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An annual study on plastic accumulation in surface water and sediment cores from the coastline of Tenerife (Canary Island, Spain)

Stefanie Reinold [a,*], Alicia Herrera [a], Nicolò Stile [b], Francesco Saliu [b], Carlos Hernández-González [c], Ico Martinez [a], Zaida Ortega [d], María Dolores Marrero [d], Marina Lasagni [b], May Gómez [a]

[a] Marine Ecophysiology Group (EOMAR), Iu-ECOAQUA, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira, 35017, Canary Islands, Spain
[b] Earth and Environmental Science Department, University of Milano Bicocca, Piazza della Scienza 1, 20126 Milano, Italy
[c] Centro Oceanográfico de Canarias, Instituto Español de Oceanografía, Santa Cruz de Tenerife, Canary Islands, Spain
[d] Departamento de Ingeniería de Procesos, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira, 35017, Canary Islands, Spain

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ABSTRACT

Sediment core samples from high tide lines and in submerged zones as well as surface water samples from eight beaches of Tenerife were analysed. Sampling was conducted over a period of one year in intervals of 5 weeks. The majority of particles were found in the high tide sediment (66%), followed by water samples (23%) and finally in sediment from submerged zones (11%). Regarding the particle amount per volume (items/L), accumulation in sediment samples was statistically higher compared to water samples. Mean values of items/L were higher in high tide sediments. In high tide and water samples, mostly white and transparent particles >1 mm were found. More than 70% were represented by fragments. In sediments from submerged zones, yellow and blue microparticles (<1 mm) were predominant and 61.9% consisted of fibres. Larger particles were mainly identified as PP, PE, PS, PTFE and PVC, while polymer types of smaller particles were more variable.

1. Introduction

Notwithstanding almost 20 years of marine plastic pollution research, global production of plastic is still rising (PlasticsEurope, 2020) while a proper waste management is lacking. As a result, global plastic pollution increments as this material are very durable and have the potential to remain for a long time in the environment. In oceans plastic particles can be transported far distances driven by wind and currents and therefore they have been found everywhere in the marine environment, including ocean surface, water column, deep sea or polar regions (Chiba et al., 2018; Choy et al., 2019; Eriksen et al., 2014; Obbard, 2018), but amounts seem to be particularly high in the coastline sediments (Wessel et al., 2016; Worm et al., 2017). The highest numbers were reported so far in South Korea (119,182.0 items/m^2), Jordan (43,947.0 items/m^2) and Spain (28,218.75 items/m^2) (Reinold et al., 2020; Serra-Gonçalves et al., 2019). Studies from all around the world have shown that plastic is not only polluting the oceans, but also accounts around 70% of the debris found on beaches (Serra-Gonçalves et al., 2019).

However, most of the given amounts consider only the recent washed ashore plastic particles as merely the superficial beach sediments were investigated (Serra-Gonçalves et al., 2019). There are very few investigations, which studied the vertical distribution of plastic pollution on coastlines in deeper layers (Carson et al., 2011; Claessens et al., 2011; Fisner et al., 2017; Moreira et al., 2016; Tran Nguyen et al., 2020; Turra et al., 2014; Yu et al., 2016). While three of these studies focused only on pellets (Fisner et al., 2017; Moreira et al., 2016; Turra et al., 2014), the rest included also fragmented particles (Carson et al., 2011; Claessens et al., 2011; Tran Nguyen et al., 2020; Yu et al., 2016). This is important to mention as plastic can become brittle and break down into smaller irregular shaped pieces, while it undergoes degradation processes (e. g. photodegradation, thermooxidative degradation, thermal degradation) (Andrady, 2011; Hidalgo-Ruz et al., 2012). This decomposition may be even faster on beaches than in the sea due to constant exposure to solar

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* Corresponding author.

E-mail addresses: stefanie.reinold101@alu.ulpgc.es (S. Reinold), alicia.herrera@ulpgc.es (A. Herrera), n.stile@campus.unimib.it (N. Stile), francesco.saliu@unimib.it (F. Saliu), carlos.hernandez@ieo.es (C. Hernández-González), ico.martinez@ulpgc.es (I. Martinez), zaida.ortega@ulpgc.es (Z. Ortega), mariadolores.marrero@ulpgc.es (M.D. Marrero), marina.lasagni@unimib.it (M. Lasagni), may.gomez@ulpgc.es (M. Gómez).

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UV radiation, higher oxygen content or temperatures (Andrady, 2011). Hence it is more likely to find fragmented particles instead of pellets on beaches. This ratio has been confirmed in several studies worldwide (de Carvalho and Baptista Neto, 2016; Karthik et al., 2018; Kusui and Noda, 2003; McDermid and McMullen, 2004; Naji et al., 2017; Santos et al., 2009; Wessel et al., 2016; Zhou et al., 2018), including beaches of the Canary Islands (Edo et al., 2019; Herrera et al., 2018; Rapp et al., 2020).

As research about vertical distribution of plastic on beach sediments is still lacking, there are no standardized methods for obtaining sample cores. Therefore, further sampling is necessary not only to establish standardized procedures, but also to define zones of plastic agglomeration on beaches in order to inaugurate a proper monitoring of marine plastic pollution. Sample cores of former studies varied in their location, in their depth and in the layers, which contained the top amounts of plastic. While superficial samplings are usually taken around the high tide line, merely two studies, which investigated the vertical distribution of plastic, included samples of the wrack line (Carson et al., 2011; Claessens et al., 2011). These two studies were also the only ones comparing plastic amounts of the obtained cores between the high tide line and lower tidal areas, whereof only Claessens et al. (2011) sampled in the subtidal zone. Sampling depths were conducted between 20 cm and 2 m, in general with decreasing particle amounts towards deeper strata. So far, no research has been done on seasonal changes of the vertical plastic distribution on beaches.

This study represents the first investigation on vertical distribution of plastic debris on Canarian strandlines. In general, plastic pollution on beaches of Canary Islands have received attention only in recent years (Álvarez-Hernández et al., 2019; Baztan et al., 2014; Edo et al., 2019; Herrera et al., 2018; Rapp et al., 2020; Reinold et al., 2020; Villanova Solano et al., 2018). Tenerife is not only the biggest and most visited island of the archipelago, but also represents the most populated island of Spain overall. Still, only three studies concerning this issue have been performed there so far (Álvarez-Hernández et al., 2019; Reinold et al., 2020; Villanova Solano et al., 2018). All of these investigations focused on the plastic accumulation of superficial beach sediment. Here, for the first time plastic accumulation in deeper strata of sandy beaches was observed during a one-year period. Furthermore, plastic amounts in cores from different tidal zones were compared. The main objective of this work is the evaluation of the long-term accumulation of plastic debris on sandy shorelines. Therefore, the temporal variability of the vertical deposition of plastic was studied in sediment cores from the high tide line as well as from submerged areas on eight beaches of Tenerife. In addition, surface water samples were taken to be able to estimate the income of particles/L on every investigated shoreline. This investigation not only aims to complete sparse data of plastic debris on the Tenerife coastline, but also to amplify information about plastic pollution in deeper beach sediments worldwide.

Fig. 1. Map of study area, indicating the sampling sites on Tenerife and the total of samples taken on each location between July 2016 and July 2017.

2. Materials and methods

2.1. Study site

This work was performed on Tenerife, an island belonging to the Canary archipelago (Spain). Subject of this study were eight beaches along the coastline, differing in their orientation and exposure to principal currents as well as tourist pressure: Almaciga (Playa de Almaciga), Arena (Playa de la Arena), Cristianos (Playa de las Vistas), Gaviotas (Playa de las Gaviotas), Poris (Playa Grande), Puertito (Playa del Puertito de Adeje), Socorro (Playa del Socorro) and Tejita (Playa de la Tejita) (Fig. 1). The study was done between July 2016 and June 2017 obtaining samples in 5 week periods. This led to a total of 240 samples, consisting of 10 sediment samples from the high tide line, 10 sediment samples from submerged zones and 10 surface water samples from each beach.

2.2. Sampling method

2.2.1. Sediment samples

Although plastic debris was detected down to 2 m on sandy beaches (Turra et al., 2014), the depths, where highest amounts of plastic were found, differed in each location. However, most strandlines on Tenerife had a thin sand layer with increasing grain sizes towards deeper strata. Hence, boulder-sized pieces (>200 mm) or even the bedrock was reached very quickly. The thickness of the sand layer also depended on seasonal changes. Less sand was observed mainly on the beaches of the northern coastline in the winter months, where grains often approached boulder size after approximately 15 cm. Carson et al. (2011) registered nearly 95% of the observed plastic debris in the top 15 cm, accounting with a total sampling depth of 25 cm. According to these findings and considering the geological conditions of the examined beaches, sediment samples were consequently taken from the top 15 cm on every beach in order to establish a standardized sampling method. To ensure reaching the proposed depth, sampling zones were chosen depending on the thickness of the sandy layers. A stainless steel tube with a diameter of 8 cm was used to extract a 15 cm deep core of the beach sediment. Samples were taken in sets of 2 cores during the low tide. One core was obtained from the last high tide line (in the following referred to as “High tide” samples), whereas the second one was extracted in the subtidal zone submerged by approximately 50 cm of water (in the following referred to as “Low tide” samples). Both samples were stored in individual metal bowls and covered with aluminium foil to prevent cross contamination until the process of density separation.

2.2.2. Surface water samples

Samples were carefully taken from the water surface (in the following referred to as “Water” samples) with a metal bowl to avoid bubble formation. Special attention was paid to take the samples from a calm surface, where possible before the surf zone, but at least between two wave breaks. After letting the sediment settle in the bowl, 1 L of water and its containing floating particles were passed into a glass jar, where it was kept stored until further processing in the laboratory.

2.3. Extraction of plastic particles

Approximately 60 L of sediments from each sampling zone (high tide and low tide) were collected during the year and processed in the COC (Centro Oceanográfico de Canarias). All sediments were oven-dried at 70 °C until the complete loss of wetness and subsequently weighed. As a result, a total of 107.4 kg of high tide samples and 98.8 kg of low tide samples were obtained. However, in order to compare sediment samples with water samples volume in litres was used as a common metric unit for all samples in this study. Hereinafter, samples underwent a density separation process to isolate plastic particles from sediment.

In 2012 the “Munich Plastic Sediment Separator” (MPSS) was introduced as a novel and highly efficient method to separate plastic particles from sediments of aquatic environments (Imhof et al., 2012). The system is based on density separation and showed recovery rates of 100% for large microplastic particles (1–5 mm) and 95.5% for small microplastic particles (<1 mm) (Imhof et al., 2012). Therefore, a smaller and modified version of the MPSS was constructed. The sediment container of the replica accounts with a diameter of 20 cm and a height of 15.5 cm. The standpipe had a length of 26 cm, decreasing its inner diameter from 20 cm to 8 cm. Adjusting to the smaller size of separator the fill-height in the sediment container was kept at 2–3 cm to guarantee a constant stirring of the sediment and therefore allow plastic particles to detach from the sediment and get into suspension. The suspension consisted of a zinc chloride solution with a density of 1.4 kg/L, assuming that density values for most plastics range from 0.8 to 1.4 g/cm^3 (Hidalgo-Ruz et al., 2012; Stile et al., 2021). Special care was taken to maintain the density at 1.4 kg/L. The following steps of the separation procedure were done as described by Imhof et al. (2012). Additionally, a defoaming agent was used when necessary, since calcareous material - like shells and corals - can favour foam production. Special care was taken that the agent did not contain silicones. The sediment inlet flange of the separator remained covered during stirring and settling time to prevent air-borne contamination from the laboratory. After the settling time the dividing chamber was mounted on the standpipe. In accordance with the smaller replica of the MPSS the inner diameter of this part reduced from 8 cm to 3/4 in. of the integrated ball valve. The dividing chamber was left to end up in an open-end after the valve instead of being connected to a filter holder. The opening was covered by a filtration device consisting of a stainless steel filter (mesh size: 25 μm), which was spanned over a stainless steel tube with a hose clamp. As described by (Imhof et al., 2012), subsequently the level of the zinc chloride solution, which carried the floating particles, was elevated up to the sampling chamber, the ball valve was closed, the fluid level was lowered and the dividing chamber was dismounted. By turning the dividing chamber upside-down the content of the sampling chamber was filtered through the stainless steel filter. The ball valve was opened and the walls of the dividing chamber were rinsed carefully with distilled water to ensure the deposition of all particles on the filter. Vacuum filtration facilitated the filtering process.

Overall, approximately 80 L of water samples were obtained through out the sampling period. Water samples, however, were directly filtered over one of the above mentioned filtration devices.

2.4. Digestion of biological materials

Filtration devices with retained sample material were stored in a stainless steel tray containing 10% KOH solution for one week at 70 °C. Potassium hydroxide solutions are an established and effective way to digest organic material without causing major damage to plastic particles (Enders et al., 2017; Kühn et al., 2017; Lusher et al., 2017). The tray was covered throughout the whole time to keep reactions of potassium hydroxide with carbon dioxide as low as possible. Evaporated liquid was replaced regularly with pure water. Subsequent to the degradation process, each filtration device was rinsed several times with pure water and then stored in a tray containing 10% EDTA solution for one day at room temperature (Reinold et al., 2021). EDTA sequesters metal ions from previous used agents or the filter material and therefore prevents salt formations on particles\` surfaces, which could disturb subsequent analysis. After rinsing each filtration device again several times with pure water, the gauze was detached and dried in a desiccator for one week. Each gauze was stored in a petri dish until they were analysed.

2.5. QA/QC procedures

White cotton lab coats and disposable latex gloves were used throughout the entire sample manipulation. Air circulation such as air conditioning, open windows/doors or other possible sources of ventilation was minimized. All filtration processes were performed under a clean bench and filters were covered at all times to avoid air-borne contamination. All used solutions were filtered through a stainless steel filter (mesh size: 25 μm) prior to their use. Additionally, zinc chloride solution was filtered through stainless steel wool before and after each use for environmental protection reasons and was therefore recycled during the whole analysing process. An artificially contaminated sample was used to determine the recovery rate and confirm the microplastics extraction.

2.6. *Identification of polymers*

All filters were analysed with a Leica Microscope (Leica S9i) in the laboratory of the Marine Ecophysiology Group (EOMAR) of the ULPGC (Universidad de Las Palmas de Gran Canaria). Suspicious particles were counted and classified by their colour and shape. A grid template with 16 colour schemes (red, brown, orange, yellow, green, blue, purple, pink, silver, grey, black, semitransparent, semitransparent yellowish, transparent, white and yellowish) and 5 types of shape (fibres, fragments, lines, films and pellets) was used. The term “fibres” included thin filamentous structures deriving mostly from clothes or other materials, while “lines” was used for coarser strings deriving commonly from fishing gears. Plastic particles smaller than 5 mm are commonly considered as microplastics and according to the proposed working definitions of NOAA (Arthur et al., 2008), but so far there is no international agreement on size definitions(GESAMP, 2015). In the present study, the size classification of particles was based on the SI nomenclature as suggested by (Hartmann et al., 2019). Due to the large number of samples throughout the year and therefore the big amount of particles, only the content of the most contaminated 25 filters (10%) were further analysed via FTIR. Macro- and mesoparticles (>1 mm) were analysed in the Departamento de Ingeniería de Procesos of the ULPGC with a Perkin Elmer Spectrum Two FTIR instrument, equipped with a diamond ATR unit and a MIR TGS detector. Microparticles (1 mm–25 μm) were analysed at the Provenance Centre of the Earth and Environmental Science Department at the University of Milano Bicocca. A Spotlight 200i FTIR Microscopy System was used, equipped with a diamond coated μATR unit and a mercury cadmium telluride (MCT) 100 * 100 μ single detector. When cooled with liquid nitrogen, this detector displays a 0.5 cm^{-1} spectral resolution and 40,000/1 RMS sensitivity for 2 min acquisition at 4 cm^{-1}. Spectra acquisition was carried out in the wave-number range 400–4000 cm^{-1} with a resolution of 4 cm^{-1} and 32 co-added scans. A point mode approach described in a previous paper (Saliu et al., 2019) was applied for the collection of the spectra of the identified particles. Every ten measurements a background spectrum was collected to check instrument performance and cleanliness. In the case of suspected cross contamination, the instrument was cleaned, and analysis was repeated. Finally, patented COMPARE™ spectral comparison algorithm was used for performing the spectral comparison with spectra available in a commercially library. A positive identification with the reference library was assigned for matches $\geq$ 75%.

2.7. *Statistical analysis*

R statistical software (R Core Team, Version 4.0.3) and its extension, Rstudio (Version 1.3.1093), was used for statistical analyses of the data. Data normality of particle abundance was analysed with the Shapiro Wilk test and homoscedasticity was graphically determined. Statistical differences between sampling zones were tested using Kruskal-Wallis test and pairwise compared with the Wilcox test. Graphics were generated with both, Rstudio and Microsoft Excel (2019).

3. Results

3.1. *Total abundance*

In total, 2509 suspicious particles were registered, whereof 66% were found in high tide sediment samples, 23% in water samples and 11% in low tide sediment samples. The average abundance of particles was overall highest in the sediments from the high tide line (Fig. 2). Although the mean abundance of the low tide samples is lower than the mean of the water samples, the amount of all items found in sediment samples is statistically higher than in water samples (Wilcox test: $p < 0.0295$). The percental distribution of each location shows a higher percentage of items/L in water samples only for Almaciga (Fig. 3). No significant difference was found between high tide and low tide sediments. Moreover, percentages of sediment samples are mostly balanced, except for Poris, Puertito and Arena, where over 50% of all particles were found in the high tide samples. In Poris this percentage reached even more than 80% and a statistical difference to all other locations was found. Maximum mean values in high tide sediment (130.64 items/L) and in water samples (23.10 items/L) were found in Poris, whereas highest mean values in low tide sediment (6.50 items/L) were detected in Cristianos (Table 1). Lowest mean values in high tide sediment (2.12 items/L) and water (1.30 items/L) presented Socorro and low tide sediment mean values were lowest in Arena (2.25 items/L).

3.2. *Temporal variability*

There was no obvious pattern neither between sampling zones nor for seasonal changes regarding the sampling zones or locations. Almaciga presented overall particle amounts of less than 20 items/L throughout the year (Fig. 4a). The highest numbers were found in the water sample from October 2016 (52.00 items/L), which not only exceeded by a magnitude of at least 3.5 all other values from the rest of the year, but also represents the second highest maximum of all water samples throughout. As a result, Almaciga accounted for generally higher particle rates in water samples (Fig. 3). On 3 sampling dates, no particles were found neither in high tide samples (August 2016, March 2017, June 2017) nor in the water samples (January 2017, March 2017, June 2017). Additionally, in June 2017 there were no items in the low tide sample.

Arena showed generally particle amounts of less than 10 items/L, except in the high tide sample from November 2016 (29.18 items/L) (Fig. 4b). Additionally, the lowest maximum values in all low tide sediment (5.31 items/L; October 2016) and water samples (8.00 items/L; August 2016) were registered at this location. No particles were found in water samples from September 2016, February 2017, May 2017 and July 2017. As for the sediment, one high tide sample (January 2017) and two low tide samples (February 2017, July 2017) were void of particles.

Low tide samples from Cristianos contained particles throughout the year with a maximum value of 14.59 items/L (June 2017) (Fig. 4c). Low tide samples presented further significantly more particles than high tide or water samples. Highest amounts of particles were found in a high tide sample in March 2017 (43.77 items/L). Particles were absent in November 2016 and April 2017 in high tide samples and in 60% of all water samples.

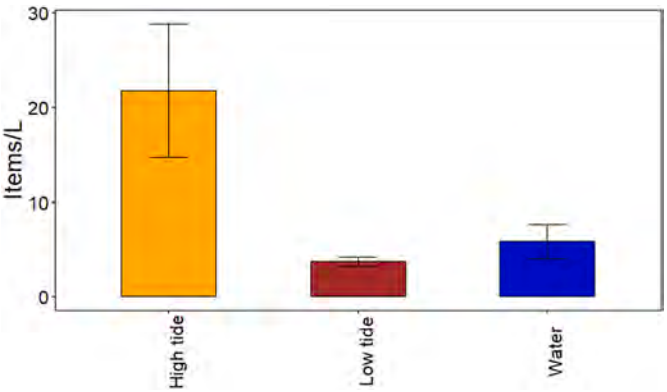

Fig. 2. Average particle abundance in items/L of each sampling zone collected from July 2016 to July 2017.

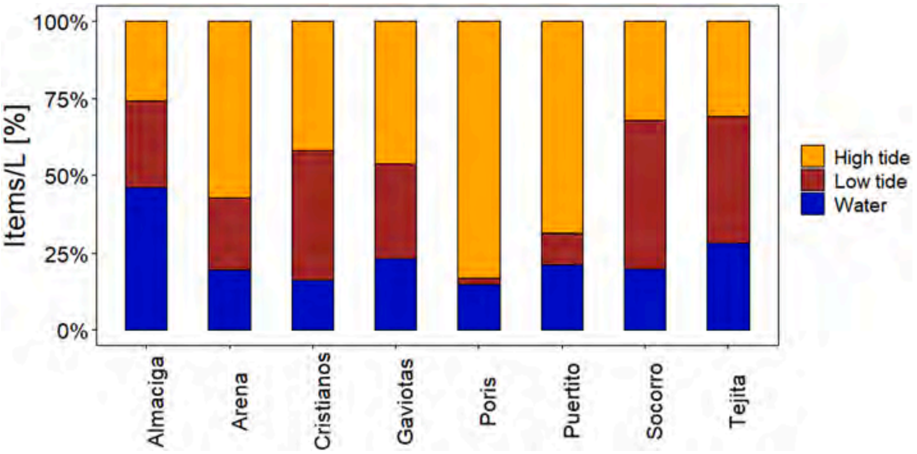

Fig. 3. Percental distribution of particles measured in items/L for each location in the three different sampling zones.

Gaviotas showed overall low amounts of particles at all sampling zones, which never exceeded 15 items/L (Fig. 4d). In fact, the highest numbers (14.59 items/L) were registered both in sediment samples (low tide: July 2016; high tide: June 2017). In water samples the maximum reached 13 items/L. All sampling zones accounted for 30% particle-free samples highlighting that in November 2016 no particles were found at all.

Overall, Poris stood out as the most contaminated location, presenting the highest amount of particles in high tide sediments (399.21 items/L; March 2017) and water (106.00 items/L; July 2016) (Fig. 4e). Maximum values in low tide sediment reached merely 9.28 items/L in July 2016. Significantly more particles were found in high tide sediments, which contained particles at any sampling point of the year. Particles were missing in 2 water samples (November 2016, February 2017) and 3 low tide samples (October 2016, February 2017, March 2017).

Puertito presented the second highest maximum of particles of all high tide samples with 83.56 items/L in June 2017 (Fig. 4f). Other than that, particle amounts did not exceed 28 items/L. No particles were found in the water samples of October 2016, the high tide sample of February 2017 and another 3 low tide samples (August 2016, March 2017, June 2017).

Samples from Socorro showed generally amounts under 6 items/L, except for the 3 maximum values (Fig. 4g). Particle numbers reached 14.59 items/L in the low tide sample from August 2016, 11.00 items/L in the water sample from December 2016 and 10.61 items/L in the high tide sample from September 2016. 10.61 items/L represented further the lowest maximum for low tide samples overall. Additionally, Socorro accounted for the highest number of particle-free samples throughout. Particles were absent in 70% of all water samples and in 3 high tide (November 2016, January 2016, February) and 3 low tide samples (September 2016, March 2017, June 2017).

Tejita showed the most opposed maximum values of all sediment samples (Fig. 4h). 22.55 items/L (December 2016) represented the highest number of particles of all low tide samples and 10.61 items/L (June 2016) is the lowest maximum found in high tide samples. No particles were found in 1 water sample (September 2016), 1 low tide sample (April 2017) and 2 high tide samples (October 2016, November 2016).

3.3. Colour

In total, 60% of all suspicious items were either transparent or white, including yellowish or rather aged particles (Fig. 5a). 14% consisted of blue particles and 7% of yellow particles. Other colours were represented by less than 5%.

Colour of water samples and high tide samples coincided more than sediment samples of different zones (Fig. 5b, c, d). While around two third were transparent and white particles in high tide sediments (65%) and water samples (60%), low tide sediments accounted for less than one third of particles with this colour (31%). The main colour in low tide sediments were yellow (24%) and blue (21%), representing almost half the complete colour range. On the contrary, these colours were less dominant in water and high tide samples. While blue particles were still present in considerable amounts over 10%, water samples and high tide sediments included only 7% and 5% of yellow particles, respectively.

The broadest spectra of colours showed Cristianos, Poris and Puertito, but only in Puertito particles of all 16 colours were present, whereas in Gaviotas half of the colours were lacking (Fig. 6). Black, blue, pink, semitransparent, transparent, white and yellow particles were found at every location, while orange was only found in Poris and Puertito. Statistical differences between beaches were found for all colours except for orange, purple, silver, transparent and yellow particles. Mostly Poris showed significantly more particles in the remaining colours. Specially, blue particles were more abundant in Poris compared to all other locations. But also grey and semitransparent particles showed statistical difference to all other beaches except Puertito (semitransparent) and Tejita (grey).

3.4. Size

Recovered particles were located in a size range between 25 μm up to 2 cm. The biggest particle was found in the most contaminated high tide sample of Poris (March 2017) and measured 20.7 mm. Overall, 62% of all particles were considered macro- or mesoparticles (>1 mm) and 38% were considered microparticles (<1 mm).

Regarding the sampling zone, size distribution in water samples was well-balanced (Fig. 7). Sediment samples showed opposite results. While in high tide samples larger particles were predominant (76%), in low tide samples the number of microparticles (90%) was leading.

In general, microparticles were significant more abundant in most of the beaches, except for Poris and Puertito. Those location also showed significantly more macro- and mesoparticles compared to the other locations except for Almaciga and Cristianos (Fig. 8). Oppositely, statistical differences for microparticles were overall found between Socorro and four other beaches (Almaciga, Poris, Puertito and Tejita) as well as between Poris and two more locations (Arena and Gaviotas).

3.5. Shape

Suspicious items were mostly represented by fragments (71%) and fibres (24%). Lines, pellets and films accounted together for only 5% (Fig. 9). Those shapes were also significantly more abundant than films, lines or pellets.

Table 1

Mean and extreme values of sampling zones at all sampling sites collected from July 2016 to July 2017. The results are presented as particle amount per volume (items/L).

Location	Almaciga			Arena			Gaviotas			Cristianos			Poris			Puertito			Socorro			Tejita		
	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]	Mean [items/L]	Max [items/L]	Min [items/L]
High tide	3.98	10.61	0.00	5.57	29.18	0.00	4.64	14.59	0.00	6.50	43.77	0.00	130.64	274.54	6.63	16.98	83.56	0.00	2.12	10.61	0.00	3.71	10.61	0.00
Low tide	4.38	14.59	0.00	2.25	5.31	0.00	3.05	14.59	0.00	6.50	14.59	2.65	3.18	9.28	0.00	2.52	6.63	0.00	3.18	14.59	0.00	4.91	22.55	0.00
Water	7.10	52.00	0.00	1.90	8.00	0.00	2.30	13.00	0.00	2.50	18.00	0.00	23.10	106.00	0.00	5.20	20.00	0.00	1.30	11.00	0.00	3.40	15.00	0.00

Overlooking the fact that the vast number of particles (89%) were found in the water and high tide sediments, the distribution of shapes also resembled more between those two sampling zones. Fragments were predominant (>70%), followed by fibres. Differently, the main shape in low tide sediments was fibres (61.9%), followed by fragments (29.6%).

Fibres and fragments were present in all locations, while pellets were only found in Cristianos and Poris (Fig. 10). There was no statistical difference for shapes between beaches except for Socorro, which accounted for a significant lower amount of fibres than Almaciga, Poris, Puertito and Tejita.

3.6. *Polymer types*

In total, 625 (25%) particles were identified by FTIR. 532 (85%) of which were macro- and mesoparticles (>1 mm) and 93 (15%) were microparticles (<1 mm).

Regarding the larger particles, most of them came from high tide sediments (68%) and surface water (29%) (Fig. 11a). Only 3% were found in low tide sediments. Polymers from high tide and water samples were mainly identified as polyethylene (PE), polypropylene (PP) or polystyrene (PS), whereas polymers from low tide sediments consisted mostly of PE, polytetrafluoroethylene (PTFE) and polyvinyl chloride (PVC). PE and PP were the only polymers, which were present in all sampling zones.

Although the majority of microparticles derived again from high tide sediments (44%), the distribution was more balanced than for macro- and mesoparticles (Fig. 11b). Despite accounting with a smaller number in general, microparticles showed a broader spectrum of polymers. Predominant polymers were PP (24%) in high tide sediments, PP (29%) and polyamide (PA) (21%) in low tide sediments and rayon (regenerated cellulose fibres) (25%) in surface water. However, PE, PP, cellulose, rayon, PA, and polyester were present in every sampling zone.

Only PP was found in all sampled locations, but PE, PS and rayon were present in 7 (88%) out of 8 beaches. Gaviotas showed the highest variability of polymer types (12), while in Almaciga, Arena and Tejita only 8 different polymer types were identified. Polymer types did not show any statistical differences, neither in their total abundance nor for zones or locations.

4. Discussion

Overall, plastic was found in all sampled locations in water samples as well as in both sediment samples. Most of the particles were found in the high tide sediment (66%), nearly a quarter (23%) came from water samples and only 11% were detected in low tide sediments. Composed mean values confirmed this increased amount of particles in high tide sediments, but statistical analysis revealed that there was no significant difference between high tide and low tide sediment. Similar results were obtained in a former study, where average concentrations of plastic particles decreased from high watermark towards the subtidal zone without showing statistical difference (Claessens et al., 2011). However, particles were significantly more abundant in sediments than in the surface water. The percental distribution of particle amounts in each location supports the statistical difference between sediments and water, as particle percent of sediment samples were mainly balanced, while percentage of water samples rarely surpassed the ones found in sediments. High amounts of plastic in sediments can result in a major issue, since especially on shorelines this type of debris may alter physical conditions of sediments, such as their permeability and heat transfer properties (Carson et al., 2011). So can different sized particles change the mean grain size on beaches and therefore increase the permeability of the soil. Also, plastic particles in the sediment cause a decrease in thermal diffusivity resulting in a slower warming-up and even lower maximum temperatures. Furthermore, correlations between nickel [Ni] concentrations, chlorophyll content, redox potential, organic matter

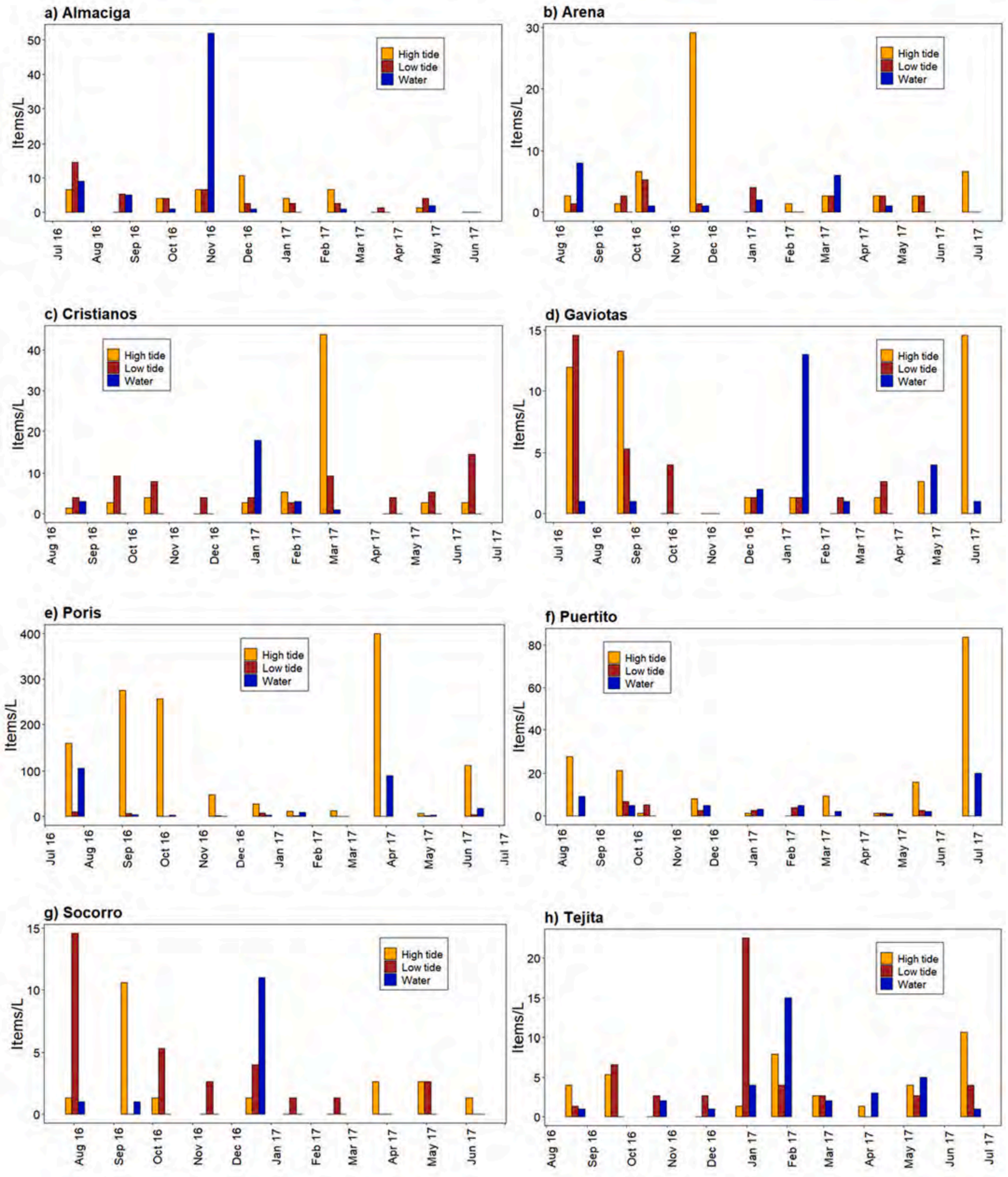

Fig. 4. Particle abundance in items/L in each sampling zone by sampling dates in a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita.

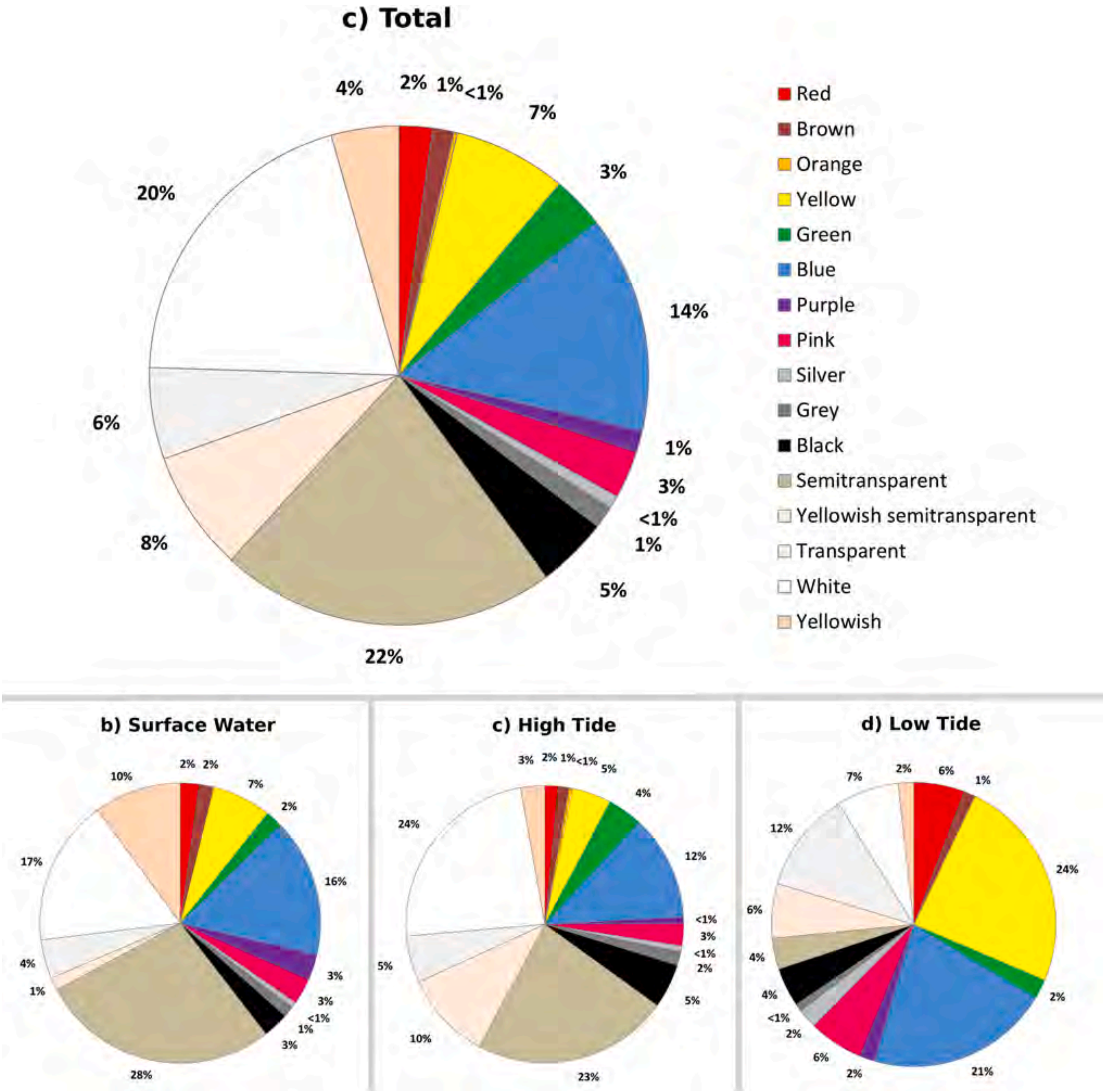

Fig. 5. Colour distribution of particles in total and from each sampling zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

content and nutrient pools of superficial beach sediments and plastic abundances were found, which can have negative effects on biota and result in lower biodiversity (Green et al., 2016; Romeo et al., 2015). However, none of these possible changes were investigated in the beach sediment of the present study.

Overall, Poris appeared to be the most contaminated location. At this beach, highest mean and maximum values in water and high tide sediments were detected. Moreover, Poris was the only location, which presented significantly higher particle amounts, precisely in high tide sediment. This result confirms the findings of former studies, which revealed Poris already as a hotspot for beach pollution (Álvarez-Hernández et al., 2019; Reinold et al., 2020). The least contaminated beach was Socorro, presenting also the lowest mean values in water and high tide sediment, followed by Arena, which showed the lowest mean in low tide sediment. Observations indicated, that the beach of Poris is less frequented than Socorro and Arena, which are visited by a large number of both locals and tourists. Moreover, Arena is located in an urban nucleus, accounting for a high amount of tourists every year.

Data results therefore support the suspicion that plastics tend to accumulate on shorelines due to wave and wind driven origins (Herrera et al., 2018; Ivar do Sul et al., 2009) rather than touristic pressure or urban nucleus as it was supposed in other studies (Ivar do Sul and Costa, 2007; Ryan et al., 2009; Thompson et al., 2009; Yu et al., 2016). Recent studies suggested furthermore a correlation between accumulation of plastic on beaches and the currents surrounding the Canary Islands (Herrera et al., 2018; Reinold et al., 2020).

While composed data determined significantly more particles in sediment samples and even an increased average for high tide sediments, subdividing data by sampling dates showed no correlation between sampling zones. More complementary data between water and high tide sediments were expected, as the incoming waves deposit particles from the water surface on the beach. However, since floating

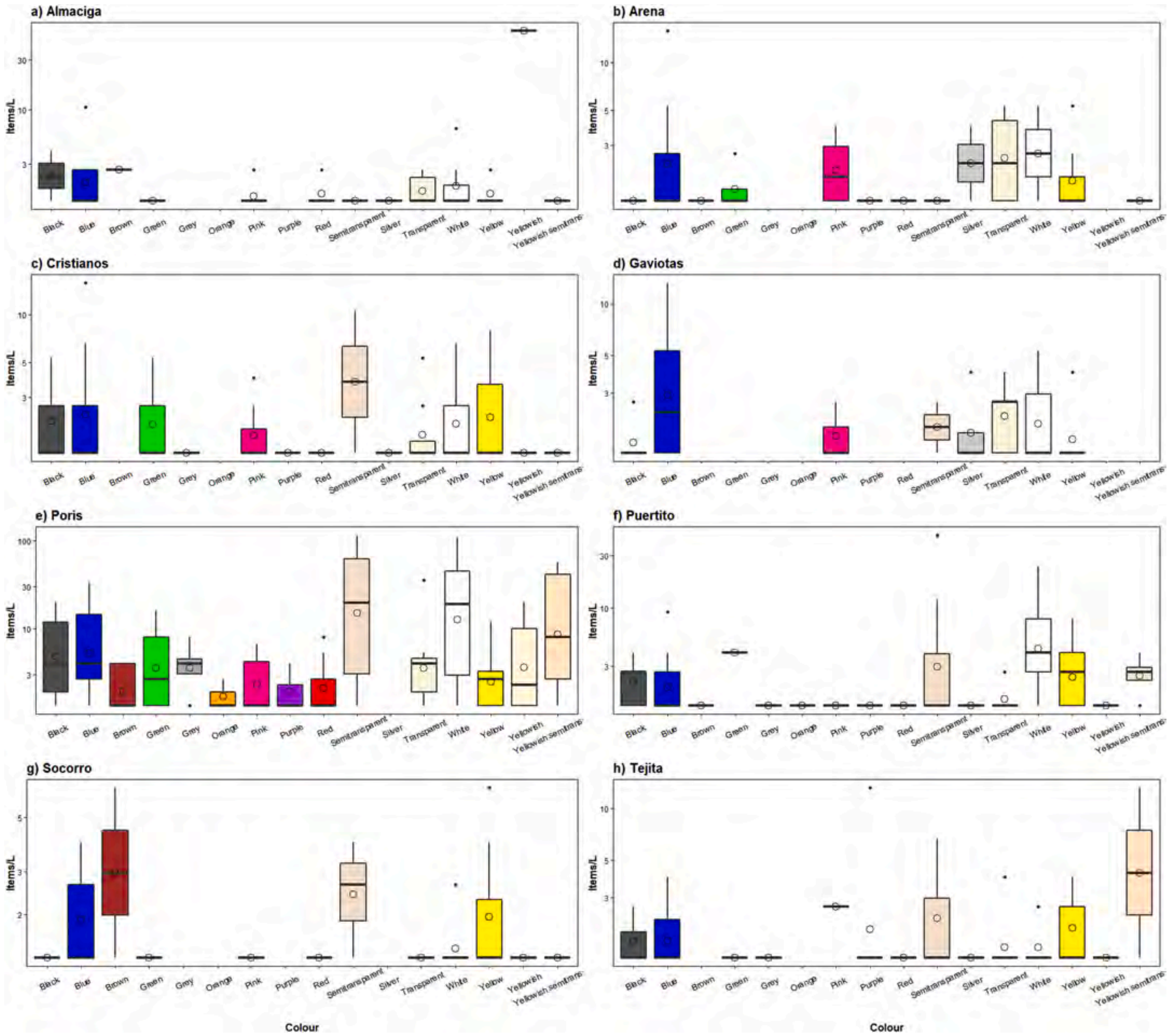

Fig. 6. Colour distribution of particles in Items/L by sampling dates in a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile range, the whiskers indicate the lowest and the highest values and the points represent the values of outliers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

particles are passive drifters and depend on wave and wind movement, particle amounts on the water surface can be very patchy. Similar to the spatial variability, no obvious patterns for seasonal changes were found either. In general, none of the locations showed consistency of particle amounts for any sampling zone. While water sample values were anticipated to be more variable, more stable numbers were expected in sediment samples throughout the year. However, this variation could derive from sampling at different points. Although samples were consequently taken from the high tide line and in shallow waters, tide changes cause wreck lines and water levels at different heights during time. The same results were found in two recent studies from the Canary Island, where temporal variability of plastic accumulation on beach surface was investigated (Rapp et al., 2020; Reinold et al., 2020). A comparison of data from the same locations showed that particle amounts of beach sediment from the surface do not correlate with deeper strata. This result in combination with high variability of particle amounts in the different sampling points throughout the year shows that the distribution of plastic on beaches is very unknown and patchy.

In general, the main colours of the collected items were blue, transparent and white, which assembled mostly from items of water and high tide sediment. These zones showed a similar distribution and besides accounted together for 89% of all particles. The present findings coincide with the results of studies from surface beach sediment of the Canary Island, where transparent and white or grey were determined as the most common colour (Edo et al., 2019; Rapp et al., 2020; Reinold et al., 2020). Assessment of colours in deeper strata of shoreline sediments from Vietnam showed overall a majority of blue and white fibres (Tran Nguyen et al., 2020). In low tide sediment transparent and white still existed in considerable percentage, but main colours were represented by blue and yellow. While yellow particles accounted for lesser amounts in beach sediments (Rapp et al., 2020; Reinold et al., 2020; Tran Nguyen et al., 2020), a recent study found a similar distribution of

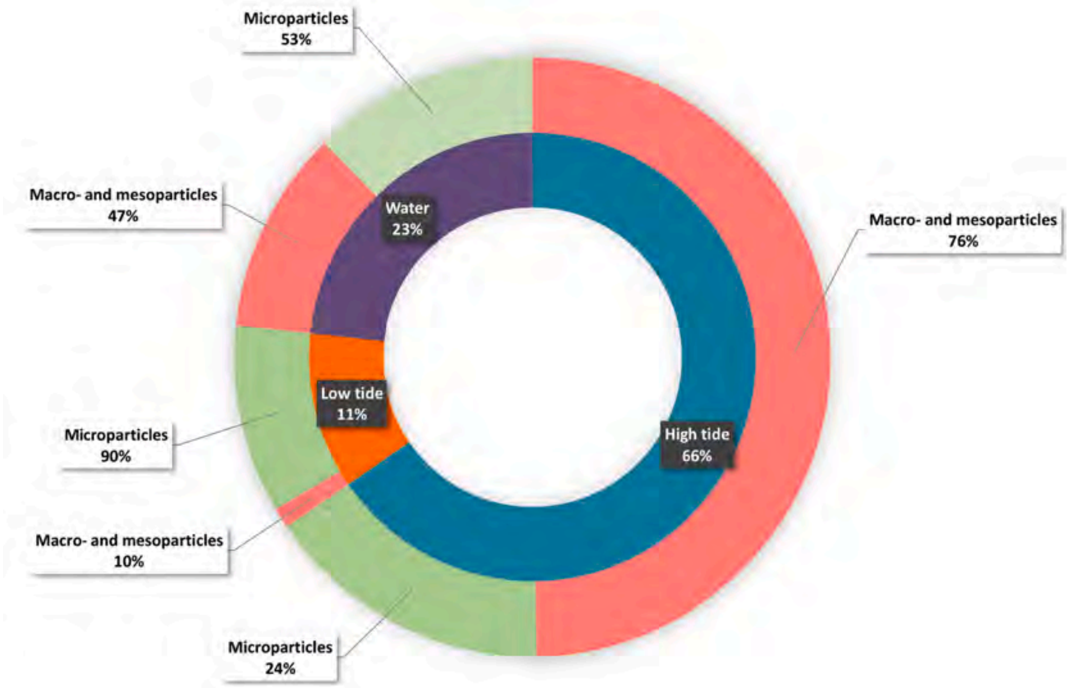

Fig. 7. Size distribution of particles: Inner donut: Particle amount in percentage at each sampling zone; outer donut: Percentage of macro- and mesoparticles (>1 mm) and of microparticles (<1 mm).

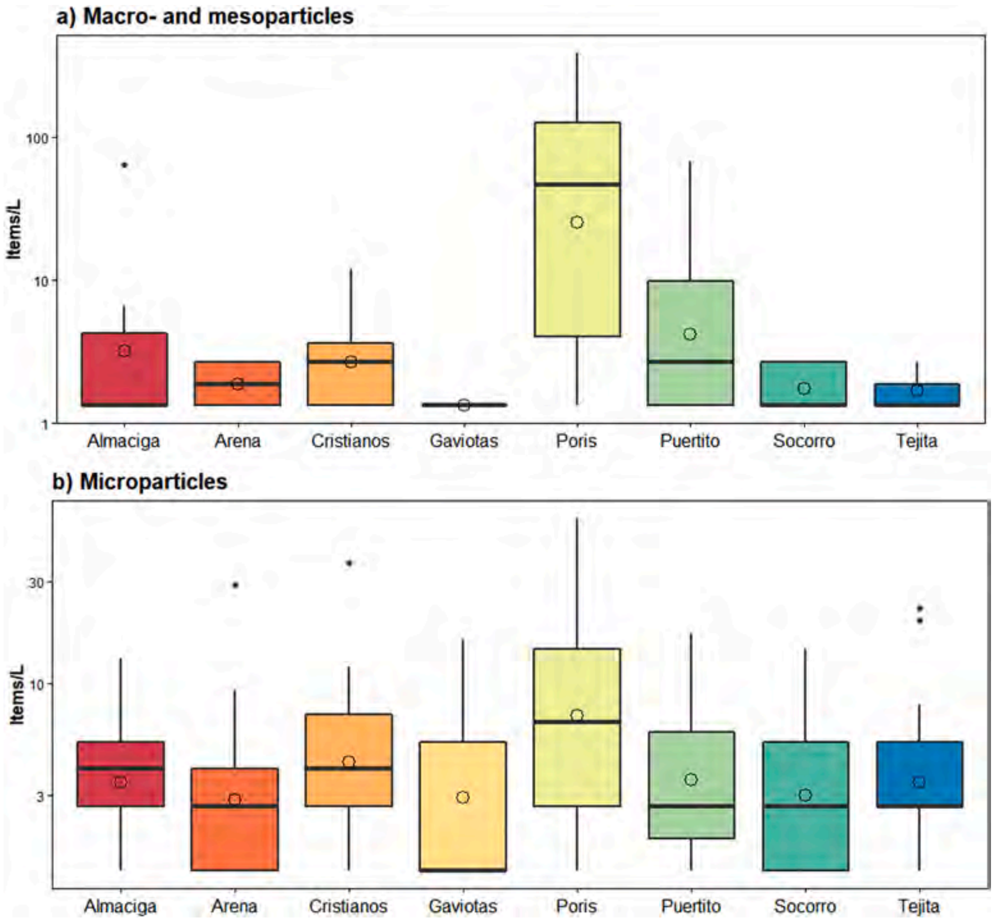

Fig. 8. Particle abundance in items/L of a) macro- and mesoparticles and b) microparticles by sampling location. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile range, the whiskers indicate the lowest and the highest values and the points represent the values of outliers.

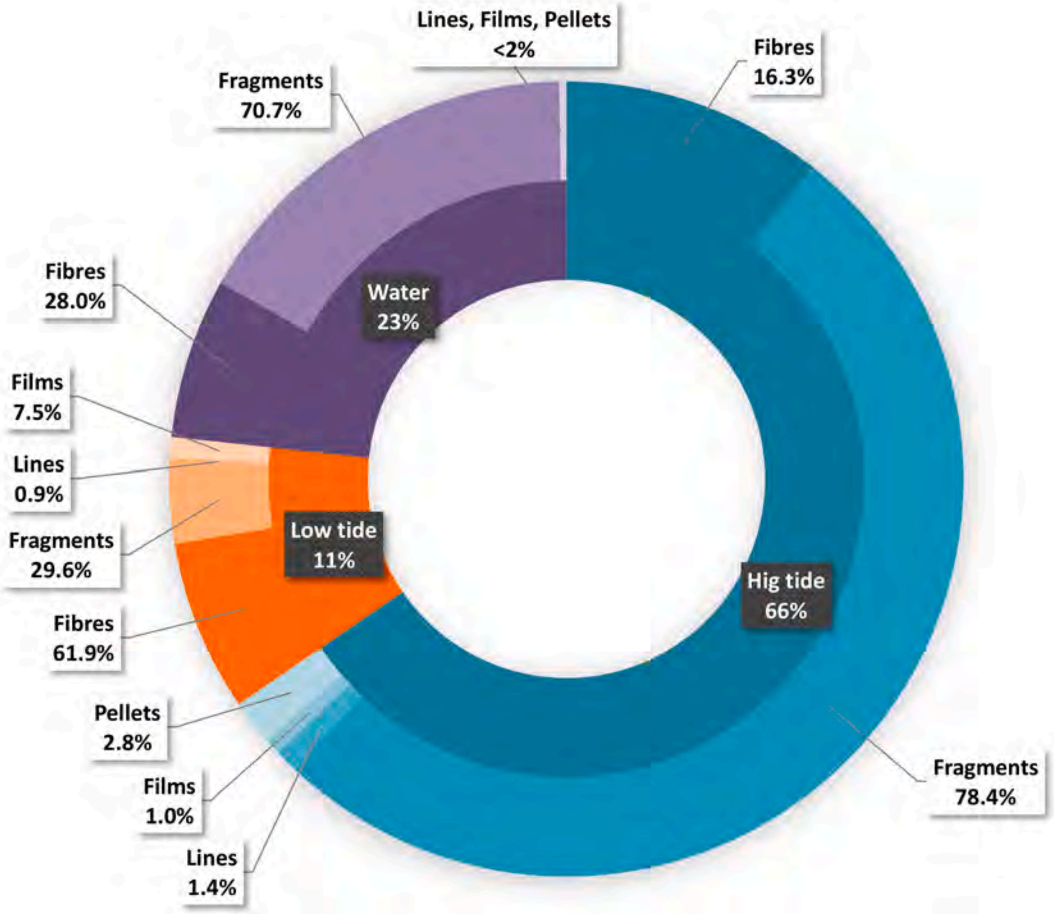

Fig. 9. Shape distribution of particles: Inner donut: Particle amount in percentage at each sampling zone; outer donut: Percentage of fibres, fragments, lines, films and pellets.

blue and yellow particles in the digestion tracts of European sea bass cultivated on the coastline of Tenerife (Reinold et al., 2021). Since similar profiles of microplastic types between fish from fish farms and nearby sediments were detected (Wu et al., 2020), Reinold et al. (2021) suggested that these particles derive from nearby urban areas, either wind-blown or expelled by sewage outflows. Subsequently, they could be dragged by the ocean velocity field as indicated by Vega-Moreno et al. (2021) and end up buried in the sediment. This implies that submerged sediments around coastlines could contain different types of polymers despite of accounting for less particle amounts compared to beach sediments. The lowest variability regarding the colours, but still including the most common colours, was found in Gaviotas, which generally showed a low particle abundance. Oppositely, Puertito presented particles of all colours, while in Poris only silver particles were missing. However, orange particles were exclusively found at these two locations. The wide colour spectrum as well as the presence of a rare colour can be explained by the high particle amounts at these two beaches in general. Despite of lacking silver particles, Poris accounted for significantly more particles for 11 colours compared to other location, which might result from the statistically higher amount of items in the high tide sediment samples. These results confirm the findings of a recent study, where Puertito, but overall Poris were already revealed as a hotspot for beach pollution (Reinold et al., 2020).

All found particles can be considered microplastic according to common classification in agreement with the proposed working definitions of NOAA (Arthur et al., 2008), as particles' sizes never exceeded 5 mm. Nevertheless, since there is no internationally agreed definition so far (GESAMP, 2015), the present study used the proposed size categorization of (Hartmann et al., 2019), which is based on the existing SI nomenclature. As a consequence, macro- and mesoparticles (>1 mm) were more abundant than microparticles (<1 mm), but the size distribution of particles was different in every sampling zone. While in water samples the size classes were almost equally dispersed, sediment samples showed an opposite picture. Low tide sediments contained mainly microparticles, whereas in high tide sediments macro- and mesoparticles dominated. A reason for these contrary results in sediment samples might be the wave moments in coastal areas. The force of breaking waves can easily drag down smaller particles like suspended solids, which subsequently could get buried in submerged sediments. Differently, larger particles get back to their floating status quickly even after water movement due to the higher mass of low density material and therefore could mainly end up washed ashore on the tidal lines. Another explanation for the high amount of macro- and mesoparticles in high tide sediments as well as in general could be the particle contribution of Poris and Puertito. These beaches not only showed the highest amounts of particles in high tide sediment, but also presented significantly more macro- and mesoparticles in general compared to all other beaches.

Overall, fibres and fragments were the predominant shape in all zones and at all locations. The percental distribution in samples from water and high tide sediment are similar. Both zones accounted for more than 70% of fragments, followed by a notable amount of fibres, while in low tide sediment more than double the percentage of fragments were found compared to fibres. Recent studies found mainly fragments and fibres in the waters surrounding the Canary Island (Herrera et al., 2020; Vega-Moreno et al., 2021). Taking in account the size distribution of

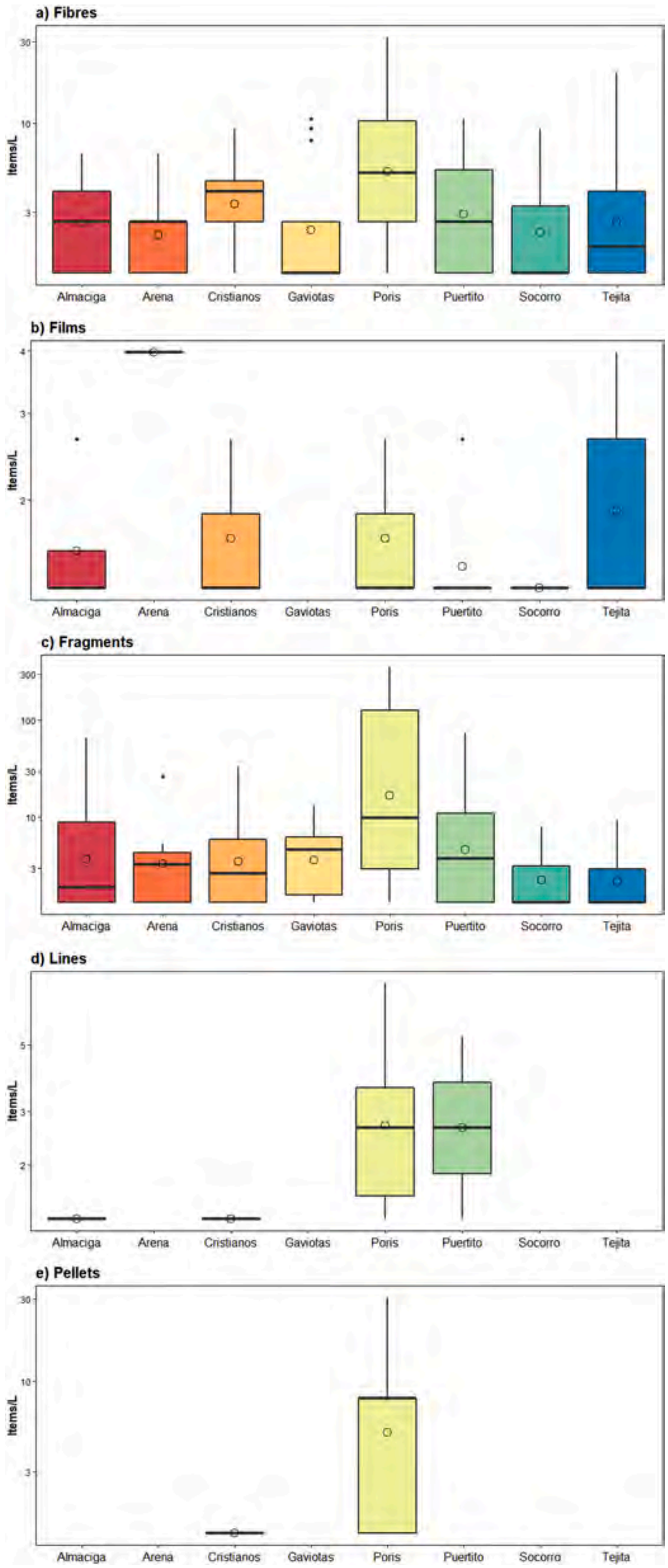

Fig. 10. Particle abundance in Items/L of a) fibres, b) films, c) fragments, d) lines and e) pellets by sampling location. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile range, the whiskers indicate the lowest and the highest values and the points represent the values of outliers.

sediment samples in the present study, former investigations found similar results. Particles in high tide sediments were mainly particles larger than 1 mm and investigations on surface beach sediments from three islands showed overall a majority in fragments regarding this size class (Álvarez-Hernández et al., 2019; Edo et al., 2019; Herrera et al., 2018; Rapp et al., 2020; Reinold et al., 2020). Other investigations on beach sediment from deeper strata, which took into account various types of plastic debris, presented also an increased amount of fragments in these particles (Carson et al., 2011; Yu et al., 2016). Considering low tide sediment samples, particles smaller than 1 mm were more abundant. Rapp et al. (2020) found the majority of these particles being fibres on beach surface of Gran Canaria as well as Claessens et al. (2011) in deeper strata down to 30 cm on the Belgian coast. Another study reported overall the presence of fibres (300-5000 μm) in beach sediment down to 10 cm (Tran Nguyen et al., 2020).

Meso- and macroplastics derived mainly from water and high tide sediment, whereas only 3% came from low tide sediment. Overall, the most identified polymer was PE, which is one of the most produced plastics. In fact, it represents currently the most demanded resin type in Europe (PlasticsEurope, 2020). In water and high tide sediment leading polymers are further PP and PS. All three plastics are commonly abundant in debris from the marine environment (Andrady, 2017; Fok et al., 2017; Frias et al., 2010; Imhof et al., 2017; Karthik et al., 2018; Zhang et al., 2017), including samples from the Canary Islands (Álvarez-Hernández et al., 2019; Edo et al., 2019). However, low tide sediment contained the same amounts of PE, PVC and PTFE. PVC and PTFE are both polymers with densities over 1.4 g/m^3 and therefore likely to be found in sediments (Gago et al., 2018), but both resin types are usually less abundant in recovered marine plastics. The higher percentage in this study might be due to the low macro- and mesoparticle amount (n = 16) found in low tide sediment in general. Microparticles were more evenly distributed throughout the sampling zones, but high tide sediment still accounted for the majority of particles. Identification showed not only a much broader variety all over, but also a more dispersed picture regarding the ratio of polymer types. However, the ones found in considerable amounts have already been reported in former studies (Bergmann et al., 2017; Castillo et al., 2016; Gago et al., 2018; GESAMP, 2015; Munari et al., 2017; Schwarz et al., 2019; Suaria et al., 2016). In Canary Island, four studies identified plastics found in beach sediment (Álvarez-Hernández et al., 2019; Cabrera Dorta, 2018; Camacho et al., 2019; Edo et al., 2019) and one study from fish deriving from close by aquaculture facilities (Reinold et al., 2021). Most common polymers were PP, PE and PS in sediments, but PET, PVC, Nylon and thermoplastic elastomers were detected (Álvarez-Hernández et al., 2019; Cabrera Dorta, 2018; Camacho et al., 2019; Edo et al., 2019). Fish, however, showed a broader spectrum of polymer types including PP, PE, PS, SAN, PA, EPDM, E/P, EVA, acrylic, polynorbornene as well as epoxy resin and phenolic resin (Reinold et al., 2021). Additionally, fibres were identified as cellulose and rayon. This gives an understanding on what materials are floating in the surrounding waters of Tenerife. Most of these polymers were also found in the present study, except SAN, acrylic and polynorbornene. However, it is well known that plastic debris is much more than only an aesthetical problem, as it has the potential to carry a wide range of pollutants (Ogata et al., 2009; Rios et al., 2010). These consist basically of chemical additives added during manufacturing or contaminants, which have been absorbed by plastic fragments during their travel through the environment (Bakir et al., 2014; Camacho et al., 2019; Lee et al., 2014; Moore et al., 2005). As plastic can accumulate concentrations of pollutants a hundred times greater than organic fractions in sediments (Wang et al., 2016), contaminants are found in marine sediments all around the world (Hermabessiere et al., 2017; Romeo et al., 2015). As a consequence, biotas and their eggs on beaches can be affected (Saliu et al., 2020; Wang et al., 2016).

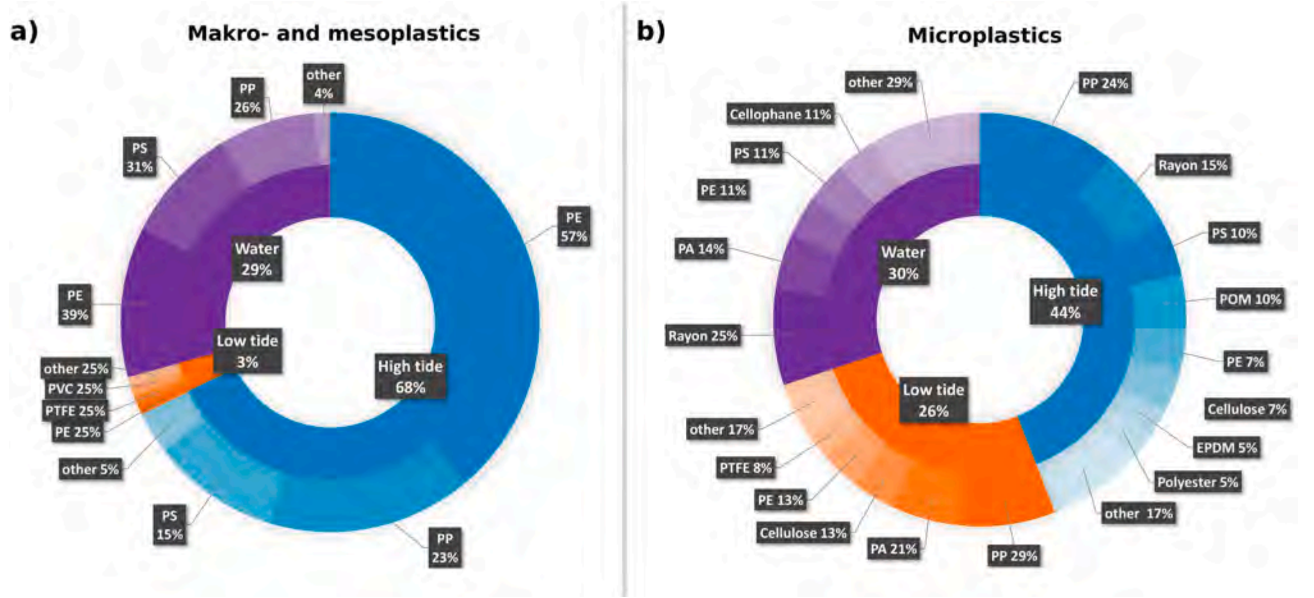

Fig. 11. Polymer types of plastics. Inner donuts: Particle amount in percentage at each sampling zone; outer donuts: Percentage of polymer types. a) Macro- and mesoplastics (>1 mm): “Other” identified polymers were: Cellulose, EPDM, ethylene/methacrylic acid ionomer, PA, PB, phenoxy resin, PP/PE copolymer, propylene/acrylic acid copolymer, PU, rayon and vinyl chloride. b) Microplastics (<1 mm): “Other” identified polymers were: Cellophane, EPDM, epoxy resin, EVA, PDMS, phenolic resin, polyetherurethane, PP/PE copolymer, POM copolymer, PS, PU, PTFE, PVA and PVDC. Abbreviations: EVA: ethylene-vinyl acetate, EPDM: ethylene-propylene-dien-monomer, PA: polyamide, PB: polybutylene, PDMS: polydimethylsiloxane, PE: polyethylene, POM: polyoxymethylene, PP: polypropylene, PS: polystyrene, PTFE: polytetrafluoroethylene, PU: polyurethane, PVA: polyvinyl alcohol, PVC: polyvinyl chloride, PVDC: polyvinylidene chloride.

5. Conclusion

In summary, our study demonstrated that sediment samples of beaches from Tenerife presented significantly more plastic than surface water from the corresponding coastline. On average, particle amounts are higher in sediments from the high tide line than from submerged zones. The particle concentrations were variable for each sampling zone throughout the year. Transparent/white fragments and fibres (>1 mm) were the most common found particles, resembling more between high tide sediments and water than between the two sediment zones. Sediments from submerged zones presented mainly blue and yellow microplastics, consisting more out of fibres than of fragments. Polymer types of particles > 1 mm were mainly represented by plastics, which are commonly recovered from the marine environment such as PE, PP, PS, PTFE and PVC. Smaller particles, however, showed a broader spectrum of polymer types including overall 24 different polymers being the most common ones: PP, PA and rayon.

CRediT authorship contribution statement

S.R. designed the experimental work, executed the sampling, processed the samples in the laboratory, performed spectroscopical analyses via FTIR, conducted statistical analysed via R (including generation of graphics), and wrote the manuscript. F.S. and N.S. performed spectroscopical analyses via μFTIR. C.H. contributed to design the experimental work. Z.O. and M.D.M. administered spectroscopical analyses of FTIR. A.H. supervised data analyses, statistical analyses and manuscript form. All authors contributed to the acquisition of the data and edited the article.

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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