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A global assessment of microplastic abundance and characteristics on marine turtle nesting beaches

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ABSTRACT

Sandy coastal beaches are an important nesting habitat for marine turtles and a known sink for plastic pollution. Existing methodologies for monitoring the spatiotemporal patterns of abundance and composition of plastic are, however, disparate. We engaged a global network of marine turtle scientists to implement a large-scale sampling effort to assess microplastic abundance in beach sediments on marine turtle nesting beaches. Sand samples were collected from 209 sites spanning six oceans, microplastics (1-5 mm) were extracted through stacked sieves, visually identified, and a sub-sample verified via Fourier-transform infrared spectroscopy. Microplastics were detected in 45 % ($n = 94$) of beaches and within five ocean basins. Microplastic presence and abundance was found to vary markedly within and among ocean basins, with the highest proportion of contaminated beaches found in the Mediterranean (80 %). We present all data in an accessible, open access format to facilitate the extension of monitoring efforts and empower novel analytical approaches.

1. Introduction

The annual global production of plastics grew from 250 million tons to 368 million tons between 2010 and 2020 (PlasticsEurope, 2020), which has contributed to the increasing ubiquity of plastic pollution in the marine environment (Barnes et al., 2009). Approximately 19–23 million tons of plastic waste enters the marine environment every year, the majority of which is derived from land-based sources and coastal tourism, while an estimated 20 % is resultant from ocean-based sources, such as fishing (Andrady, 2011; Borrelle et al., 2020). Harmful implications of plastic debris in the marine environment include habitat degradation, transportation of invasive species, and entanglement and ingestion by marine fauna, which may lead to injury or death (Derraik, 2002; Duncan et al., 2017; Nelms et al., 2016; Wright et al., 2013).

Additionally, small pieces of plastic, termed microplastics, are of concern as their smaller size means they can interact with a greater number of species and life stages, across trophic levels, and can permeate habitats (Botterell et al., 2019; Wright et al., 2013). Microplastics are characterised as plastic particles <5 mm in size and can be further categorised into large microplastics (1–5 mm) and small microplastics (<1 mm; Andrady, 2011; Thompson et al., 2004). Primary microplastics are manufactured purposely for industrial or domestic use, for example: microbeads found in exfoliating facial scrubs, nurdle pellets used in the plastic industry, or microfibres released during the washing of synthetic textiles (Andrady, 2011; Barnes et al., 2009; Browne et al., 2011). The majority of primary microplastics enter the ocean via domestic and industrial drains, waste effluent from wastewater treatment works, and industrial spills (Napper et al., 2015; Napper and Thompson, 2016). Secondary microplastics are formed from the repeated fragmentation of larger pre-existing plastic items through ultraviolet radiation, mechanical abrasion, and weathering processes (Barnes et al., 2009). Microplastics are now found to contaminate all marine ecosystems including sea ice, sea surface, water column, deep-sea sediments, coral reefs, seagrass beds, mangroves, and beaches (Carson et al., 2011; Eriksen et al., 2014; Nor and Obbard, 2014; Peeken et al., 2018; Tekman et al., 2020; Walther and Bergmann, 2022; Woodall et al., 2014).

Beaches represent a major sink for microplastics with accumulation increasing over the last fifty years (Barnes et al., 2009; Carson et al., 2011; Thompson et al., 2004). Coastal beaches can be transformed into microplastic “hot spots” due to their proximity to urban areas and physical processes, such as currents and winds, that aid their resuspension, transportation, and deposition (Barnes et al., 2009; Cózar et al., 2014; Wu et al., 2020). Although existing literature allows some understanding of microplastic spatial distribution on beaches, significant gaps in locational knowledge remain (Balladares et al., 2023; Duncan et al., 2018; Jones et al., 2021; Novillo-Sanjuan et al., 2022; Zhang et al., 2022). Robust quantitative spatial comparisons and investigations into temporal relationships in microplastic pollution are also scarce (Mesquita et al., 2022) and are hindered by discordant units of measure and the lack of a uniform methodology (Alvarez-Zeferino et al., 2020; Besley et al., 2017; Choi et al., 2021; Duncan et al., 2018; Mesquita et al., 2022; Pagter et al., 2018). Quantifying and mapping the current extent of global microplastic distribution is key to understanding patterns of dispersal, subsequent ecological impacts, and in targeting strategic remediation intervention in polluted areas (Auta et al., 2017).

Knowledge of microplastic distribution could focus efforts to protect and preserve areas identified as key habitats for endangered species, such as marine turtles, that rely on these beach habitats for reproduction (Beckwith and Fuentes, 2018; Fuentes et al., 2023a, 2023b; Nelms et al., 2016). The irregular properties of microplastics can disturb the natural beach environment, for example increasing sediment permeability, which flushes greater volumes of water through the beach (Carson et al., 2011). In addition, plastics have a higher specific heat capacity than sand, especially dark pigmented plastics, which, when mixed with sediments, may increase sand temperature leading to reduced nesting success (Andrady, 2011; Fuentes et al., 2023a, 2023b).

Given the implicit interest in beach microplastics for marine turtle biology and conservation, we set out to engage the marine turtle research community to conduct a global survey. In light of calls for standardisation (Bonita et al., 2023; Tiwari et al., 2023), we aimed to develop and apply an internationally viable methodology for sample collection, laboratory analysis, and reporting of microplastic (1–5 mm) abundance within beach sediments at a global scale. The methodology and consequent dataset generated are intended to provide an international baseline of quantified global beach microplastic abundance, allowing collaborators the ability to extend the dataset and further increase global understanding of microplastic distribution. We aimed to: 1) quantify the composition, abundance, and spatial variation of microplastics on multiple beaches located across the world on which turtles nest, 2) investigate how these microplastics are distributed across nesting beaches, and 3) assess how microplastics vary spatially by particle type and polymer composition, which may, in time, help identify source locations and inform evaluation of ecological threat.

2. Materials and methods

2.1. Sample collection

Marine turtle conservation and research community email lists (CTURTLE and MEDTURTLE) were used to identify potential collaborators willing and able to voluntarily collect sand samples from marine turtle nesting beaches around the world. Samples of beach sand were gathered from a total of 209 turtle nesting beaches from 39 different countries between August 2018 and January 2020. These locations spanned six continents and six ocean basins: the Mediterranean ($n = 39$), Indian Ocean ($n = 44$), North and South Atlantic $n = 70$, $n = 20$ respectively), and North and South Pacific ($n = 28$, $n = 8$ respectively). A detailed methodology, labelling materials, and datasheets were sent electronically to the recruited collaborators to sample a nesting beach or beaches that best represented their local area (**Supplementary Materials** Fig. 1).

A standardized sampling methodology was followed at each nesting beach. Total beach length (TBL) was measured in kilometres and a total of 10 sites were sampled for sand on five transect lines located at 10 % TBL, 30 % TBL, 50 % TBL, 70 % TBL and 90 % TBL. Here, beach was defined by the local teams and was typically the marine turtle monitoring nesting site, which could vary in length, be a discrete bay or a subsection of a long sandy shore. At each transect point, one sample was taken from the “strand line” and the “turtle nesting line” **(Supplementary Materials** Fig. 1**)**. The strand line was defined as the highest line of debris left by the retreating tide. In the case of there being more than one tide line visible due to tidal variation, the representative line chosen was the most recent line present. The turtle nesting line was approximated as the halfway point between the strandline and the outer limit of the beach within which turtles were found to nest, thus the medial nesting zone. Visual identification of 1) marked nests and 2) nesting pits, aided the approximation of this area (Duncan et al., 2018). Any nesting line sampling sites that were found to coincide with an active turtle nest were relocated two metres to the left or right to avoid disturbing the clutch. A metal spoon or trowel was used to remove the top 2 cm of sand in a 25 × 25 cm quadrat, a volume of approximately 1.25 L. To prevent post-collection fragmentation and contamination, any visually large macroplastic items (>5 mm) were removed and recycled where possible. At all sample locations, GPS coordinates were recorded in decimal degrees (longitude/latitude: World Geodetic System (WGS) 1984 format).

Sand samples were emptied into a glass bowl or beaker, weighed and sub-sampled to allow for practical postage and transportation to the University of Exeter, UK, for analysis. Sub-sampling was achieved by first mixing the sample with a metal spoon to prevent separation of the sand and plastic pieces, then 75 % of the sand (by weight or volume) was removed. The remaining 25 % was sent for further processing. The sand sample was air dried and deposited into Ziploc plastic bags for shipping.

Plastic bags were chosen due to the lightweight and durable qualities for international shipping.

2.2. Extraction of microplastics 1–5 mm

Sand samples were dried at 60 °C for 48 h and then processed individually using a previously developed method (Lots et al., 2017). The dry weight of each sample was recorded to the nearest of 0.01 g and volume to nearest 10 mL, the sand was then passed through a sieve cascade of 5 mm and 1 mm to separate the microplastics in the size range 1–5 mm only (Andrady, 2011). Visual identification with the aid of a magnifying glass and microscope (Leica, 6.3×–40×) allowed isolation of microplastics from organic material found in the range of 1–5 mm within each sample (Duncan et al., 2018). Suspected microplastics were picked out using tweezers and placed onto a glass fibre filter paper for further analysis.

2.3. Microplastic identification and classification

Filter papers were visually inspected under a microscope (Leica, 6.3×–40×) for suspected microplastic particles. The criteria reported by (Norén, 2007) were used for the identification of synthetic items in this study: microplastic has no cellular or organic structure and should be consistent in thickness with no taper towards the end. Additionally, the fibres should demonstrate a three-dimensional bending and be clear or homogeneously coloured (blue, black, red, yellow (Norén, 2007)). Suspected microplastics were classified into five types of user and industrial plastics in accordance with categories defined by (Van Franeker et al., 2011): (1) Industrial plastic pellets (IND) included any small cylindrical, granular, or spherically shaped pellets (known as nurdles, pellets, beads, or granules). User plastics (all non-industrial remains of plastic objects) cover the further four categories: (2) Foams (FOAM), which include synthetic foams, polystyrene, and foamed polyurethane in mattresses or construction foam. (3) Fragments (FRAG), degraded particles of hard macroplastics used in a large number of applications. (4) Sheetlike user plastics (SHE), broken down parts of plastics bags, sheets, and clingfilm. (5) Threadlike user plastics (THR), remains of ropes, nylon line, packaging straps, and clothing fibres.

Particles of large microplastic from each category were counted and the total amount in each category was weighed to nearest 0.0001 g for every sand sample. These measurements, in combination with the dry sand sample weight and volume, allowed multiple units of measure to be calculated. Plastic weight per kg of dry sediment (g kg^{-1}), plastic particle number per kg of dry sediment (particle kg^{-1}), plastic weight per m^{-3} of dry sediment (g m^{-3}), and plastic particle number per m^{-3} of dry sediment (particle m^{-3}).

2.4. Polymer identification

Suspected microplastic particles from a subsampled number of plastic contaminated beaches were analysed using a PerkinElmer Frontier Fourier-Transform Infrared (FTIR) spectrometer equipped with a universal diamond Attenuated Total Reflectance (ATR) attachment. Each suspected microplastic particle was manipulated using pre-cleaned forceps and placed onto the centre of the crystal surface (after pre-cleaning the surface with analytical grade ethanol), before applying a consistent force using the sample clamp. FTIR spectra (mid-infrared) were obtained for each suspected microplastic particle by scanning in the wave number range 4000–650 cm^{-1}, at a resolution of 4 cm^{-1}, and acquiring a minimum of four scans per item (up to a maximum of 16 scans per item for some samples in order to obtain clearer spectra). All spectra obtained were processed using PerkinElmer's Spectrum™ 10 software (version 10.5.4.738), enabling post-acquisition background subtraction and normalisation of the data and subsequent comparison against a number of commercially available spectral libraries covering polymers, polymer additives and adhesives (adhes.dlb, Atrpolym.dlb, ATRSPE~1.DLB, fibres.dlb, IntPoly.spl, poly1.dlb, polyadd1.dlb and POLYMER.DLB). When analysing the FTIR output, readings with confidence levels of 70 % or greater (Lusher et al., 2013) were considered a reliable specific spectral match. Those with a plastic polymer match of <70 % confidence were classified as unknown.

The selected beaches covered all five ocean basins in which suspected microplastics were found. For beach sand samples with a total plastic count of <50 (n = 54), all plastic particles were analysed. For those samples with a plastic count of >50 (n = 3), an adapted method was used where a total of 100 plastic particles were selected for identification. For each of these beaches, the microplastic type with the greatest particle number was identified and all particles were divided equally into numbered 2 mL vials. These vials were selected using a random number generator and particles within were sampled until a total of 50 particles had been sampled. A total of 50 particles were then sampled randomly from the remaining microplastic types and the sample number of each type was calculated as a proportion.

2.5. Quality assurance/quality control

During sample collection in the field, participants were instructed to use glass and metal equipment where possible to reduce contamination. Any larger pieces of plastic (>5 mm) were removed from the sand sample to avoid post-collection fragmentation during transport. However plastic bags were used for ease of international transport. To take this potential source of contamination into account, all sample bags were checked to ensure that were intact and only microplastics 1–5 mm were investigated.

In the laboratory, standard microplastic quality control procedures were employed. These included thorough cleaning of all work surfaces with Chemgene HLD4 wipes, all equipment thoroughly rinsed twice with Milli-Q, wearing of a cotton lab coat, and keeping samples covered using tin foil when not in use. As small fibres were not included in the larger microplastics (1–5 mm) analysis, no atmospheric contamination control was collected.

2.6. Statistical and mapping analyses

All data were analysed using Microsoft Excel (Microsoft Corporation, 2018) and the statistical software R (version 3.4.1, R Development Core Team, 2017). Data were tested for normality using a Shapiro-Wilk test and homogeneity of variance was assessed by using the Fligner-Killeen test.

Wilcoxon signed rank tests were used to assess the abundance of microplastics between the turtle nesting line and the strand line (for both particle number and weight). To integrate within-site variation, the plastic abundances of both the nest or strandline were averaged across the transect points, as the longshore plastic distribution will vary in different ways depending on a range of factors including orientation, geomorphology and prevailing currents and/or swells. A Kruskal Wallis test, with subsequent pairwise comparison using Dunn's post hoc test, was also used to compare the abundance of microplastics (both by weight and number) among ocean basins. A Pearson's Chi-squared test of contingency, with following Chi-squared post hoc test was used to assess differences in the relative presence/absence of microplastics across ocean basins. The significance level for all tests was set at $\alpha = 0.05$.

Microplastic abundance and spatial pattern was mapped in the spatial analysis software: QGIS (QGIS.org, 2021. QGIS Geographic Information System. QGIS Association). Geographical location of beaches sampled were provided as longitude and latitude (WGS1984). Land and coastline data were sourced from Natural Earth (https://www.naturalearthdata.com/).

3. Results

3.1. Overview

A total of 2062 sand samples from 209 turtle nesting beaches were gathered. For some beaches ($n = 8$) not all 10 samples were obtained due to beach topography preventing access to transect locations or damage during international transit ($n = 18$ transect samples across eight beaches). The 209 nesting beaches spanned 39 countries, six continents, and six ocean basins: the Indian Ocean ($n = 44$), North Atlantic ($n = 70$), South Atlantic ($n = 20$), North Pacific ($n = 28$), South Pacific (n = 8), and the Mediterranean ($n = 39$). Suspected microplastics were found in samples from 94 of the 209 (45 %) beaches (Fig. 1a; **Supplementary Table 1**).

3.2. Within beach variation

Values on the beach strandline showed more variation than those on the nest line in microplastic abundance by both weight (g kg $^{-1}$) and particle number (particles kg $^{-1}$), but there was no significant

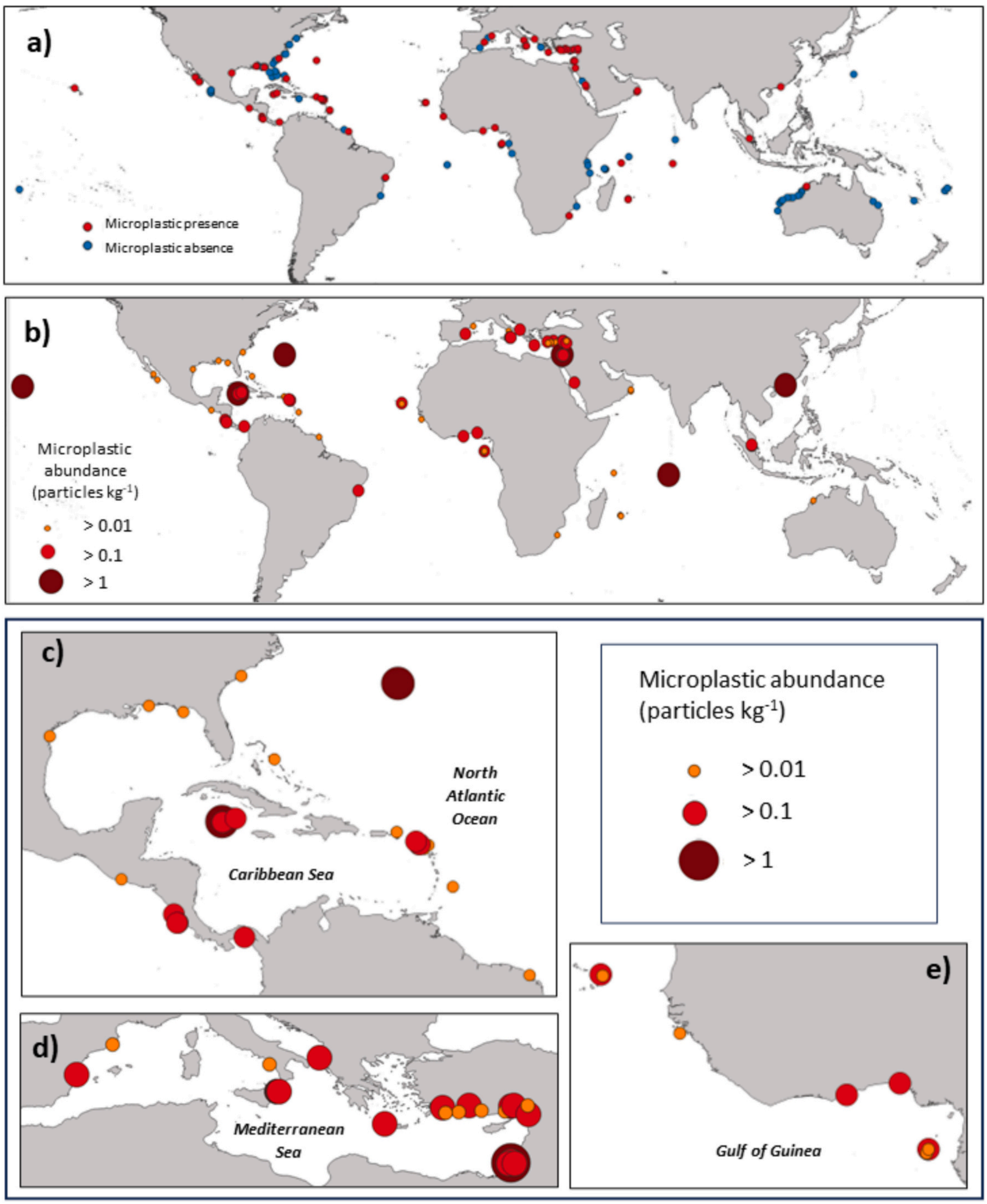


Fig. 1. a) Location of beaches ($n = 209$) with microplastic present (red, $n = 94$) and beaches with no microplastic found (blue, $n = 115$); **b)** Microplastic abundance by particle number (particles kg^{-1}); **c)** Microplastic abundance (particles kg^{-1}) within the Caribbean, North-West Atlantic and Central Pacific; **d)** Microplastic abundance (particles kg^{-1}) within the Mediterranean; **e)** Microplastic abundance (particles kg^{-1}) along central and west Africa. See **Supplementary Table 1**. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differences in the variances across the groups (Fligner-Killeen test, $X^2{}_{(1)} = 2.24$, $P = 0.13$ and $X^2{}_{(1)} = 1.52$, $P = 0.22$ respectively, (**Supplemental Fig. 2a**; Fig. 2b). However, whether samples were from the turtle nesting line or the strand line did not significantly affect the number of plastic particles (Wilcoxon signed-ranks, $W = 8695$, $P = 0.9$) or weight of plastic present (Wilcoxon signed-ranks, $W = 8093$, $P = 0.35$).

3.3. Spatial distribution and ocean basin variation

Suspected microplastics were found on 34.1 % of Indian Ocean beaches ($n = 15$), 79.5 % of Mediterranean beaches ($n = 31$), 42.9 % of North Atlantic beaches ($n = 30$), 39.2 % of North Pacific beaches (n = 11), 35 % of South Atlantic beaches (n = 7) and 0 % of South Pacific beaches ($n = 8$). Presence or absence of microplastics on a beach was found to vary significantly across oceans (Pearson's Chi-squared test of contingency, $\chi^2_{(5)} = 28.71$, $P = 2.6 \times 10^{-5}$) (Fig. 2a). Following a Chi-squared post hoc test, the Mediterranean was found to have significantly higher prevalence microplastics ($P < 0.0005$) in comparison to all other ocean basins.

There was a significant difference of microplastic weight (g kg^{-1}) between the ocean basins (Kruskal-Wallis test, $X^2_{(5)} = 26.5$, $P = 7.1 \times 10^{-5}$), (Fig. 2b). Pairwise comparisons using Dunn's test indicate that the Mediterranean beaches had significantly more plastic by weight, (g kg^{-1}) than all other oceans ($P < 0.05$), other than the North Pacific ($P = 0.06$). The number of plastic particles (particles kg^{-1}) also varied significantly across the ocean basins (Kruskal-Wallis test, $X^2_{(5)} = 25.1$, $P = 1.3 \times 10^{-4}$), (Fig. 2c). Pairwise comparisons using Dunn's test indicate that the Mediterranean again had significantly more microplastics by particle number than all other ocean basins ($P < 0.05$), except the North Pacific ($P = 0.059$).

The top five beaches for average microplastic abundance by weight were: Well Bay Beach, Bermuda (0.57 g kg^{-1}), Sham Wan, Hong Kong (0.19 g kg^{-1}), Index Beach, Diego Garcia, Chagos Archipelago (0.03 g kg^{-1}), Kahuku, Hawaii (0.02 g kg^{-1}), and Gdor, Israel (0.02 g kg^{-1}). The same beaches were also the top five for average abundance by particle number: Sham Wan (433.5 particles kg^{-1}), Well Bay Beach (63.3 particles kg^{-1}), Index 18.5 particles kg^{-1}), Gdor (3.9 particles kg^{-1}), and Kahuku (3.1 particles kg^{-1}). Four of the five locations with the highest abundances, were islands and had the highest microplastics abundances for the North Atlantic, North Pacific and Indian Ocean. Three of these locations are remote islands surrounded by an expanse of ocean (Bermuda, Hawaii, Chagos Archipelago).

3.4. Types of microplastics

A total of 15,430 particles from all five categories of microplastics (industrial, foam, fragment, sheet, and thread) were found on the turtle nesting beaches. Two beaches dominated: Sham Wan beach, Hong Kong, contained a total of 11,176 particles of foam weighing 3.392 g, and Well Bay beach, Bermuda contained a total of 2271 fragment particles weighing 20.638 g. Of the five categories, fragments contributed to most of the microplastic weight (25.99 g), followed by foam (4.06 g), industrial (3.08 g), thread (0.37 g) and sheet (0.33 g) plastics (**Supplemental Fig. 3a**). In comparison by particle number, foam contributed the most with 12,202 particles, then fragment (2812 particles), followed by industrial (167 particles), sheet (125 particles) and thread (124 particles) (**Supplemental Fig. 3b**). Despite removal of the two most contaminated beaches, Sham Wan and Well Bay, fragments still contributed the most weight (5.093 g) and foam was still the most numerous microplastic item found (1010 particles) (**Supplemental Fig. 3c & d**).

All five types of microplastics were identified within four of the ocean basins, with only industrial pellets and foam found in the South Atlantic. Between ocean basins, fragments were predominantly found within the North Atlantic and the Mediterranean (Fig. 3a). Whereas foam was most commonly found in the North Pacific and Indian Ocean (Fig. 3a). Industrial pellets were the most common microplastic type found in the South Atlantic, however there was a low number of microplastics identified.

3.5. Polymers identified

Analysis by FTIR spectroscopy on the subsampled isolated particles ($n = 562$) identified 88.3 % ($n = 496$) to be plastic polymers with a ≥ 70 % confidence. Of the remaining particles, 10.7 % ($n = 60$) had a very low FTIR confidence of <50 % and were considered unspecified, 1.1 % (n = 6) were not plastic polymers.

Spectral matches identified polyethylene (PE, $n = 242$) as the most common polymer, accounting for 48.8 % of the plastic particles, followed by polypropylene (PP) accounting for 26.2 % ($n = 130$) (Fig. 3). Other spectral matches identified the polymers polystyrene, polybutene, polydimethylsiloxane, polycyclohexylenedimethylene terephthalate as well as other ethylene derivatives. These were found to vary across particle type and ocean basin (Fig. 3).

Among the ocean basins, the greatest diversity of polymer types was found within the North Atlantic (Fig. 3**b**). Polyethylene was the most common polymer identified within the North Atlantic, South Atlantic and Mediterranean Sea. Whereas polystyrene was most commonly found within the Indian Ocean and North Pacific (Fig. 3b**)**.

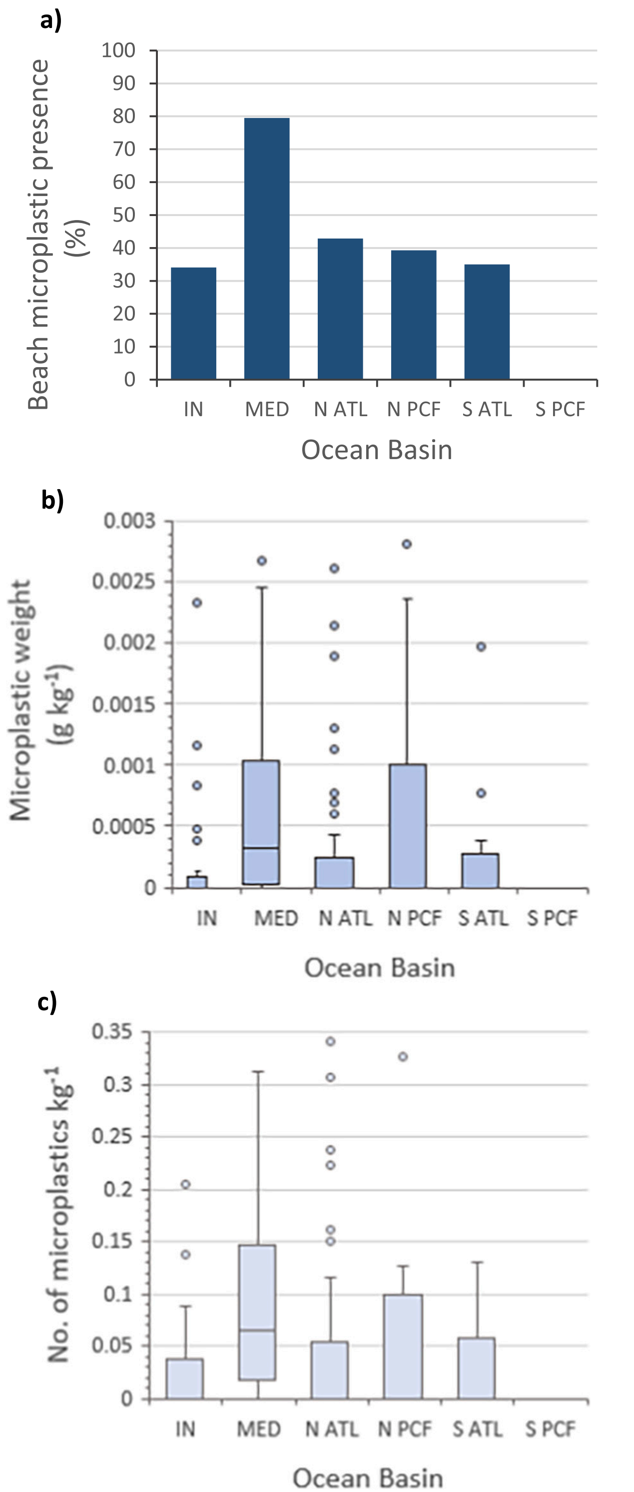
4. Discussion

This study is the first to investigate the abundance, composition, and spatial distributions of microplastics on turtle nesting beaches worldwide. Through effective mobilisation and collaboration between scientific professionals, we have generated important global baseline data with a simple methodology which is easily modified and could be further enhanced to develop and expand the dataset further.

4.1. Microplastic abundance and spatial distribution

We provide baseline microplastic concentrations for beach locations in each ocean basin and highlight that the Mediterranean had the highest average microplastic (1–5 mm) abundance. The identification of the Mediterranean, along with several island locations, as hotspots of microplastic debris is worthy of further investigation. Existing literature has reported high levels of microplastic pollution in the Mediterranean (Alomar et al., 2016; Cózar et al., 2014; Expósito et al., 2021; Lots et al., 2017). The Mediterranean is a confined ocean basin with limited currents, tides, and waves which may geographically trap microplastics. This coupled with high population density and source input contribute to concentrated microplastic pollution (Sharma et al., 2021). Mapping of microplastic pollution within this study suggests a higher abundance on beaches located towards the eastern basin, although further sample collection from the central and western Mediterranean would better clarify this. Previous studies have also concluded that the eastern basin has comparatively higher levels of microplastic than the rest of the Mediterranean. Additionally, beaches in Cyprus (eastern Mediterranean) have among the highest levels of microplastics thus far recorded globally (range: 637–131,939 particles m^{-3}) (Duncan et al., 2018). Oceanographic modelling showed the plastic particles identified in Duncan et al. (2018), also originated from the eastern basin, offering further validation to the robustness of the methodology and validity of Mediterranean microplastic variation found within this study (Duncan et al., 2018; Lots et al., 2017).

In addition to the Mediterranean, island locations were noted as microplastic hotspots. It is believed that oceanic movements around remote islands promote accumulation and trapping of microplastics as a result of their topography (Vogt-Vincent et al., 2023). Additionally, eddy systems that are generated by deep water islands are potentially responsible for concentrating and transporting microplastics (Brach



(caption on next column)

Fig. 2. Relative incidence of microplastics (1-5 mm) according to ocean basin IN = Indian (n = 44), MED = Mediterranean (n = 39), N ATL = North Atlantic (n = 70), S ATL = South Atlantic (n = 20), N PCF = North Pacific (n = 28), S PCF = South Pacific (n = 8). **a)** Percentage of beaches with microplastic present **b)** Box and whisker plots of the average microplastic weight on beaches in each ocean basin (Mean ± SD, IN =0.0009 ± 0.004 g kg^{-1}, MED = 0.001 ± 0.003 g kg^{-1}, N ATL = 0.009 ± 0.07 g kg^{-1}, N PCF =0.008 ± 0.04 g kg^{-1}, S ATL = 0.0003 ± 0.0008 g kg^{-1}, S PCF = 0 g kg^{-1}). Values >0.003 g kg^{-1} were not shown here but were included within statistical analysis (IN: n = 2, MED: n = 3, N ATL: n = 6, N PCF: n = 2, S ATL: n = 1). **c)** Box and whisker plots of the average number of microplastic particles on beaches (particles kg^{-1}), categorised by ocean basin (Mean ± SD, IN =0.5 ± 2.8 particles kg^{-1}, MED = 0.2 ± 0.6 particles kg^{-1}, N ATL = 1 ± 7.6 particles kg^{-1}, N PCF =15.6 ± 81.9 particles kg^{-1}, S ATL = 0.06 ± 0.1 particles kg^{-1}, S PCF = 0 particles kg^{-1}). Values >0.35 particles kg^{-1} were not shown here but were included within the statistical analysis (IN: n = 2, MED: n = 2, N ATL: n = 5, N PCF: n = 2, S ATL = 2).

et al., 2018; Laffoley et al., 2011; Piedeleu et al., 2009). This may explain why some remote oceanic islands such as the Chagos Archipelago, Bermuda, and Hawaii hold some of the highest microplastics abundances within this study. The identification of remote islands as microplastic hotspots is in alignment with several other local island studies that report high microplastic concentrations including the Galapagos Archipelago (range: 0–74.6 particles kg^{-1}, size: 1–5 mm; Jones et al., 2021) and Hawaii (range: 700–1700 particles m^{-2}, size: 500 µm-5 mm; Rey et al., 2021). Furthermore, remote island beaches are less likely to be cleaned in comparison to those that are easily accessible or are in tourist areas. This would naturally lead to a build-up of not just microplastics, but larger macroplastic items which can then fragment into microplastics (Barnes et al., 2009).

4.2. Microplastic characterisation

Understanding the global abundance and spatial distribution of microplastic characteristics is crucial for identifying their main sources and routes to the marine environment, as well as the threats they pose to marine ecosystems. The five types of microplastic sampled (Industrial pellets, Foam, Fragments, Sheet, and Threads) varied in their abundance depending on whether they were reported by particle weight or particle number which may be a result of physical property differences. These differences highlight why it is important to record microplastic abundance by both particle number and weight. Current modelling of microplastics within the marine environment has already demonstrated that physical properties of microplastics define their movement, distribution, residency time, and rate of biofouling within the ocean (Chubarenko et al., 2016; Fang et al., 2018). Some microplastics have high bio-fouling rates where their surface composition attracts an accumulation of microorganisms, plants and algae causing them to sink (Chubarenko et al., 2016). In comparison, other microplastics have low densities and reside at the sea surface where widely variable wind, weather and current systems are responsible for their movement (Critchell and Lambrechts, 2016).

The most abundant particle type found was foam (78 %), followed by fragments (16 %). Microplastics (1–5 mm) classed as foam, such as synthetic sponges and polystyrene, are lightweight and easily broken down therefore contribute greatly to microplastic particle numbers (Fok and Cheung, 2015). Foam type particles accounted for 99.1 % of microplastics found on Sham Wan beach in Hong Kong. This may be explained by the large-scale use of expanded polystyrene across Hong Kong and southern China, a foam plastic used for the transport of many different foods (Chan and Not, 2023; Fok and Cheung, 2015). Hong Kong has previously been reported to have the highest microplastic pollution on record with 92 % of microplastics found being classed as polystyrene (PS) (Fok and Cheung, 2015). Other studies assessing microplastic abundances on beaches have also reported fragments as

Fig. 3. a) Composition of large microplastic (1–5 mm) types by ocean basins. **b)** Composition of large microplastic (1–5 mm) polymers between oceans (IN = Indian, MED = Mediterranean, N ATL = North Atlantic, N PCF = North Pacific, S ATL = South Atlantic). PCT = Polycyclohexylenedimethylene terephthalate. **c)** Composition of large microplastic (1–5 mm) polymer by microplastic type (IND = Industrial plastic pellets, FOAM = Foams, FRAG = Fragments, SHE = Sheetlike plastics, THR = Threadlike plastics).

one of the most common types of microplastic found (Duncan et al., 2018; Novillo-Sanjuan et al., 2022; Zhang et al., 2022). This is unsurprising as hard plastics are the most commonly produced plastic items (Plastics Europe, 2022) and high concentrations of fragments would be consistent with the breakdown of larger plastic items that have been in the environment for an extended period of time.

Surprisingly, threads also known as fibres, were the least commonly found type of microplastic in our study. Previous research has highlighted fibres as the most prevalent anthropogenic particle identified not only within beach sediment samples (Bridson et al., 2020; Lots et al., 2017; Prata et al., 2020), but also other environmental samples, such as sea surface water (Botterell et al., 2022; Lindeque et al., 2020), water column (Bagaev et al., 2018; Vega-Moreno et al., 2021), and sea floor sediment (Cincinelli et al., 2021; Zhao et al., 2018). However, the lack of fibres found in our samples may be due to size of the microplastics (1–5 mm) we investigated, with the other studies including much smaller microplastics <1 mm. The smooth surface and high length to width ratio of fibres make them difficult to capture, as they can easily pass through sieve meshes (Rochman, 2015). A future addition and enhancement to our protocol would be to include the use of Sediment-Microplastic Isolation (SMI) units, which uses the principle of density floatation to extract microplastics from sediments (Coppock et al., 2017). In combination with rigorous contamination controls, the separated media could then be filtered over a fine mesh size to retain fibres but also smaller sized microplastics.

4.3. Microplastic polymer identification

Understanding specific polymer composition of microplastics and their relative spatial distributions further aids understanding of their origin, transportation, and ecological threat (Schwarz et al., 2019). The specific polymers reported in this study include polyolefins (PE, PP and PB), polyesters (PCT), polystyrenes (PS) and silicone-based plastic polymers (PDMS). Global data reports the polyolefins (PE and PP) to be the most abundantly produced plastic, accounting for 46.2 % of global plastic demand (PlasticsEurope, 2022). It is now agreed that PP and PE are some of the most pervasive and invasive pollutants in our marine environment (Erni-Cassola et al., 2019; Schwarz et al., 2019). Studies are beginning to report polymer specific toxicological effects of plastic particles. For example, polyolefins have been found to leach toxic chemicals, such as antimony and bromide compounds, and polyesters have shown release additives and toxic gases, such as methane (Hope et al., 2020). These act cumulatively and as a result, microplastics with properties that induce more effects, subsequently present a higher ecological threat within the marine environment (Pagter et al., 2018; Pellini et al., 2018). Furthermore, these particles will be detrimental in comparatively smaller quantities (Syberg et al., 2015). Past research has already called for more detailed characterisation of physical and chemical properties of microplastics (Abbott and Sumaila, 2019). Understanding the combinations of properties that may exist will improve scientific evaluation of their specific ecological threat (Everaert et al., 2020; Hope et al., 2020). Within the current literature there also is an absence of findings reporting spatial variation of marine plastic polymers. The results of this study therefore provide a unique insight into variation of specific plastic polymers across ocean basins. PE and PP show overall dominance across all oceans except the North Pacific where PS is most abundant. Particles of foam commonly have the chemical composition of PS which explains why the North Pacific showed similar high abundances when reporting foam and PS, especially for Hong Kong.

4.4. Within beach variation

In addition to understanding the composition, abundance, and spatial variation of microplastics on turtle nesting beaches globally, we investigated how these microplastics are distributed across the nesting beaches. Our study found no significant variation between microplastic abundance and nest/strandline across the 209 beaches. This may be because there was limited topographical variation among the beaches in this study and biophysical and morphological elements, such as beach width, length, and slope, are thought to influence nesting preferences of marine turtles. Turtle nesting beaches are therefore less likely to be diverse in their general topography than non-nesting beaches (Yamamoto et al., 2012). A future consideration may be to consider geomorphology of beaches and whether sand is being sampled from a long sandy coastline or a discrete bay or pocket beach.

4.5. Implications for marine turtles

The lack of variation in microplastic abundance found between the strandline, an area often surveyed in marine debris surveys, and the turtle nesting line in this study suggest microplastic abundance has similar prevalence around turtle nests. The pollution levels found on sampled beaches within this study do not appear to be of immediate conservation threat in comparison to direct and indirect anthropogenic take, predation by domestic and invasive species, sex ratio change and reduced nesting success resulting from global climate change (Fuentes et al., 2023a, 2023b; Rees et al., 2016). However, beach sediments are now thought to act as microplastic sinks for wider oceans and levels of beach microplastics are only likely to increase (Barnes et al., 2009). A recent study by Sousa-Guedes et al. (2022) showed that under a high density of plastic debris (5 cm in size, average of 128 pieces/49 g per nest) there was a decrease in the emergence success of hatchlings and the synchronized emergence was affected, with more scattered and smaller groups emerging. Synchronized and larger group emergence increases the individual chance of survival, by reducing predation risk (Martins et al., 2021; Tucker et al., 2008). Whilst the exact mechanism for this impact is unknown, it has been hypothesised that the effects seen may be due to the plastics changing the substrate humidity and water holding capacity which when high may lead to fungal growth (Gleason et al., 2020) and when low, may lead to desiccation of the eggs (Carson et al., 2011). It could also be due to mechanical effects, whereby hatchlings heavily depend on the direct physical contact to stimulate final emergence (Sousa-Guedes et al., 2022). Crucially, in this study we are already reporting microplastics abundances on turtle nesting beaches above the high-density level reported by Sousa-Guedes et al. (2022). Whilst it remains unclear what abundance of smaller plastic debris would be required to elicit the same effect; it is evident that microplastics pollution within beach sediments is only going to increase.

The growing evidence reporting detrimental effects from microplastic exposure on all turtle life stages highlights the need to continue global monitoring of microplastic abundances on nesting beaches, while also expanding the dataset by employing the uniform methodology to further nesting beaches. Additional development of this study to include a nest depth sampling methodology would provide a more representative idea of the distribution of actual microplastic abundances at nest depth (Duncan et al., 2018). Further experimental studies investigating nest environments under experimentally controlled microplastic densities are required to better understand the impacts of microplastic pollution, such as toxicology and desiccation (Beckwith and Fuentes, 2018; Duncan et al., 2018; Fuentes et al., 2023a, 2023b).

4.6. Call for standardisation

Our method utilised a simple and low-cost beach sampling protocol, with visual identification of microplastics in combination with FTIR analysis, on a subset of suspected microplastics. Whilst FTIR analysis is costly, requires training and sample processing at a suitable facility, it is now becoming a minimum requirement for publication of microplastic research (STOTEN, 2024). This methodology has enabled the global spatial quantification of beach microplastics. Comparative studies are crucial to better understand the increasing abundance and global spatial distribution of microplastics, however, this requires standardisation within the field (Duncan et al., 2018). Comprehensive comparisons between studies are currently limited due to the range of methodologies, units reported, and particle size ranges employed in the literature (Bridson et al., 2020). For example, we are currently unable to rank beaches, ocean basins and countries by the numerical extent of their microplastic concentration because at least seven different units of measurement have been used during beach sediment sampling (Duncan et al., 2018).

Disparity across all areas of methodology and units creates quantitative study divergence, which further amplifies the inter-study variance in reported values of microplastic abundance. To avoid inter-study variability, methodologies should elaborate on how they avoided site selection bias which may consist of state of tide at time of sampling, recent weather conditions, beach morphology, and prior prevailing wind, and wave direction (Bosker et al., 2018; Dharmadasa et al., 2021; Prata et al., 2020; Wilson et al., 2021). The inclusion of various measurements of sand and microplastics within samples provide an ability for dynamic change or development to reported units, which facilitates future dataset expansion. The current international dataset presented has also established the first clear and robust scale for beach microplastic abundance, allowing individual locations to be ranked by the level of pollution present.

4.7. Future work

The addition of more beach samples to our baseline dataset is essential to the further spatial understanding of global microplastic distribution. Areas identified as devoid of data, for example coastal areas of the South Atlantic or South Pacific should be prioritised to ensure the dataset is fully representative and capable of monitoring global microplastic pollution and the effects of any mitigation efforts. It would be beneficial to increase the volume of sand sampled to increase our detection threshold. Our current methodology detects microplastics (1–5 mm) when they are present at high concentrations. It is very possible that we have missing values especially on beaches that may have low microplastic abundances. This combined with sand being subject to sieving in situ, would greatly enhance the ability of a greater number of teams being engaged in the study, with larger sand volumes being processed. Contamination from very small microfibres (<1 mm) poses a constant challenge when conducting environmental microplastic fieldwork especially when assessing microplastics from the smallest size ranges (1 μm-1 mm). The addition of contamination controls during the collection and processing phases would allow for analysis of smaller microplastics (<1 mm) and provide further insights into microplastic characteristics, their abundance and distribution. Initial work looking at sand from a subsample of sites found small microplastics to be ubiquitous. We did not present them here as without contamination control, it was inconclusive as to their origin.

Collaboration between individuals and projects within an international scientific community has been of paramount importance in generating the dataset presented within this study. This could not have been achieved individually within a similar study period and emphasises the power of collaborative work. The method in this study offers further opportunities for microplastic quantification research. Available temporal studies are currently limited. However, if this study is repeated over time intervals, in previously sampled areas, it is possible to initiate a global temporal monitoring program and aid our understanding of microplastic movements (Ryan et al., 2009). It would also highlight possible seasonal trends that would not be recognised within this study at this time. The continued monitoring of microplastic concentrations found at field sites, combined with a better understanding of plastic inputs into the environment will help to develop more accurate future microplastic concentrations, which is essential for the development of effective risk assessments (Botterell et al., 2023).

5. Conclusion

In summary, this study has shown that 45 % ($n = 209$) of global turtle nesting beaches had microplastics 1–5 mm in size present. The Mediterranean was the most contaminated ocean basin and based on limited sampling, the South Pacific was least affected. Additionally, some remote island beach locations were also identified as microplastic hotspots. The predominant microplastic types identified were foam and fragments, with polyethylene being the most common polymer identified by FTIR analysis. Through collaboration with the international marine turtle conservation community, this investigation has effectively established a dataset for microplastics (1–5 mm) that is globally comparable. Monitoring and further investigation of larger sample sizes could improve the completeness of our global knowledge of microplastics and guide the regulation of widespread pollution.

CRediT authorship contribution statement

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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.2025.117768.

Data availability

Data will be available open access through the BODC data repository link: https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/2d63df35-b445-7964-e063-55d1a68be8a3.

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