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A year-long field study of buried plastics reveals underestimation of plastic pollution on Hawaiian beaches

Astrid E. Delorme [a,b,c,*], Olivier B. Poirion [d], Laurent Lebreton [c,e], Pierre-Yves le Gac [a], Kimeona Kāne [f], Sarah-Jeanne Royer [b,c]

[a] *Ifremer RDT, Research and Technology Development Unit, 1625 route de Sainte-Anne, Plouzané 29280, France*
[b] *Hawai'i Pacific University, Center for Marine Debris Research, HI, United States of America*
[c] *The Ocean Cleanup, Rotterdam, the Netherlands*
[d] *The Jackson Laboratory, Farmington, CT, United States of America*
[e] *The Modelling House Limited, Raglan, New Zealand*
[f] *Community Scholar, Chairperson of the Waimānalo Neighborhood Board, Cultural Practitioner, United States of America*

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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 %) with an average mean max length of 6.7 ± 4.4 mm. This study offers new insights into subsurface plastic, exposing a previously hidden vertical distribution of plastic pollution. 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 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 plastic." 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 plastic 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 and 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.

Hawai'i 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

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[*] Corresponding author at: Ifremer RDT, Research and Technology Development Unit, 1625 route de Sainte-Anne, Plouzané 29280, France.
E-mail address: astrid.delorme@ifremer.fr (A.E. Delorme).

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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 and Corcoran, 2010; McDermid and McMullen, 2004; Ribic et al., 2012; Young and Elliott, 2016).

The handful of studies that have investigated buried plastic—on 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 and 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 (collected from depths at 10.1–100 cm) accounted for 84 % of the total abundance of plastic particles on sandy beaches across the Azorean archipelagos. Another study by Lavers et al. (2019) on the Cocos Islands (Australia) revealed that between 10 and 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 × 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 Hawaiʻi and contribute to more comprehensive monitoring of broader trends of plastic pollution in the Pacific Ocean.

This study also includes an initially unplanned but informative collaboration with a Kanaka ʻŌiwi (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. 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 Discussion.

2. Methods

2.1. Study area

The field sampling for this study was conducted on Oʻahu 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 Hawaiʻi (Fletcher et al., 2012). Oʻahu 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 Oʻahu (as shown in Fig. 1), also known as the windward side due to the predominant easterly trade winds that consistently hit Oʻahu'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 Oʻahu'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, Hawaiʻi is in a micro-tidal zone, 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 Oʻahu facing and being in proximity to the NPGP, the influence of northeast and easterly trade winds, brings significant amounts of plastic debris to the shores on the windward side of Oʻahu (Cooper and Corcoran, 2010; Kubota, 1994). Studies comparing the leeward and windward sides of Oʻahu 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 Oʻahu, 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 and 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.

2.2. 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, resulting in six sampling surveys per beach. Sampling was conducted using three quadrats (60 × 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). We sampled all three quadrats at a given beach on the same day (Fig. 2). However, the three beaches were sampled on different days within each sampling month, resulting in three separate sampling days per month with 1–7 days between sampling at each beach. The same quadrat was never resampled during the field surveys. By positioning the quadrats 5–10 m from the locations of the previous quadrats from the preceding sampling campaign three months prior (the quadrats were moved parallel to the water line). The six sampling surveys (November 2022–February 2024) at a given beach were all within a section of the beach ranging approximately from 20 to 50 m. The morphology of the beach within the selected sections did not change significantly.

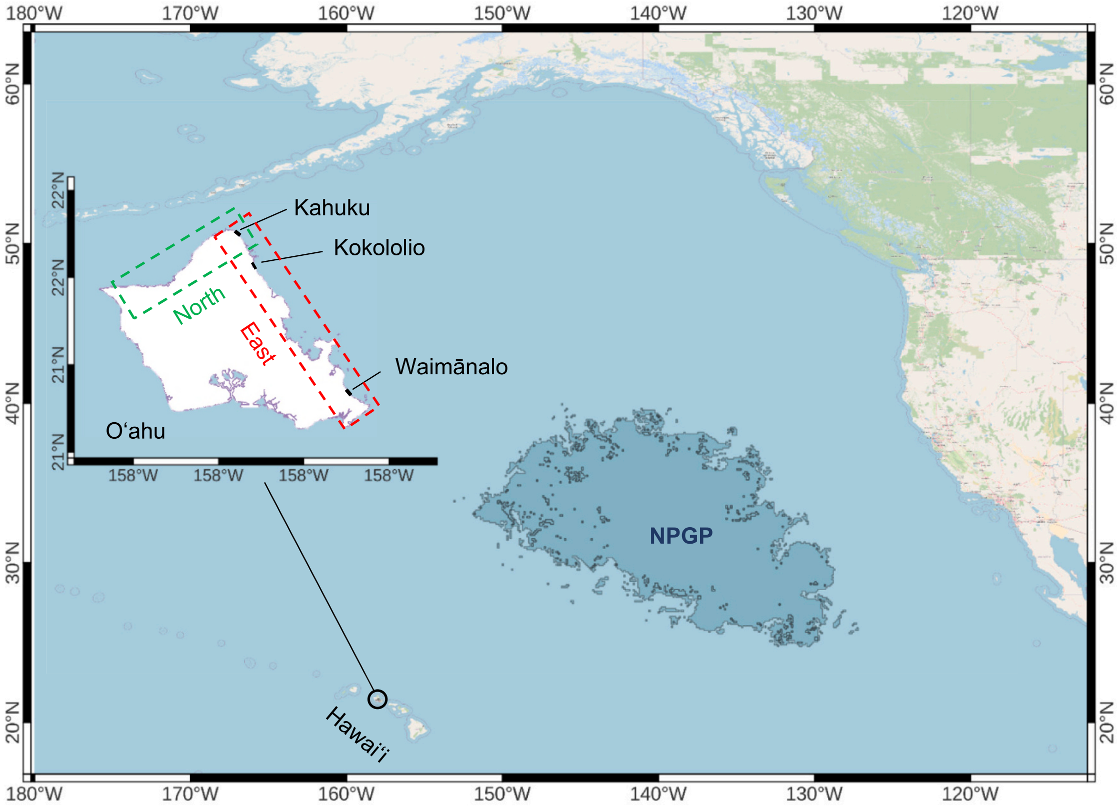

Fig. 1. Predicted location of the North Pacific Garbage Patch (NGPG) for June 2023, based on the numerical model presented in Lebreton et al. (2018), showing its position relative to the Hawaiian Islands. The main map highlights the NGPG's proximity to Hawai'i, with a focus on the central Pacific region. 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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 anthropogenic activities). 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	~6500	20–40	Medium to very fine	Largest of the three beaches, located in a bay. Exposed to easterly trade winds and winter swells.

2.3. Beach plastic extraction

The quadrats used were four-sided hollow boxes with dimensions of 60 × 60 cm and a width of 20 cm and were made on O'ahu by Pac Pro Hawai'i (https://www.ppg-hi.com/) using 16-gauge galvanized steel with welded corners. Inside the metal frame, markings at 2 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-gal bucket (22.7 L), which had a marking of 7.2 L (corresponding to the volume of sand from 60 × 60 × 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 O'ahu 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. Ocean water was pre-filtered through a 250 μm mesh bag before being added to the BSD and stirring the sand, preventing potential plastic contamination from the ocean water in the sampling. No control sample was used, however all equipment, including the BSD, shovels and 5-gal buckets, were rinsed and washed with pre-filtered water to minimize cross-contamination between samples. The water from the hoses is used to stir the sand and to separate the

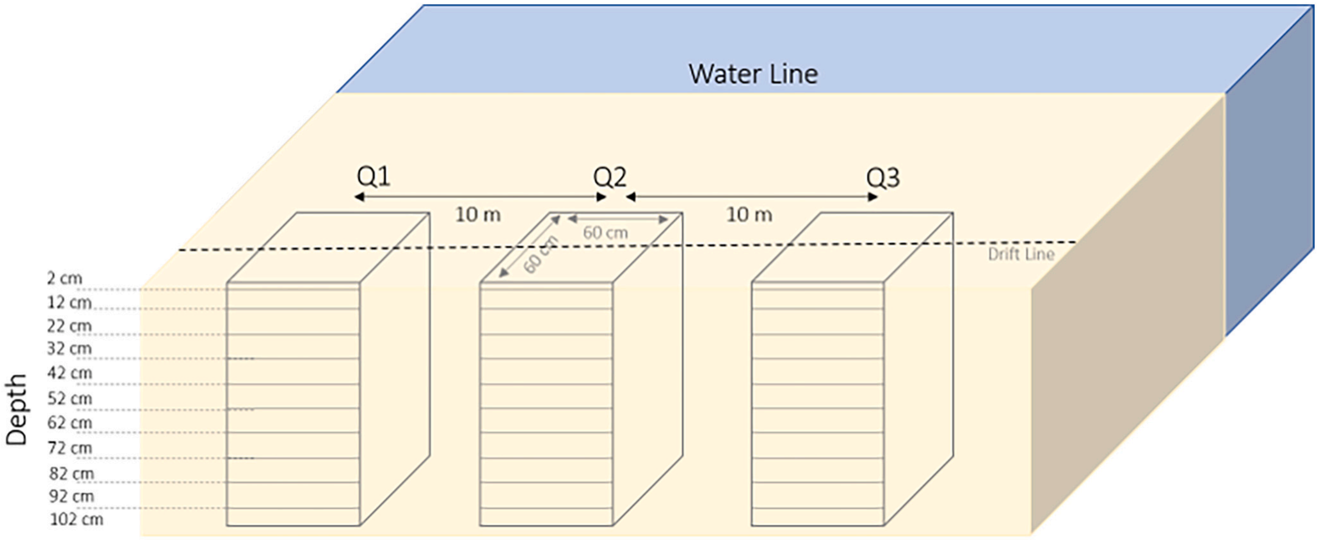

Fig. 2. Illustration of stratified sand column sampling for plastic debris at the drift line of the beach sites. Buoyant plastic debris was collected inside triplicate quadrats, Q1, Q2, and Q3, of the dimensions 60 cm × 60 cm, from stratified 11 layers with the first one being the surface layer of 2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

buoyant debris from the sand. By positioning the BSD at a tilted angle, the floating debris moves toward 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-gal 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 × 60 × 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 processed sand was returned to its original location to restore the area. A detailed field survey method, with step-by-step pictures, are provided in the SI. The fieldwork was conducted under the consistent supervision of two lead scientists (A.E. Delorme and S.-J. Royer), along with 2–4 Marine Science MSci students.

2.4. *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 natural debris by the naked eye, with the separation conducted based on criteria such as particle shape, texture, and color. Through infrared analysis of a subsample of particles (as described in the following section) whose spectra matched synthetic polymers in the infrared spectral library were confirmed as plastics, whereas those that did not match were classified as natural debris. FTIR analysis of randomly selected subsamples revealed that approximately 4 % of these particles were natural debris. Since not all particles were analyzed using FTIR, the actual misclassification rate remains uncertain, and we cannot rule out the possibility of plastic particles being misclassified as natural debris and excluded during sorting. Thus, we estimate a rough misclassification error to be approximately ±4 % of the total particle counts. The visually separated 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.

2.5. *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. Sample sizes ranged from 0 to 2079 particles per sample. For each sample containing >60 particles, a random subset of 60 particles was selected (using the Segmentation Model) for polymer identification 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™ 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™. 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).

2.6. 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.

2.7. 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 method to collect many data points without the need to extract sand from beaches.

2.8. Permits

The beach site at Kahuku was located just outside James Campbell National Wildlife Refuge, requiring a permit for access. This permit was secured through the US Fish and Wildlife Department 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), since only plastic was removed.

2.9. 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. This and together with our collaboration with Kimeona Kāne provided guidance for how we reflected on our work in Hawaiʻi.

3. Results

3.1. 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 (hard fragment, pellet, line, and foam). 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. 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. Whereas the observed plastic abundance within the 1-m 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. 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.

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 m 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).

3.2. Plastic sizes

The size distribution of the recovered plastic particles was measured using the Segmentation Model (Royer et al., 2024). By rounding up the maximum length computed by the Segmentation Model to 0.1 mm, we

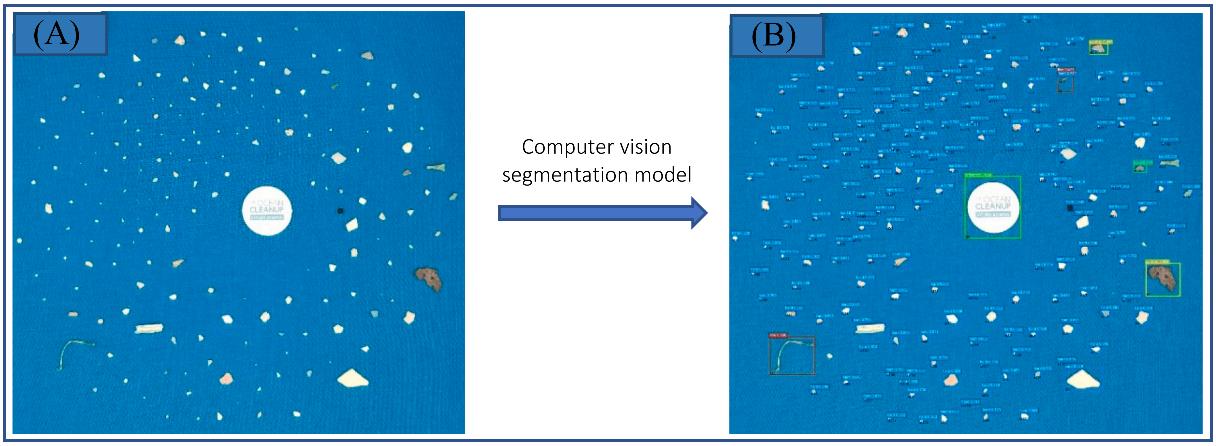

Fig. 3. (A) Image of plastic sample collected from quadrat 2 at Kokokolio in November 2022 from the sand column layer at a depth of 92–102 cm. The image is processed using the Segmentation Model developed by The Ocean Cleanup (Royer et al., 2024), with (B) the output image of the model processing.

investigated the distribution of particle lengths by calculating the mean max length (mean max 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 max. Lengths per layer in the sand column were measured to be 7.4 ± 5.5 mm at Kahuku, 7.1 ± 4.7 mm at Kokololio, and 6.1 ± 3.8 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. 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); 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.

3.3. 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., >90 % of particles recovered on the windward side of Oʻahu 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.

4. Discussion

4.1. Data analysis

Our study provides, to the best of our knowledge, the first insights into the presence of plastics in the deeper layers of the sand column on Hawaiian beaches. Notably, the majority of plastic particles (92 %) recovered from the 1-m sand column were buried beneath the surface rather than located at the surface. The 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. To date, it remains unclear how plastics become buried at such depths (2–102 cm).

As revealed by the 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 4269 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 is commonly known to be the most polluted beach on Oʻahu (Brignac et al., 2019; Young and 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. Factors such as beach width, slope, and sand renewal time may play a significant role in the depth distribution of

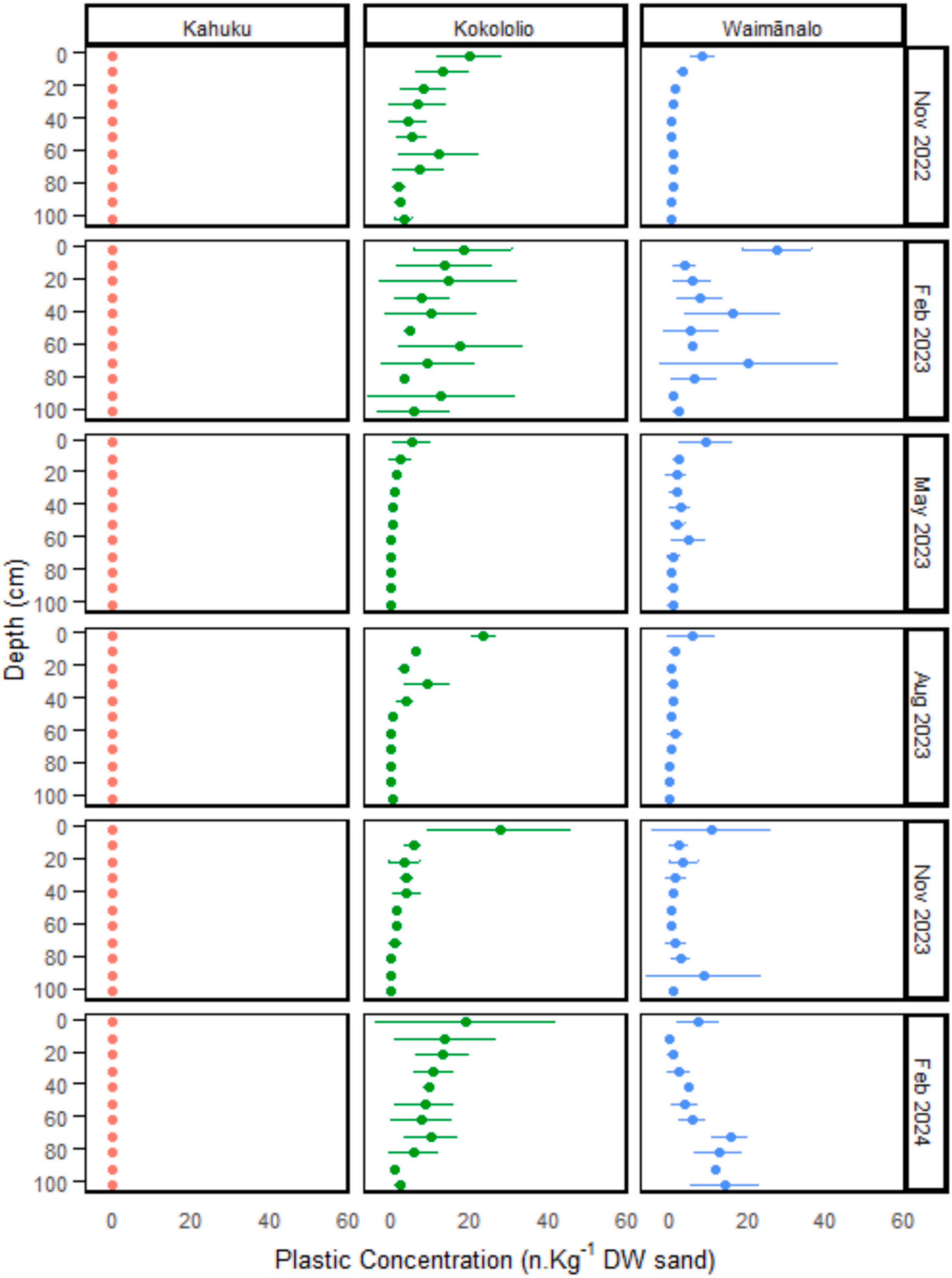

Fig. 4. The average concentration of plastic particles, expressed as counts (n) per dry weight (DW) of sand, along the sand column. The sand column is divided into 11 layers: the first 2 cm corresponds to the surface layer, followed by 10 cm strata extending down to 102 cm. The vertical distribution 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

plastics, which require further investigation for a clearer understanding.

The quarterly surveys revealed variations in the observed abundance of plastic particles within the sand column down to 1 m 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.

We also observed a potential positive correlation between the sand gain sizes and the plastic particles max length. 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 which we are currently further investigating.

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.

The dominance of buoyant polymers such as PE and PP in our samples (89 % of total particles analyzed) aligns with the findings of Brignac et al. (2019), who reported that >90 % of particles recovered on the windward side of O‘ahu are less dense plastics. The prevalence of hard fragments (94 % of particles) further points to the secondary fragmentation of larger plastic items, likely accelerated by mechanical abrasion and UV degradation, particularly as Hawai‘i's windward beaches, due to their proximity to the North Pacific Subtropical Gyre, receive significant amounts of heavily weathered marine debris from the North Pacific Garbage Patch (Berg et al., 2024; Carson et al., 2013; Brignac et al., 2019). The lack of variation in polymer type, class, and color with depth and across beaches suggests that vertical mixing in the sampled 1-m sand-column and burial processes likely do not preferentially sort plastics based on these characteristics. However, the consistent recovery of buoyant materials using the BSD method highlights the need to consider how this selectivity may exclude denser polymers from our dataset, potentially underestimating the diversity of plastic pollution present in the sand column.

4.2. Reflection of research approach in Hawaiian context

In conducting this research, we prioritized quantifiable metrics –

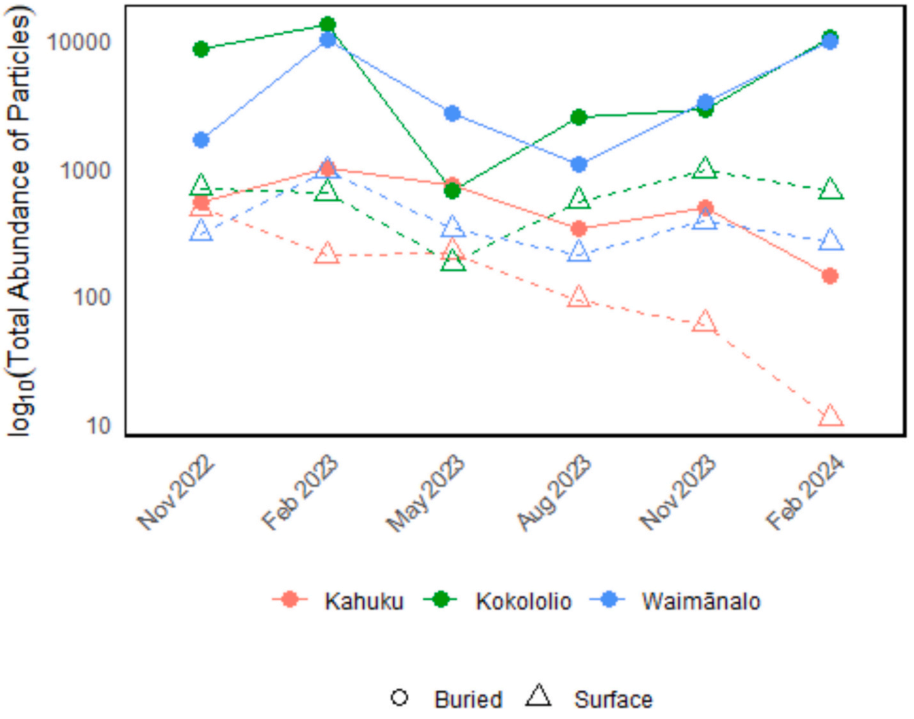

Fig. 5. Variation in the observed total abundance of plastic particles in the surface layer (Δ), at 0–2 cm, and buried in the sand column (○), at 2–102 cm, at all three beaches: Kahuku (red), Kokololio (green), and Waimānalo (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

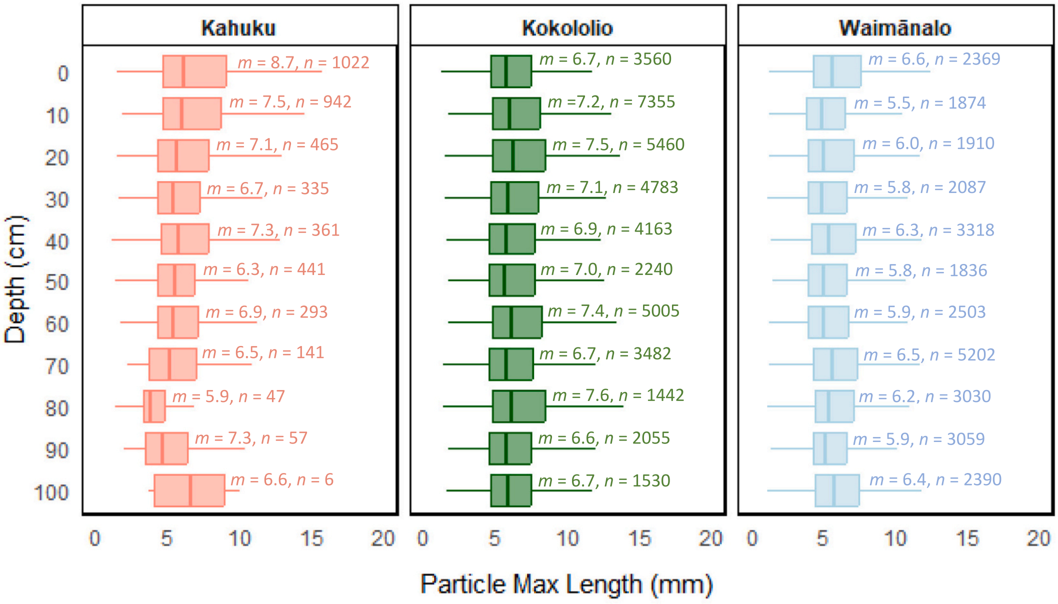

Fig. 6. Boxplots represent the distribution of maximum particle lengths in mm showing the mean (*m*) max. Length (in mm) and counts of plastic particles per layer in the sand column (*n*), excluding the lines, collected at the three beach sites; Kahuku (red), Kokololio (green), and Waimānalo (blue) and across the six sampling months. Outliers have been removed for clarity (outliers are included in Fig. S12 in the SI with the error bars representing the overall range of particle sizes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

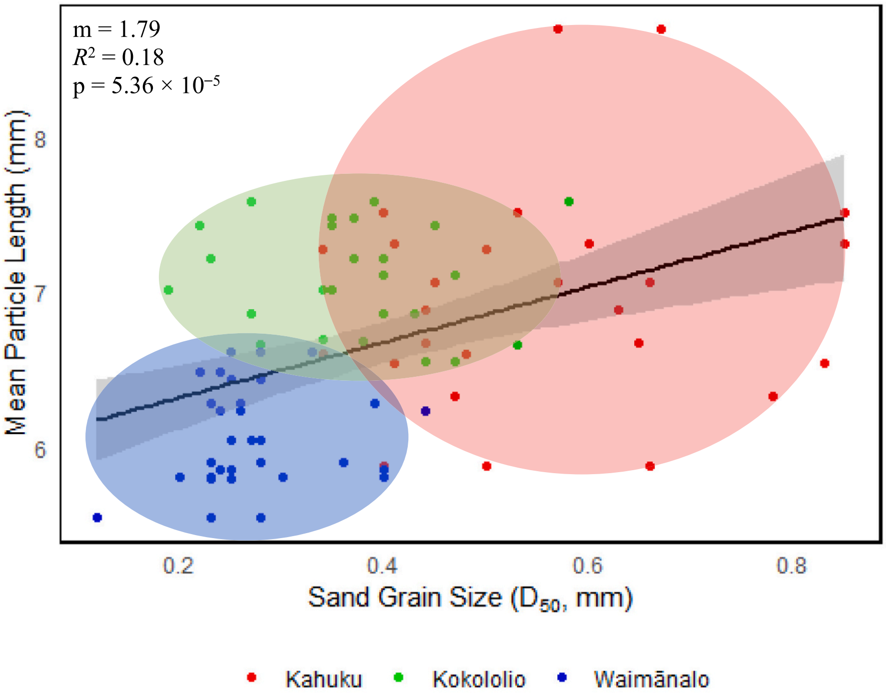

Fig. 7. Potential correlation between sand grain size and the mean particle lengths of sampled plastic particles at each depth strata in the sand column, with sand grain size measured using SandSnap at each layer in the sand column. The solid black line represents the regression line prediction, and 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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 Hawaiʻi, 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

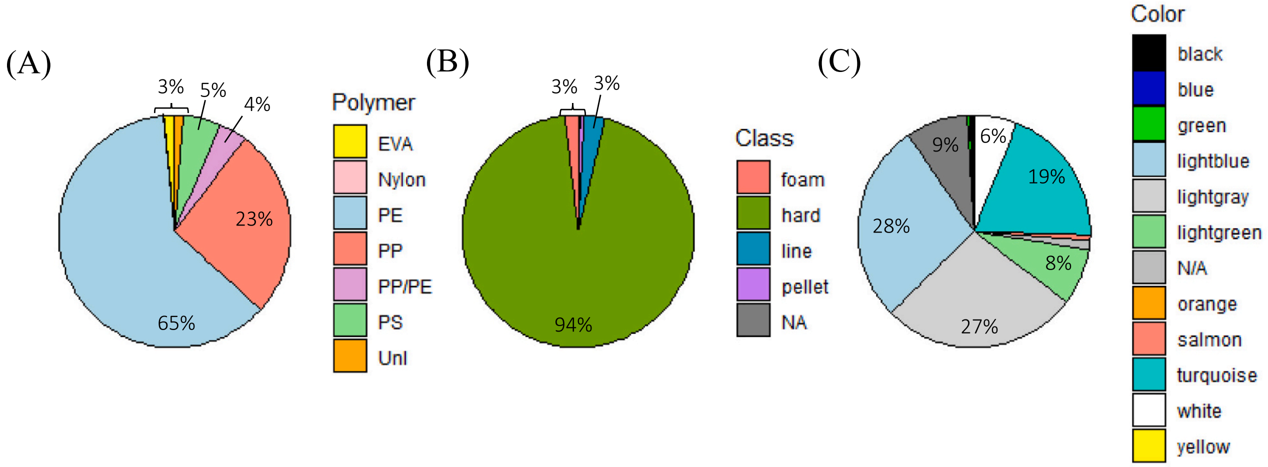

Fig. 8. Pie charts representing (A) the composition of polymer types, (B) relative abundance of plastic class composition, and (C) the distribution of plastic colors across Kahuku, Kokololio, and Waimānalo. The class and color compositions reflect the relative abundance of the total abundance of plastic 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.

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.

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. 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 and Liboiron, 2021).

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(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. 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 and Liboiron, 2021; Peryman et al., 2024; Liboiron, 2021a; Liboiron, 2021b). 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 and 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). 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.

5. 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 PE and PP. This substantial yet often invisible plastic load, characterized primarily by small particles, indicates a more severe plastic pollution problem on the beaches of Hawaiʻi. We also observed higher plastic abundance in the 1-m 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. 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.

CRediT authorship contribution statement

Astrid E. Delorme: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Olivier B. Poirion:** Writing – review & editing, Software, Data curation. **Laurent Lebreton:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Pierre-Yves le Gac:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Kimeona Kāne:** Writing – review & editing, Methodology. **Sarah-Jeanne Royer:** Supervision, Methodology, Funding acquisition, Conceptualization, Writing – review & editing, Investigation, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117712.

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.

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