at Kahuku, are typically a result of high-energy beaches with steep slopes, while on sheltered beaches with low-energy conditions, finer and smaller sand grain sizes are more likely to be present (Jaubet *et al*., 2021; McFall, 2019). Beach dynamics, the steepness of the beach, the exposure to waves, and the wind are factors that are also likely to influence the plastic concentration on the surface and in the sand column of the beach. Kahuku can be classified as a high-energy beach, in which the beach face changes dramatically over short periods, with dynamic and large erosion and accretion events which could also explain the low plastic particle concentration in the sand column.

2.3. Polymer ID, Plastic Class & Color

From the FTIR/ATR analyses, we observed that polyethylene (PE) and polypropylene (PP) were the dominant polymers recovered within the sand columns, accounting for 89% of the total plastic particles analyzed. On average, 65% of the particles recovered were PE and 24% were PP, as shown in Fig. 8(A). The other polymers identified were polystyrene (PS), polymers composed of PP and PE mixtures (PP/PE), ethylene-vinyl acetate (EVA), and nylon, which all together made up 10% of the total abundance of particles subjected to FTIR/ATR analyses. It should be noted that only buoyant polymers were recovered using the BSD in the field to separate the plastic from the sand. However, as referenced in Brignac *et al*., more than 90% of particles recovered on the windward side of O‘ahu are less dense plastic materials and predominantly buoyant plastics.

The Segmentation Model classified the majority (94%) of the total abundance of the sampled plastic particles as hard fragments, as illustrated in Fig. 8(B). The next dominant class was line, which accounted for 3% of the total abundance of recovered particles. The Segmentation Model also depicted that the most prevalent colors were light blue (28%), light grey (27%), and turquoise (19%), as observed in Fig. 8(C). Most of the particles collected were off-white, which the Segmentation Model may have recognized as light blue and light grey.

The polymer ID, class, and color composition distribution per beach and along the sand column is in the Fig. S15 in the SI, and it shows that the dominant plastic classes, colors, and polymer types remained consistent with depth in the sand column and across different beaches, showing no significant variation.

2.4. Reflection of Research Approach in Hawaiian Context

2.4.1. Research Methods and Data Collection

In conducting this research, we prioritized quantifiable metrics – such as plastic particle abundance and distribution – and did not include cultural considerations. Such metrics can be advantageous for refining models of plastic pollution in high-accumulation zones. At the same time, the pursuit of this data risks causing unintended harm, particularly in Hawai‘i, where cultural practices, worldviews, and the environment are deeply interconnected. One example is the burial of iwi (ancestral bones) on the beach, which are considered sacred in Native Hawaiian traditions. Disturbance of iwi is a violation of cultural and spiritual practices (Hall, 2010). Such violations are akin to desecrating a grave, representing a profound disrespect for both ancestors and the living communities who care for them. It was through ongoing conversations with cultural practitioner Kimeona Kāne that we began to recognize the potential harm our research could inflict due to oversights in our methodology, highlighting the need to engage with community and cultural practitioners at the outset of the research.

Furthermore, our focus on physical metrics and disconnect from the culture led us to overlook how plastics might affect not only the environment but also the cultural practices tied to the stewardship of the land and ocean. For instance, we did not account for the potential impacts of plastics on culturally significant species like sand turtles (mole crabs) and other intertidal species living in the sand column. These species, once abundant and used as fishing bait, also play a role in maintaining ecological balance. In Hawaiian worldviews, including the principle of mālama ‘āina (to care for and live in harmony with the land), there is an emphasis on the interconnectedness of all life forms and the responsibility to maintain the balance between people, the environment, and its living beings. For example, ensuring that sand turtles remain undisturbed by pollution and continue to thrive is essential for this balance. Our study, by not foregrounding the principle of mālama ‘āina, missed an opportunity to incorporate culturally grounded understandings of ecological balance into our scientific framing. However, as Ngata reminds us, that merely addressing the limitations of Western scientific paradigms cannot be resolved with “more research” or “better research”—for instance, by conducting additional studies on the plastic pollution impact on sand turtles. Indigenous communities have long been hindered by colonial barriers that prevent them from implementing their own knowledge. The solution may be as straightforward as stepping aside, breaking down colonial barriers and letting Indigenous scientists and communities, who already possess vital knowledge and solutions, to lead the way (Ngata & Liboirion, 2021). Ngata’s argument emphasizes the necessity of letting Indigenous scientists to ask the questions that matter most to their communities—questions such as who is harmed, who is displaced, and whose futures are altered by the presence of plastics.

None of the initial researchers were from Hawaiʻi or Oceania, and collaboration with a cultural practitioner and Kanaka ʻŌiwi leader began only toward the end of the study, who played a transformative role in illuminating the broader ecological and cultural impacts of plastic pollution, for example by highlighting the significance of beaches as cultural space and on the significance of mālama ʻāina. As a result, the research questions, methods, and interpretations were shaped without local cultural perspectives. As scholars such as O'Neil (2016) have highlighted, the creation of data is always shaped by subjective choices: what to measure, how to measure it, and which variables are considered important. Co-producing research with the local communities where it is conducted not only has the potential to reduce the risk of unintended harm but also enables the creation of knowledge that is more culturally relevant and context specific. In this way, integrating community perspectives from the outset of shaping the research inquiries leads to research that is both more representative and more respectful of the place and people it aims to study and ultimately serve.

While we recognize that our initial approach did not engage communities from the beginning, we view this as an opportunity for growth, improvement, and (un)learning. The implications of not incorporating local perspectives carry significant socio-ecological costs for Indigenous communities and, ultimately, for all of us (Stein *et al.* 2024). As also advocated by Arshad-Ayaz *et al.* (2020), by naming our missteps and failures, we hope to interrupt ingrained habits in our research practices and learn from them, rather than continue reproducing them. In our commitment to advancing more ethical and accountable research in our field, we acknowledge that our research should have been developed in collaboration with the community in which it was conducted—Hawaiʻi. We recognize that if plastic pollution research aims to support the communities most affected, it should be co-produced or designed in collaboration with those communities. Moving forward, we will strive to adopt more accountable, reciprocal, and culturally aware research practices. We draw inspiration from work carried out by scholars such as Alegado *et al.* (2021) and Winter *et al.* (2020), who have contributed to rethinking research partnerships through the development of the Kūlana Noiʻi framework, which encourages researchers to engage in deeper, reciprocal relationships with communities. We also engage with the perspectives and insights of scholars like Liboiron and Ngata, who advocate for anti-colonial research practices in plastic pollution research (Ngata & Liboiron, 2021; Peryman, *et al.* 2024, Liboiron, 2021a; Liboiron, 2021b).

2.4.2. Permitting for Field Work

For the removal of plastics from the beaches at Waimānalo and Kokololio, no permits were required. However, for Kahuku at James Campbell National Wildlife Refuge, a permit was obtained due to its protected status. While our initial focus was on meeting regulatory requirements, we now recognize the need for a more proactive approach that ensures our research respects the cultural and ecological relationships of the sites studied. The Kapaʻakai analysis, a legal framework used to assess the impact of proposed actions on Native Hawaiian cultural resources, could serve as a model for integrating cultural considerations into environmental research (University of Nations, 2020; McGuire & Mawyer 2023). Similarly, tools like the Mai Ka Po Mai management plans can help researchers align their projects with Indigenous cultural practices, leading to more respectful, place-based research (OHA, 2021; Quiocho, *et al.* 2023). This would represent a step toward more responsible, culturally informed research practices in Hawaiʻi. However, beyond adopting frameworks and as advocated by the Kūlana Noiʻi it is important to engage with the community of the study area early and build mutually respectful relationships on common goals with local communities from the beginning of shaping the research inquiry (Alegado *et al.* 2021).

2.4.3. Research as a source of waste and pollution

While efforts were made to minimize waste and pollution generation, we acknowledge that research activities can still produce waste. Equipment and materials used during fieldwork, such as rubber mallets, sampling mesh bags, and plastic containers, can inadvertently contribute to plastic waste at study sites through wear and tear, breakage, or shedding. For instance, the rubber mallets occasionally broke pieces when hitting the metal frame into the sand with and while visible fragments were collected, some pieces may have been unintentionally left behind.

3. Conclusion

This study provides the first insights into plastic concentration and distribution along the sand columns of Oʻahu's windward beaches, revealing that 91% of the total plastic abundance is located below the surface layer, extending down to 1 m. These findings underscore the necessity of considering subsurface plastic pollution when evaluating the extent of plastic contamination in coastal zones. The majority of plastic particles identified throughout the sand columns were small hard fragments, predominantly composed of polypropylene and polyethylene. This substantial yet often invisible plastic load, characterized primarily by small particles, indicates a more severe plastic pollution problem on the beaches of Hawaiʻi. It further emphasizes the challenges posed by these micro-sized pollutants in sandy environments and highlights the urgent need for upstream remediation efforts to prevent plastic from reaching the shores of Hawaiʻi. We also observed higher plastic abundance in the 1-meter sand column during winter months and lower concentrations during summer months, which requires further investigation to better understand this variation. Furthermore, the potential positive correlation between plastic particle length and sand grain size could further describe plastic particle dependencies on beach characteristics. Ongoing research is focused on exploring the correlation between plastic burial in the sand column and beach dynamics, with the goal of refining models for plastic pollution transportation and accumulation. By deepening our understanding of plastic quantities and fluxes in subsurface sand layers, this research aims to improve assessments of ocean plastic pollution and the effectiveness of upstream mitigation strategies.

Our study also critically evaluates our methods and the cultural impacts of our work. By prioritizing quantifiable metrics over cultural and ecological considerations, we risk harming significant sites and cultural practices. This reflection underscores the importance of integrating local perspectives and values into research methodologies from the outset of shaping research inquiries. Such an approach not only reduces the potential for unintended harm but also leads to a more holistic understanding of plastic pollution's impacts. It further allows for the creation of sustainable solutions tailored to the unique needs of the ocean ecosystems and coastal communities our research seeks to serve.

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CRediT authorship contribution statement

Astrid E. Delorme: Conceptualization, Formal analysis, Methodology, Investigation, Resources, Writing – original draft, Visualization, Project administration, Funding acquisition. **Olivier B. Poirion**: Segmentation Model Development, Writing – review & editing. **Laurent Lebreton:** Methodology, Supervision, Writing – review & editing. **Pierre-Yves Le Gac:** Writing – review & editing, Supervision, Project administration. **Kimeona Kāne**: Conceptualization, Writing – review & editing. **Sarah-Jeanne Royer:** Methodology, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

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Sustainable Development 2021-2030 and is attached to the Ocean Decade Programme "15. Early Career Ocean Professionals (ECOPs), and volunteers for sample collection assistance.

Data Availability

Data related to this manuscript will be made available on the Zenodo Community 'Horizon-Europe-STORAGE' (https://zenodo.org/communities/horizon-europe-storage/) once published.

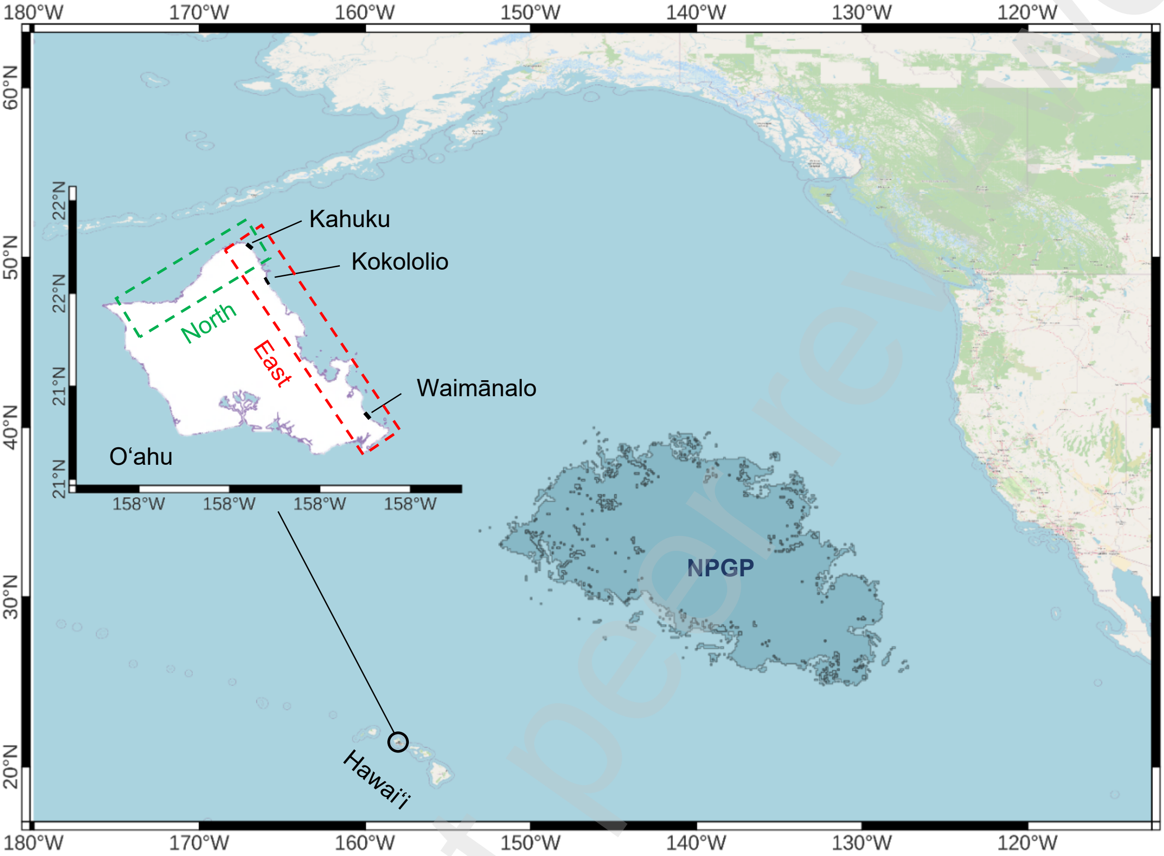

Fig. 1. Predicted location of the North Pacific Garbage Patch (NGPG) for June 2023, based on the numerical model presented in Lebreton *et al.* (2018), showing its position relative to the Hawaiian Islands. The main map highlights the NGPG's proximity to Hawai'i, with a focus on the central Pacific region. The inset map of O'ahu indicates the locations of Kahuku, Kokololio, and Waimānalo beach sites, and the East and North sides of the islands are highlighted in the red and green dashed boxes, respectively. Map created using QGIS version 3.34.9 (www.qgis.org).

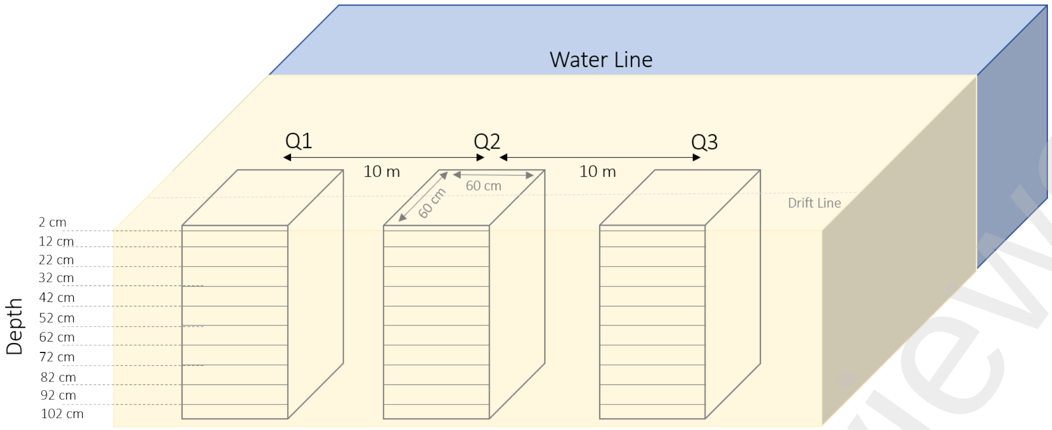

Fig. 2. Illustration of stratified sand column sampling for plastic debris at the drift line of the beach sites. Buoyant plastic debris was collected inside triplicate quadrats, Q1, Q2, and Q3, of the dimensions 60 cm × 60 cm, from stratified 11 layers with the first one being the surface layer of 2 cm depth, then 10 layers of 10 cm depth down to 102 cm.

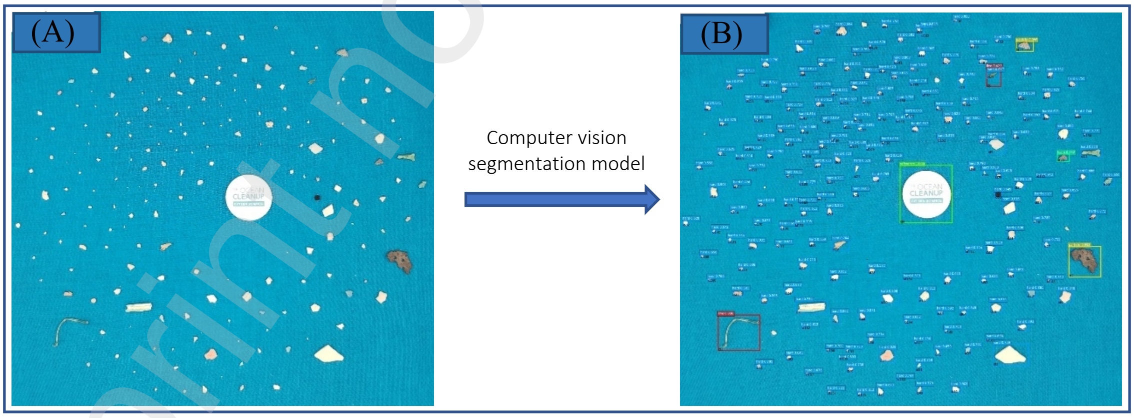

Fig. 3: (A) Image of plastic sample collected from quadrat 2 at Kokokolio in November 2022 from the sand column layer at a depth of 92-102 cm. The image is processed using the Segmentation Model developed by The Ocean Cleanup (Royer *et al.*, 2024), with (B) the output image of the model processing.

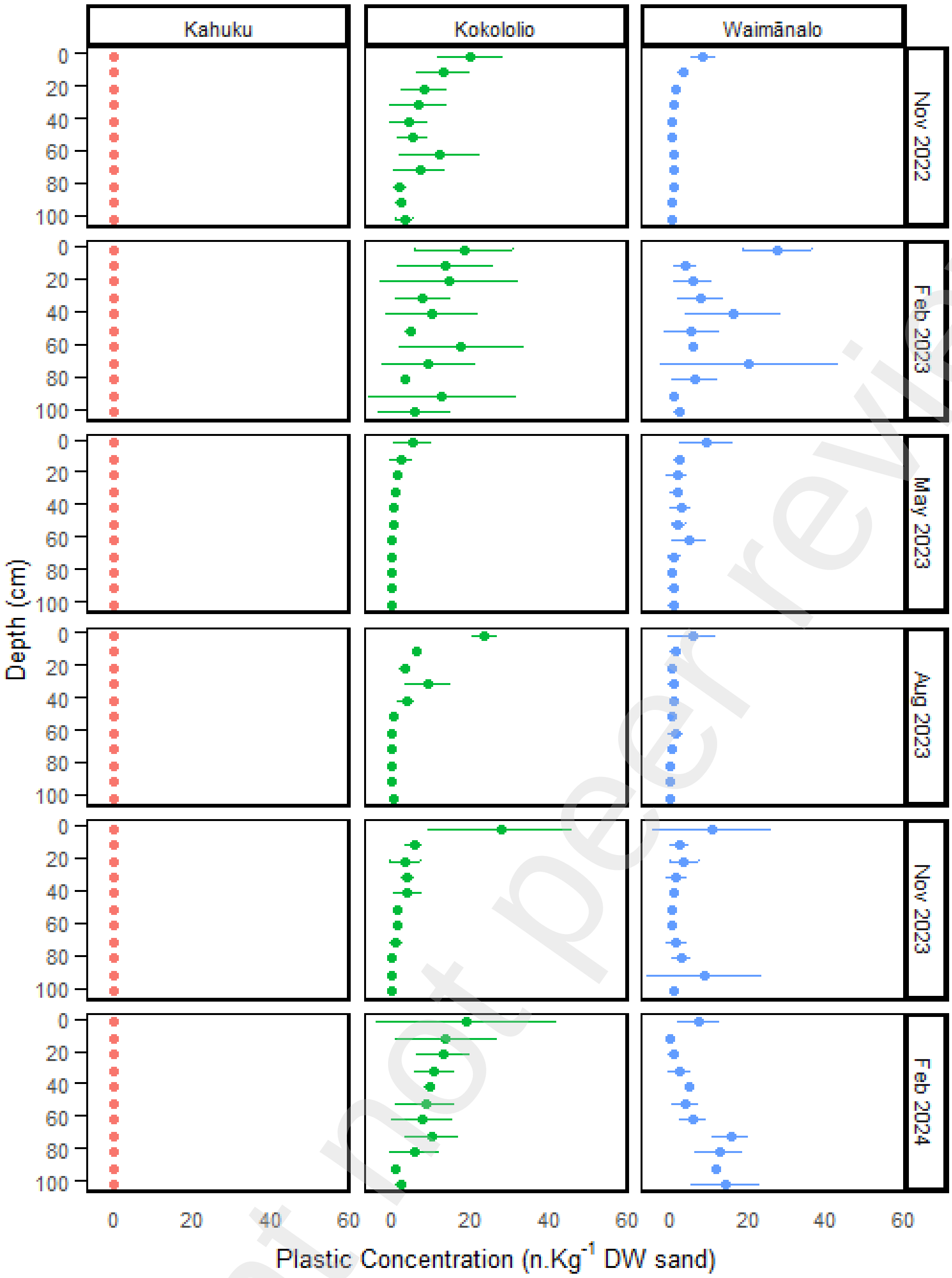

Fig. 4. The average concentration of plastic particles, expressed as counts (n) per dry weight (DW) of sand, along the sand column. The sand column is divided into 11 layers: the first 2 cm corresponds to the surface layer, followed by 10 cm strata extending down to 102 cm. The vertical distribution of plastic particle concentration is shown for the three beaches; Kahuku (red), Kokololio (green), and Waimānalo (blue), and across the six sampling months. The

average concentration and standard deviation error are calculated from the three quadrats sampled per sampling day.

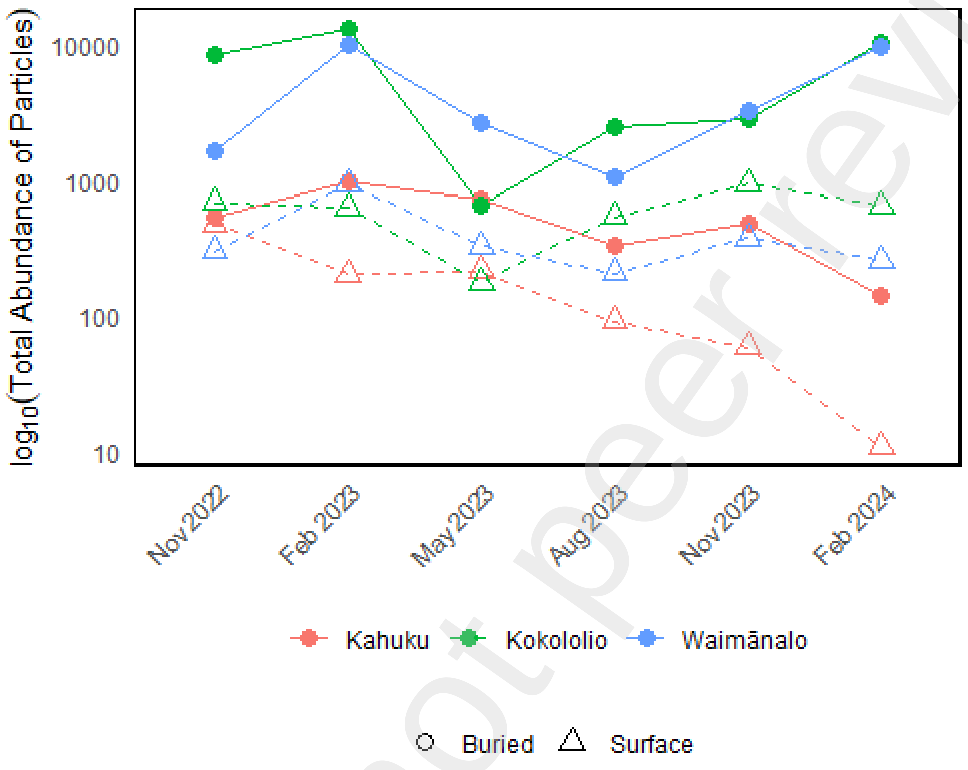

Fig. 5. Variation in the observed total abundance of plastic particles in the surface layer (Δ), at 0-2 cm, and buried in the sand column (○), at 2-102 cm, at all three beaches: Kahuku (red), Kokololio (green), and Waimānalo (blue).

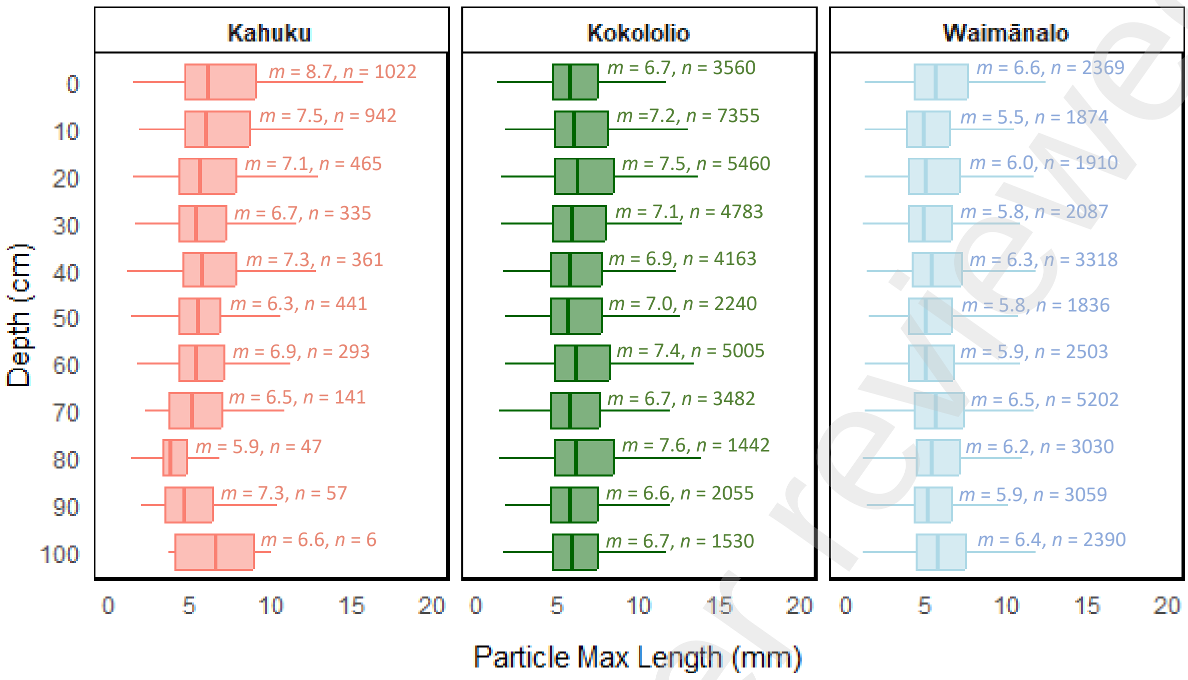

Fig. 6. Boxplots represent the distribution of maximum particle lengths in mm showing the mean (*m*) max. length (in mm) and counts of plastic particles per layer in the sand column (*n*), excluding the lines, collected at the three beach sites; Kahuku (red), Kokololio (green), and Waimānalo (blue) and across the six sampling months. Outliers have been removed for clarity.

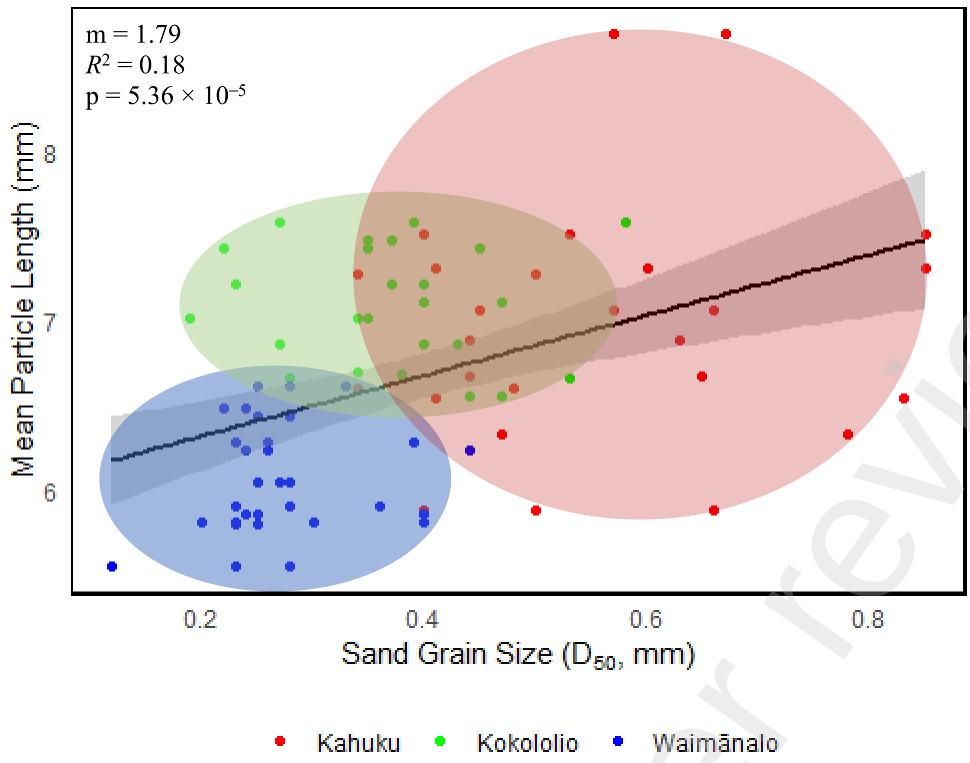

Fig. 7. Potential correlation between sand grain size and the mean particle lengths of sampled plastic particles at each depth strata in the sand column, with sand grain size measured using SandSnap at each layer in the sand column. The solid black line represents the regression line prediction, and the confidence interval is in the shaded area. The plastic particles with the sand grain size measured at the different beaches are highlighted in shaded circles by color: Kahuku (red), Kokololio (green), and Waimānalo (blue).

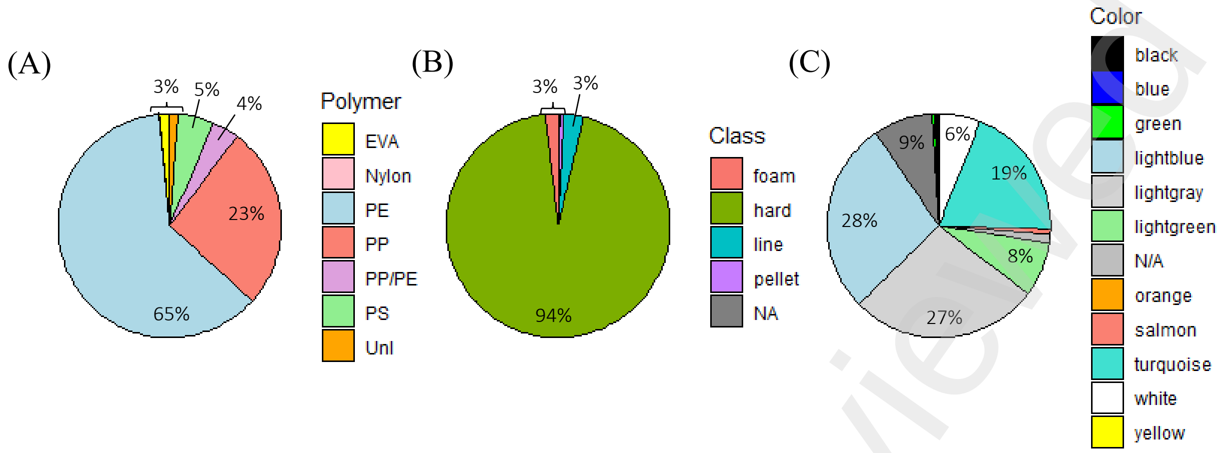

Fig. 8. Pie charts representing (A) the relative abundance of plastic classes, (B) the distribution of plastic colors, and (C) the composition of polymer types across Kahuku, Kokololio, and Waimānalo. The class and color compositions reflect the relative abundance of the total abundance of plastic particles sampled during field campaigns, as analyzed using the Segmentation Model. Polymer compositions were determined from ATR/FTIR analysis of the randomly selected aliquots of plastic particles from each sample collected.