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Polymer identification of floating derelict fishing gear from O'ahu, Hawai'i

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ABSTRACT

Discarded fishing gear (DFG) comprises most of the plastic in the North Pacific Ocean and causes environmental and economic losses. Building evidence on the material construction of fishing gear types is critical to develop solutions to reduce DFG amounts and impacts. We forensically assessed the construction and chemical composition of eight different gear types removed as DFG around O'ahu, Hawai'i. A thorough dissection and novel analysis was conducted including the documentation of gear constructions, polymer identification using attenuated total reflection-Fourier transform infrared spectroscopy and differential scanning calorimetry, and elemental additive detection using X-ray fluorescence. Twenty-six different polymers were identified, and most gear consisted of polyethylene variants or blends. This inventory of physical and chemical characterization of DFG can help future polymer identification of particular gear types through visual techniques. Additionally, it can aid in identifying sources of these gear types and promote recycling options.

1. Introduction

Globally, discarded fishing gear (DFG), (commonly abbreviated as ALDFG) makes up 19.2 % of the total input of plastic in the ocean (Lebreton et al., 2018) and can represent up to 86 % of the total mass of plastic found in the North Pacific Garbage Patch (Lebreton et al., 2022). Large quantities of floating DFG often wash ashore in the Hawaiian Islands and Palmyra Atoll located in the Central North Pacific Ocean (Royer et al., 2023). Adverse impacts of DFG can include entanglement (Duncan et al., 2017; Hyrenbach et al., 2020; Currie et al., 2019; Butterworth, 2016; Bradford and Lyman, 2015; Berg et al., 2022; Work et al., 2015), navigational hazards for fishers (Jeffrey et al., 2016), introduction of invasive species and diseases (Haram et al., 2021), fragmentation into microplastics (Montarsolo et al., 2018; Lusher et al., 2017; Napper et al., 2022), plastic ingestion by marine animals (Derraik, 2002; Clukey et al., 2017), and damage to the coral reef as it washes ashore (Suka et al., 2020).

The transition of fishing gear construction from natural to synthetic materials occurred in the 1960s as plastics became available, which are inexpensive, lightweight, widely available, and long-lasting (Laist, 1987). Plastic polymers are very diverse in their chemical composition, physical properties, affordability, and applications. Globally, polyethylene (PE) is the most commonly used plastic (Geyer, 2020) and has several variants with the most common being high-density PE (HDPE), low-density PE (LDPE), and linear LDPE (LLDPE). PE is a cost-effective thermoplastic and is easily modified based on application needs (Dhakal and Ismail, 2020). In regard to fishing gear fibers, PE, polypropylene (PP), nylon, and polyester (PEST) are commonly used; selection of a polymer is based on specific characteristics such as density, strength, diameter, and weather resistance (Radhalekshmy and Gopalan Nayar, 1973).

Understanding the physical and chemical properties of DFG is crucial for sourcing and repurposing plastic waste, but few studies have explored these in detail. DFG can be composed of nets, lines, hard plastic mesh, floats, and other gear types that have various chemical signatures. Turner (2017) analyzed nets, cords, ropes, and fishing lines removed from shorelines of Cornwall, England and found that 90 % were PE; the remaining were PP, PE/PP blends, and nylon. However, no distinctions were made between gear types. On the other hand, Weißbach et al. (2021) specifically examined components from gillnets found on the seafloor of the Baltic Sea identifying nylon 6, PP, polyethylene terephthalate (PET), and lead weights. These two studies provide some

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insight into the chemical composition of DFG, but there are few other published resources. Efforts have been made to quantify the abundance and distribution of DFG (Uhrin et al., 2020), but the specific gear complexities and polymer composition are not well understood.

The density of each polymer can help predict their fate in the ocean (Brignac et al., 2019). Plastic types that are less dense than seawater, such as PE and PP, float and are the most common polymers found on the sea surface (Cincinelli et al., 2017; Ter Halle et al., 2017) while those denser than seawater will sink (Erni-Cassola et al., 2019) unless they are attached or entangled to more buoyant material. In terms of fishing gear, polymer types are selected based on many characteristics, one of which is whether the plastic needs to sink or float. Trawl fisheries commonly use more buoyant plastic netting, such as PE, whereas purse seine fisheries dominantly use nylon (Basurko et al., 2023). Therefore, understanding the polymer composition of DFG could provide insight into the source fishery.

The only large-scale options for DFG disposal are landfilling, recycling, or thermal processing. Studies have shown that mechanical recycling is the most environmentally sustainable option in terms of global warming, fossil fuel consumption, and metal depletion (Andrady, 2015; Schneider et al., 2023). Therefore, in order to move society in this direction, it is essential to understand the chemical composition of DFG so that certain polymers can be sorted for mechanical recycling. Different polymers have different melting temperatures, compatibilities, properties, and toxicities. If all DFG were to be mechanically recycled together, it would result in inconsistent products, poor quality, and inadvertent health hazards. For example, polyvinyl chloride (PVC) is commonly used in fishing floats (Kumar, 2015) which can release toxic gasses, such as hydrochloric acid, and dioxin-like products when heated (Akovali, 2012). Plastic additives (i.e., compounds added to plastic products to improve performance, including elements and organic compounds) are also a concern for recycling (Hahladakis et al., 2018). For this reason, having a baseline of the chemical composition of DFG can inform recycling concepts and research.

Several instrumental techniques are currently being used for polymer identification. These include attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) and differential scanning calorimetry (DSC) (Jung et al., 2018; Schick, 2009). ATR-FTIR has been validated in its use to identify plastics collected from a variety of environmental matrices (Jung et al., 2018; Brignac et al., 2019; Rice et al., 2021), as well as DFG (Weißbach et al., 2021; Turner, 2017). However, ATR-FTIR has limitations when it comes to multilayer composites as the spectra produced are from a surface scan. Moreover, differentiating PE variants of environmental samples with ATR-FTIR is not possible due to the alteration of the 1377 cm^{-1} band when samples have been exposed to UV radiation (Lynch et al., in prep). However, DSC can capture physical properties of polymers, such as melting temperatures, glass transitions, and enthalpy changes (Schick, 2009) that ATR-FTIR cannot. For weathered marine debris samples, it has been shown that DSC can differentiate LDPE and HDPE with confidence, but ATR-FTIR cannot (Lynch et al., in prep). DSC has also shown to be useful in quantifying polymer blend percentages (Larsen et al., 2021). Together these two techniques can be complementary when identifying polymer compositions. Further chemical characterization of DFG through trace metal analysis by Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) and X-ray fluorescence (XRF) has been explored for recycling, sourcing, and identifying environmental concerns (Turner, 2017; Pasumpon and Vasudevan, 2022; Weißbach et al., 2021).

Here we applied forensic and novel analytical techniques to fishing gear that are commonly found within floating DFG washing ashore in Hawai'i. Data discussed herein are representative of a larger continually growing database of gear types, constructions, and polymer composition of DFG removed from across Hawai'i. Understanding the material and chemical composition of DFG can aid in sourcing the material to the fishery or gear manufacturer and provide necessary information for mechanical recycling. Long-term monitoring of DFG chemical composition may reflect changes in fishing gear technologies (e.g., if the industry shifts towards more degradable materials).

2. Methods

2.1. Sample collection

This study selected a subset of samples from a large database and archive of DFG events detected and removed between 2009 and 2021 in the North Pacific Ocean (Royer et al., 2023; McWhirter et al., 2022). In the larger study, 253 DFG events were removed from the ocean, then transported to a warehouse for disentangling and sampling using one of five different protocols (four corners, one of all, hybrid, disentangle, or reverse engineer) as described in great detail in McWhirter et al. (2022). Samples (at least 7539 in the larger study) were taken to the laboratory, categorized by gear type, color (blue, green, white, black, grey, clear, red, pink, orange, yellow, brown, purple, and silver), described, measured, and polymer identified according to McWhirter et al. (2022). Nets and lines were identified by construction type (*Z*-twist, S-twist, or braided), twine/line diameter, and fiber type (monofilament, multifilament, film, or staple). Nets were further described by net construction style (twisted-knotted, twisted-knotless, braided-knotted, braided-knotless, or monofilament-knotted) and mesh stretch size. Mesh size, shape, and thickness were determined for hard plastic mesh, while width, thickness, and length were taken for oyster spacers. Floats were described by shape (oval, spherical, skinny rectangular, and bullet) and material (foam versus rigid). Eel trap entrance samples were categorized by component (basket, fingers, or both). The categories and measurements for the various gear types are described in Fig. S1. All multi-component samples of lines, nets, and floats were disassembled so color, fiber type, polymer identification, and description could be determined for each component. The information collected from each sample is stored in an in-house database.

2.2. Sample selection

From the database described above, specific samples ($n = 316$ with a total of 452 components) were selected for in-depth polymer identification, and fewer ($n = 60$) for elemental concentrations. Selected samples were from 23 DFG events that were collected from O'ahu, Hawai'i between October 2019 to December 2021. Multiple samples were targeted for each of the seven gear types: twisted/braided nets, monofilament nets (i.e., gillnets), twisted/braided lines, monofilament lines, floats, eel trap entrances, and hard plastic mesh (Fig. S2). Oyster spacers were included as an eighth gear type because they are a common debris type found on Hawai'i's beaches but were rarely found in the large DFG events. Thus, 20 oyster spacers collected from Kahuku Beach, O'ahu in May 2017 from a previous study were randomly selected (Brignac et al., 2019). Within each gear type, five to 20 samples of each color, size or other variable specific to each gear type were targeted to ensure a great diversity and sample sizes were large enough for statistical comparison among descriptive variables. For rare sample categories, all samples available fitting that description were chosen. For abundant sample categories, samples were selected randomly from all samples available.

Among nets, samples were selected carefully to represent the diversity of net types in the sample archive. The selection process began with trying to find 20 nets of each color (black, blue, green, orange, red, yellow, grey, clear, and white) with ten of each net color having mesh stretch >6.0 cm, while the other ten had <6.0 cm (McWhirter et al., 2022). Within each mesh size class, five of each fiber type (monofilament and multifilament) were targeted. All nets with staple fibers ($n = 4$) were selected; no film fiber nets were available. Among twisted/braided lines, a minimum of 20 were selected from each fiber type (monofilament, multifilament, staple, and film). The final selection for twisted/braided nets and lines with sample size based on desired metrics can be found in Fig. S3. Eel trap entrances were selected so that ten samples of baskets and ten samples with fingers were included. Five floats were targeted for each shape (bullet, oval, spherical, and rectangular). Twenty-five hard plastic mesh and 20 monofilament lines were selected randomly without attempts to obtain equal sample sizes of different variables. For all gear types, if there were not enough samples to fulfill the desired fiber type, mesh size, or color, the sample size from other desired metrics was increased when possible. Table S1 provides the resulting sample sizes of the selected samples listed by gear type.

2.3. ATR-FTIR

Thermo Fisher Scientific Nicolet iS5 (Madison, WI USA) and Agilent Cary 630 (Santa Clara, CA USA) ATR-FTIR spectrometers were used to collect spectra on all samples ($n = 452$) from 4000 cm^{-1} to 500 cm^{-1}. Scans were set to 16, with resolution at 4 cm^{-1}, and a data interval of 1 cm^{-1}. The diamond crystal was cleaned with 70 % isopropanol and a background scan was performed between every sample. All samples were cut and cleaned with 70 % isopropanol to avoid biofouled regions of the material and to produce the best spectra. Peak signatures were used to identify the polymer type according to the methods in Jung et al. (2018).

2.4. DSC

All samples, excluding those identified as PVC by ATR-FTIR, ($n = 439$) were run on a TA Instruments Discovery Series 250 DSC (New Castle, DE USA) with a refrigerated cooling system (RCS) 40 to collect calorimetry curves. A burnout and an indium calibration were performed at the start of every day to prevent contamination and ensure data quality. Each sample was sealed in TA Tzero aluminum pans and lids with a target mass of 3 mg to 5 mg, weighed on a Sartorius microanalytical balance with a 0.001 mg resolution. Twelve samples of low density filled the pan without reaching the target mass. A maximum set temperature was determined as 200 °C or 300 °C based on the suspected melting and decomposition point for crystalline polymers, informed by ATR-FTIR identifications (Lynch et al., in prep). The following heat-cool-heat method was used: equilibrate at 50 °C, hold isothermal 1 min, ramp 10 °C/min to 200 °C or 300 °C, hold isothermal 5 min, ramp 10 °C/min to 50 °C, hold isothermal 1 min, and ramp 10 °C/min to 200 °C or 300 °C. The TA peak integration function was used on the second melt curve to determine peak melting temperatures (T_m) of each visible peak, which were used to confirm ATR-FTIR polymer results, differentiate variants of PE and nylon according to cutoffs in Lynch et al. (in prep), and identify polymer blends. For amorphous polymers, the same heat-cool-heat method was used except for the cooling rate ramping at 5 °C/min to 50 °C. Glass transitions were calculated on the second melt curve and used to confirm polymer identification. Samples identified as PVC by ATR-FTIR were not analyzed on the DSC due to the potential release of toxic chemicals upon melting.

2.5. HDPE/PP blend quantification

Polymer standards from Hawai'i Pacific University's Center for Marine Debris Research (CMDR) Polymer Kit 1.0 were used to manually create known blend percentages. Six blends were created to form a calibration curve (0:100, 25:75, 50:50, 60:40, 80:20, 100:0 mass to mass fraction) using HDPE (sample HDPE.1 in the polymer kit) and PP. These polymer standards were weighed and sealed in TA Tzero pans and analyzed on the DSC with a maximum melting temperature of 200 °C as described above. The enthalpy from integrating the HDPE peak in the second melt curve was used, along with the known blend ratios, to create a calibration curve (Fig. S4, $R^2 = 0.9982$). Using this calibration curve, blend ratios were calculated for DFG HDPE/PP blends.

2.6. Multicomponent line case study

One twisted line (sample ID OAH_08_0290800) with an extraordinary fiber complexity was selected and thoroughly dissected into individual fibers as a case study. A 6.5 cm piece of the line was cut, and the three strands were untwisted. All fibers from each strand were laid out separately and described by color, construction, opacity, fiber type, and polymer identification (Fig. 1). ATR-FTIR was performed on each fiber group for all three strands (Fig. S5) to ensure all unique fibers were accounted for. Each unique fiber was analyzed on the DSC as described above. Once polymer identification was complete on all components, similar components from all strands were matched based on color, construction, opacity, fiber type, and polymer identification.

2.7. XRF

A subset of samples were selected for XRF analyses, including 60 DFG samples and 17 new/unused fishing gear (NFG) samples donated by a net manufacturer were analyzed. Of the 60 DFG samples, 33 were nets that were analyzed as a part of this study, while the remaining were DFG samples from the larger database. An Olympus Vanta VCA (Waltham, MA USA, software 3.22.41) XRF handheld instrument was used to measure 35 elements from uranium (U) to magnesium (Mg) on the periodic table. NIST SRM 2711a Montana Soil II and European Reference Material EC618m were used as reference materials. Prior to use, a calibration was performed and a Goodfellow silica blank sample was analyzed. Measured concentrations of 14 elements were in agreement with the certified values (Al, Si, P, Ca, Ti, Mn, Fe, Cu, Zn, As, Sr, S, Cd, and Pb). The remaining elements were outside of the certified values, so only presence/absence was considered in the samples (Table S2).

2.8. Statistics

Significant differences in polymer identification (% of total samples/components on the y-axis) across descriptive groupings of DFG samples (x-axis, e.g., colors of nets) were tested using Fisher's exact tests in R because the chi-squared assumptions were not met. To our knowledge there are no post-hoc tests for a Fisher's exact test, so the visual differences are described after a significant result. For continuous variables (e.g., line diameter on the y-axis), samples were binned by polymer (x-axis) and ANOVAs or Wilcoxon tests were performed in JMP (SAS Institute) depending on the results from the Shapiro Wilk test and Levene's tests. The polymer identification of components was used in tests for differences across colors, fiber type, and eel trap components. The polymer identification of the dominant component of twisted/braided lines was used to compare across line construction and average diameter.

The Nondetects and Data Analysis for Environmental Data (NADA2) R package was used for the elemental concentration when some concentrations were below the limit of detection (Table S2). Summary statistics were achieved using the Kaplan-Meier or regression on order statistical models based on the percentage of censored data (Helsel, 2005). Differences in elemental concentrations between DFG and NFG samples were determined by parametric or nonparametric tests depending upon assumptions of normality and homogeneity of variance. To compare element concentrations of different colors, each element was evaluated separately. Elements that did not contain censored data did not meet parametric assumptions, so Kruskal-Wallis tests were performed in R following a Dunn Test. For the elements that contained censored data, parametric (Cenanova) or nonparametric (Peto-Peto) tests were used depending on the results of the cenregQQ normality test. If the censored data did not meet the assumptions within those tests, pairwise comparisons were performed using cendiff or cenmle based on the results of the Shapiro-Wilk and Bartlett's test.

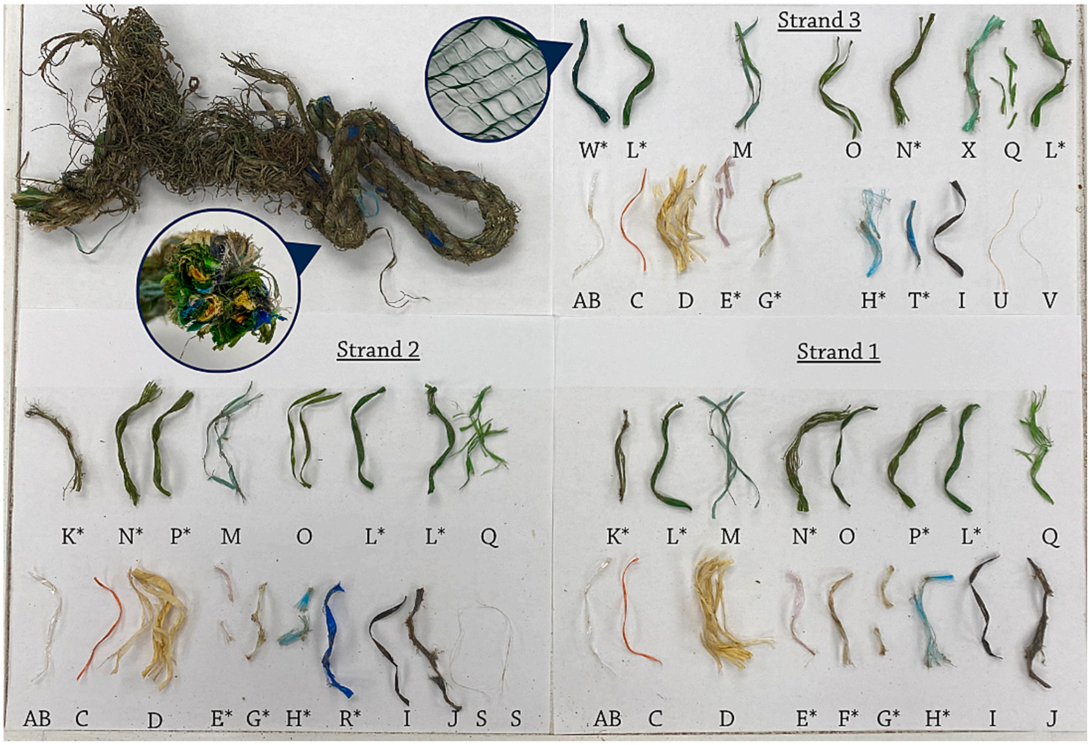


Fig. 1. Photograph of the full and cross-section of the case study three-strand twisted line sample (ID OAH_08_0290800 in upper left). Individual fibers from each strand were dissected and analyzed. Similar letters represent the same fiber type based on color, opacity, construction, and polymer identification. *Indicates that the construction type is fibrillated, pictured pulled apart in the top circular image.

3. Results and discussion

All gear types assessed in this study cause environmental damages when they become derelict fishing gear. Nets cause damage to coral reefs (Suka et al., 2020), lines and floats entangle humpback whales (Bradford and Lyman, 2015), eel trap entrances get caught on endangered monk seal snouts (Berg et al., 2022), monofilament fishing lines are one of the leading causes of death to sea turtles in Hawai'i (Work et al., 2015), oyster spacers are the most common gear type washing ashore on the windward beaches in Hawai'i (Brignac et al., 2019), and hard plastic mesh along with other gear types are ingested by sea turtles in the north Pacific (Clukey et al., 2017). Understanding the physical and chemical

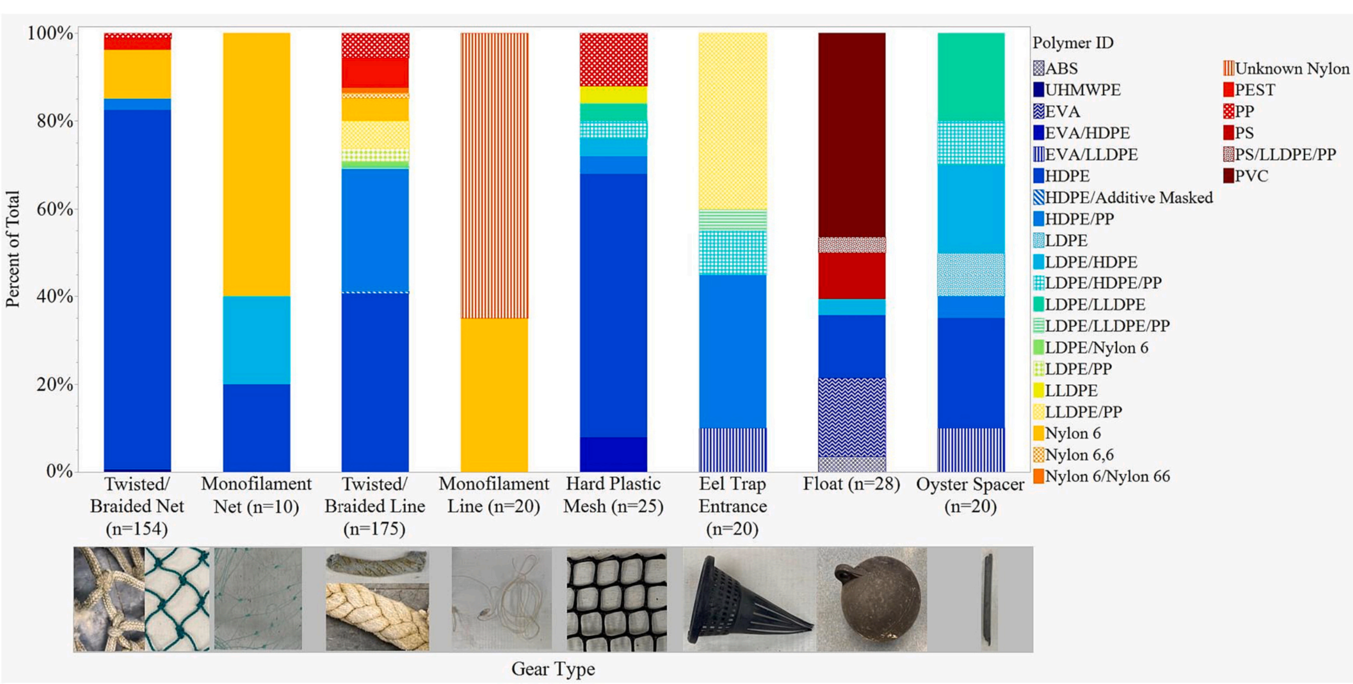


Fig. 2. Polymer composition of the eight gear types that were sampled from floating derelict fishing gear removed from nearshore waters or shorelines of O'ahu, Hawai'i. A Fisher exact test revealed significant differences in polymer composition among gear types ($p < 0.001$).

composition of these gear types can better inform sources, and ultimately lead to prevention and mitigation strategies.

Among all samples and components ($n = 452$), 26 polymers were identified. The majority of the samples identified as HDPE (43.3 %) or blended materials (26.5 %) (Fig. 2). The most common blend was HDPE/PP which made up 13.7 % of the total samples and 51.7 % of the blended samples. To our knowledge, this study is the first to investigate DFG polymer composition beyond a one-step method, like ATR-FTIR, for several gear types. The revealed polymer diversity indicates that manufacturers of these gear types use a wide array of polymers and blends, but the DFG floating into O'ahu is made predominantly of polymers that are less dense than seawater.

The polymer composition significantly differed among the eight gear types ($p < 0.001$; Fig. 2). Monofilament lines were the least diverse, composed of only two polymers; while twisted/braided lines were the most diverse, made of 12 different polymers. In the following subsections, the polymer composition of each gear type was further investigated to determine if polymer could be predicted by the gear type's construction styles, dimensions, shapes, and colors. Data, including metrics and polymer identification, collected from all individual samples and components from the eight gear types can be found in Table S1.

3.1. Twisted/braided nets and lines

Distinct nets, distinct lines, and conglomerates (which are large, tangled masses of mostly net and line pieces) make up most DFG events in the Hawaiian Islands (Royer et al., 2023). Nets and lines make up 87.6 % of the items or 98.6 % of the mass of an average conglomerate that washes ashore on O'ahu (McWhirter, 2022). Understanding their chemical composition may aid in sourcing the largest fraction of DFG to fisheries or gear manufacturers and inform different recycling options.

The 154 samples of twisted/braided nets were identified as six different polymers. HDPE was dominant, representing 81.8 % of this gear type with nylon 6 as the second highest (11.0 %). Seventy twisted/braided lines were analyzed. Of these, 40 had only one component, 17 had two (i.e., a tracer yarn in one strand), and 13 had three or more, totaling 175 components. Four samples had more than ten components, which demonstrates the production complexity of some lines. Twelve different polymers were identified in the twisted/braided line gear type, with the majority being HDPE (40.6 %) and blended polymers (40.6 %) such as HDPE/PP, LLDPE/PP, LDPE/PP, LDPE/nylon, nylon 6/nylon 66, LDPE/LLDPE/PP, and HDPE/additive masked.

The fiber types of twisted/braided nets and twisted/braided lines were significantly different in their polymer composition ($p < 0.001$and $p < 0.001$, respectively, Fig. 3a). Film fibers were present only in twisted/braided lines and consisted of nine different polymers, making them the most polymer-diverse fiber type. Three fiber types (multifilament, staple, and monofilament) were present in twisted/braided nets and twisted/braided lines. The multifilament fibers were primarily nylon variants (65.4 % of nets and 46.4 % of lines), whereas the staple fibers were all HDPE/PP blends (100 % for both twisted/braided nets and twisted/braided lines). All twisted/braided nets and 89.7 % of the lines made of monofilament fibers were HDPE. The omnipresence of HDPE comprising the monofilament-fiber, twisted/braided nets makes sorting this particular polymer out of DFG for recycling much simpler. Polymer identification of this particular gear today can be assumed visually, without in-depth chemical analysis. This is especially helpful because this gear type is one of, if not the most dominant DFG in Hawaii.

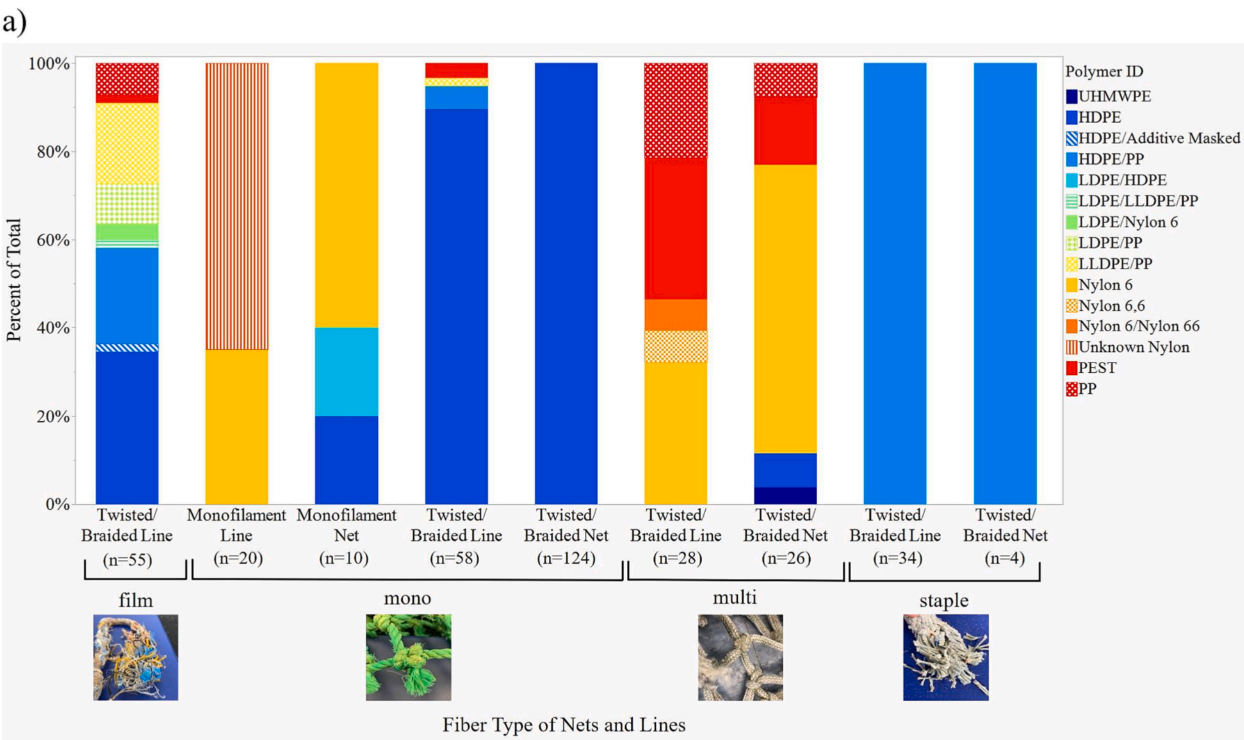
The three construction styles (*Z*-twisted, S-twisted, or braided) were significantly different in their polymer composition for nets ($p < 0.001$) but not for lines ($p = 0.33$) (Fig. S6). HDPE was the predominant polymer in all three net construction styles. PEST was only present in braided nets and made up 30.8 % of them, while PP and HDPE/PP were only present in Z-twisted nets and made up 4.9 % collectively. Twist direction or braiding is a poor predictor of polymer, but the combination of line construction and polymer may aid in sourcing the gear.

Colors of twisted/braided nets and lines were also shown to be significantly different in polymer composition ($p < 0.001$and $p < 0.001$, respectively). For nets, HDPE was the predominant polymer type in all eight colors, except for red, which were all ($n = 5$) nylon 6 (Fig. S7). Out of all the other colors, black had the lowest HDPE presence at only 42.9 % with the other 57.1 % consisting of PEST or nylon 6. Blue and green were both composed of 100 % HDPE and the remaining samples were ≥84.6 % HDPE. Lines were much more diverse in composition, but HDPE was present across all colors (Fig. S8). A wide array of colorants are intentionally added to plastic products for marketing and other reasons. In fishing gear, certain colors may be selected based on fishing depth and catch efficiency, especially in gillnets that need to be low visibility for the target species (Jester, 1973). While colors were different in polymer composition, these differences were likely caused by other confounding variables. For example, all five red nets had twine diameters <1 mm which indicated they were likely gillnets; gillnets are typically made of nylon (Cerbule et al., 2022). The blue and green nets were made of monofilament fibers, which are always HDPE. Color and polymer composition are likely selected together by fishers based on purpose, performance, and preference. Colorants are the largest plastic additive chemical class in production (Andrady and Rajapakse, 2016) and can increase the concentration of certain elements in plastic products (Turner, 2017), which is discussed below.

The construction style for braided/twisted nets (e.g., knotted or knotless) was significantly different in polymer composition ($p < 0.001$; Fig. 3b). Nearly all knotless nets ($n = 12$) were HDPE, with one twisted-knotless net made out of ultrahigh molecular weight PE (UHMWPE). PEST was only present in braided-knotted nets and represented 50.0 % of this gear type, while 37.5 % was HDPE and 12.5 % was nylon 6. Twisted-knotted nets were the most abundant construction style ($n = 125$) and were 84.4 % HDPE. This style is commonly used for two of the largest commercial fishing industries: trawling and purse seining. These two industries, however, differ in the polymer they use for nets. Trawlers use PE nets and purse seiners use nylon nets (Basurko et al., 2023), because PE is less dense and nylon is denser than seawater. Since the majority of these DFG net samples were HDPE, the major source is likely from trawl fisheries.

The polymer composition was significantly different for twisted/braided net twine diameter ($p < 0.001$) and mesh stretch ($p = 0.002$) (Fig. S9). HDPE, HDPE/PP, and nylon 6 had smaller twine diameter and mesh stretch compared to PEST. The dominant polymer composition for twisted/braided lines was also significantly different for line diameter ($p < 0.001$) (Fig. S10). HDPE twisted/braided lines were on average, thinner than HDPE/PP lines and these two polymers were the most abundant within this gear type. Nylon variants (nylon 6, nylon 66, and nylon 6/nylon 66 blend) were not different in line diameter from each other, but were thinner than HDPE/PP as well. It is conceivable that different polymers are used to make nets with larger mesh stretch or twine/line diameter due to durability or performance needs. There may also be other confounding factors to explain differences in the diameters. For example, monofilament fibers were found to be primarily HDPE, while staple fibers were dominantly HDPE/PP blends.

This deep dive of comparing various metrics of nets and lines to polymer identification aids in not only the understanding of what derelict fishing gear is made of, but provides which metrics can best predict the polymer composition of stockpiles of DFG. The fiber type of nets and lines are good indicators of polymer identity. Monofilament-fibered twisted/braided nets ($n = 123$) were always made of HDPE and staple-fibered twisted/braided nets ($n = 4$) and twisted/braided lines ($n = 34$) were always HDPE/PP blends. While a large portion, although not 100 %, of monofilament-fibered twisted/braided lines were HDPE. On the other hand, when looking at multifilament-fibered twisted/braided nets, the polymer composition inference is best made when paired with the net construction style. Eighty-nine percent of twisted-knotted multifilament-fibered nets ($n = 18$) were nylon 6, five of which were red and were all nylon 6, the twisted-knotless multifilament-a)



b)

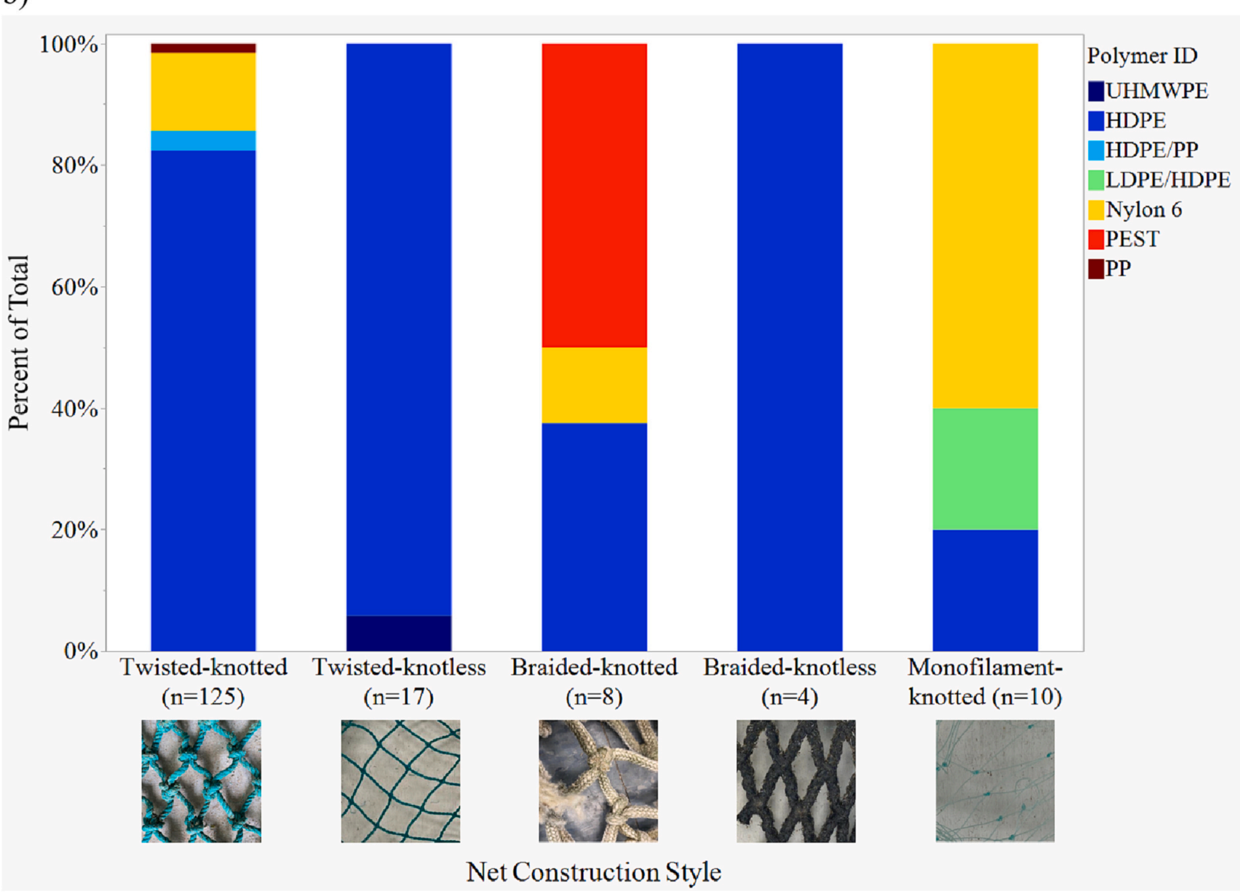


Fig. 3. Polymer composition of different a) fiber types of monofilament and twisted/braided nets and lines and b) net construction styles from monofilament and twisted/braided nets sampled from floating derelict fishing gear removed from nearshore waters or shorelines of O'ahu. Three Fisher exact tests revealed significant differences in polymer composition among a) fiber types for twisted/braided lines ($p < 0.001$) and for twisted/braided nets ($p < 0.001$) and b) net construction styles ($p < 0.001$).

fibered nets ($n = 3$) were made of PE (either HDPE or UHMWPE), and the braided-knotless multifilament-fibered nets ($n = 5$) were dominantly PEST.

With this study, we now can manually and visually pull particular gear out of conglomerates with a reasonable certainty of its polymer type without the need of more time consuming characterization and expensive chemistry instrumentation. This is especially important for nets and lines as they make up a vast majority of fishing gear that wash ashore on O'ahu (McWhirter, 2022), so understanding these materials can inform recycling options of a large marine debris feedstock. Mechanically recycling fishing nets is a growing field of interest across the world as it is the most environmentally sustainable disposal option and the incorporation of recycled plastic materials can aid in the performance of certain products (Andrady, 2015; Schneider et al., 2023; Pae et al., 2022). Recycled nylon fishing nets have shown to improve the mechanical performance of mortar cement in terms of tensile strength, flexural strength, and material toughness (Orasutthikul et al., 2017; Spadea et al., 2015; Srimahachota et al., 2020). Furthermore, recycled PE has shown to improve post-crack performance in gypsum-based materials (Bertelsen and Ottosen, 2021).

3.2. Monofilament net (gillnet) and line

Single fiber monofilament-knotted nets used in gillnet fisheries are rarely encountered in DFG events washing ashore on O'ahu. Less than 4 % of samples from conglomerates removed from O'ahu were of this gear type (McWhirter, 2022 Ch 3 Fig. 3.34). Samples of this net construction style were HDPE, LDPE/HDPE, and nylon 6 (Fig. 3b). Colors of monofilament nets were significantly different in polymer composition ($p = 0.005$) (Fig. S11). Of the ten samples, all clear and green monofilament nets were nylon 6 whereas the black samples were PE variants (HDPE and LDPE/HDPE). Gillnets are traditionally made out of thin nylon filaments because of their high breaking strength, drag reduction, and elasticity (Radhalekshmy and Gopalan Nayar, 1973; Cerbule et al., 2022). The black monofilament nets were unlike typical gillnets as the filaments were thicker, not transparent, and are not made of a sinking polymer, suggesting these could have a different purpose and/or source. This finding demonstrates the importance of combining net construction with polymer identification for more accurate gear sourcing.

Monofilament line samples were composed of only nylon variants, 35 % were nylon 6 and 65 % were an unknown nylon variant. The 13 nylon samples that could not be differentiated appear to be nylon 6 in ATR-FTIR spectra through analyzing the peak signatures; however, the melting temperature for those samples ranged from 187.32 °C to 192.63 °C, which is lower than typical nylon 6 and within the range other nylon variants, such as the first melt of nylon 11 (Dhanalakshmi and Jog, 2008; Lynch et al., in prep). Since the ATR-FTIR and DSC data were not in agreement, without further chemical investigation, these samples were classified as unknown nylons. The unknown nylon monofilament lines were significantly greater in line diameter compared to nylon 6 ($p = 0.04$; Fig. S12). The median line diameter for the unknown nylons were 2.02 mm while nylon 6 was 0.86 mm. Even though the unknown nylons had a lower melting temperature than those identified as nylon 6, it is possible that the 13 samples could be nylon 6 but contain more plastic additives affecting the melting temperature and/or experienced greater UV radiation. Additives can reduce the melting temperature (Lynch et al., 2022). Therefore, it is possible that thicker monofilament lines are made with more additives to make them that much more durable. However, this idea would need to be explored with further chemical testing. On the other hand, An et al. (2023) saw a 15 °C decrease in the melting temperature of nylon 6 fishing line after one month in an accelerated weathering chamber. Therefore, the thicker monofilament lines could have experienced greater UV exposure, which altered the melting temperature and complicated nylon differentiation.

Five known-source samples of monofilament lines used as branch lines by the Hawaiian and American Samoan longline fishery all show similar patterns to the unknown nylon samples. They all measured >1.5 mm in diameter, appeared to be nylon 6 using ATR-FTIR, but melted between 188.17 °C and 189.75 °C. Therefore, even though further investigations are needed to confidently determine the nylon variant, this pattern could help infer the source and fishing method of this gear. Longline fishing gear is composed of several monofilament lines in the mainline, branch line, and buoy drops, hooks, and various attachments such as floats, snap clips, and lead weights (Walcott et al., 2009; Watson and Kerstetter, 2006). Since the 1970s, nylon monofilament line has been the primary gear used in commercial pelagic longline fisheries (Watson and Kerstetter, 2006). According to a longline fishing workshop in Palau, vertical configurations are composed of a mainline and branch line of different diameters, 3 mm and 2 mm, respectively (Beverly, 2003). Similarly, a schematic from longline fishing constructions from the 1980s in Venezuela depict the branchline being 2 mm in diameter. In contrast, handline fishing using a monofilament line can range from 0.2 mm to 3 mm in diameter depending on the method used and where that component lies within the construction (Prado, n.d.). Although the use of monofilament lines is not limited to these two techniques, these schematics provide some evidence that the diameter of the line could be a clue to the source fishery. These commercial longline fishing fleets often accidentally hook large floating conglomerates of DFG (Uhrin et al., 2020), providing a mechanism that adds a small amount of otherwise sinking gear into floating DFG that washes ashore in Hawai'i.

3.3. Floats

Fishing floats are a common type of DFG found in the Hawaiian archipelago. They provide buoyancy along the float line of gillnets and purse seine nets, at points along a trawl net, and within rafts of drifting fish aggregating devices (dFADs). Twenty-two floats of great diversity of shape and material form (foam or rigid) were analyzed. PVC and ethylene-vinyl acetate (EVA) were the most prominent polymers making up 42.3 % and 19.2 % of the float samples, respectively. Six floats had two components (i.e., foam exterior with a hard plastic core). Both components from the same sample were always the same polymer.

Fishing float shapes, forms, and colors significantly differ in their polymer composition ($p = 0.01$, <0.001, 0.02, respectively) (Figs. 4, S13). Yellow floats made up 31 % of the float samples and two polymers were present, EVA (44.4 %) and PVC (55.6 %). PVC is represented for almost all colors whereas HDPE was only present in three, EVA in two, and all other polymers were only in one color (Fig. S13). This could be due to both the popularity in polymer used and/or the manufacturer's availability. PVC floats appear to come in multiple colors, whereas EVA is more limited. Foam floats ($n = 14$) consisted primarily of PVC (64.3 %) and EVA (21.1 %), with only one (7.1 %) being HDPE. PVC and EVA were not present in the rigid floats ($n = 9$), rather these were polystyrene (PS), HDPE, LDPE/HDPE, acrylonitrile butadiene styrene (ABS), and PS/LLDPE/PP. Rigid floats also make up all spherical and skinny rectangular float shapes and one oval (Fig. S3). This shows that rigid floats that are either spherical or skinny rectangular in shape have the potential to be one of many polymers. Bullet and oval shapes predominantly have foam exteriors and are made of EVA and PVC. Shape and form are likely to be better predictors of fishing source, but polymer identity could be useful for manufacturing source and recycling efforts.

Before plastic, floats were historically made out of natural materials such as wood and cork or glass. In the 1970s PVC became a common material as it was cheaper, moisture resistant (unlike wood which becomes waterlogged), and buoyant when blown into foam (Kumar, 2015). To date, according to Fitec Commercial Fishing, PVC is the most common polymer used worldwide for floats for affordability, hydrophobicity, and compatiblity with additives that better protect the float from UV radiation, cracking, or other damage (Fitec Commercial Fishing, n.d.; Duralite Industries, n.d.). On the other hand, EVA is commonly used in purse seine fisheries for great buoyancy and elasticity that prevents permanent deformation under pressure at depth, although EVA

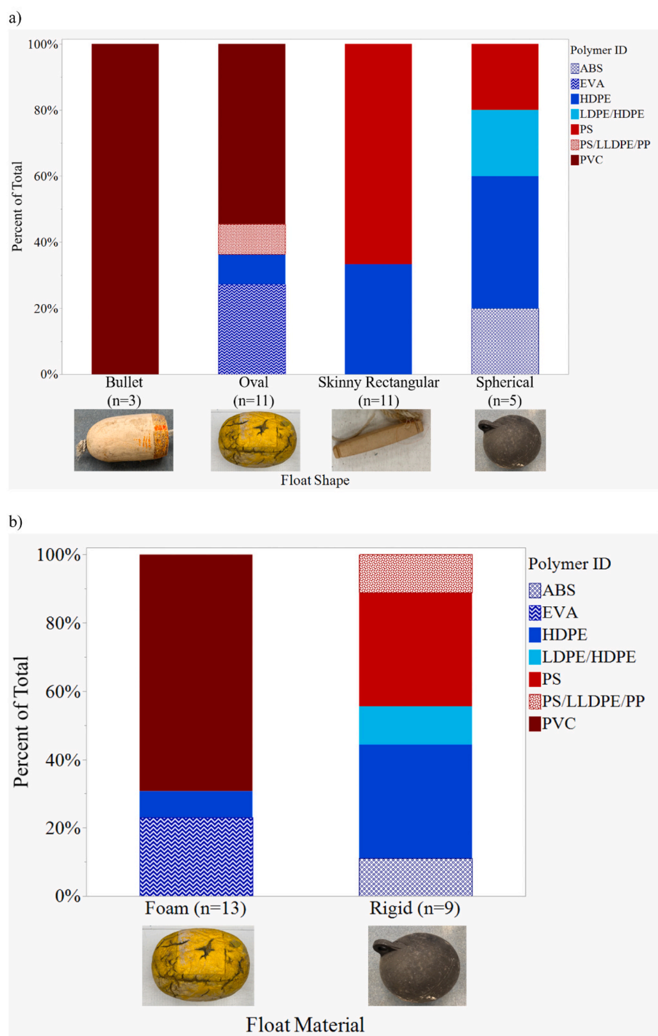


Fig. 4. Polymer composition of floats categorized a) into different shapes or b) into foam or rigid plastic forms that were sampled from floating derelict fishing gear removed from nearshore waters or shorelines of O'ahu. Two Fisher exact tests revealed significant differences in polymer composition among float shapes ($p = 0.01$) and again for foam vs. rigid forms ($p < 0.001$).

floats are not as affordable as PVC (Fitec Commercial Fishing, n.d.; Duralite Industries, n.d.). This is in line with our findings, as PVC was the most common polymer present within DFG floats.

3.4. Hard plastic mesh

Hard plastic mesh is commonly used in aquaculture to create enclosures such as bags, pens, or cages (Flimlin et al., 2008), but can also be used in terrestrial construction, yard work, and industry. This gear type made up 3.8 % of sample numbers, but negligible sample mass, collected from DFG conglomerates that washed ashore on O'ahu (McWhirter, 2022). Eighty-eight percent of the 25 samples analyzed here were a PE variant or a blend with PE, while the other 12 % were PP.

Hard plastic mesh of different colors significantly differed in polymer composition ($p = 0.02$) whereas mesh size, mesh shape, and thickness categories did not ($p = 0.32$, 0.09, and 0.33) (Figs. S13, S14, S15). Black and orange hard plastic mesh had the most diversity in polymers, while green was composed of only one polymer type (HDPE). The hexagon mesh shapes ($n = 7$) were only HDPE, while all other mesh shapes (square, circle/oval, rectangle, and diamond) consisted of more than one polymer (Fig. S15). It is possible that hexagon-shaped mesh comes from only a few manufacturers that only use HDPE. Other shapes do not predict the polymer. It is not surprising that mesh size and thickness are not polymer specific because a manufacturer likely makes multiple sizes and thickness for different uses from the same plastic pellet source. According to Industrial Netting, a US manufacturer, PE plastic mesh is understood to be more flexible, durable in cooler weather conditions, and resistant to fracturing compared to PP (Industrial Netting, n.d.). These properties, and thus PE hard plastic mesh, could be preferred in aquaculture, resulting in more abundant PE than PP in our samples. Likewise, these properties could be preferred for thicker mesh material, because the thickest samples were made with HDPE (Fig. S14).

3.5. Eel trap entrances

Eel traps made of plastic were first manufactured in Korea, and are now the most common construction, consisting of a plastic cylinder that has various hole sizes and is fitted with one or two detachable eel trap entrances (Kato, 1990). Other variations of eel traps use buckets, trash cans, or barrels instead of the typical cylinder (Kato, 1990). The entrances are easily recognizable, commonly found along the shorelines of the Hawaiian Islands (Brignac et al., 2019) and were frequently tangled into DFG events removed from the Hawaiian region (Royer et al., 2023). The eel trap entrances consist of two components, baskets and fingers. Ten of each were analyzed. Five baskets and five fingers were found separated, while five intact entrances provided the other five baskets and fingers. One intact entrance had the two pieces snapped together, but could be disconnected. The other four intact entrances appeared to have the basket and fingers stuck together, like they were molded as one item or melted together after being assembled.

The eel trap entrances were composed of five different polymers, all of which were blends (LLDPE/PP, HDPE/PP, LDPE/HDPE/PP, LDPE/LLDPE/PP, EVA/LLDPE). LLDPE/PP was the most common polymer overall, making up 40 % of the baskets and 40 % of the fingers (Fig. 5a). HDPE/PP comprised 35 % of all samples. Only two baskets were EVA/LLDPE, whereas all other samples were some variant(s) of PE mixed with PP. EVA compared to LDPE and PP has a lower tensile strength and yield strength, but a higher elongation percentage (Jhumur et al., 2018). Therefore, there are physical property trade-offs when using one polymer over another and the blend of materials can enhance specific characteristics of interest.

The polymers comprising the baskets were significantly different from the fingers ($p = 0.04$). HDPE/PP was present in 60 % of the fingers but in only one basket. Three other polymers, EVA/LLDPE, LDPE/HDPE/PP, and LDPE/LLDPE/PP, were identified in the baskets but absent in the fingers. Of the five intact eel traps, only two of them had baskets and fingers composed of the same polymer (components were inseparable) and three had mismatched polymers (two had inseparable components and one was the snap-together style). Components of the snap-together style are not produced with standard dimensions for mix and match use, so fingers from one model do not always snap onto a basket from another model. Therefore, it is interesting, but perhaps unexpected, that the two components of the snap-together entrance were made with different polymers since the same manufacturer likely made both components. It is equally intriguing that two entrances with inseparable baskets and fingers were made with mismatched polymers. The results suggest that manufacturers intentionally select different polymer blends for the two components for enhanced performance. HDPE may be favored for the fingers, because PE is more flexible than PP which would allow eels to enter the traps with less breakage of the fingers (Industrial Netting, n.d.). The reason for polymer selection in the production of these items is unknown to us, but may be due to different manufacturers, performance reasons, or resources available.

3.6. Oyster spacers

Oyster spacers are typically tubes with smooth cut ends that rarely tangle into large DFG conglomerates, but they are frequent debris items

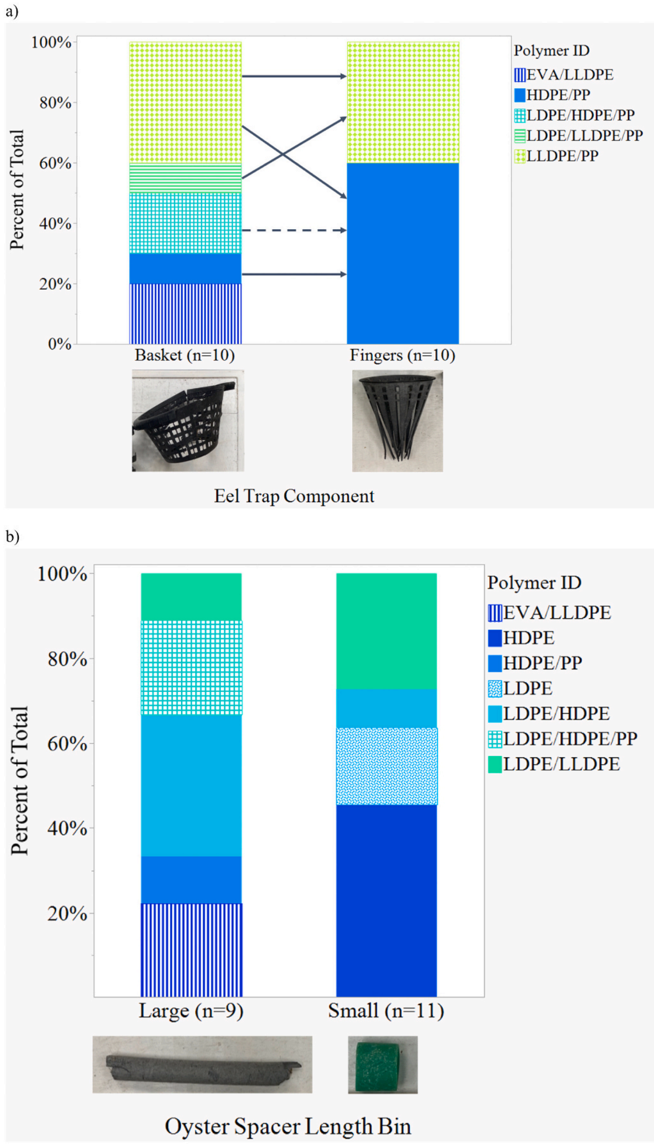


Fig. 5. Polymer composition of a) eel trap entrance parts and b) oyster spacer length, large (>5 cm) vs. small (<5 cm), sampled from floating derelict fishing gear removed from nearshore waters or shorelines of O'ahu. The arrows represent the five samples that had the fingers and basket attached to each other when collected in the field showing how diverse the polymers can be within a sample. The solid line represents the four eel trap entrances that have inseparable components and the dotted line is the snap-together kind. Two Fisher exact tests revealed significant differences in polymer composition between the a) eel baskets and fingers ($p = 0.04$) and b) length bins ($p = 0.01$).

found on Hawaiian shorelines (Brignac et al., 2019). Overall, the sampled oyster spacers consisted of seven different polymers, with the three most abundant being HDPE (25 %), LDPE/HDPE (20 %), and LDPE/LLDPE (20 %) (Fig. 2).

Length and color of oyster spacers influenced the polymer type ($p =$ 0.01 and 0.01), whereas thickness and width did not ($p = 0.76$, 0.08; Figs. 5b, S13, S16). All long oyster spacers (>5 cm in length) were composed of blended materials, LDPE/LLDPE, LDPE/HDPE/PP, LDPE/HDPE, HDPE/PP, and EVA/LLDPE, whereas 63.6 % of shorter oyster spacers (<5 cm) were made of a single polymer, LDPE or HDPE. It is unknown as to why different lengths are made of different materials. There are various methods used to farm oysters, but oyster spacers are commonly used in between shells or as some form of collector for spat, a life stage in which an oyster attaches to a surface (Fujiya, 1970; Matthiessen, 2008). According to Matthiessen (2008), the smaller oyster spacers are used during the initial collection process and traded out with longer ones during the juvenile stage to allow for growth while preventing overcrowding.

Black oyster spacers had the greatest diversity of polymers representing five different polymers. LDPE/HDPE was only present in grey oyster spacers whereas LDPE/HDPE/PP, LDPE, and HDPE/PP were only in black. Lastly, LDPE/LLDPE was only present in blue and green oyster spacers. It is unclear if differences in polymer composition are intentionally chosen for performance or based on cost and availability of plastic pellets. It is conceivable that manufacturers produce particular colors that are preferred culturally within their market. If this is found to be true, the combination of polymer and color may be traceable to a particular market or manufacturer.

3.7. dFADs

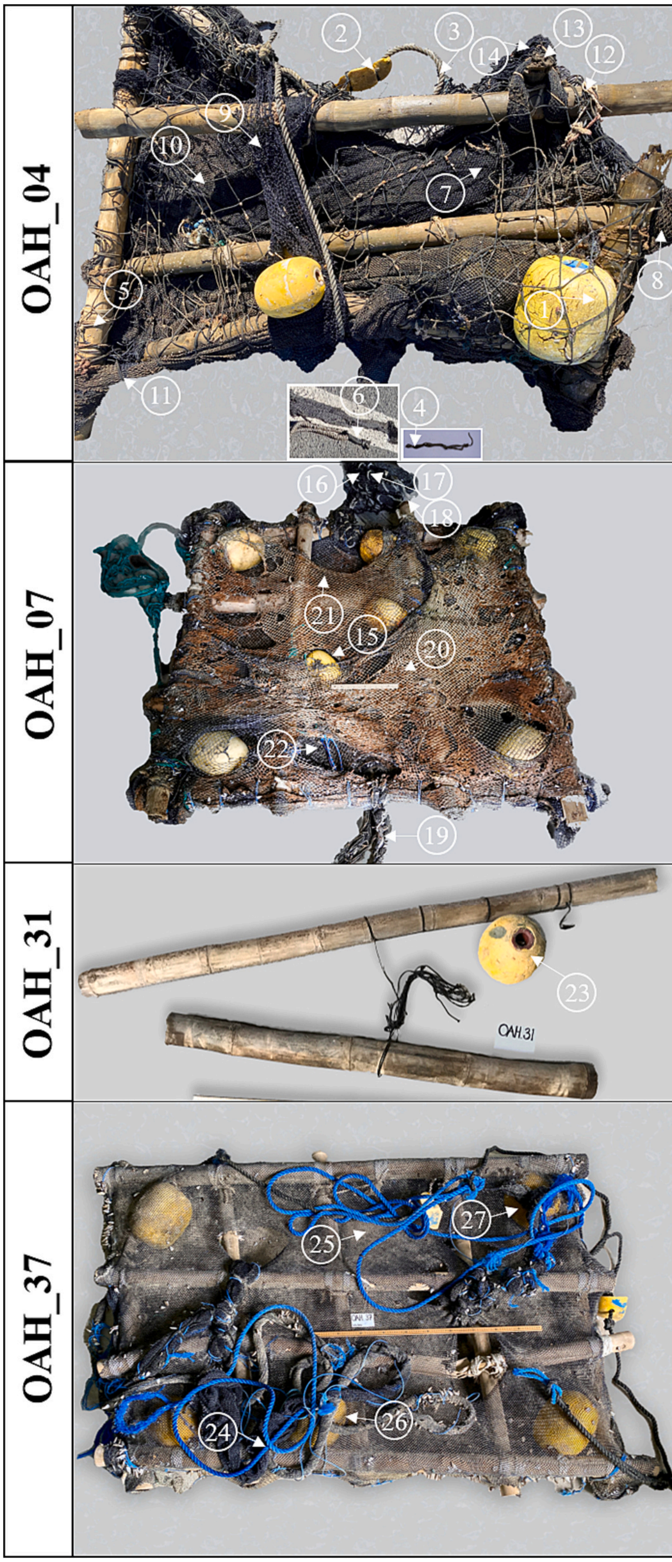
Drifting fish aggregating devices (dFADs) are used by portions of the tropical tuna purse seine fishery and arrive in Hawai'i as marine debris after drifting out of the fishing grounds. dFAD components represented 21 % of DFG events studied in the Main Hawaiian Islands (Royer et al., 2023). They have three major parts: a raft, tail, and buoy. A typical dFAD in the Pacific Ocean is made of a bamboo raft with yellow foam floats gored with line and wrapped together in black netting connected to a tail, or appendage, of additional netting or line that hangs below the raft. This tail can reach 100 m, but more commonly ranges from 50 m to 59 m in the Pacific Ocean (Escalle et al., 2023). A satellite buoy attached to the raft via a line provides the GPS location of the dFAD to the fishing vessel and often has a built-in echo sounder to estimate fish biomass under the dFAD.

The floats, netting, and lines of four dFADs that washed ashore on O'ahu were included in the analyses above. Here the data are isolated to provide polymer composition of specific dFAD components. All five floats were oval, had a hole through the center, and were yellow foam on the outside (one component) with a hard plastic core (second component). Both components on a single float were always identified as the same polymer. Three floats were PVC while two were EVA (Fig. 6). All eleven nets were black and contained multifilament fibers but varied in construction. Majority of the nets were nylon 6 ($n = 9$) while two were PEST (Fig. 6). The two PEST nets were found on the same dFAD, one wrapping the bamboo raft while the other was part of the tail, and had mesh stretch sizes >20 cm while all nylon nets had mesh stretch <10 cm. The lines ($n = 11$) were the most variable in polymers with five identified (nylon 6, PEST, HDPE, LLDPE/PP, and HDPE/PP) (Fig. 6). Ten of the lines had one component, eight were nylon 6, one PEST, and one HDPE. One line had four components all of which were PE variants blended with PP.

3.8. Polymer blends

Within all gear types analyzed, 118 or 26.3 % of the samples were identified as blended materials, which includes 13 blends (Fig. 2). All but one blend included a PE variant. The most common blend, HDPE/PP, was found in 62 samples (four twisted/braided nets, 49 twisted/braided line components, seven eel trap entrance components, one oyster spacer, and one hard plastic mesh). Using the HDPE/PP calibration curve, the percentage of HDPE in these samples was quantified (Fig. 7). The majority of twisted/braided line components, all twisted/braided nets, and all eel trap entrance components were made of less HDPE than PP. Twisted/braided line components ranged from 3.85 % to 93.1 % HDPE, and the twisted/braided nets ranged from 20.8 % to 23.3 % HDPE. On the other hand, the single oyster spacer and hard plastic mesh samples were made of more HDPE than PP, 70.8 % and 94.6 % HDPE, respectively.

The eel trap entrance components ranged from 6.24 % to 12.6 % HDPE. One eel trap entrance, which had an inseparable basket from



No.	Gear Type	Color	Polymer ID
1	Line	Yellow, Blue	PVC
2	Line	Black	Nylon 6
3	Line	Grey	HDPE
4	Line	White	Nylon 6
5	Line	White	Nylon 6
6	Line	Black	Nylon 6
7	Net	Black	Nylon 6
8	Net	Black	Nylon 6
9	Net	Black	Nylon 6
10	Net	Black	PEST
11	Line	Black	Nylon 6
12	Line	White	Nylon 6
13	Line	White	Nylon 6
14	Net	Black	PEST
15	Float	Yellow, Pink	PVC
16	Net	Black	Nylon 6
17	Line	White	Nylon 6
18	Line	Brown	PEST
19	Line	White	Nylon 6
20	Net	Black	Nylon 6
21	Net	Black	Nylon 6
22	Net	Black	Nylon 6
23	Float	Yellow, Red	PVC
24	Line	Blue (x2), Green, Red	LLDPE/PP (dominant blue, green, red) and HDPE/PP (blue)
25	Net	Black	Nylon 6
26	Float	Yellow	EVA
27	Float	Yellow	EVA

Fig. 6. Polymers comprising samples from four drifting fish aggregating device (dFAD) rafts recovered from shorelines of O'ahu. The event name is to the left of each photo. Sample identification numbers are circled and referenced in the table.

fingers, had the same percentage of polymer blends (9.3 % HDPE and 90.7 % PP) in both components. These two components unintentionally served as a quality control for precision, showing agreement between duplicates analyzed in our method.

Polymer blends have been a growing field of focus since the 1970s as it is more cost-effective to blend materials than to create new materials for different application purposes (Robeson, 1984). PE and PP are both very abundant plastics that have similar properties. Blends of these materials are common and have been studied since the 1980s because their similar densities make them difficult to separate in the recycling process (Teh et al., 1994; Aumnate et al., 2019). PP generally has high tensile strength and stiffness, but poor toughness and ductility (Aumnate

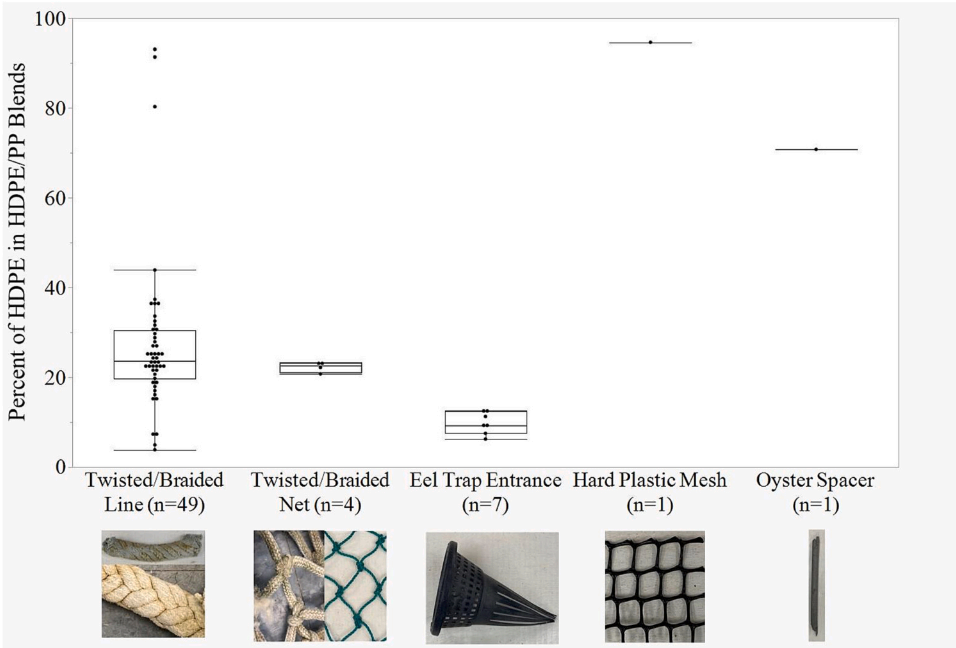


Fig. 7. The percentage of HDPE in individual fishing gear samples or components that were identified as a blend of HDPE/PP. Samples were from floating derelict fishing gear removed from nearshore waters or shorelines of O'ahu.

et al., 2019; Parameswaranpillai et al., 2019). However, when HDPE is added these physical properties are improved and increase the impact performance (Teh et al., 1994; Parameswaranpillai et al., 2019; Lin et al., 2015). To our knowledge, the scientific literature is devoid of research on why blends are used in fishing gear. Are blend types and ratios used for specific applications, or are they simply more cost-effective and readily available?

However, there are also drawbacks to polymer blends as they are commonly immiscible and result in incompatibility, which can also create obstacles for recycling polymer blends (Dorigato, 2021). Often to recycle polymer blends, re-compatibilization needs to occur and the impact properties need to be modified (Utracki and Wilkie, 2002). Taufiq et al. (2017) compared virgin PE/PP to recycled PE/PP and saw a decrease in tensile strength with recycled PE/PP by 57 % and morphological impurities. Therefore, in terms of mechanical recycling, it is important to understand which gear types are composed of blends as they will pose a different set of challenges.

3.9. Case study of a multiple component line

Performing polymer identification on highly complex lines can be challenging. Different components of a line, such as a tracer yarn, can be made of different fiber and/or polymer types than the rest of the yarns or strands, making it important to analyze each component to understand the complete material make-up of the line. To showcase this challenge, one of the most complex lines in our larger study was analyzed in detail. A preliminary assessment identified ten components based on color and fiber type alone, assuming that fibers of a similar appearance were the same material both within and between strands. One clear film component was polymer identified as PEST on ATR-FTIR, but HDPE on the DSC. This discrepancy spurred a complete dissection of the line to fully understand its components and show the utility of the polymer identification methods. After dissecting the line, 14 additional components (24 total fiber groupings) were identified within the three strands based on color, fiber type, opacity, construction, and polymer composition (Fig. 1). Although there are many similarities between the strands with 13 similar fibers found in all three strands, each strand is unique. Eight fibers were present in only one strand and different numbers of fiber types in each strand (17, 18, 18) (Table S3). Eleven fiber groupings were fibrillated (see Fig. 1) while the remaining were singular fibers. The line was composed of eight different polymer types, HDPE, HDPE/additive masked, HDPE/PP, LDPE/LLDPE/PP, LDPE/nylon 6, LLDPE/PP, PEST, and PP (Table 3S). The clear film fiber that caused the initial PEST vs. HDPE discrepancy turned out to be two different clear fibers (AB in Fig. 1). One was PEST while the other was HDPE on one side and additive masked on the other. Each clear fiber was present in each of the three strands. Of the six groupings that were identified as HDPE/PP, the percentage of HDPE ranged from 3.85 % to 80.3 %.

The reason for producing such a complex line consisting of many polymers and fiber types is unknown. Fibrillated fibers are typically used in concrete mixtures as a substitute for welded wire fabric since the 1980s as a secondary reinforcement to manage plastic shrinkage cracking (Banthia and Gupta, 2006; Bertelsen, 2019). Through online market research, we found that manufacturers fabricate these fibers with different polymer compositions, nylon, PE/PP blends, and PP that have various properties, applications, and advantages. Studies have shown recycling applications of DFG into fibers used in concrete (Bertelsen, 2019; Srimahachota et al., 2020), but no studies have discussed the use of fibrillated fibers for the fishing industry.

Due to the complexity of this line, the fiber production process would likely be very complex and cost ineffective, and the line would be difficult to mechanically recycle. Therefore, we suspect the line manufacturer used scrap fibers from other production lines, a form of recycling post-industrial plastic waste and the assortment of fibers could be due to availability at the time of strand production. These intricacies make polymer identification difficult and time consuming. Three other lines analyzed in this study had $\geq$10 components and even more are inventoried in the in-house DFG database.

3.10. Elemental concentrations

Characterization of plastic debris should go further than identification of the bulk polymer. Plastic additives or adsorbed chemicals onto the DFG from the environment are concerns for toxicity. Concentrations of certain elements could not be reported with confidence because the XRF measured values did not match the certified values of the reference materials. Of these elements, non-essential rubidium, antimony, thorium, uranium, and tungsten, and essential cobalt were present in >10 % of the DFG samples (Table S4). Concentrations of five non-essential and nine essential elements that could be quantified were significantly different in 60 DFG samples (mostly nets) compared to 17 new/unused fishing gear (NFG) (Fig. 8, Table S5). Calcium, iron, manganese, phosphorus, lead, sulfur, strontium, titanium, and zinc were greater in DFG, while aluminum concentrations were greater in NFG. One explanation for greater concentrations in DFG than NFG is that plastics can absorb metals from the marine environment (Yu et al., 2019; Rochman et al., 2014). Specifically, for calcium concentrations, we likely see an increase due to marine organism growth. Rochman et al. (2014) examined the concentrations of aluminum, iron, zinc, lead, and other metals in five polymers that were deployed for a year in various locations throughout San Diego Bay. They found an increase in concentration of all metals within the various polymers (Rochman et al., 2014). The NFG samples, while not a perfect comparison to DFG since they could be made with different elements, were intended to provide baseline concentrations to help explain if DFG elements were sourced from plastic additives or adsorbed from the environment. Therefore, the decreased concentrations of aluminum seen in the DFG compared to NFG is likely due to material and manufacturing differences and not due to the loss of aluminum in the environment.

Elements are used as plastic additives, especially as colorants (Turner and Filella, 2021), so concentrations were compared among DFG colors (Table S6). Greater concentrations of lead and arsenic were observed in orange and black DFG, copper in blue and green, and manganese in red DFG. The increased lead concentrations in orange nets was similar to Turner (2017), which may be from colorants like lead chromates. However, unlike Turner (2017), chromium was detected in only one DFG sample. Copper is common in plastic colorants, such as copper phthalocyanine that produces vibrant blue and green colors. Colorants are a likely source of the elevated copper in these DFG colors. Likewise, iron oxide pigments are very commonly used to produce red and orange plastic products.

The elements detected in the DFG could have been intentionally added or adsorbed from the environment. Regardless, it is important to understand their concentrations in the DFG for wildlife exposure after plastic ingestion and human exposure during debris removal, sorting and possible recycling activities. Of the elements that could be quantified, arsenic and lead in a few of the DFG samples exceeded thresholds set by the European Commission for toy safety and food contact plastics (Turner and Filella, 2021). Zinc concentrations in several DFG samples exceeded the food contact, but not the toy safety thresholds.

4. Conclusions

This study provided breadth and depth of material and chemical composition of different gear types commonly found in floating DFG that washes into the nearshore waters of O'ahu. Understanding polymer composition is important for gear sourcing and ultimately, the management of DFG reduction. Using the combination of both ATR-FTIR and DSC we provide more accurate polymer identification, including detecting multilayer composites and blends, determining blend proportions, and differentiating polymer variants. By combining the physical characteristics (color, construction, dimensions) with the chemical composition of different gear types, we can now make visual inferences and separate particular gear within conglomerates with a reasonable certainty of its polymer type or at least have a narrower list of the polymer without further chemical techniques. For nets and lines, which make up the largest contribution by mass of floating DFG in the Hawaiian archipelago (McWhirter, 2022), the combination of construction and fiber type can provide insights into the polymer makeup. Monofilament-fibered twisted/braided nets were always HDPE and staple-fibered twisted/braided nets were always HDPE/PP, with twisted/braided lines showing a similar pattern, but not 100 % for those composed of monofilament fibers. Monofilament lines were always a variant of nylon, while monofilament nets were either HDPE (black) or nylon 6 (clear or green). Float shape, form, and color can narrow down the options of the polymer composition. Although interesting patterns were found with oyster spacers, eel trap entrances, and hard plastic mesh, due to the complexities it would be difficult to infer the chemical composition without the continued use of chemical instrumentation. Across all gear types, HDPE made up a majority of the samples (43.3 %).

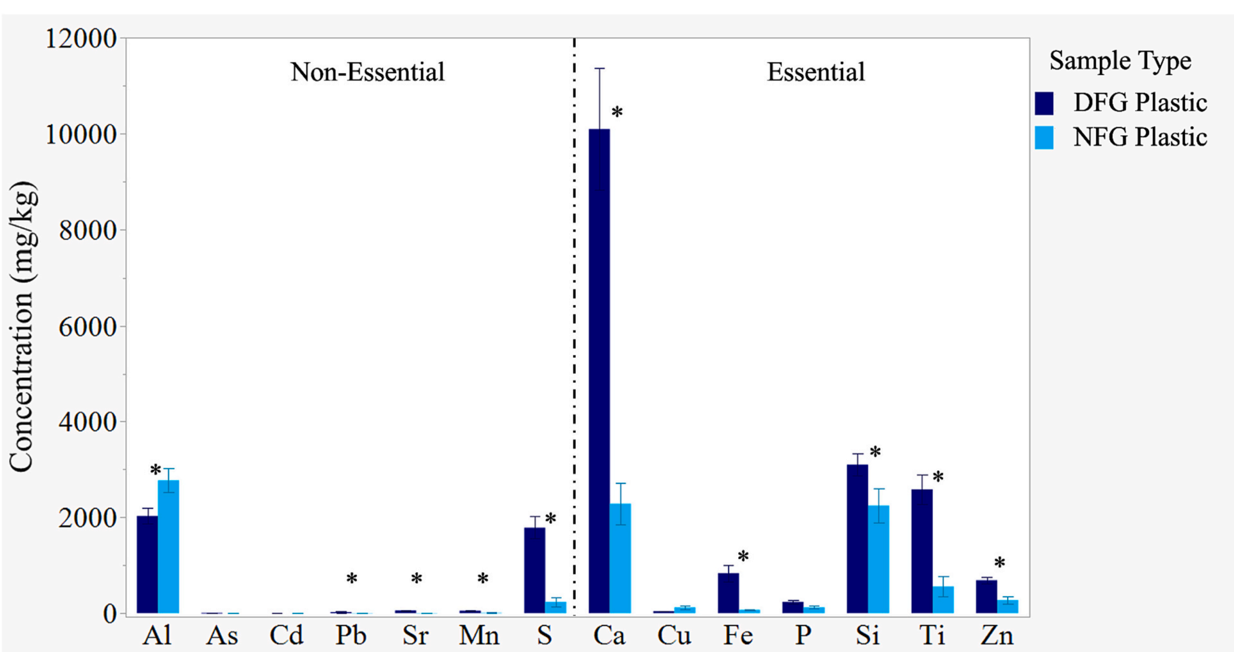


Fig. 8. Elemental concentrations (mg/kg) in plastic components of floating derelict fishing gear (DFG) removed from waters or shorelines near the Hawaiian Islands compared to new/unused fishing gear samples (NFG). Elements are categorized based on whether they are essential for life; the non-essential elements may be considered more toxic. *Denotes significant differences between DFG and NFG concentrations using R NADA cendiff ($p < 0.05$).

Fewer gear samples were made of polymers denser than seawater (nylon, PEST, PVC). Polymers are versatile; one has different characteristics more suitable for certain applications than others, so the differences found in this study could be due to performance needs, or it could be due to cost, resource availability, or manufacturer differences. Understanding the makeup of the material is important not only for sourcing the material, so that the problem of DFG can be mitigated or prevented, but also for recycling applications.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115570.

NIST disclaimer

Certain commercial equipment, instruments, or materials are identified in the present study to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

CRediT authorship contribution statement

Raquel N. Corniuk: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Katherine R. Shaw:** Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Andrew McWhirter:** Data curation, Investigation. **Harry W. Lynch:** Data curation, Investigation, Methodology, Resources. **Sarah-Jeanne Royer:** Data curation, Investigation, Writing – review & editing. **Jennifer M. Lynch:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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.

Data availability

I have shared all raw data in the SI files.

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