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Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean

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ABSTRACT

Microplastics in the world's oceans are a global concern due to the potential threat they pose to marine organisms. This study investigated microplastic abundance, distribution and composition in the Atlantic Ocean on a transect from the Bay of Biscay to Cape Town, South Africa. Microplastics were sampled from sub-surface waters using the underway system of the RV *Polarstern*. Potential microplastics were isolated from samples and FT-IR spectroscopy was used to identify polymer types. Of the particles analysed, 63% were rayon and 37% were synthetic polymers. The majority of microplastics were identified as polyesters (49%) and blends of polyamide or acrylic/polyester (43%). Overall, fibres (94%) were predominant. Average microplastic abundance in the Atlantic Ocean was 1.15 ± 1.45 particles m^{-3}. Of the 76 samples, 14 were from the Benguela upwelling and there was no statistically significant difference in microplastic abundance between upwelled and non-upwelled sites.
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1. Introduction

Within the past decade, microplastics in the world's oceans have emerged as an issue of global importance (UNEP, 2011). Concern regarding these particles stems from their ubiquity, persistence and the potential threat they pose to marine organisms. The gravity of the situation is compounded by the fact that even if the introduction of plastic debris to the marine environment were to be halted, microplastic abundances are projected to increase as a result of the fragmentation of plastics that are already in the world's oceans (Thompson, 2015).

Global concern about microplastics, i.e. plastic particles < 5 mm in diameter (Arthur et al., 2009), has prompted numerous investigations regarding this type of marine debris. Microplastics have been discovered in oceanic waters, deep sea sediments, sea ice and marine organisms (Lusher, 2015). Studies that investigated microplastics in surface and sub-surface waters of the world's oceans found that microplastic abundance was highest in the convergence zones of the five sub-tropical gyres which are regarded as biological deserts due to their low levels of marine biodiversity (Cozar et al., 2014; Polovina et al., 2008).

Even though information exists regarding microplastics in the world's oceans, a greater understanding of microplastic abundances in biota rich waters is particularly important due to the enhanced possibilities for interactions between microplastics and organisms (Cole et al., 2015). Areas which experience coastal upwelling sustain high primary productivity and it is this enhanced productivity which supports more complex food webs comprising biota from a range of trophic levels. Coastal upwelling in the Atlantic Ocean occurs primarily at the (i) Canary Upwelling Ecosystem (CUE) which is comprised of three zones (12–19°N, 21–26°N, 26–35°N) and, (ii) Benguela Upwelling Ecosystem (BUE) which stretches from the southern tip of Africa to approximately 15°S where it is bounded by the Angola front (Santos et al., 2012; Cropper et al., 2014).

Effectively addressing the issue of microplastics in the marine environment requires information on the abundance, distribution and composition of microplastics in the world's oceans. Information from the natural environment is particularly important as it (i) provides an indication of the extent of the problem and, (ii) informs laboratory studies by providing data on the environmentally relevant concentrations of microplastics that biota are exposed to in the natural environment. More specifically, information about microplastics at coastal upwelling sites in the Atlantic Ocean is particularly important as it could provide (i) an indication of the probability of encounter between organisms and microplastics at such sites and, (ii) insight into the potential effect of oceanographic phenomena such as upwelling on microplastics in the world's oceans. The present study investigated microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. The specific aim was to determine whether microplastic abundance in upwelled areas were significantly different from non-upwelled areas.

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2. Materials and method

2.1. Sample collection

This study was conducted onboard the RV *Polarstern* during Expedition PS95 and covered 7345 nautical miles (13,603 km) between Bremerhaven, Germany and Cape Town, South Africa. Sub-surface oceanic waters pumped onboard the vessel via the underway system were sampled for microplastics using the method described by Lusher et al. (2014). Sampling was conducted during November 2015 (1st to 28th) at vessel speeds of between 8 and 13 knots. Since each sample constituted the filtration of 2000 L of water (Lusher et al., 2014), the survey effort for this study was 152,000 L of water (76 samples).

Seawater from a continuous intake located at the keel of the ship (depth 11 m) was pumped onboard the vessel using a Klaus Union Sealex Centrifugal Pump (Bochum, Germany) at a flow rate of 25 m^3/h and transported to the laboratory via stainless steel pipes. Prior to reaching the laboratory, the seawater passed through a primary filter (pore size 2 mm) to remove large debris items. The inclusion of this primary filter was standard operating procedure onboard the vessel and thus was beyond the control of the investigator. Potential contamination of the seawater intake by waste water generated onboard did not occur since grey water from the vessel was stored onboard for subsequent treatment. In the laboratory, seawater from the vessel's underway system was allowed to flow through a covered stainless steel sieve (250 μm) by means of a connection hose fitted into a wooden sieve cover. For the duration of the sampling, the stainless steel sieve was supported in a wooden stand. For each sample, 2000 L of water was filtered. The length of time taken for the filtration of the specified volume of water was determined by calculation of the flow rate of the seawater. Once the specified volume of water was filtered, the sieve was removed and distilled water used to wash retained material from the sieve into a clean container. The collected material was then filtered under vacuum onto glass microfiber paper (GF/C); Whatman: 47 mm, pore size: 1.2 μm, using a Buchner funnel and a vacuum flask (Lusher et al., 2014). Each filter paper was then placed into a clean petri dish, covered and stored in a freezer (−20 °C) until returned to the laboratory. At the start and at the end of each sample, positioning data were collected. Data for various environmental variables were obtained from the vessel's (i) thermosalinometer-keel (water temperature, salinity, conductivity), (ii) ferrybox (chlorophyll *a* and pH), and (iii) weather station (wind speed, wind direction).

2.2. Method validation and contamination prevention

Method blanks and controls were used to determine whether there was any contamination during sample processing. Clean petri dishes and filter paper were left exposed to the air during vacuum filtration to determine if there was any airborne contamination. To determine whether there was any additional contamination during vacuum filtering, distilled water was passed through clean GF/C filter paper under vacuum. During visual identification of potential microplastics in samples, checks were also made for airborne contamination by exposing a clean petri dish and filter paper to the air. In order to prevent contamination in the laboratory, the following measures were taken (i) lab coats, cotton clothing and gloves were worn during sample processing, (ii) a wooden cover was placed over the stainless steel sieve to prevent airborne contamination, and (iii) all containers used during sample processing were covered and cleaned using distilled water before reuse (Lusher et al., 2014).

2.3. Laboratory analyses

Samples were removed from the freezer and left to dry. Individual filter papers were then visually examined under a dissecting microscope (Olympus SZX10) equipped with a polariser and camera (Q Imaging Retiga 2000R). Potential microplastics were identified based on characteristic features such as (i) colour- homogenous colour, shininess, unnatural colours, (ii) thickness-fibres homogenous in thickness and, (iii) bending-fibres demonstrated three dimensional bending. Potential microplastics from each sample were photographed and length measurements were taken prior to transferring to a clean filter paper. Filter papers with potential microplastics from each sample were stored in clean, labelled petri dishes. Potential microplastics were assigned to two broad categories (fibres, fragments) and to five length categories: 0.25–0.5 mm, 0.5–0.75 mm, 0.75–1.0 mm, 1.0–2.0 mm, 2.0–5.0 mm.

All potential microplastics as well as a subset of particles not considered to be microplastics ($n = 499$) were analysed by Fourier transform infrared (FT-IR) spectroscopy on a Bruker Vertex 70 Infrared Spectrometer coupled to a Hyperion 1000 microscope. The instrument was equipped with a potassium bromide (KBr) beamsplitter and an internal mercury cadmium telluride (MCT) detector. Microscope-transmission sampling was performed using a Specac DC-2 Diamond Compression cell. Spectra were recorded as the average of 32 scans in the spectral wave number range of 4000–600 cm^{-1} at a resolution of 4 cm^{-1} (Blackman-Harris 3-term apodisation). Bruker's Opus 7.5 spectroscopy software was used for processing and evaluating all spectra. Prior to analysing each sample, background scans were performed and sample spectra were automatically corrected. Each sample spectrum was compared with those of known standard polymers in the (i) Bruker Optics Attenuated Total Reflectance (ATR) Polymer and (ii) Synthetic Fibres ATR libraries. An initial hit quality with a score ranging between 0 and 1000 was produced for each match between sample and reference spectra, with the highest score representing the closest match. Following this preliminary matching, the top ten matches for each sample spectrum were then further evaluated using the Quick Identity Test/Euclidean Distance (ED) option. A hit quality ranging between 0 and 2 was produced for each match between the sample spectrum and the reference spectra, with the lowest number representing the closest match. Overall, matches with >70% similarity were accepted while those with 60–70% similarity were individually examined to ensure that there was clear evidence of peaks from the sample corresponding to known peaks of standard polymers. Samples which produced spectra with a match <60% were automatically rejected.

2.4. Statistical analyses

All statistical analyses were performed using R version 3.2.3 (R Core Team, 2015). Descriptive statistics, histograms and box plots were generated and tests of normality (Supplementary Table 1) were conducted on all data sets to determine whether parametric or non-parametric statistical analyses were appropriate. Univariate (Kruskal Wallis test) and multivariate (Principal Component Analysis) analyses were conducted to determine whether sampling occurred in the Benguela and Canary Upwelling Ecosystems. Correlation analyses were performed to determine whether there were any correlations between individual environmental variables and microplastic abundance. A generalized additive model (GAM) was also developed to determine which environmental variables had an effect on microplastic abundance.

3. Results

3.1. Quality control

Microplastics were not found in the (i) air contamination controls set up during sample collection ($n = 4$), (ii) method blanks set up during vacuum filtration of distilled water ($n = 8$), and (iii) air contamination controls set up during visual identification ($n = 76$). This indicates that microplastics were not introduced into the samples either as a result of airborne contamination or as a result of contamination during the vacuum filtration process. Airborne contamination by microplastics

during the filtration of each sample was prevented by the use of a wooden cover over the stainless steel sieve.

3.2. Confirmation of sampling in upwelling ecosystems

Kruskall Wallis tests indicated that there were statistically significant differences in both water temperature (Kruskal-Wallis chi-squared = 16.599, df = 2, p-value = 0.0002) and chlorophyll a concentrations (Kruskal-Wallis chi-squared = 28.086, df = 2, p-value = 7.967e−07) amongst non-upwelled sites, Canary upwelling sites and Benguela upwelling sites. Post hoc tests indicated that there were statistically significant differences in water temperature and chlorophyll a concentrations between (i) non-upwelled sites and Benguela upwelling sites (water temperature: Nemenyi test-p value = 0.0026, Dunn's test-p value = 0.0011; chlorophyll: Nemenyi test-p value = 0.0003, Dunn's test-p value = 4.1e−07) and, (ii) between Canary upwelling sites and Benguela upwelling sites (water temperature: Nemenyi test-p value = 0.0005, Dunn's test-p value = 0.0003; chlorophyll: Nemenyi test-p value = 0.0005, Dunn's test-p value = 9.3e−07). The fact that the Benguela upwelling sites exhibited water temperatures that were significantly lower than those of all other sites and chlorophyll a concentrations that were significantly higher than those of all other sites suggests that sampling in this study occurred within the Benguela upwelling ecosystem. However, the same cannot be said for the Canary upwelling ecosystem.

Multivariate analyses were also utilised to confirm whether sampling occurred within upwelling ecosystems in the Atlantic Ocean. PCA conducted on available data (n = 76) revealed that principal components 1 (PC1), 2 (PC2) and 3 (PC3) accounted for 84.48% of the variation. Eigenvectors indicated that PC1 was governed by increasing temperature (0.601), decreasing chlorophyll (−0.595) and decreasing wind speed (−0.519), PC2 was governed by decreasing salinity (−0.719) and PC3 was governed by increasing pH (0.803). The biplot (Fig. 1) revealed that while the majority of sites were located towards the middle of the plot, there were a few distinct groups of sites. Of importance is the group of sites located in the upper left quadrant of the biplot characterised by low water temperatures, high chlorophyll a concentrations, high wind speeds and low salinities. Since the majority of these sites were located within the region where the Benguela upwelling was expected to occur (i.e. from the southern tip of Africa to 15°S) and certain features (low water temperatures, high chlorophyll concentrations) could be attributed to the phenomenon of upwelling, these sites were henceforth referred to as 'upwelling sites'.

3.3. Overview of findings

Of the 499 particles analysed by FT-IR spectroscopy, 37% were confirmed as synthetic polymers (n = 183) and 63% as Rayon (n = 316). The majority (96%) of synthetic polymers were <5 mm in length (Fig. 2) and thus were considered as microplastics (n = 175), with only a small percentage (4%) of synthetic polymers >5 mm in length; all fragments were <1 mm in length. The majority of the microplastics were fibres (n = 165) with only a few fragments (n = 10) while the Rayon particles were solely fibres. Seventy-two percent of the microplastics were blue, 9% were transparent, 8% were pink and 11% were comprised of other colours such as purple, brown, red, green, grey, black, yellow and white (Fig. 3). Microplastic polymer types included polyester (n = 86), blends (n = 76), polyamide (n = 4), polypropylene (n = 3), acrylic (n = 2), polyvinyl chloride (n = 2), polystyrene (n = 1) and polyurethane (n = 1). The overall category

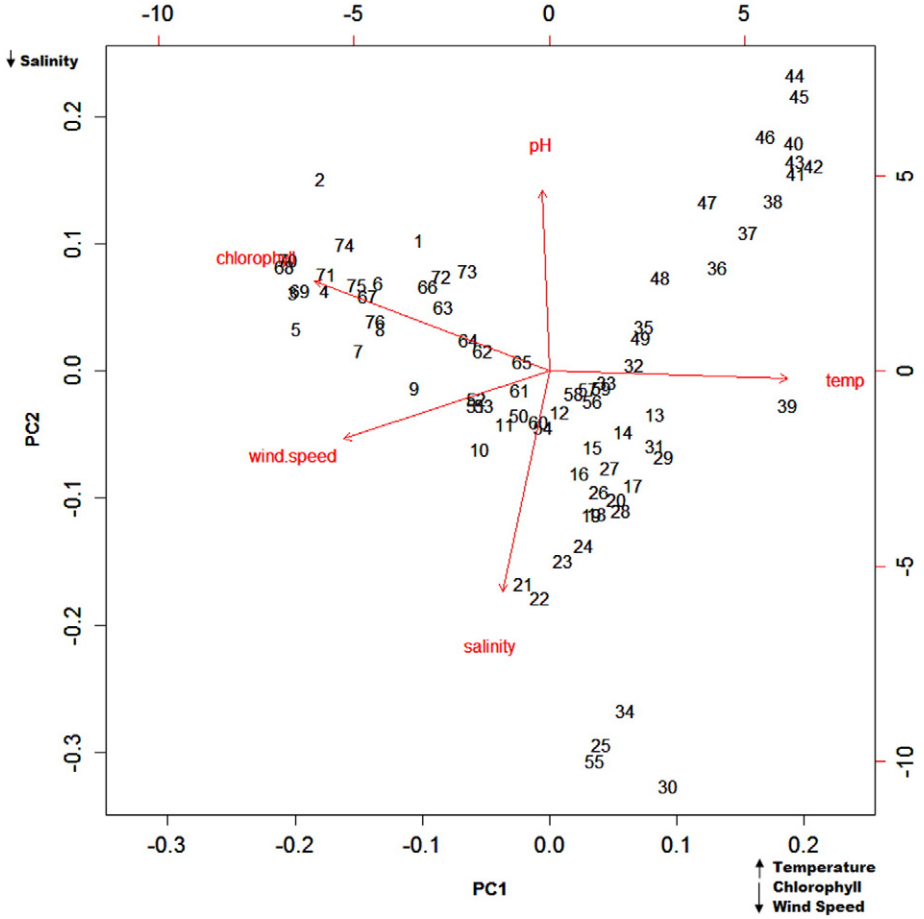

Fig. 1. Biplot showing sampling sites based on environmental variables.

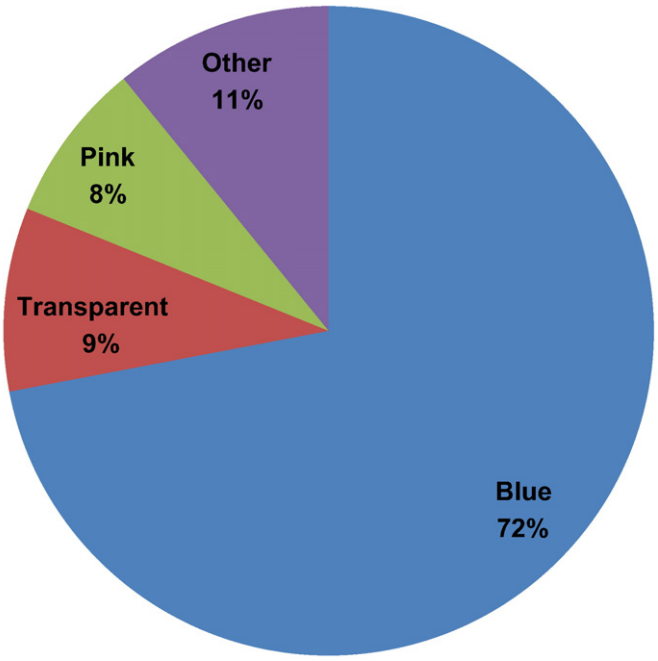

Fig. 2. Colours of confirmed microplastics.

of polyester also included particles identified as polyethylene terephthalate (PET), ($n = 18$). Particles identified as blends were either polyamide blends or acrylic/polyester blends and the polyamides were comprised of specific polymers such as nylon and Kevlar.

3.4. Microplastic abundance and distribution in the Atlantic Ocean

Microplastic abundance along the North/South latitudinal gradient in the Atlantic Ocean ranged from 0 to 8.5 particles m^{-3} (Fig. 4). For the majority of sampling sites, microplastic abundance ranged between 0 and 2.5 particles m^{-3}. However, the areas where this range was exceeded included (i) offshore of Namibia (8.5 particles m^{-3}), (ii) off the west coast of Morocco (6–6.5 particles m^{-3}), (iii) the Bay of Biscay (3.5 particles m^{-3}), and (iv) off the western coast of Portugal (3.5 particles m^{-3}). A Mann-Whitney Wilcoxon test indicated that there was no statistically significant difference (Wilcoxon rank sum test p-value $= 0.7111$) in microplastic abundance between the Benguela upwelling sites and all other sites considered as non-upwelled sites (Fig. 5).

3.5. Influence of environmental variables on microplastic abundance

Correlation analyses were conducted to determine whether environmental variables influenced microplastic abundance. Overall, there were no statistically significant correlations between microplastic abundance and: chlorophyll, pH, salinity and wind speed (Supplementary Table 1). However, there was a statistically significant weak negative correlation between microplastic abundance and: sub-surface water temperature (Spearman's rank correlation, rho $= -0.25$, p-value $= 0.03$); and conductivity (Spearman's rank correlation, rho $= -0.27$, p-value $= 0.02$).

A generalized additive model (GAM) was developed to further determine the influence of environmental variables on microplastic abundance. In this model, the response variable was microplastic count (number of microplastics per sample) and initial explanatory variables included location (latitude, longitude), physico-chemical properties associated with sub-surface waters (temperature, pH, salinity), chlorophyll *a* concentration, weather data (wind direction, wind speed), presence of upwelling and duration of filtration. In the model, (i) the Poisson family distribution of error terms was specified with a log link function due to the fact that microplastic abundance data was count data, and (ii) the explanatory variable water temperature was included as the difference between the highest and lowest water temperature recorded during sample collection (Δ water temperature). The output of the initial model was examined and based on this non-parametric smoothers (s) were applied to all explanatory variables except latitude, temperature, wind speed and upwelling. Non-significant explanatory variables (as evidenced by their p-values) were eliminated in a stepwise manner until a GAM with the lowest Akaike Information Criterion (AIC) score (283.334) and the fewest explanatory variables was obtained. The final GAM (R-sq $= 0.548$) was as shown below:

$$\text{Microplastic count} \sim \textbf{latitude} + s(\textbf{longitude}) + \textbf{Δwater temperature} + +s(\textbf{wind direction}) + \textbf{wind speed} + \text{upwelling} + s(\textbf{salinity})$$

Of the explanatory variables that were present in the final model, latitude, longitude, water temperature, wind direction, wind speed and salinity were the six variables found to have a significant effect on the abundance of microplastics in the Atlantic Ocean (Table 1).

4. Discussion

Interactions between microplastics and marine organisms are of particular interest due to the potential negative effects that this category of anthropogenic debris may have on marine organisms. The assessment of microplastic abundance in 'biota rich' waters is therefore

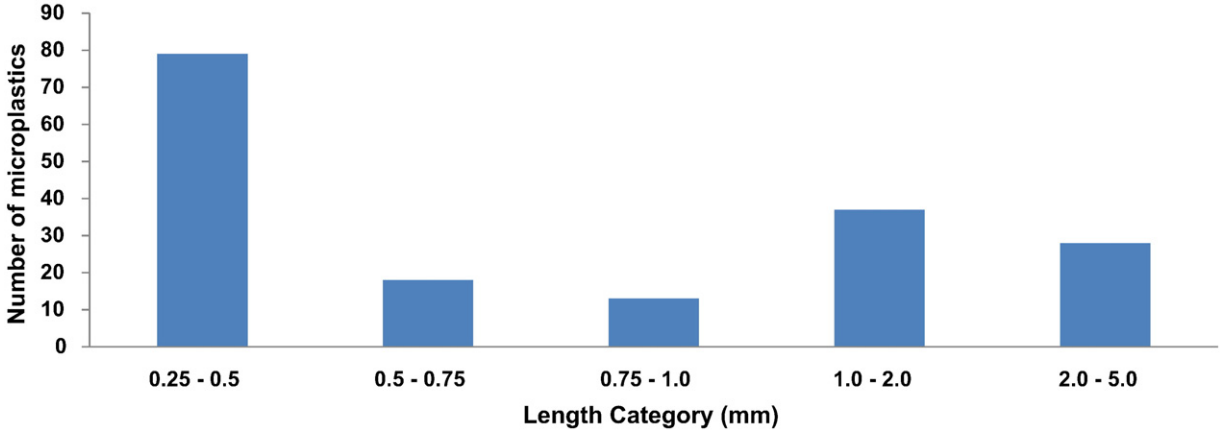

Fig. 3. Lengths of confirmed microplastics.

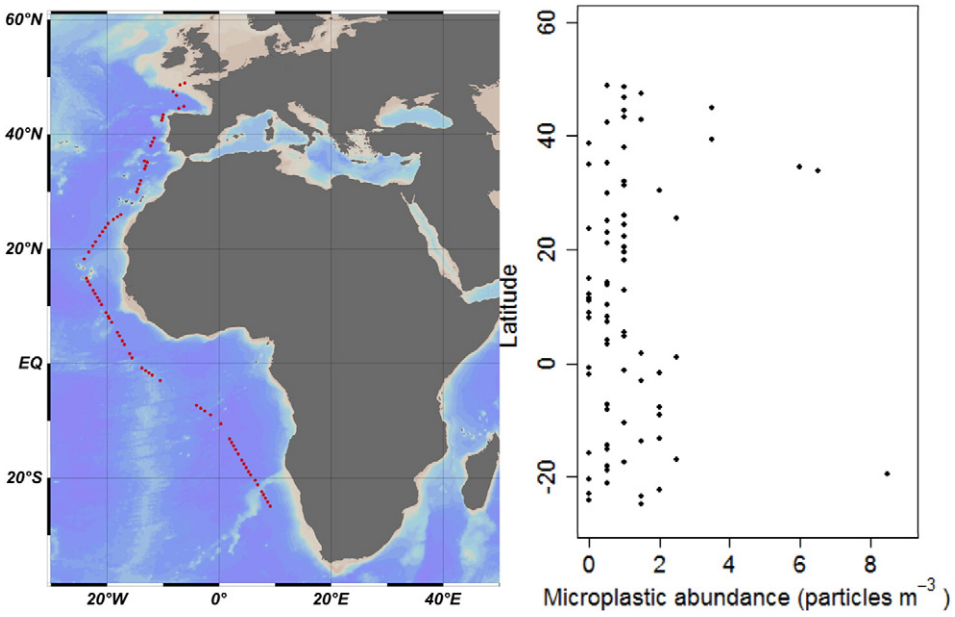

Fig. 4. Map of sampling locations and microplastic abundance along the north/south transect in the Atlantic Ocean.

particularly important due to the potential that exists for enhanced interactions between these particles and abundant biota at such sites. Along the western coast of Africa, there were two areas considered 'biota rich' of specific interest: Canary Upwelling Ecosystem (CUE) and the Benguela Upwelling Ecosystem (BUE). The present study availed of a platform of opportunity aboard a research vessel transit; consequently the investigators had no influence over the vessel's track. Both univariate and multivariate analyses indicated that although the Benguela upwelling was definitely sampled, the same could not be said for the Canary upwelling. This was possibly due to the fact that in the region where the Canary upwelling was expected to occur, the research vessel was too far offshore from the African continent. The present study found that there were no statistically significant differences between microplastic abundance in upwelled and non-upwelled areas in the Atlantic Ocean. Previous studies had suggested that upwelling may (i) provide a source of deepwater with relatively low levels of microplastics and, (ii) lead to a dilution of plastics in surface waters thus resulting in lower plastic abundances at sites within close proximity to such oceanic phenomena (Desforges et al., 2014; de Lucia et al., 2014). The findings of the present study must be taken in the context that only 14 of the 76 samples for microplastics were taken in the Benguela upwelling. More definitive statements about the microplastic abundance at upwelling regions in the Atlantic Ocean can only be made if more intensive sampling is conducted in such regions in the future.

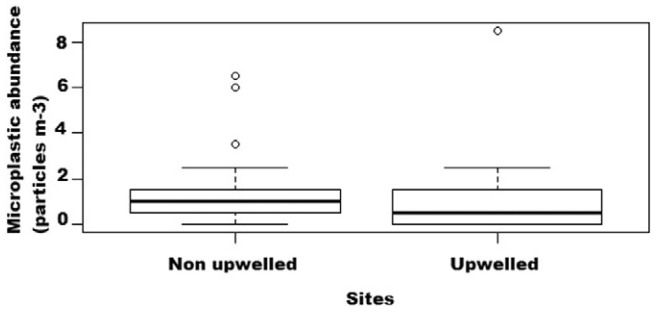

Fig. 5. Comparison of microplastic abundances at upwelled and non-upwelled sites in the Atlantic Ocean.

In certain respects, the composition of microplastics along the North/South Atlantic transect was comparable to that found in other marine environments across the world. The predominance of fibrous microplastics noted in this study was consistent with similar previous findings in both surface and sub-surface waters (Cole et al., 2014; Desforges et al., 2014; Lusher et al., 2014; Zhao et al., 2014; Enders et al., 2015; Lusher et al., 2015). It has been suggested that an important source of microplastic fibres in the environment may be from the washing of clothes, with laboratory experiments demonstrating that a single garment may potentially produce >1900 fibres per wash (Browne et al., 2011) and an average 6 kg load of acrylic fabric could release over 700,000 fibres (Napper and Thompson, 2016). While fibres may in fact be more dominant in the natural environment, it is important to note that as a category of microplastics, they are generally more discernible than other categories of microplastics. Fragments, for example, have a higher chance of being disregarded due to their similarity in appearance to natural materials. Cole et al. (2014) suggests the presence of an 'operator selection bias' towards fibrous microplastics.

Analytical techniques such as FT-IR spectroscopy are immensely useful in microplastic studies as they confirm whether particles from environmental samples are indeed synthetic and, if so, identify the polymer type. In this present study, the major polymer types included polyester (50%) and blends that were either polyamide or acrylic/polyester (42%) with a minority (8%) of acrylic, polyamide, polypropylene, polyvinyl chloride, polystyrene and polyurethane. While previous studies have reported the presence of similar polymer types in their samples, low density polymers such as polyethylene and polypropylene were not as abundant in this study when compared to other studies which sampled microplastics in surface waters or even from shallower sub-

Table 1
Explanatory variables included in the final best fit GAM.

Explanatory variables	*p* value
Wind Direction	9.12e−09
Δ Temperature	9.25e−05
Latitude	5.23e−05
Wind Velocity	0.000333
Longitude	0.008280
Salinity	0.014380
Upwelling	0.050666

surface depths (Hidalgo-Ruz et al., 2012; Cole et al., 2014; Obbard et al., 2014; Frias et al., 2014; Enders et al., 2015; Lusher et al., 2015; Kang et al., 2015a; Woodall et al., 2015). This raises the question as to whether sampling depth within the water column influences microplastic composition due to differences in the densities and buoyancies of particular polymer types (Cole et al., 2013; Desforges et al., 2014; Woodall et al., 2015). Although techniques such as FT-IR spectroscopy can identify polymers, this information does not allow the investigator to pinpoint the exact origin of the polymers in the environment but instead reduces the possibilities (Claessens et al., 2011; Desforges et al., 2014). The synthetic polymers that were found in this study may have been derived from clothing, ropes, fishing gear (nets, lines, etc), plastic beverage bottles, as well as packaging materials (Smith, 1999; Andrady, 2011; Claessens et al., 2011; Napper and Thompson, 2016).

In the quest to assess microplastic abundance and composition in the marine environment, one of the issues that has emerged is the prevalence of rayon fibres in the environment. Rayon is essentially regenerated cellulosic material, it is man-made and is therefore considered as semi-synthetic (Mishra, 2010). In addition to being used in textiles, rayon has also been used in cigarette filters and personal hygiene products (Woodall et al., 2015). This study found that 63% of the particles analysed by FT-IR spectroscopy were rayon fibres. Previous studies have also reported that rayon fibres were the most prevalent synthetic microparticle in (i) fish from the English Channel (58%), (Lusher et al., 2013), (ii) surface and sub-surface waters in the Arctic Ocean (30%), (Lusher et al., 2015), (iii) sea ice cores from the Arctic Ocean (54%), (Obbard et al., 2014), (iv) deep sea sediments (57%), (Woodall et al., 2015), and (v) coastal sediments from Portuguese shelf waters (81%), (Frias et al., 2016). The prevalence of rayon fibres in the marine environment suggests heightened propensity for the potential impact of this material upon biota. Ladewig et al. (2015) suggested that although natural fibres may exhibit different degradability and chemical sorption behaviours when compared to synthetic fibres, natural fibres may still warrant environmental concerns, for example, in chemical pollution dispersion. Remy et al. (2015) further suggested that while the natural material of cellulose may not be an issue, the associated dyes or additives in the semi-synthetic fibres may pose a threat to biota.

Beyond the provision of data about microplastic abundance in the world's oceans, it is important that there is an understanding of the environmental variables that may potentially influence this issue. In this study, a generalized additive model (GAM) was developed to gain a preliminary insight into the environmental variables which had an effect on microplastic abundance in the Atlantic Ocean. A GAM model was chosen in lieu of the more common general linear model (GLM) in order to better capture the relationship between the response variable and the explanatory variables without assuming a parametric form (Crawley, 2013). The best fitting GAM generated in this study indicated that location (latitude, longitude), certain physico-chemical parameters of oceanic waters (water temperature, salinity) and atmospheric variables (wind direction, wind speed) had a significant effect on

Table 2
Microplastic abundances reported for surface and sub-surface oceanic waters across the world.

Location	Microplastic abundance (particles per m^3)	Method for surface waters (unless otherwise indicated)	Study
Arctic Ocean			
Svalbard, Norway	0.34 ± 0.31; 0–1.31 (mean, range) 2.68 ± 2.95; 0–11.5 (mean, range)	Manta trawl (333 μm) Underway system (250 μm)[a]	Lusher et al. (2015)[1]
Pacific Ocean			
Southern California, USA	7.25 (mean)	Manta trawl (333 μm)	Moore et al. (2002)
Santa Monica Bay, USA	3.92 (mean)	Manta net (333 μm)	Lattin et al. (2004)
South Californian current	0–3.141	Manta net (505 μm)	Gilfillan et al. (2009)
Southeast Bering Sea	0.004–0.19	Sameoto neuston/manta net (505 μm)	Doyle et al. (2011)
NP Subtropical Gyre	0.425 (median)	Manta net (333 μm)	Goldstein et al. (2012)
North eastern Pacific Ocean	279 ± 178 (mean)	Underway system (62.5–250 μm)[a]	Desforges et al. (2014)[2]
Geoje Island, South Korea	0.4–54	Manta trawl (330 μm)	Song et al. (2014)
East China Sea	0.167 ± 0.138 (mean)	Neuston net (333 μm)	Zhao et al. (2014)
Southern Sea of Korea	1.92–5.51; 2.3–38.77 (2012) 582–924; 10–375 (2013)	Manta trawl (330 μm) Hand Net (50 μm)	Kang et al. (2015a)
Geoje and Jinhae Bays, Korea	1.92 ± 1.84; 5.51 ± 11.2 (2012) 1.68 ± 0.81; 1.07 ± 0.34 (2013)	Manta Trawl (330 μm)	Kang et al. (2015b)
East Asian Sea	3.7 ± 10.4; 0.03–491 (mean, range)	Neuston net (350 μm)	Isobe et al. (2015)
Indian Ocean			
Southeast South Africa	257.9–1215	WP-2 type net (80 μm)	Nel and Froneman (2015)
Atlantic Ocean			
Bristol Channel, UK	0–100	Lowestoft plankton sampler (270 μm)	Morris and Hamilton (1974)
Offshore Ireland	2.46 ± 2.43; 0–22.5 (mean, range)	Underway system (250 μm)[b]	Lusher et al. (2014)[3]
Western English Channel	0.27	Plankton nets (200, 500 μm)	Cole et al. (2014)
Portuguese coastal waters	0.002–0.036	WP2 (180 μm), Neuston (280 μm), LH Plankton Recorder (335 μm)	Frias et al. (2014)
St. Peter/St. Paul Archipelago, Brazil	0.01	Plankton net (300 μm)	Ivar do Sul et al. (2013)
Western Tropical Atlantic Ocean	0.015–0.04	Manta trawl (300 μm)	Ivar do Sul et al. (2014)
North Atlantic Ocean	13–501	Underway system (10, 300 μm)[b]	Enders et al. (2015)[4]
Atlantic Ocean	1.15 ± 1.45; 0–8.5 (mean, range)	Underway system (250 μm)[b]	This study[5]
Mediterranean and European Seas			
West Coast, Sweden	167–2400 72–141	Plankton net (80 μm) Zooplankton net (450 μm)	Noren (2007)
West Sardinian Coast	0.15	Manta trawl (500 μm)	de Lucia et al. (2014)
Southwest Finland	0–0.74	Manta trawl (333 μm)	Magnusson (2014)
Baltic Sea	10^2–10^4	WP2 net (90 μm mesh)	Gorokhova (2015)

[a] Sub-surface waters sampled at the following depths ([1]6 m, [2]4.5 m).
[b] Sub-surface waters sampled at the following depths ([3]3 m, [4]3 m, [5]11 m).

microplastic abundance. These findings must be taken in the context that the model in this study was based on data from 76 samples in the Atlantic Ocean. Notwithstanding this, GLMs based on datasets from the Northeast Atlantic and Arctic Ocean also indicated that sea surface temperature and wind affected microplastic abundance (Lusher et al., 2014; Lusher et al., 2015). Based on the combination of field data and a theoretical model, Kukulka et al. (2012) indicated that that wind stress results in vertical mixing of buoyant microplastics in the surface mixed layer of the ocean. Overall then, it appears that microplastic abundance is influenced by a combination of factors, some of which include location, atmospheric parameters and oceanographic conditions.

While comparison of microplastic abundances between studies is possible, one must be cognisant of the differences between sampling, processing and analytical techniques for microplastic identification. These differences may account for some of the variation in the findings between studies. Bearing that in mind, average microplastic abundance (1.15 ± 1.45 particles m^{-3}) in sub-surface waters along the North/South Atlantic transect in this study was lower than that reported for sub-surface waters in the north eastern Pacific Ocean (279 ± 178 particles m^{-3}), Arctic Ocean (2.68 ± 2.95 particles m^{-3}) and north eastern Atlantic Ocean (2.46 ± 2.43 particles m^{-3}), (Table 2). The lower microplastic abundances that were reported in this study were possibly due to the fact that the vessel (i) did not traverse waters where microplastics have been known to accumulate (i.e. either the North Atlantic or the South Atlantic Sub-Tropical Gyre), (ii) was too far offshore the African continent to sample nearshore sites which usually have higher microplastic abundances than open oceanic sites, or (iii) was sampling from a different vertical fraction in the water column. Although microplastic abundance in the present study was comparable to abundances reported for surface waters in the Atlantic Ocean, Pacific Ocean and the Mediterranean and European Seas, considerably higher microplastic abundances in surface waters were reported for nearshore sites in the US, Korea, South Africa, UK and Sweden (Table 2). The comparisons of microplastic abundance in sub-surface waters must be taken in the context of variations in the depth (3–11 m) at which seawater was sampled and mesh sizes (62.5–300 μm) of the sieves that were used amongst the studies. For surface water samples, there were also variations in the mesh sizes (50–505 μm) of the nets that were used. These factors may influence microplastic abundance as (i) there may be vertical stratification of microplastics in the water column and, (ii) smaller mesh sizes would increase the quantity of microplastics collected during sampling. Standardisation and intercalibration protocols for sampling microplastics in surface and sub-surface waters are key issues to be addressed by the scientific community if greater comparability between studies is to be achieved.

5. Conclusion

This study provided an assessment of microplastics in sub-surface waters along a North/South latitudinal gradient in the Atlantic Ocean. Overall, average microplastic abundance as reported by this study for the Atlantic Ocean (1.15 ± 1.45 particles m^{-3}) was lower than was reported for sub-surface waters across the world. Additionally, there were no statistically significant differences between microplastic abundance at Benguela upwelling sites ($n = 14$) and all other non-upwelled sites ($n = 62$). Rayon (63%) was the predominant polymer of the particles that were analysed. Of the confirmed microplastics, the most abundant polymer types were polyester (49%) and blends of polyamide or acrylic/polyester (43%). Fibres (94%) were also the predominant type of microplastics. The information provided by this study is important as it provides an indication of the environmentally realistic concentrations and types of microplastics that biota are exposed to in the natural environment.

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References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.
Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA, University of Washington Tacoma, WA, USA.
Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179.
Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47 (12), 6646–6655.
Cole, M., Webb, H., Lindeque, P.K., Fileman, E.S., Halsband, C., Galloway, T.S., 2014. Isolation of microplastics in biota-rich seawater samples and marine organisms. Sci. Report. 4 (4528), 1–8.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ. Sci. Technol. 49, 1130–1137.
Cozar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, A.T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. 111 (28), 10239–10244.
Crawley, M.J., 2013. The R Book. John Wiley & Sons Limited, Sussex, United Kingdom.
Cropper, T.E., Hanna, E., Bigg, G.R., 2014. Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012. Deep-Sea Res. I Oceanogr. Res. Pap. 86, 94–111.
de Lucia, G.A., Caliani, I., Marra, S., Camedda, A., Coppa, S., Alcaro, L., Campani, T., Giannetti, M., Coppola, D., Cicero, A.M., Panti, C., Baini, M., Guerranti, C., Marsili, L., Massaro, G., Fossi, M.C., Matiddi, M., 2014. Amount and distribution of neustonic micro-plastic off the western Sardinian coast (Central-Western Mediterranean Sea). Mar. Environ. Res. 100, 10–16.
Desforges, J.-P.W., Galbraith, M., Dangerfield, N., Ross, P.S., 2014. Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar. Pollut. Bull. 79, 94–99.
Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Mar. Environ. Res. 71, 41–52.
Enders, K., Lenz, R., Stedmon, C.A., Nielsen, T.G., 2015. Abundance, size and polymer composition of marine microplastics ≥10 μm in the Atlantic Ocean and their modelled vertical distribution. Mar. Pollut. Bull. 100, 70–81.
Frias, J.P.G.L., Otero, V., Sobral, P., 2014. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. Mar. Environ. Res. 95, 89–95.
Frias, J.P.G.L., Gago, J., Otero, V., Sobral, P., 2016. Microplastics in coastal sediments from southern Portuguese shelf waters. Mar. Environ. Res. 114, 24–30.
Gilfillan, L.R., Ohman, M.D., Doyle, M.J., Watson, W., 2009. Occurrence of Plastic Micro-debris in the Southern California Current System. 50. California Cooperative Oceanic Fisheries Investigations, pp. 123–133.
Goldstein, M.C., Rosenberg, M., Cheng, L., 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biol. Lett. 8, 817–820.
Gorokhova, E., 2015. Screening for microplastic particles in plankton samples: how to integrate marine litter assessment into existing monitoring programs? Mar. Pollut. Bull. 99, 271–275.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.
Isobe, A., Uchida, K., Tokai, T., Iwasaki, S., 2015. East Asian seas: a hot spot of pelagic microplastics. Mar. Pollut. Bull. 101, 618–623.
Ivar do Sul, J.A., Costa, M.F., Barletta, M., Cysneiros, F.J., 2013. Pelagic microplastics around an archipelago of the Equatorial Atlantic. Mar. Pollut. Bull. 75, 305–309.
Ivar do Sul, J., Costa, M., Fillmann, G., 2014. Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean. Water Air Soil Pollut. 225, 1–13.
Kang, J.-H., Kwon, O.Y., Lee, K.-W., Song, Y.K., Shim, W.J., 2015a. Marine neustonic microplastics around the southeastern coast of Korea. Mar. Pollut. Bull. 96, 304–312.
Kang, J.-H., Kwon, O.-Y., Shim, W.J., 2015b. Potential threat of microplastics to zooplanktivores in the surface waters of the southern sea of Korea. Arch. Environ. Contam. Toxicol. 69, 340–351.
Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D.W., Law, K.L.C.L., 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophys. Res. Lett. 39, 1–6.
Ladewig, S.M., Bao, S., Chow, A.T., 2015. Natural fibers: a missing link to chemical pollution dispersion in aquatic environments. Environ. Sci. Technol. 49, 12609–12610.
Lattin, G.L., Moore, C.J., Zellers, A.F., Moore, S.L., Weisberg, S.B., 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Mar. Pollut. Bull. 49, 291–294.
Lusher, A., 2015. Microplastics in the marine environment: distribution, interactions and effects. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 245–307.
Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99.
Lusher, A.L., Burke, A., O'Connor, I., Officer, R., 2014. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar. Pollut. Bull. 88, 325–333.
Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Report. 5 (14947), 1–9.
Magnusson, K., 2014. Microliter and Other Microscopic Anthropogenic Particles in the Sea Area off Rauma and Turku, Finland. Swedish Environmental Research Institute, Stockholm, Sweden.
Mishra, S.P., 2010. A Textbook of Fibre Science and Technology. New Age International Publishers, New Delhi, India.
Moore, C.J., Moore, S.L., Weisberg, S.B., Lattin, G.L., Zellers, A.F., 2002. A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. Mar. Pollut. Bull. 44, 1035–1038.
Morris, A.W., Hamilton, E.I., 1974. Polystyrene spherules in the Bristol Channel. Mar. Pollut. Bull. 5 (2), 26–27.
Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112 (1–2), 39–45.
Nel, H.A., Froneman, P.W., 2015. A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. Mar. Pollut. Bull. 101, 274–279.
Noren, F., 2007. Small Plastic Particles in Coastal Swedish Waters. N-research, Sweden.
Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future. 2, pp. 315–320.
Polovina, J.J., Howell, E.A., Abecassis, M., 2008. Ocean's least productive waters are expanding. Geophys. Res. Lett. 35, 1–5.
R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Remy, F., Collard, F., Gilbert, B., Compère, P., Eppe, G., Lepoint, G., 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environ. Sci. Technol. 49, 11158–11166.
Santos, F., Gomez-Gesteira, M., de Castro, M., Alvarez, I., 2012. Differences in coastal and oceanic SST trends due to the strengthening of coastal upwelling along the Benguela current system. Cont. Shelf Res. 34, 79–86.
Smith, B., 1999. Infrared Spectral Interpretation: A systematic approach. CRC Press, Boca Raton, Florida.
Song, Y.K., Hong, S.H., Jang, M., Kang, J.-H., Kwon, O.Y., Han, G.M., Shim, W.J., 2014. Large accumulation of micro-sized synthetic polymer particles in the sea surface microlayer. Environ. Sci. Technol. 48, 9014–9021.
Thompson, R.C., 2015. Microplastics in the marine environment: sources, consequences and solutions. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 185–200.
United Nations Environment Programme (UNEP), 2011. UNEP Year Book: Emerging Issues in Our Global Environment. United Nations Environment Programme (UNEP), Nairobi, Kenya.
Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2015. The deep sea is a major sink for microplastic debris. R.Soc. Open Sci. 1 (140317), 1–8.
Zhao, S., Zhu, L., Wang, T., Li, D., 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar. Pollut. Bull. 86 (1–2), 562–568.