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Plastic pollution on coastlines of Tenerife and its impact on farmed fish

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Universidad de las Palmas de Gran Canaria

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D/Dª DANIEL MONTERO VÍTORES COORDINADOR DEL PROGRAMA DE DOCTORADO ACUICULTURA SOSTENIBLE Y ECOSISTEMAS MARINOS DE LA UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

INFORMA,

De que la Comisión Académica del Programa de Doctorado, en su sesión de fecha .... tomó el acuerdo de dar el consentimiento para su tramitación, a la tesis doctoral titulada "Plastic pollution on coastlines of Tenerife and its impact on farmed fish" presentada por la doctoranda D/Dª Stefanie Reinold y dirigida por la Doctora May Gómez Cabrera.

Y para que así conste, y a efectos de lo previsto en el Artº 11 del Reglamento de Estudios de Doctorado (BOULPGC 04/03/2019) de la Universidad de Las Palmas de Gran Canaria, firmo la presente en Las Palmas de Gran Canaria, a ... de .... de dos mil.....................

PLASTIC POLLUTION ON COASTLINES OF TENERIFE AND ITS IMPACT ON FARMED FISH

MEMORIA PRESENTADA PARA OPTAR EL GRADO DE DOCTOR POR LA UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

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Esta tesis está dedicada a la persona que debo mi vida,
MI MADRE

"No llores porque ya se terminó, sonríe porque sucedió."

„Weine nicht, weil es vorbei ist. Lächle, weil es passiert ist"

Auch wenn ich oft weine, weil du nicht mehr in meinem Leben bist, weiß ich, dass du an meiner Seite bist und mir hilfst immer wieder aufzustehen und weiter zu machen.

Agradecimientos

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- **Yanyi & Yadira**: Por ayudar generosamente a una completamente extraña se formó una amistad y posteriormente amor. **Yanyi:** Me ayudaste todos los días desde pagar la gasolina, a ayudar a recoger muestras durante horas de madrugada y de noche, a ser mi chófer y asistente del laboratorio cuando me lastime la mano, a seguirme por la vuelta de Europa y mudarte (3 veces), a empujarme de no rendirme cuando las cosas eran difíciles hasta tener la paciencia y quedarte a mi lado durante todo el proceso del doctorado. **Yadira:** Me trataste desde el primer momento como una hija, aconsejándome y escuchando mis preocupaciones y dolores. Ustedes dos se convirtieron en estos años en la familia, que pensé que nunca volvería a tener.
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- **Jay**: La única persona que creyó en mi cuando nadie más lo hizo. Gracias por recordarme todos los días que el doctorado es mi "hueso para el perro"
- **Andreas**: Gracias por horas analizando el MPSS con el fin de fabricarme una réplica adaptado a mis necesitades para poder realizar este trabajo
- **Andreas y Schlicki**: Gracias por proporcionarme un techo cada vez que regresé a Alemania
- **Rosi**: Gracias por creer e "invertir" en mí.

Índice

Abreviaturas

ABS	Acrilonitrilo butadieno estireno
BDE209	Éter de decabromodifenilo
COP	Contaminante orgánico persistente
DBP	Ftalato de dibutilo (Dibutilftalato)
DDT	Dicloro difenil tricloroetano
DEHP	Ftalato de di-(2-etilhexilo) (di-2-etilhexilftalato)
DEP	Ftalato de dietilo (Dietilftalato)
EPS	Poliestireno expandible
EPDM	Caucho de etileno propileno dieno
FAO	Food and Agriculture Organization of the United Nations
FTIR	Fourier-transform infrared spectroscopy (Espectrofotómetro de transformada de Fourier)
HBCD	Hexabromociclododecano
HCH	Lindano (Hexachlorociclohexano)
INE	Instituto Nacional de Estadística
PA	Poliamida
PAH	Hidrocarburo aromático policíclico
PBDE	Polibromodifenil éteres

PC	Policarbonato
PCB	Bifenilos policlorados (Policlorobifenilos)
PE	Polietileno
PET	Tereftalato de polietileno
PMMA	Polimetilmetacrilato
PP	Polipropileno
PS	Poliestireno
POM	Polioximetileno
PTFE	Politetrafluoroetileno
PUR	Poliuretano
PVC	Cloruro de polivinilo
SAN	Estireno acrilonitrilo
WoRMS	World Register of Marine Species

Anotaciones de interés

Nombre y Municipio de las ocho playas investigadas por la presencia de residuos plásticos:

Playa de Almaciga: denominada “Almaciga”; Municipio: Santa Cruz de Tenerife

Playa de la Arena: denominada “Arena”; Municipio: Santiago del Teide

Playa de la Tejita: denominada “Tejita”; Municipio: Granadilla de Abona

Playa de las Gaviotas: denominada “Gaviotas”; Municipio: Santa Cruz de Tenerife

Playa de las Vistas: denominada “Cristianos”; Municipio: Arona

Playa del Puertito de Adeje: denominada “Puertito”; Municipio: Adeje

Playa del Socorro: denominada “Socorro”; Municipio: Los Realejos

Playa Grande: denominada “Poris”; Municipio: Arico

Normativas y reglamento

El Reglamento de Estudios de Doctorado de la Universidad de Las Palmas de Gran Canaria, aprobado por el Consejo de Gobierno el 17 de diciembre de 2012 (BOULPGC de 09/01/2013) y su última modificación del 26 de febrero de 2019 (BOULPGC de 04/03/2019), establece en el artículo 12 los requisitos para obtener una tesis doctoral por compendio:

Artículo 12.- Tesis por compendio de publicaciones

1. Para la presentación de tesis por compendio de publicaciones será necesario:

a. Un mínimo de tres publicaciones, con unidad temática, indexadas en el Journal Citations Reports, Arts and Humanities Citation Index o equivalentes, de las que el doctorando sea el primer autor o autor principal. Al menos una de ellas deberá haber sido publicada en una revista cuyo índice de impacto la sitúe dentro de la primera mitad en orden decreciente de índice de impacto entre las revistas del área.

b. Para acreditar la condición de autor principal, esta deberá ser reconocida por el resto de los autores de las publicaciones presentadas como núcleo de la tesis doctoral, al mismo tiempo que estos deberán renunciar a utilizar estas publicaciones como núcleo principal de otras tesis doctorales, sin perjuicio de que dichas publicaciones puedan ser presentadas como méritos complementarios en las tesis doctorales que pudieran presentar los otros autores de dichas publicaciones.

c. En áreas de especial incidencia tecnológica dos de estas publicaciones podrán ser sustituidas por patentes en explotación o publicaciones en congresos reconocidos por la ANEP en sus baremos para la obtención de sexenios.

d. Que en las publicaciones o patentes conste la ULPGC a través de la filiación del director o del doctorando.

2. Las tesis doctorales presentadas como compendio de publicaciones deberán ajustarse al formato establecido en los apartados del 1 al 3, del artículo 11 del presente Reglamento y contener los apartados siguientes:

a. Una introducción en la que se presenten los objetivos de la tesis, los trabajos publicados y la justificación de la unidad temática de la tesis.
b. Una copia de los trabajos publicados.
c. Las conclusiones finales.
d. En el caso de que lo dispuesto en los apartados a y c se haya redactado en una lengua diferente del español, deberá incluirse un resumen en español según el artículo 10 del presente reglamento.

Adaptaciones a la presente tesis doctoral

De acuerdo con el artículo 12 del Reglamento de Estudios de Doctorado de la Universidad de Las Palmas de Gran Canaria se elaboró el documento de la tesis doctoral. Se presentan tres publicaciones utilizadas como compendio cuya primera autora es la doctoranda y siendo publicadas en una revista científica del ámbito temático indexadas con un alto factor de impacto en el Journal Citations Reports

1. **Reinold, S.**, Herrera, A., Hernández-González, C., Gómez, M., 2020. Plastic pollution on eight beaches of Tenerife (Canary Islands, Spain): An annual study. Marine Pollution Bulletin 151, 110847. https://doi.org/10.1016/j.marpolbul.2019.110847 (Q1; IF: 5.553)

2. **Reinold, S.**, Herrera, A., Stile, N., Saliu, F., Hernández-González, C., Martinez, I., Ortega, Z., Marrero, M.D., Lasagni, M., Gómez, M., 2021. An annual study on plastic accumulation in surface water and sediment cores from the coastline of Tenerife (Canary Island, Spain). Marine Pollution Bulletin 173, 113072. https://doi.org/10.1016/j.marpolbul.2021.113072 (Q1; IF: 5.553)

3. **Reinold, S.**, Herrera, A., Saliu, F., Hernández-González, C., Martinez, I., Lasagni, M., Gómez, M., 2021. Evidence of microplastic ingestion by cultured European sea bass (*Dicentrarchus labrax*). Marine Pollution Bulletin 168, 112450. https://doi.org/10.1016/j.marpolbul.2021.112450 (Q1; IF: 5.553)

En conformidad con lo establecido en el artículo 12.1.a se justifica la unidad temática de las publicaciones aportadas:

Normativas & Reglamento

La unidad temática de las publicaciones que integran esta tesis por compendio es manifiesta, pues todas versan sobre la contaminación marina por microplásticos en general, teniendo en cuenta tanto la contaminación en el mar abierto como en las franjas costeras. En esta temática entra además la contaminación en sedimentos y biota relacionados con el mar y experimentos con tales

Resumen

La contaminación marina por plásticos es un problema bien conocido hoy en día y se ha investigado a nivel global. La presencia de plástico se ha reportado en el agua del mar, en las costas y en una amplia gama de organismos marinos en todos los partes del planeta. La mayoría de estos estudios se centran en las aguas superficiales de los océanos, como en los denominados "parches de basura", en las capas superficiales de sedimentos en playas arenosas como indicación de magnitud de partículas arrastradas a la costa y en los tractos digestivos de animales marinos como prueba de su ingestión.

Sin embargo, los estudios sobre contaminación de playas en las Islas Canarias y especialmente en Tenerife son escasos (Álvarez-Hernández et al., 2019; Villanova Solano et al., 2018), aunque por su ubicación existe un alto riesgo de acumulación de plásticos en las costas arrastrados por la Corriente de Canarias, que forma parte del Giro del Atlántico Norte, el cual está altamente contaminado. Además, en ninguno de los citados estudios se investigó la distribución vertical del plástico en sedimentos costeros ni la cantidad entrante de plásticos en agua superficial cercana a la costa.

Por otra parte, las Islas Canarias – en particular Gran Canaria y Tenerife – juegan un importante papel en la producción acuícola de peces en España, pero hasta ahora solo se han investigado los peces salvajes que habitan en las regiones costeras de las Islas Canarias en cuanto a la ingestión de plástico (Herrera et al., 2019).

El presente estudio se diseñó con la intención de continuar la investigación sobre la contaminación marina por plásticos en las Islas Canarias y especialmente en Tenerife, centrándose en dos puntos claves:

1. La variabilidad anual de la contaminación por plástico en playas arenosas con diferentes orientaciones y presión antropogénica.
2. La ingestión de plástico en peces cultivados en jaulas de acuicultura en la zona costera.

Por lo tanto, se han atendido los siguientes objetos específicos:

- Evaluación de composición de los residuos marinos arrastrados a la orilla en ocho playas arenosas de Tenerife con el objetivo de identificar los "hotspots" de acumulación de plástico tanto en las propias localizaciones como a lo largo de cada playa.
- Extracción e identificación de residuos de plástico de sedimentos de capas más profundos en diferentes zonas costeras con el objetivo de investigar las diferencias de acumulación entre zonas.
- Extracción e identificación de los residuos de plástico de agua superficial cercano a la costa con el objetivo de comparar el plástico entrante con la acumulación de plástico en los sedimentos de la playa.
- Evaluación e identificación de partículas de plástico ingeridas por peces de cultivo para evaluar los riesgos para animales destinados al consumo humano.

Esta tesis se presenta como un compendio de tres artículos, que describen los resultados y la interpretación de los análisis visuales y espectroscópicos realizados. Dichos artículos están publicados en una revista de alto impacto científico (IF: 5.553), que además ocupa la posición 3 de un total de 110 revistas en la lista de MARINE & FRESHWATER BIOLOGY.

Este trabajo representa el primer estudio anual de la contaminación por plásticos en la costa de Tenerife, incluyendo tanto sedimentos superficiales como sedimentos más profundos procedentes de diferentes zonas de playas arenosas y el agua superficial de cada costa. Además, se investigaron peces cultivados en jaulas cercanas a la costa de la isla.

Abstract

Marine plastic pollution is a well-known problem nowadays and it has been investigated all over the globe. The presence of plastic was reported worldwide in sea water, on coastlines and in a wide range of marine organisms. Most of these studies focus on the surface waters of the oceans such as in so called “garbage patches”, the superficial sediment layers on sandy beaches as indication of washed ashore particle amounts on coastlines and the digestive tracts of marine animals as evidence of ingestion.

However, studies on beach pollution in the Canary Islands and specially in Tenerife are scarce (Álvarez-Hernández et al., 2019; Villanova Solano et al., 2018), although due to its location there is a high risk of plastics accumulating on shorelines dragged by the Canary Current, which is part of the highly polluted North Atlantic Gyre. Moreover, none of these investigated the vertical distribution of plastic in coastal sediments nor the incoming amount of plastics in near coastal surface water.

The Canary Islands – particularly Gran Canaria and Tenerife – furthermore play an important role in the aquaculture production of fish in Spain, but so far only wild fish inhabiting coastal regions of the Canary Islands have been investigated for ingested plastic (Herrera et al., 2019).

The present study was designed with the intention to continue the research on marine plastic pollution in Canary Islands and especially in Tenerife, focusing on two key points:

1. Annual variability of plastic pollution on sandy beaches with different orientations and anthropogenic pressure.
2. Ingestion of plastic by fish cultured in coastal waters.

Therefore, the following specific objects have been attended:

- Evaluation of the composition of washed ashore marine debris on eight sandy beaches of Tenerife with the aim to identify hotspots for plastic pollution as in locations themselves as well as alongside every beach.
- Extraction and Identification of plastic debris of sediments of deeper strata from different coastal zones with the aim to investigate accumulation differences between zones.
- Extraction and Identification of plastic debris of near coastal surface water with the aim to compare incoming plastic with accumulation of plastic in beach sediments
- Evaluation and Identification of plastic particles ingested by cultured fish to assess risks for animals destinated for human consumption

This thesis is presented as a compendium of three articles, which describe the results and interpretation of the conducted visual and spectroscopic analyses. These articles are published in a journal of high scientific impact (IF: 5.553), which is in addition ranked at position 3 out of 110 journals in the list of MARINE & FRESHWATER BIOLOGY.

This work represents the first annual study of plastic pollution on coastlines of Tenerife, including both superficial sediments as well as sediment cores deriving from different areas of sandy beaches and the corresponding surface water of each shore. Additionally, fish cultivated close to the coast of the island were investigated.

Capítulo I

Antecedentes y Objetivos del estudio

CAPÍTULO I: ANTECEDENTES Y OBJETIVOS DEL ESTUDIO

1 Plástico

1.1 Definición

"All plastics are polymers but not all polymers are plastics."

Los plásticos son materiales hechos principalmente de polímeros orgánicos de alto peso molecular (Gorycka, 2009; Zalasiewicz et al., 2016). Son eficientes en cuanto a recursos, derivados de productos orgánicos como la celulosa, el almidón, el carbón, el gas natural, la sal y, por supuesto, el petróleo crudo (Gilbert, 2017; Gorycka, 2009). La descomposición térmica de la materia prima conduce a la extracción de monómeros (el etileno, el propileno, el butano/butilenos y los aromáticos) y es seguida por el proceso de polimerización (Gorycka, 2009). Las características importantes de los plásticos son sus propiedades técnicas, como la maleabilidad, la dureza, la elasticidad, la resistencia a la rotura, la resistencia a la temperatura, la resistencia al calor y la resistencia química, que pueden variar dentro de unos límites amplios mediante la elección de macromoléculas, los procesos de fabricación y, por regla general, la mezcla de aditivos (Gorycka, 2009; Hartmann et al., 2019). Actualmente los diferentes materiales se clasifican habitualmente según su comportamiento frente al calor en dos categorías:

1.1.1 1. *Termoplásticos*

Los termoplásticos son plásticos formados por moléculas lineales largas (Goldstein, 2012). Al añadir calor, estos materiales se vuelven blandos y maleables repetidamente y finalmente se funden (Gorycka, 2009). Se les puede dar la forma deseada y, una vez que la pieza se ha enfriado, conservan su forma. Este proceso es reversible por el comportamiento de las macromoléculas filamentosas y lineales (Goldstein, 2012; Gorycka, 2009). Algunos ejemplos comunes son PE, PET, PP, PVC y PS (UNEP, 2016). La variedad de termoplásticos es mucho mayor, y se han clasificado en tres grupos (Gilbert, 2017):

a) Los plásticos básicos son materiales de alto volumen de consumo y de bajo coste

b) Los plásticos de ingeniería son generalmente más caros, y con menor consumo

c) Los plásticos de alto rendimiento son materiales de alto coste y bajo volumen de consumo

1.1.2 2. *Termoestables*

Los termoestables son polímeros que se producen en un proceso de endurecimiento a partir de una fusión o solución de los componentes creando una red tridimensional (Goldstein, 2012). Esta reacción irreversible por el comportamiento de las macromoléculas espacialmente reticuladas y suele ser provocada por el calentamiento (Andrady, 2017; Gorycka, 2009). El recalentamiento no conduce a la maleabilidad del plástico, sino sólo a su descomposición. Por lo tanto, los termoestables endurecidos suelen ser duros y resistentes al calor (Gorycka, 2009). Algunos ejemplos comunes son PUR, las resinas epoxi o revestimientos (UNEP, 2016).

1.2 La historia del plástico

El inicio del uso de polímeros se remonta al menos al siglo XVI a. C., cuando las antiguas culturas mesoamericanas procesaban el caucho natural, adquiriendo látex del árbol de *Castilla elástica* y mezclándolo con el jugo de *Ipomoea alba* (Hosler et al., 1999). Del material resultante hicieron pelotas de goma maciza, figuras humanas de goma maciza y hueca, bandas anchas de goma para sujetar las cabezas de las hachas de piedra a los mangos de madera y otros artefactos (Hosler et al., 1999). La industrialización sin embargo empezó en el siglo XIX, época de la que también está bien documentada la producción. El material que se considera comúnmente como el primer plástico es realmente caucho vulcanizado, que se formó debido a una reacción entre caucho y azufre bajo calor. Dicha vulcanización fue descrita primero por Charles Goodyear y poco después por Thomas Hancock, que patentaron el descubrimiento casi al mismo tiempo (Hancock: 1843 en Inglaterra; Goodyear: 1844 en Estados Unidos) (Gilbert, 2017; Goodyear, 1844; Hancock, 1843; Slack, 2002). En las extensiones de este trabajo sobre la vulcanización obtenían un producto duro llamado ebonita o “caucho duro” (Gilbert, 2017; Massy, 2017). La ebonita se suele pasar por alto en la historia de los materiales plásticos. Sin embargo, su importancia radica en que la ebonita fue el primer material plástico termoestable que se preparó y también el primer material plástico que supuso una modificación química distinta de un material natural (Gilbert, 2017; Massy, 2017; Seymour, 1981). A mediados del siglo XIX, el inventor inglés Alexander Parkes inventó “parkesina” – el primer termoplástico, también considerado el primer plástico fabricado por el hombre, pero aún no totalmente sintético (Gilbert, 2017; Massy,2017; Rasmussen, 2021). Se fabricó a partir de celulosa tratada con ácido sulfúrico y ácido nítrico (también conocido como piroxilina o nitrocelulosa) mezclado con aceites modificados y pequeñas proporciones de disolventes orgánicos, así como con cloruros metálicos (Rasmussen, 2021). La parkesina no es tan conocida como su sucesor, el celuloide, ya que su época sólo duró hasta 1868 debido al fracaso económico de Parkesine Co., Ltd y por tanto al cese de la producción (Gilbert, 2017; Rasmussen, 2021). Dos años más tarde John Wesley Hyatt y su hermano obtuvieron una patente en Estados Unidos para un proceso de producción de un material similar utilizando nitrato de celulosa y alcanfor, de lo cual el resultado todavía se conoce como celuloide (Gilbert, 2017; Massy, 2017; PlasticsEurope, 2013; Rasmussen, 2021). Mientras que la parkesina y el celuloide fue el primer material plástico obtenido por modificación química de un polímero que se explotó, los fenólicos fueron las primeras resinas totalmente sintéticas de éxito comercial. Aunque la capacidad del formaldehído para formar sustancias resinosas ya había sido observada por los químicos en la segunda mitad del siglo XIX, el primer plástico totalmente sintético es considerado la baquelita, desarrollada por Leo Baekeland y patentada en 1907 (Crespy et al., 2008; Gilbert, 2017; PlasticsEurope, 2013). Con la explotación comercial de la baquelita, la era del plástico había comenzado: El nylon, el PS, el PVC, el PE y el PTFE empezaron a producirse a finales de los años 30 y 40, el PP y la espuma del EPS en los años 50, y el PET se patentó en 1973 (Zalasiewicz et al., 2016). El desarrollo de nuevos tipos de plástico continúa hasta hoy en día.

1.3 Producción y demanda de plástico

En los últimos 100 años, no sólo ha aumentado la diversidad de los plásticos, sino también la demanda y por lo tanto la producción global se ha incrementado enormemente. Tras el descubrimiento de la baquelita en 1907, se creó la General Bakelite Company en 1910 (Gilbert, 2017). En pocos años, el material se impuso en muchos campos, en particular para el aislamiento eléctrico. Cuando Baekeland falleció en 1944, la producción mundial de solamente resinas fenólicas era del orden de 175.000 toneladas al año (Gilbert, 2017). Incluyendo todo tipo de plásticos disponibles, en 1950 se fabricaron 1.7 millones de toneladas (MT) de plástico al nivel global (PlasticsEurope, 2013). Desde entonces la extraordinaria expansión mundial de este material puede verse en un espectacular aumento, llegando a los 368 MT que se producen anualmente en la actualidad (Fig. 1) (PlasticsEurope, 2020).

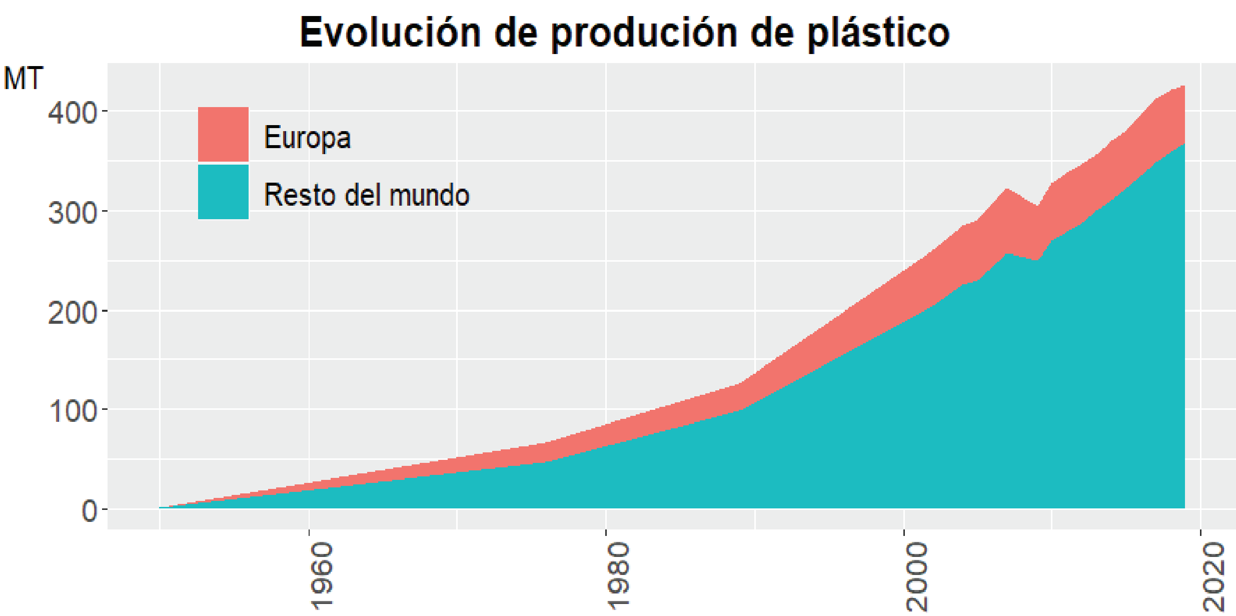

Fig. 1: La evolución de producción de plástico en millones de toneladas (MT) desde 1950 a nivel europeo y global (Datos obtenidos de PlasticsEurope, 2020, 2019, 2018b, 2018a, 2016, 2015, 2014 y 2013).

Más de la mitad (51%) de todo el plástico producido se fabrica en Asia, incluyendo el 31% que recae solamente sobre China (PlasticsEurope, 2020). Además, una gran cantidad se produce también en los países de TLCAN (19%) y en Europa (16%) (PlasticsEurope, 2020). Mientras que la producción global de plástico mostró un crecimiento continuo desde el principio, las cifras de producción en Europa se mantuvieron estables entre 55-65 MT anuales desde 2002 (PlasticsEurope, 2020, 2018a, 2016, 2015, 2013). Aunque la demanda en Europa también se mantuvo estable en torno a los 50 MT anuales en los últimos años desde 2014, se puede observar una tendencia ligeramente creciente – excepto en el año 2019 (PlasticsEurope, 2020, 2019, 2018b, 2018a, 2016, 2015). Desde 10 años (2011) seis países europeos cubren casi el 70% de la demanda europea – Alemania, Italia, Francia, España, Reino unido y Polonia (PlasticsEurope, 2020, 2018a, 2016, 2014). Alemania e Italia son los países líderes con aproximadamente un 25% y un 14% respectivamente, pero España sigue formando parte de los países que convierten más de 3 MT de plástico al año (PlasticsEurope, 2020).

1.4 Tipos de plásticos y su uso

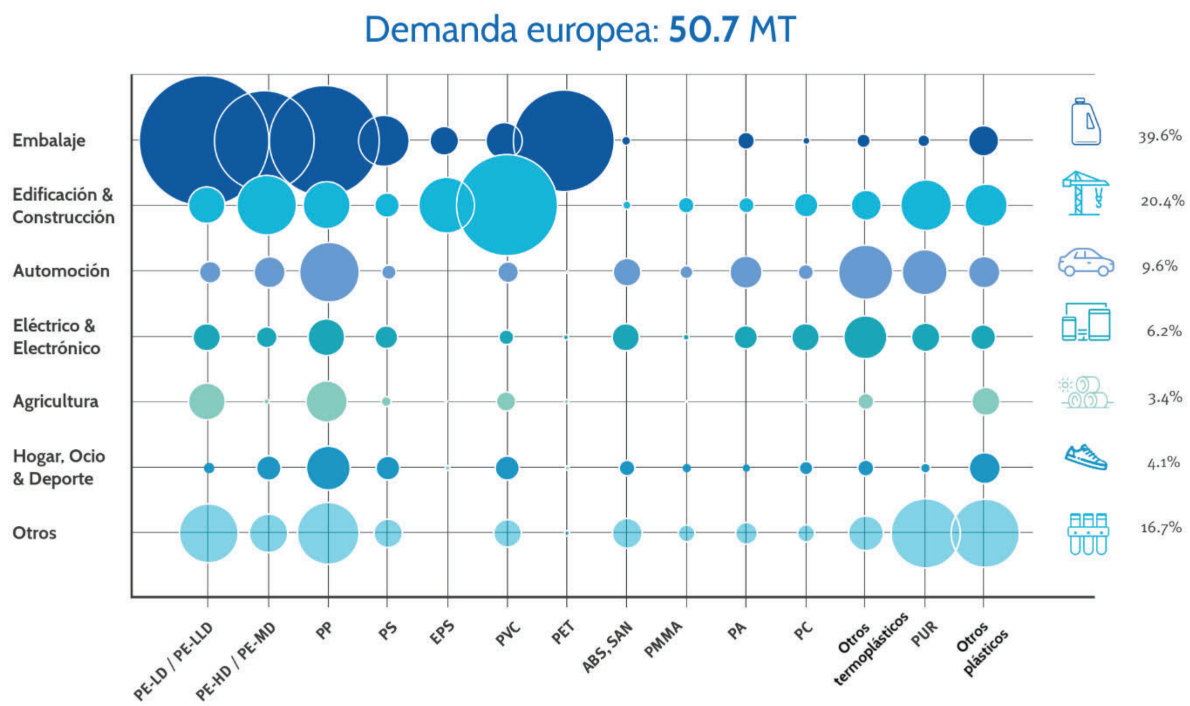

Fig. 2: La demanda europea de plásticos por polímeros y sus usos in 2019 (Gráfico adaptado de PlasticsEurope, 2020).

Actualmente, en Europa los tipos de plástico más solicitados son las poliolefinas, como el PE y el PP. Precisamente estos dos representan casi la mitad (49.2%) de todo el plástico demandado en Europa y se utilizan principalmente en embalajes (Fig. 2) (PlasticsEurope, 2020). El PP se utiliza sobre todo para el envasado de alimentos, envoltorios de dulces y aperitivos, tapas abatibles y contenedores para microondas, pero también para tuberías, piezas de automóviles y billetes de banco (PlasticsEurope, 2020). En cambio, el uso del PE depende de su densidad. Así, el PE de baja densidad (LDPE) se utiliza para bolsas reutilizables, bandejas y contenedores, película agrícola, película para envasar alimentos, etc. y el PE de alta densidad (HDPE) se utiliza para botellas de leche, botellas de champú, tuberías, juguetes y artículos para el hogar (PlasticsEurope, 2020). Una demanda alta se observa además para el PVC (10%), el PUR (7.9%) el PET (7.9%) y el EPS/PS (6.2%) (PlasticsEurope, 2020). Mientras el PET se utiliza – igual que el PP y el PE – principalmente en envases como botellas para agua, refrescos, zumos, limpiadores, etc. el PVC se produce en su mayor parte para la construcción, por ejemplo, para marcos de ventanas, revestimiento de suelos y paredes, tuberías, aislamiento de cables, mangueras de jardín o piscinas hinchables (PlasticsEurope, 2020). El PUR se utiliza en la construcción, la automoción, la eléctrica y electrónica y para productos de hogar, ocio y deporte, pero menos en la agricultura o el embalaje (PlasticsEurope, 2020). Al igual que el PUR, el PS se utiliza en una amplia gama de aplicaciones, mientras que el EPS se utiliza casi exclusivamente en la construcción y en menor medida en los envases (PlasticsEurope, 2020). ABS/SAN, PA, PC, PMMA y son otros ejemplos de tipos de plástico importantes, pero con una demanda anual de menos de 1.5 MT (PlasticsEurope, 2020). Los porcentajes restantes corresponden a otros plásticos, el 11.3% de los cuales son otros termoplásticos (PlasticsEurope, 2020).

1.5 Gestión de plástico en Europa

A diferencia de materia orgánica, minerales o metales, el plástico se convierte en basura al final de su vida útil, que se tiene que recoger y tratar. Teniendo en cuenta, que algunos productos tienen una vida útil de menos de un año, y otros de 50 años o más, la cantidad de basura de plástico no tiene por qué coincidir con la demanda de plásticos del mismo año. Hasta 2015 la humanidad produjo ya 6300 millones de toneladas métricas (MMT) de residuos plásticos, de los cuales aproximadamente sólo el 9% se recicló (Geyer et al., 2017). Una Estimación para 2010 mostró, que China era, con diferencia, el país con mayor índice (8.82 MMT/año) de residuos plásticos mal gestionados, de los cuales aproximadamente 1.32 – 3.53 MMT se convirtieron en basura marina (Jambeck et al., 2015). Aunque ningún país europeo entro en aquella estimación en los 20 principales países, si se hubieran considerado colectivamente los países costeros de la Unión Europea (23 en total), habrían ocupado el decimoctavo lugar (Jambeck et al., 2015). Sin embargo, al igual que la demanda en Europa, la cantidad de los plásticos recogidos se mantuvo estable en torno a los 25 MT anuales hasta 2014, cuando empezaron a incrementar (PlasticsEurope, 2020, 2018b, 2016). En 2018 se recogieron 29.1 MT de plástico post-consumo, lo que suponía un aumento del 19% desde 2006 (Fig. 3)

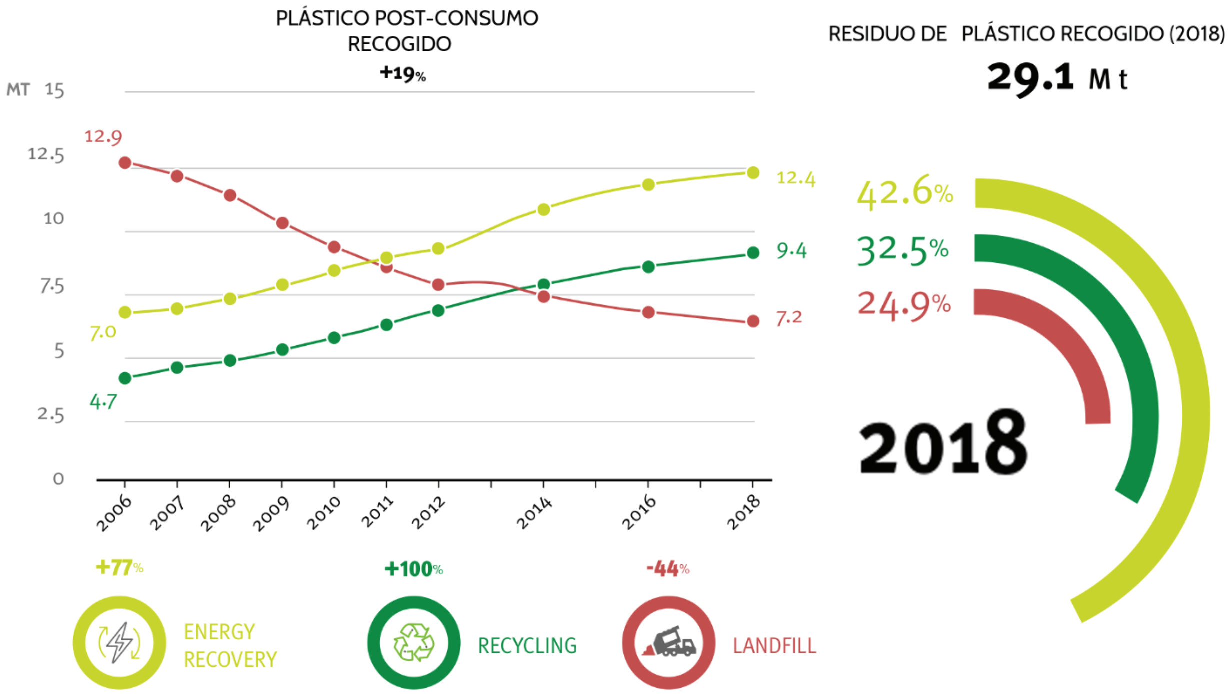

Fig. 3: Evolución del tratamiento de los residuos plásticos post-consumo desde 2006 y distribución en porcentaje de tratamiento en 2018 (Gráfico adaptado de PlasticsEurope, 2020).

(PlasticsEurope, 2020). El 42.6% de esta basura se sometió a recuperación de energía, el 32.5% ha sido reciclado y el 24.9% acabó en los vertederos (PlasticsEurope, 2020). Esto corresponde a una reducción del uso de vertederos por un 44%, y a la vez un aumento del uso de la recuperación de energía por un 77%, del reciclaje incluso de un 100% desde 2016 (PlasticsEurope, 2020). Es esencial llegar a la meta “cero plástico” en los vertederos para llegar a una economía circular del material, pero hasta ahora sólo 3 países han alcanzado este objetivo – Suiza, Austria y los Países Bajos (PlasticsEurope, 2020). Sin embargo, estos países tampoco son los lideres en cuanto a reciclar, sino Noruega y España, los únicos países europeos con un porcentaje encima de 40% (PlasticsEurope, 2020). Mientras que Noruega es uno de los países en los que se restringe el uso de los vertederos y, por lo tanto, presenta un índice bajo en dicho tipo de gestión, España utiliza los vertederos (38.8%) casi tanto como el reciclaje (41.9%) para el tratamiento de los residuos plásticos (PlasticsEurope, 2020). Eso corresponde a casi 1 MT Mientras el uso de la recuperación de energía (+59%) y del reciclaje (+ 2.3x) se incrementó constantemente desde 2006, el uso de los vertederos disminuyó significante solamente hasta 2012 (PlasticsEurope, 2020). Desde entonces, la tasa prácticamente se ha estancado, llegando a una reducción total de 41% desde 2006 (PlasticsEurope, 2020).

2 Plástico en el medio marino

2.1 Historia y situación actual

La contaminación por plásticos en el medio marino no es un tema nuevo. Desde principios de los años 70 se sabe que el plástico contamina los océanos (Carpenter and Smith, 1972; Colton et al., 1974; Gregory, 1978, 1977; Scott, 1972; Shiber, 1979), pero se consideraba principalmente un problema estético y por lo tanto era básicamente insignificante para la ciencia (Derraik, 2002). Sin embargo, el tema ha ganado relevancia en los últimos 20 años y la presencia de plástico en el mar se ha convertido en un problema importante a nivel mundial (GESAMP, 2019; UNEP, 2016). Jambeck et al. (2015) calculó que en el año 2010 entraron en el mar entre 4.8 y 12.7 MMT de plástico, procedentes solamente de países costeros. Para finales de 2013 se estimó un total mundial de desechos marinos de plástico en 86 MT, con una entrada de 4.2 MT para este año (Jang et al., 2015). Según una predicción, la masa estimada de residuos plásticos mal gestionados aportados al océano por las poblaciones que viven a menos de 50 km de una costa en 192 países podría ascender a 50-150 MMT de plásticos para 2020 y, en el peor de los casos, incluso a 250 MMT para 2025 (Jambeck et al., 2015). Sin duda, el comportamiento humano inadecuado y la falta de reciclaje conducen a una contaminación continua con plástico (Barnes et al., 2009).

2.2 La incorporación

Independientemente de la cantidad de plástico que entra en el mar, los residuos tienen diferentes orígenes, y la mayor parte (80%) proviene de una fuente terrestre (Andrady, 2011). Según Barnes et al. (2009), la mayor liberación de plásticos al medio ambiente es el resultado de un comportamiento humano inadecuado, por ejemplo, tirar basura. Esta basura puede proceder de actividades domésticas, agrícolas e industriales (Koutsodendris et al., 2008). Los residuos arrojados al azar en el paisaje pueden ser fácilmente arrastrados por el viento y llegar así a cualquier cuerpo de agua (Barnes et al., 2009). Por tanto, los ríos pueden llevar cantidades enormes de plástico al océano. Por ejemplo, el Rin – uno de los ríos más importantes de Europa – desemboca con un promedio de 892,777 partículas/km^2 en el Mar del Norte, lo cual forma parte del Atlántico Norte (Mani et al., 2015). Aunque, las concentraciones de microplásticos eran diversas a lo largo y ancho del río, reflejando diversas fuentes y sumideros, como plantas de tratamiento de agua, afluentes y presas, los resultados demostraron un aumento de la carga de microplásticos durante el tramo del Rin, debido a una acumulación de los vertidos, del número de habitantes, y de las plantas industriales a lo largo del río (Mani et al., 2015). Por lo tanto, más del 66% de todos los microplásticos recuperados se encontraron en un área metropolitana de Alemania (la región Rin-Ruhr), llegando a un máximo de 3.9 millones de partículas/km^2 (Mani et al., 2015). Esto demuestra la gran influencia de centros urbanos, centros industriales y vertidos en la aportación de plástico a los ríos y así al medio marino. Sin embargo, estas fuentes no solamente aportan basura a los ríos, sino también directamente al mar en zonas costeras. Por lo tanto, el plástico se acumula más en las zonas de presión turística o cerca de los núcleos urbanos (Ivar do Sul and Costa, 2007; Ryan et al., 2009; Thompson et al., 2009; Yu et al., 2016). Los emisarios submarinos pueden ser una fuente importante de microplásticos en el sedimento costero (Reinold et al., 2021), ya que el agua de los sumideros sigue descargando una media de 4.9 fibras/L, respectivamente 8.6 partículas/L en el océano (Talvitie et al., 2015). En las zonas urbanas, esta cantidad puede llegar incluso a 14-50 partículas/L (Dris et al., 2015). Pero el plástico no sólo puede ser de origen terrestre, sino también marítimo. Al igual que la basura arrojada al azar puede ser fácilmente arrastrada por el viento en tierra, esto también puede ocurrir en plataformas marinas o en barcos y los pellets de plástico (materia prima para producir objetos plásticos) pueden entran en el medio marino a través de derrames accidentales durante el transporte, tanto en tierra como en el mar (Andrady, 2011; Cole et al., 2011). Una fuente marítima importante de plástico en el océano, proviene de la industria pesquera, ya que los modernos equipos de pesca están hechos principalmente de poliolefinas y nylon (Andrady, 2011; Reinold et al., 2021).

2.3 Circulación en el mar

Dado que este material es muy duradero y tiene el potencial de permanecer durante mucho tiempo en el medio ambiente, una vez en el océano las partículas de plástico pueden ser transportadas a grandes distancias. Dependiendo de sus características, las partículas de baja densidad pueden ser impulsadas por el viento y las corrientes y así formar islas de basura en la superficie de los océanos (Eriksen et al., 2014, 2013; Law et al., 2010; Lebreton et al., 2018; Moore et al., 2001), y/o terminar en las costas del planeta (Iñiguez et al., 2016; Li et al., 2016), donde representan alrededor del 70% de los residuos encontrados en las playas (Serra-Gonçalves et al., 2019). Las cifras más elevadas hasta ahora han sido reportadas en Corea del Sur (119,182.0 partículas/m²), Jordania (43,947.0 partículas/m²) y España (28,218.75 partículas/m²) (Reinold et al., 2020; Serra-Gonçalves et al., 2019). En cambio, los plásticos de mayor densidad o bien por procesos de bioincrustación se hunden y a continuación están presentes en la columna de agua e incluso llegan a las profundidades marinas (Chiba et al., 2018; Choy et al., 2019; Van Cauwenberghe et al., 2013). Por último, sobre todo los pequeños plásticos (fragmentos y fibras) están relacionadas en gran medida con las corrientes y los procesos de mesoescala como remolinos o “litter windrows” y terminan moviéndose en la columna de agua (Vega-Moreno et al., 2021). Esto demuestra que el plástico tiene el potencial de derivar muy lejos del punto de entrada original.

2.4 Degradación y microplásticos

Los plásticos que terminan en el océano, con el tiempo pueden volverse frágiles y, en consecuencia, romperse en trozos más pequeños de forma irregular debido a procesos de degradación como la fotodegradación, la degradación termooxidativa o la degradación térmica (Andrady, 2011; Hidalgo-Ruz et al., 2012). Esta descomposición puede ser incluso más rápida en las playas que en el mar debido a la constante exposición a la radiación UV solar, al mayor contenido de oxígeno o a las temperaturas (Andrady, 2011). Pero no sólo los procesos de degradación, sino también influencias mecánicas, como abrasiones por la acción del oleaje (Andrady, 2011; Barnes et al., 2009; Cole et al., 2011) y/o ataques por peces (Carson, 2013) pueden contribuir a fragmentar las partículas más grandes. El resultado son microplásticos – partículas menores de 5 mm según las definiciones de la NOAA (Arthur et al., 2008) –, que a su vez pueden dividirse en 2 categorías.

2.4.1 1. Microplásticos primarios

Con el termino de microplásticos primarios se refiere a partículas la materia prima, que se fabrican para un uso posterior, ya sea en forma de pellets (~ 5 mm), que se suelen fundir para producir objectos de plástico más grandes, o en un tamaño microscópico, que se usan en productos como tales (Fig. 4). Dichos microplásticos microscópicos se suelen utilizar frecuentemente en limpiadores faciales y cosméticos (por ejemplo: "exfoliantes") o en la tecnología de soplado de aire, lo cual consiste en el chorreado en maquinaria, motores y cascos de barcos para eliminar el óxido y la pintura (Cole et al., 2011). También, se ha reportado su uso en la medicina como vector farmacológico (Patel et al., 2009). Los microplásticos primarios entran en el medio ambiente principalmente a través del uso apropiado como material de embalaje, de la salida directa de las plantas de procesamiento o de derrames accidentales durante el transporte (Cole et al., 2011).

2.4.2 2. Microplásticos secundarios

Los microplásticos secundarios representan diminutos fragmentos o fibras de plástico derivados de la descomposición de residuos plásticos de mayor tamaño, como se ha explicado anteriormente (Fig.4). Con el tiempo, un conjunto de procesos físicos, biológicos y químicos puede reducir la integridad estructural de los residuos plásticos y provocar su fragmentación (Cole et al., 2011).

Fig. 4: Microplásticos primarios (pellets) y microplásticos secundarios (fragmentos y fibras) en la línea de marea alta en la playa de Almaciga. Por comparación de tamaño se colocó una moneda de un céntimo encima.

2.5 Aditivos y COPs

El plástico tiene el potencial de transportar una amplia gama de contaminantes. Estos consisten básicamente en aditivos químicos añadidos durante la fabricación o contaminantes hidrofóbicos, en su mayoría COPs, que han sido adsorbidos por el plástico en el medio acuático (Bakir et al., 2014; Camacho et al., 2019; Gorycka, 2009; Lee et al., 2014; Moore et al., 2005; Ogata et al., 2009; Rios et al., 2010).

Los aditivos químicos son un grupo diverso de sustancias, que suelen ser utilizados para mejorar las propiedades y el rendimiento general de los plásticos, tal como para reducir los costes (GESAMP, 2015; Gorycka, 2009; Hartmann et al., 2019). Por ejemplo, algunos son moléculas orgánicas complejas como antioxidantes, otros son materiales básicos como el talco y el monoestearato de glicerilo (Gorycka, 2009). La mayoría de los aditivos para plásticos tienen un uso comercial, como los estabilizadores de la luz, los retardantes de llama, los suavizantes, los compuestos antiadherentes, las fragancias y los colorantes (Gorycka, 2009; Hartmann et al., 2019). Otros aditivos son los plastificantes, los estabilizadores (antioxidantes, antiozonantes, bioestabilizadores, etc.), los lubricantes, los antiestáticos, los modificadores de flujo, los auxiliares de procesamiento, los modificadores de impacto y los agentes espumantes y de acoplamiento (Gorycka, 2009; Hartmann et al., 2019) Por lo general, sólo se utilizan unos pocos aditivos en la producción de plásticos, sin embargo, pueden llegar a utilizarse entre 10 y 20 aditivos para mejorar el producto y dar al plástico las propiedades finales que necesita para cumplir su uso (Gorycka, 2009). Aditivos comunes son DPB, DEP, DEHP, HBCD, PBDEs o ftalatos (UNEP, 2016).

Además de los contaminantes añadidos, las pequeñas partículas de plástico y de resina de plástico pueden acumular altos niveles de COPs, hidrocarburos y metales en su superficie (Goldstein, 2012). Los COPs se describen como tóxicos, de larga vida en el medio ambiente (persistentes), bioacumulables (a menudo denominados lipofílicos), mayoritariamente hidrofóbicos, semivolátiles y, por tanto, fácilmente transportables a larga distancia (Gorycka, 2009). Todos los COPs tienen en común una o más estructuras de anillos cíclicos aromáticos o alifáticos, una ausencia de grupos funcionales polares y un número variable de sustituyentes halógenos (Gorycka, 2009). El convenio de Estocolmo proporciona una lista de COPs, conocida como la "docena sucia", que están reguladas debido a sus efectos dañinos, su presencia en el medioambiente y su persistencia en el interior del cuerpo humano (UNEP, 2020). Sin embargo, un programa de seguimiento global llamado “International Pellet Watch” (IPW), que opera desde 2005, ha encontrado COPs, principalmente PCB, pero también otras sustancias como DDTs, HCHs, Hopanos, PAHs y BDE-209 asociados a partículas de plástico de unos 200 lugares de todo el mundo (http://www.pelletwatch.org/). En particular, PCBs, DDTs y PAHs han sido bien investigados y mostraron altos valores en los microplásticos marinos (Camacho et al., 2019; Gorycka, 2009; Hirai et al., 2011; Mato et al., 2001; Ogata et al., 2009; Van et al., 2012). Las partículas de plástico pueden alcanzar un equilibrio de sorción de estos COPs en el agua de mar en 24 horas (Bakir et al., 2014; Teuten et al., 2007), lo que supone un problema, ya que el aumento de la superficie de los microplásticos que acompaña a la fragmentación de los plásticos erosionados aumenta aún más su capacidad de captación y transporte de COP (Teuten et al., 2007).

2.6 Impacto en el medio marino:

2.6.1 Sedimentos y costas marinas

Fig. 5: Contaminación por plástico en la playa de Poris.

Como se mencionó anteriormente en el apartado "2.3 Circulación en el mar", las partículas de plástico se han encontrado en todas las zonas del medio marino, incluyendo los sedimentos de las profundidades del mar y de las costas del mundo (Fig. 5) (Iñiguez et al., 2016; Li et al., 2016; Serra-Gonçalves et al., 2019; Van Cauwenberghe et al., 2013). Los plásticos de distinto tamaño – principalmente debido a la fragmentación – pueden cambiar el tamaño medio de los granos en las playas y, por tanto, aumentar la permeabilidad del suelo (Carson et al., 2011). Asimismo, las partículas de plástico en el sedimento provocan una disminución de la difusividad térmica, lo que resulta en un calentamiento más lento e incluso en temperaturas máximas más bajas (Carson et al., 2011). Adicionalmente, se encontraron correlaciones entre las concentraciones de níquel [Ni], el contenido de clorofila, el potencial redox, el contenido de materia orgánica y las reservas de nutrientes de los sedimentos superficiales de las playas y la abundancia de plástico (Green et al., 2016; Romeo et al., 2015). También existe una mayor acumulación de contaminantes químicos en los sedimentos marinos debido a la presencia de plástico que puede acumular concentraciones cien veces mayores que las fracciones orgánicas de los sedimentos (Wang et al., 2016). Por lo tanto, los contaminantes se encuentran en los sedimentos marinos de todo el mundo incluyendo la zona costera (Hermabessiere et al., 2017; Romeo et al., 2015).

2.6.2 Fauna marina

Los efectos de plástico en la fauna marina son diversos incluyendo el enredo, la ingestión y el "hitch-hiking" de especias invasores (Gregory, 2009). Los objetos de plástico de gran tamaño, como por ejemplo las redes de pesca, son la causa principal de enredos de las especies marinas grandes como tortugas, aves marinas, peces, tiburones y mamíferos (Browne et al., 2015; Franco-Trecu et al., 2017; Gall and Thompson, 2015; Gregory, 2009; Nelms et al., 2016; NOAA, 2014; Roul et al., 2018). La ingestión de estos objectos puede causar una obstrucción el digestivo y así conducir hasta la muerte por inanición (Pham et al., 2017; Pierce et al., 2004; Tourinho et al., 2010). En cambio, los microplásticos han sido encontrados básicamente en todos los organismos marinos: mamíferos, aves, tortugas, tiburones, peces e invertebrados incluyendo el zooplancton (Alomar and Deudero, 2017; Avery-Gomm et al., 2018; Bravo Rebolledo et al., 2013; Camedda et al., 2014; Davidson and Dudas, 2016; Hernandez-Gonzalez et al., 2018; Herrera et al., 2019; Lusher et al., 2018; Setälä et al., 2014). Estudios en peces e invertebrados demostraron que, aunque los pequeños trozos de plástico también pueden causar obstrucción intestinal en estos animales, una mayor amenaza proviene de los problemas de salud como las respuestas inflamatorias de las células, la alteración de la microbiota intestinal, las ulceraciones, las lesiones internas, pérdida de peso y un efecto creciente en la mortalidad (Besseling et al., 2013; Gall and Thompson, 2015; Hoss and Settle, 1990; Jabeen et al., 2018; Jin et al., 2018; Mazurais et al., 2015; von Moos et al., 2012). Además, los microplásticos no solamente se han localizados en los intestinos, sino también en el tejido muscular, el hígado, el cerebro e incluso en los huevos de peces, lo que prueba que tienen el potencial de trasladarse dentro de un organismo (Abbasi et al., 2018; Ding et al., 2018; Garcia et al., 2020; Pitt et al., 2018).

Sin embargo, el material plástico por sí mismo no es el único peligro para la fauna marina. Los sustancias químicas (aditivos, COPs, etc.) que se ingieran juntos con el plástico pueden traspasar las paredes del intestino de los animales y por lo tanto bioacumularse en los tejidos y entrar en la red alimentaria (Bakir et al., 2014; Camacho et al., 2019; Engler, 2012; Lee et al., 2014; Moore et al., 2005; Ogata et al., 2009; Panio et al., 2020; Rios et al., 2007; Saliu et al., 2020; Tanaka et al., 2013; Teuten et al., 2007). Algunas investigaciones con peces mostraron que la combinación de estos químicos y el plástico puede causar una amplia gama de problemas de salud como toxicidad hepática, alteración del sistema endocrino, efectos neurotóxicos, estrés oxidativo e incluso cambio de comportamiento en los animales (por ejemplo: comportamiento de natación, letargo, rendimiento depredador) (Barboza et al., 2018c, 2018b; Chen et al., 2017; Luís et al., 2015; Oliveira et al., 2013; Rainieri et al., 2018; Rochman et al., 2013, 2014; Zhang et al., 2019). Debido a la acumulación de contaminantes químicos, los organismos y sus puestas en las costas pueden verse afectados, resultando en una disminución de la biodiversidad (Romeo et al., 2015; Saliu et al., 2020; Wang et al., 2016).

3 Animales incluidos en el estudio

3.1 Características de lubina (*Dicentrarchus labrax*)

Fig. 6: Lubina en Las Canteras, Gran Canaria (Imagen: Alberto Navarro).

Según Froese (2021) y la información en "FishBase" (https://www.fishbase.se/), la lubina habita en la zona litoral, en estuarios, lagunas y ocasionalmente ríos de regiones subtropicales entre 8°C - 24°C. Entra en las aguas costeras y en las desembocaduras de los ríos en verano, pero migran a alta mar en épocas más frías y aparecen en aguas profundas durante el invierno. Los adultos manifiestan un comportamiento demersal, quedándose en aguas costeras hasta unos 100 m de profundidad, pero son más comunes en aguas poco profundas. Mientras los juveniles se alimentan de invertebrados, los adultos son piscívoros. *D. labrax* se encuentra en el Atlántico oriental desde Noruega hasta Marruecos, las Islas Canarias y Senegal, pero también se conoce en el Mediterráneo y el Mar Negro. Están ausentes en el Mar Blanco, el Mar de Barents, el Mar Báltico y el Mar Caspio (Fig. 6).

La especie tiene una gran importancia comercial, principalmente en países europeos según la FAO (https://www.fao.org/). La lubina fue la primera especie marina no salmónida que se cultivó comercialmente en Europa y actualmente es el pez comercial más importante que se cultiva ampliamente en las zonas del Mediterráneo. Aparte de ser cultivados, estos peces también son muy buscados por los pescadores deportivos (https://www.fishbase.se/).

3.2 Efectos del plástico en *D. labrax*

Pese a que *D. labrax* es un pez comercialmente muy importante, la información sobre la interacción entre plástico y lubinas en su hábitat natural es escasa. Aparte de la investigación en el presente trabajo, solamente existe un estudio que reporta la presencia de plástico en animales juveniles provenientes de un estuario en Portugal (Bessa et al., 2018).

En cambio, los efectos de ingestión de plástico solo o en combinación con contaminantes están bien documentados debido a una gran cantidad de ensayos experimentales con lubinas. Los microplásticos por sí solos pueden causar alteraciones intestinales patológicas, inflamación celular, neurotoxicidad, estrés y daño oxidativo, disminución de la actividad de las enzimas antioxidantes y la depresión de la inmunidad (Barboza et al., 2018b, 2018c; Espinosa et al., 2018, 2019; Pedà et al., 2016). Adicionalmente, su ingestión puede cambiar el comportamiento de los peces, incluyendo la reducción de la velocidad de natación, el tiempo de resistencia y el comportamiento de natación letárgico o errático (Barboza et al., 2018c). Se ha demostrado que los microplásticos pueden translocarse dentro del organismo, ya que se han encontrado en el hígado y el tejido muscular (Zeytin et al., 2020; Zitouni et al., 2021). Las larvas de *D. labrax* muestran incluso un aumento de la tasa de morbilidad después de alimentarles con microplásticos (Mazurais et al., 2015). La combinación con sustancias químicas o metales aumentó los efectos tóxicos en todos los estudios con lubinas. Aparte los microplásticos provocan la acumulación de contaminantes en los tejidos (Barboza et al., 2018b; Herrera et al., 2022; Zitouni et al., 2021) y así aumentan su biodisponibilidad (Granby et al., 2018).

4 Área de estudio y objetivos de la tesis

Teniendo en cuenta todas estas consideraciones, el objetivo del presente estudio fue evaluar el estado actual de la contaminación por plástico en las costas de la isla de Tenerife, así como la presencia de plástico en peces cultivados en Canarias.

Fig. 7: Imágenes de satélite de Google Earth: Isla de Tenerife con los puntos de muestreos: Demarcaciones amarillos: Localización de las playas estudiadas; Cuadrados rojos: Localización de jaulas de acuicultura (Fuente: Google Earth Pro, ©2022 / GRAFCAN, Maxar Technologies; Data SIO, NOAA, U.S. Navy, NGA, GEBCO).

Las Islas Canarias están situadas en el Giro del Atlántico Norte, el cual muestra una alta concentración de residuos plásticos (Eriksen et al., 2010; Law et al., 2010). La corriente principal pasa por las Azores y Portugal y se convierte en la corriente de Canarias, trayendo basura a las costas de las Islas. Adicionalmente, especies invasoras pueden llegar al Archipiélago a través del “hitch-hiking” (Gregory, 2009), y así suponer una amenaza para especies endémicas. Las Islas Canarias, debido a su origen volcánico, su ubicación y su topografía, tienen un ecosistema sensible, que puede ser fácilmente perturbado. A pesar de su alto riesgo de acumular plástico y considerando sus impactos en el medio marino, hasta la fecha el número de investigaciones sobre el tema en el Archipiélago es moderado (Álvarez-Hernández et al., 2019; Baztan et al., 2014; Edo et al., 2019; Hernández-Sánchez et al., 2021; Herrera et al., 2020, 2018; Rapp et al., 2020; Villanova Solano et al., 2018). En especial, Tenerife, que representa no solamente la isla más grande del archipiélago sino de toda España, ha sido poco estudiada (Álvarez-Hernández et al., Villanova Solano et al., 2018). También es la isla más poblada del país según el INE (https://www.ine.es/) y recibe anualmente casi 6 millones de personas, el mayor número de turistas del archipiélago según los datos de ISTAC (http://www.gobiernodecanarias.org/istac/). Conforme con los datos del INE la cantidad total de residuos urbanos recogidos llegaron en 2018 a 1,331,187 toneladas, de los cuales solamente 5 toneladas eran plásticos y la cantidad per cápita era de 527.4 kg por habitante incluyendo todas las Islas Canarias. En el mismo año solamente un 66.46% de los hogares en el archipiélago reciclaron plástico (tetrabriks y latas incluidos) según el ISTAC y la tasa era aún más baja en Tenerife con un 65.02%. Además, las Canarias representan una de las comunidades más fuertes en el sector de la acuicultura de España, sobre todo en la producción de las lubinas (APROMAR, 2020). Los peces se cultivan habitualmente en instalaciones de acuicultura en el mar con el fin de ser consumidas por los humanos. Debido a la translocación del plástico al tejido muscular y a la bioacumulación de sustancias potencialmente tóxicas en los peces (Barboza et al., 2018b; Herrera et al., 2022; Zeytin et al., 2020; Zitouni et al., 2021), los humanos corren el riesgo de consumir alimentos contaminados. Sin embargo, la magnitud de la exposición de los humanos al plástico y las sustancias asociadas a través de los alimentos de origen marino aún no ha sido investigado, pero las preocupaciones por la salud humana aumentan en los últimos años (Barboza et al., 2018a; Lusher et al., 2017; Rochman, 2016; Seltenrich, 2015; Smith et al., 2018).

En este estudio por primera vez se evaluó la evolución anual de acumulación de residuos de plástico en las costas de Tenerife, tanto en sedimentos superficiales a lo largo de las playas, como en estratos más profundos y en el agua superficial cerca de la orilla. El objetivo de este trabajo fue analizar la variabilidad espacial, tanto entre lugares de muestreo como en diferentes zonas de cada playa con el fin de detectar sitios de alto riesgo de contaminación. Esta información será necesaria para establecer futuros protocolos de seguimiento de residuos de plástico. Adicionalmente se estudió por primera vez la ingestión de plástico en *D. labrax* procedente de instalaciones de acuicultura con el fin de evaluar los riesgos de contaminación en peces destinados para el consumo humano.

Capítulo II

Resultados y Discusión

CAPÍTULO II: RESULTADOS Y DISCUSIÓN

1 Residuos marinos a lo largo de ocho playas de Tenerife

En el primer estudio, para obtener una visión general, todo tipo de residuos arrastrados a la orilla fue documentado, incluyendo plásticos, materias orgánicas, papeles, cigarrillos, metales y materiales indefinidos. Por lo tanto, se tomaron muestras de sedimentos superficiales cada 35m en toda la longitud de ocho playas de Tenerife a lo largo de la línea de marea alta (Fig. 7). El muestreo se llevó a cabo cada 5 semanas durante un año con el fin de evaluar la variabilidad temporal y espacial de los residuos. Las partículas evaluadas incluyeron material mayor a 2mm, que se subdividió en mesopartículas (2-10mm) y macropartículas (>10mm). Las partículas de plástico adicionalmente fueron pesados y clasificados por sus colores.

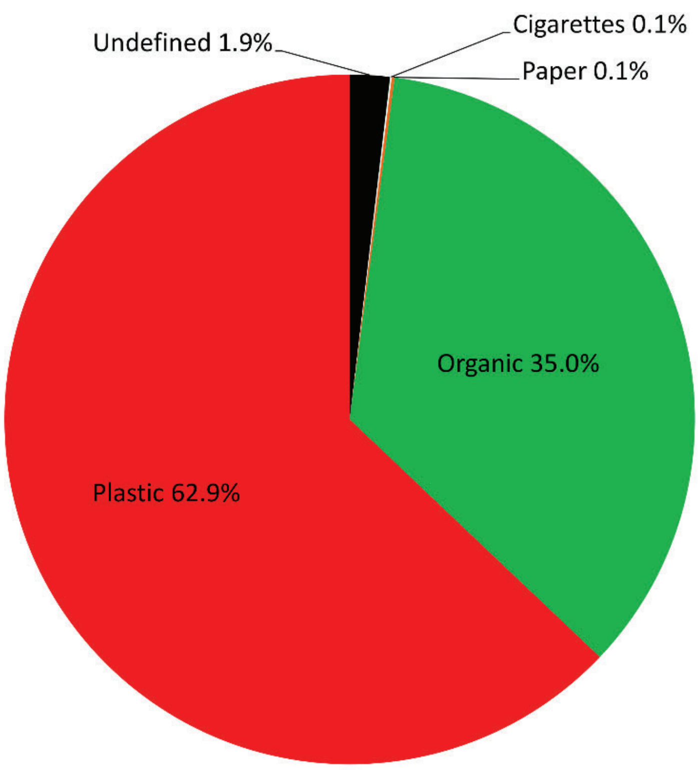

Fig. 8: Composición de residuos marinos encontrados en las playas en general

Mesopartículas eran más abundantes que macropartículas y en general, el plástico (62,9%) fue el principal tipo de residuos encontrados en las playas, seguido por material orgánico (35,0%) (Fig. 8). En todas las localizaciones el color blanco/transparente fue dominante en las partículas de plástico. Aunque todas las playas presentaron contaminación por plástico, hubo una gran variabilidad de la abundancia de plásticos con respecto a los lugares y las fechas de muestreo (Fig. 9).

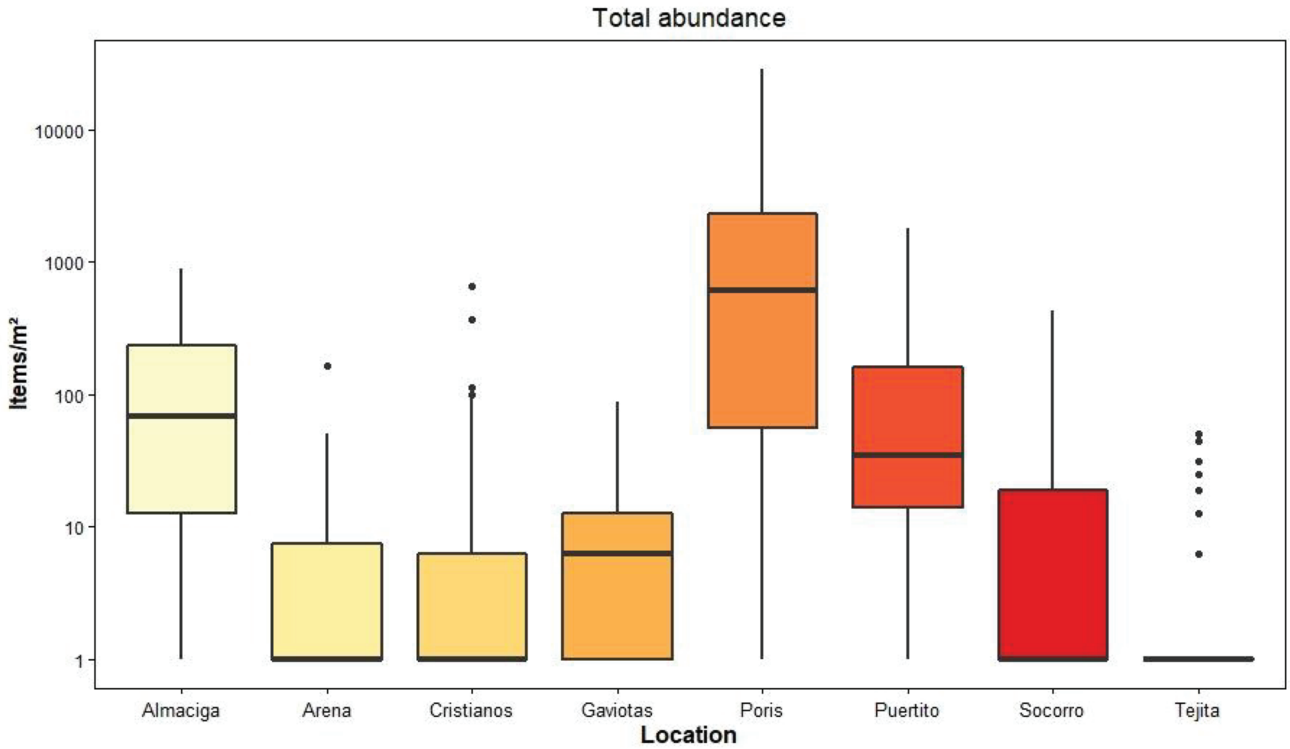

Fig. 9: Abundancia total de plásticos en ítems/m² por ubicación recogida de julio de 2016 a julio de 2017. La línea gruesa central de cada caja designa la mediana; la altura de la caja muestra el rango intercuartil; las líneas verticales encima y debajo de cada caja indican los valores más altos y más bajos; los puntos señalan los valores atípicos. Para la presentación gráfica en escala logarítmica se sustituyeron los valores de 0 por valores de 1.

Por el contrario, la presencia de plásticos a lo largo de las playas mostró consistencia y zonas uniformes de alta y baja acumulación (Fig. 10). Las playas más contaminadas fueron sobre todo Poris, seguido por Puertito y Almaciga. Aunque los tres lugares son poco frecuentados, Poris y Almaciga están muy afectados por las corrientes principales. Eso confirma la teoría de que el movimiento por las olas y el viento es la principal causa para la acumulación de plástico en las costas. En cambio, Puertito casi no se ve afectado por las corrientes principales, pero se encuentra en una bahía cerrada, que recibe menos atención en términos de la limpieza que las otras dos playas. Este estudio no sólo demuestra que las playas de Tenerife están muy afectadas por contaminación y en especial por residuos plásticos, sino que también revela por primera vez que los residuos arrastrados a la orilla se acumulan en zonas restringidas en playas arenosas.

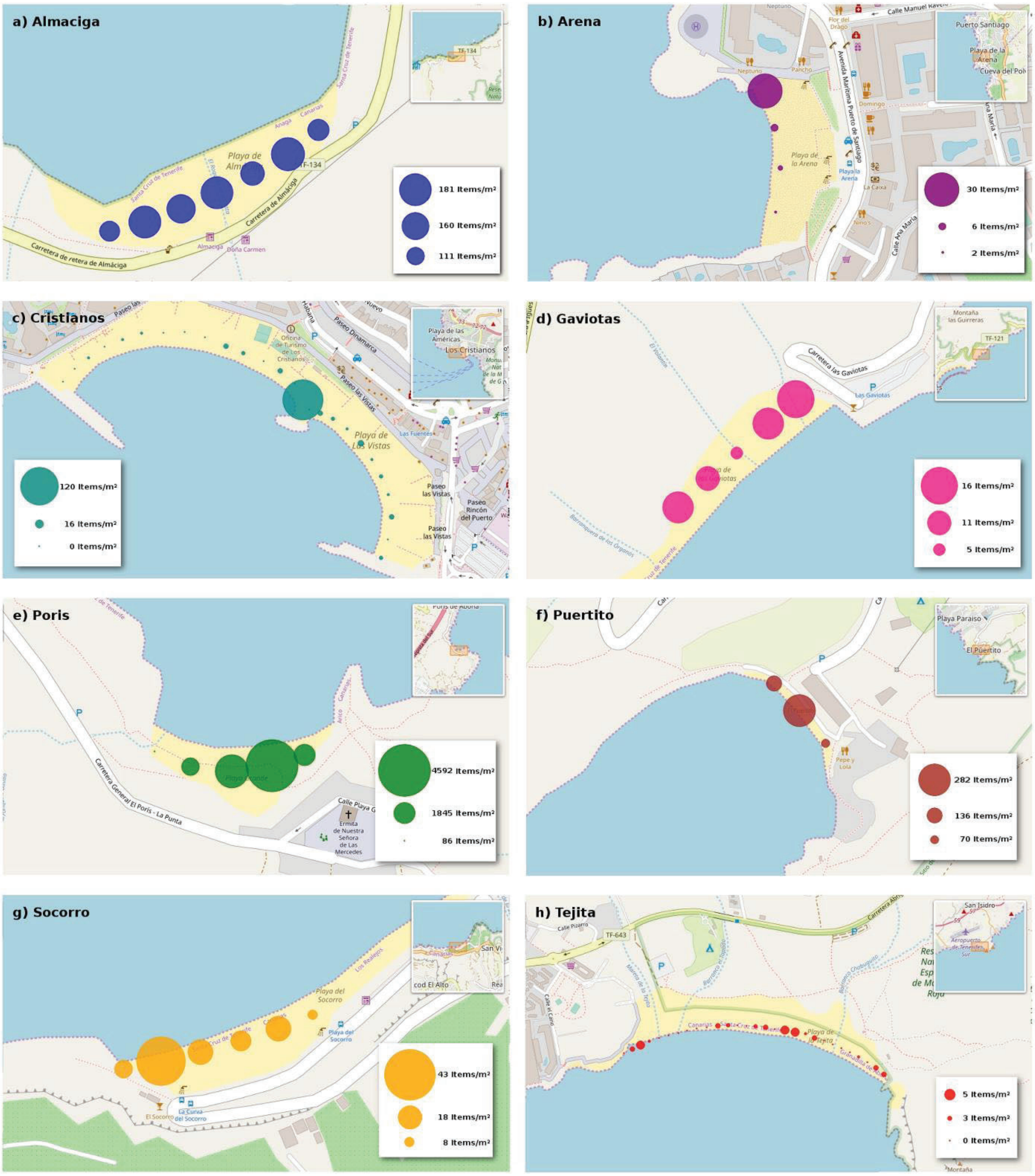

Fig. 10: Variabilidad espacial de la abundancia de plásticos en a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro y h) Tejita. Los círculos indican la abundancia media en ítems/m² en cada playa.

2 Presencia de plástico en sedimentos profundos y aguas superficiales

El segundo estudio se enfocó en la cantidad de plástico que llega a la costa de Tenerife y permanece en el sedimento. Con el fin de cuantificar la carga de plástico en diferentes zonas de las ocho playas estudiadas (Fig. 7), se tomaron muestras de capas de sedimentos más profundas (15 cm) en la línea de marea alta y en una zona sumergida, así como muestras de agua superficial (1 L) en la zona de orilla. El muestreo se realizó igual que el anterior durante un año en intervalos de 5 semanas para evaluar la variabilidad temporal de la acumulación de residuos de plástico. Las partículas de plástico encontradas fueron categorizadas por sus colores (16), tamaños y formas (5) según la zona y la playa. Adicionalmente, las partículas de un 10% de las muestras fueron identificados por FTIR para determinar el tipo de polímero.

La mayor parte de las partículas se encontró en los sedimentos de marea alta (66%), seguido por las muestras de agua (23%) y por último en los sedimentos de zona sumergida (11%). La abundancia media de partículas fue mayor en los sedimentos de la línea de marea alta (Fig. 11).

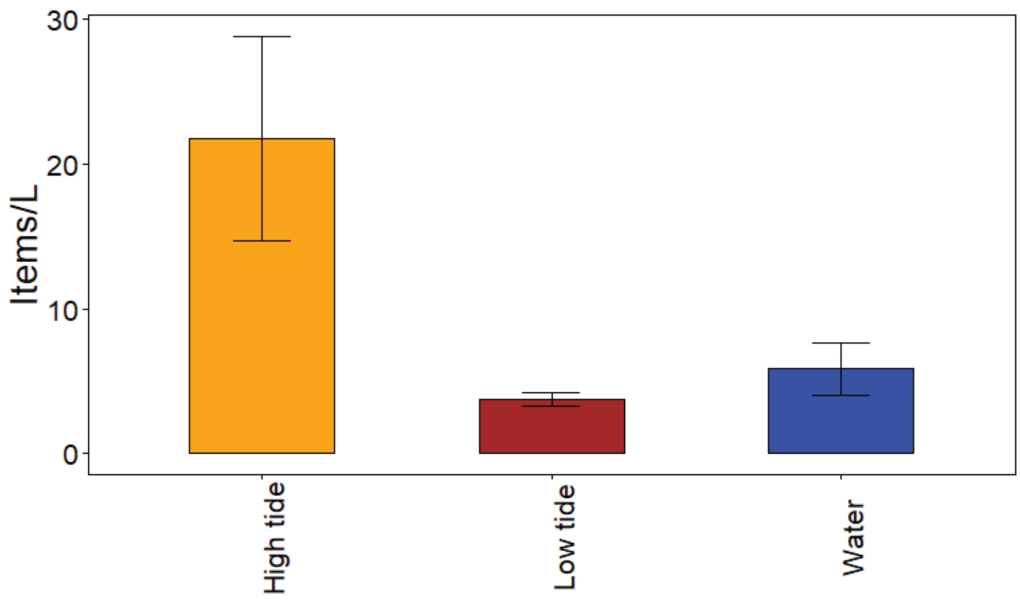

Fig. 11: Abundancia media de partículas (Items/L) de cada zona de muestreo recogido desde julio de 2016 hasta julio de 2017.

Sin embargo, las muestras de sedimentos presentaban una cantidad de partículas significativamente mayor que las muestras de agua del litoral correspondiente. La distribución porcentual de cada lugar respalda la diferencia estadística, ya que los porcentajes de las muestras de sedimentos estuvieron principalmente equilibrados, mientras que los porcentajes de las muestras de agua rara vez superaron a los porcentajes de los sedimentos (Fig. 12).

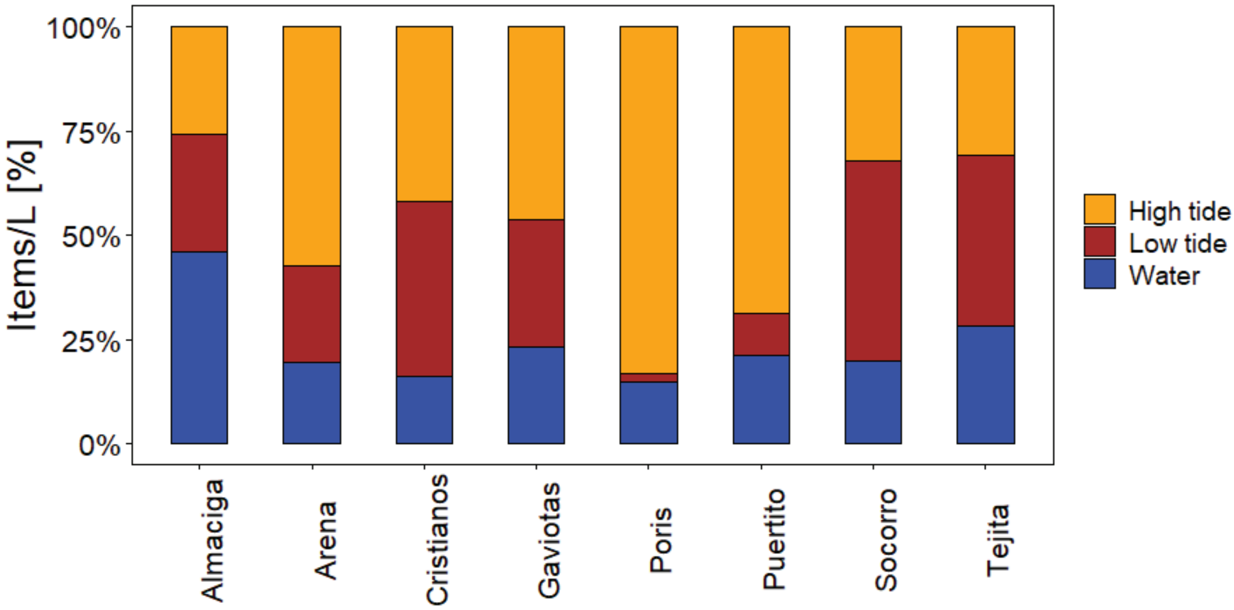

Fig. 12: Distribución porcentual de las partículas (Items/L) para cada lugar en las tres zonas diferentes del muestro.

Igual que en el estudio anterior no se encontró ningún patrón temporal, más bien la cantidad de partículas fue variada respecto a la zona y al lugar durante el año, siendo Poris de nuevo la ubicación más contaminada en general. En cuanto a las características se encontraron principalmente fragmentos mayores a 1mm de color blanco o transparente. Esta combinación refleja sobre todo la imagen que se ve en muestras de sedimentos de la línea de marea alta, que a la vez aportaron la mayoría de partículas en general (Fig. 13). Sin embargo, las distribuciones fueron diferentes en muestras de agua, pero en especial en sedimentos de zona sumergida. Mientras los fragmentos de color blanco y transparente siguieron siendo las partículas más abundantes en muestras de agua, el porcentaje entre macro- y mesopartículas (>1 mm) y micropartículas (>1 mm) fue más equilibrada, incluso con una ligera elevación de la cantidad de micropartículas (Fig. 13). En cambio, las muestras de sedimentos de zona sumergida presentaron en su mayoría fibras menores a 1 mm de color azul o amarillo (Fig. 13).

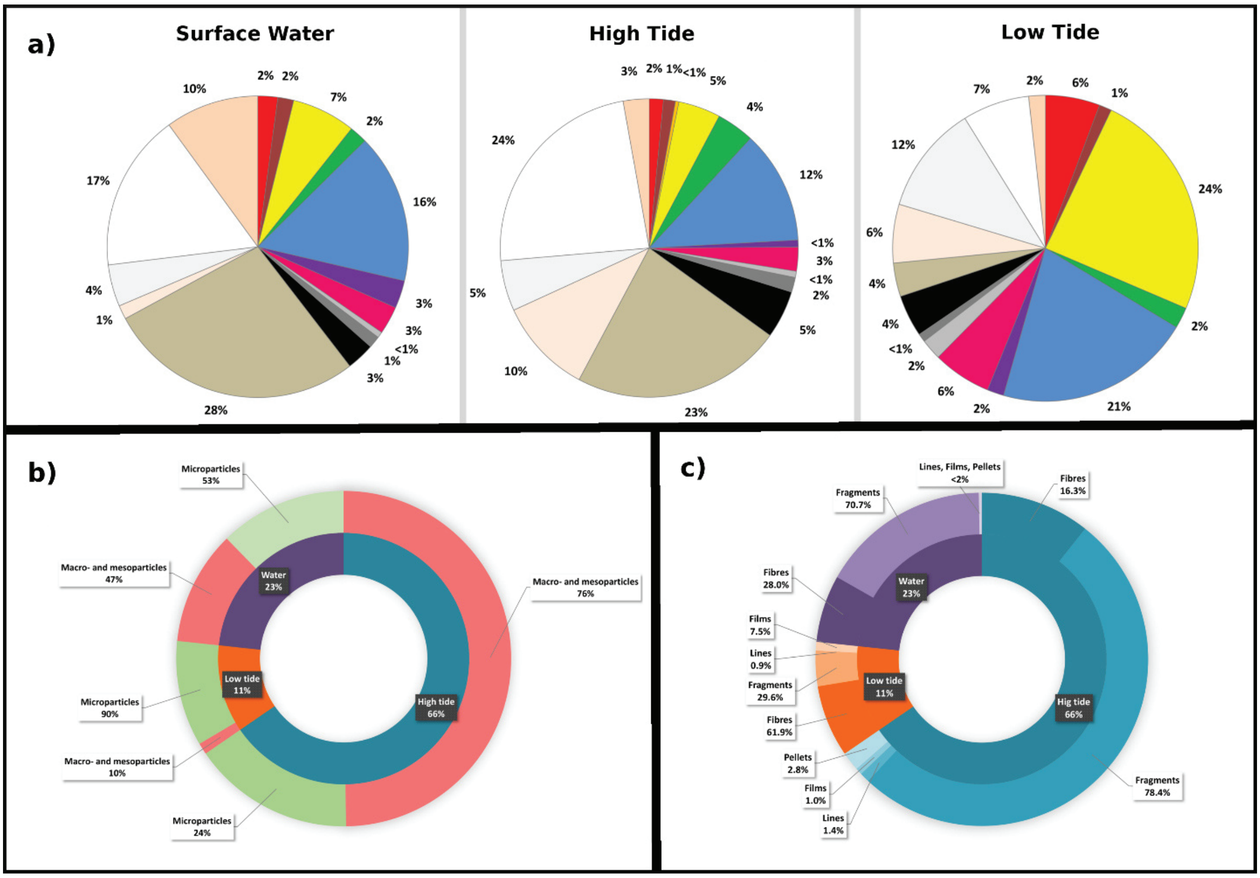

Fig. 13: Características de las partículas encontradas en las ocho playas de Tenerife: a) Distribución de los colores de partículas en cada zona de muestreo; b) Distribución del tamaño de partículas: Donut interior: Cantidad de partículas en porcentaje en cada zona de muestreo; Donut exterior: Porcentaje de macro- y mesopartículas (>1 mm) y micropartículas (<1 mm); c) Distribución de la forma de partículas: Donut interior: Cantidad de partículas en porcentaje en cada zona de muestreo; Donut exterior: Porcentaje de fibras, fragmentos, líneas, películas y pellets.

La comparación entre localizaciones reveló que fragmentos y fibras fueron presentes en todas las playas. En cuanto a los colores, todas las ubicaciones contaron con partículas amarillas, azules, blancas, negras, rosadas, semitransparentes y transparentes, siendo Puertito el único lugar donde se encontraron todos los colores (16). Las micropartículas fueron significativamente más abundantes en la mayoría de las playas, excepto en Poris y Puertito. Estos dos lugares mostraron las mayores cantidades de partículas en las muestras de sedimentos de la línea de marea alta, lo que pudo llevar a la anteriormente mencionada mayoría de fragmentos mayores a 1mm de color blanco o transparente en total. Con respecto a las macro- y mesopartículas que fueron analizado por FTIR resultaron principalmente PE, PP, PS, PTFE y PVC – representando plásticos que se recuperan habitualmente en el medio marino (Fig. 14). Las micropartículas mostraron un espectro más amplio de tipos de polímeros, incluyendo en total 24 polímeros diferentes, siendo los más comunes PP, PA y rayón.

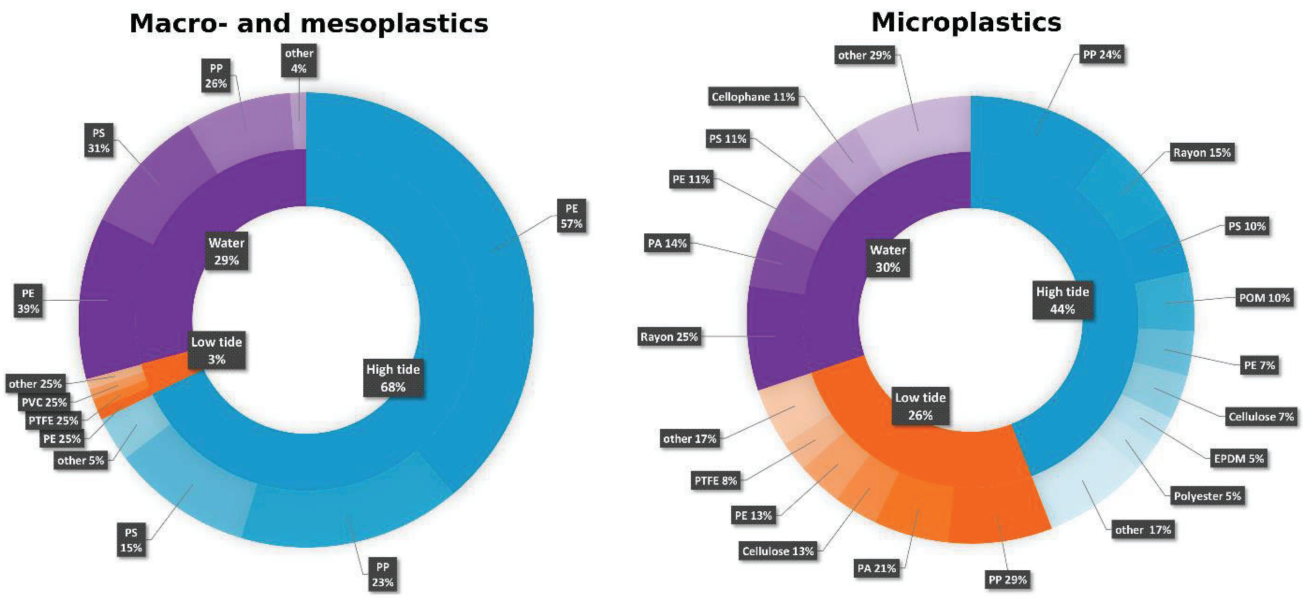

Fig. 14: Tipos de polímeros de macro- y mesoplásticos y de microplásticos. Donut interior: Cantidad de partículas en porcentaje en cada zona de muestreo; Donut exterior: Porcentaje de tipos de polímeros.

3 Evidencia de ingestión de plástico por peces de jaulas de cultivo frente a las costas de Tenerife

En la última parte del trabajo se analizaron tractos gastrointestinales de lubinas (*Dicentrarchus labrax*) procedentes de instalaciones de acuicultura ubicados cerca de la costa en el sur de Tenerife (Fig. 7). Se recibieron siete lotes de 10 individuos cada uno y un lote de 13 individuos de dos empresas distintas de acuicultura de diferentes épocas del año. Las partículas encontradas fueron clasificadas como en el segundo estudio por sus colores (16), tamaños y formas (5) y un 10% de las muestras fue analizado con el FTIR con el fin de identificar los tipos de polímeros.

Fig. 15: Contenido gastrointestinal de una lubina del último lote.

La mayoría (65%) de los animales examinados presentó algún tipo de microplástico en su tracto digestivo con una media de entre 1,43 ± 1,75 (SD) partículas por pez (n=83). En total, se encontraron 119 partículas, de los cuales 97,5% tuvieron un tamaño inferior a 5 mm. Sin embargo, un individuo había ingerido objectos más grandes – tres líneas que superaron los 5 mm de longitud (Fig. 15).

Los microplásticos eran principalmente fibras (81%), pero también fragmentos (12%) azules, amarillos, negros y transparentes (Fig. 16). Mientras investigaciones anteriores reportaron con frecuencia los colores azul, negro y transparente, el amarillo se encontró normalmente en menores proporciones. Sin embargo, en este estudio se detectaron cantidades considerablemente altas de partículas amarillas (23,7%). La presencia de estas microplásticos en los tractos digestivos de las lubinas pude ser el resultado tanto de una ingestión directa por aspirar accidentalmente partículas microscópicas como de una ingestión indirecta debido al ataque a objetos de plástico amarillos o a la transferencia trófica a través de presas, que por su parte ingirieron previamente microplásticos, que atravesaban la malla de la jaula. Además, la proporción de partículas amarillas y azules se asemeja al porcentaje que presentaron las muestras de sedimentos de zona sumergida del segundo estudio, respaldando los hallazgos de Wu et al. (2020), que encontró perfiles similares de tipo de microplásticos entre los sedimentos y los peces de acuicultura.

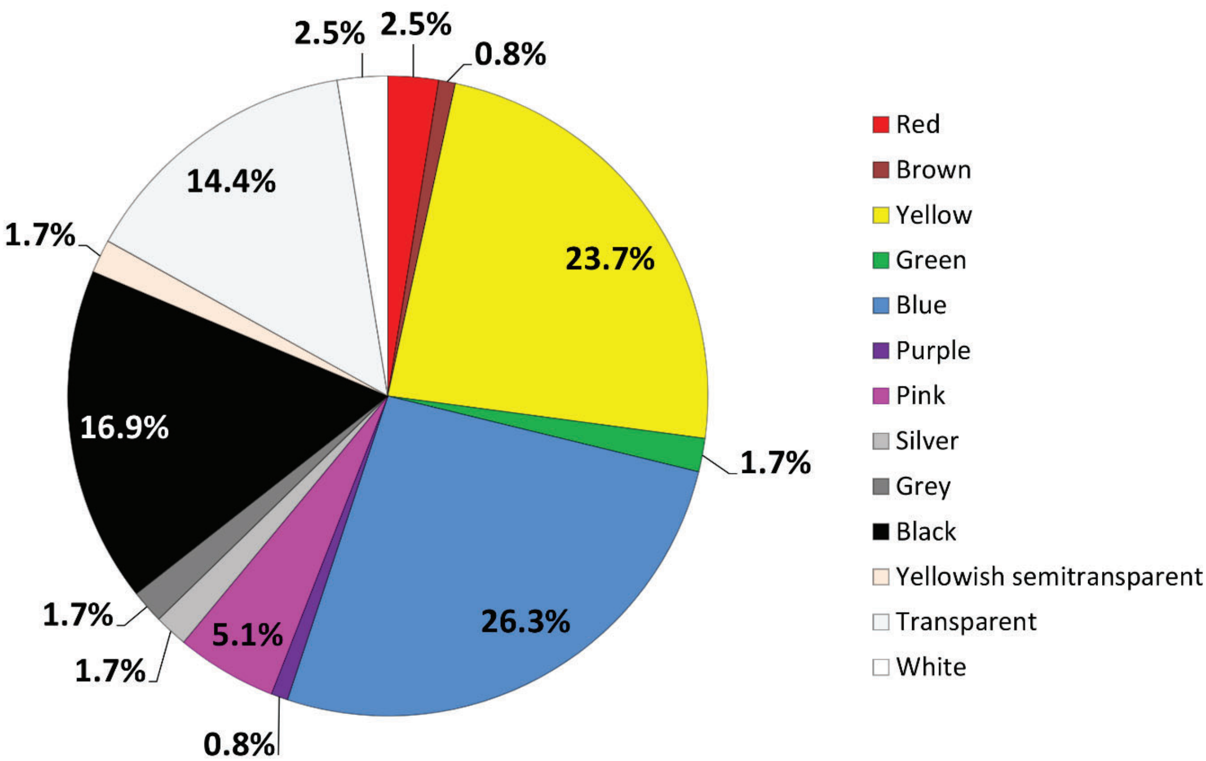

Fig. 16: Distribución de los colores de partículas encontradas en los tractos gastrointestinales de las lubinas.

Las fibras se identificaron mayoritariamente como celulosa y nylon, mientras que en los fragmentos predominaron los polímeros PE y PP (Fig. 17). Ya que la celulosa y el nylon se utiliza habitualmente en la industria textil, se sospecha que la presencia de estas fibras está relacionada con los emisarios submarinos locales y en consecuencia que la contaminación local desempeña un papel importante.

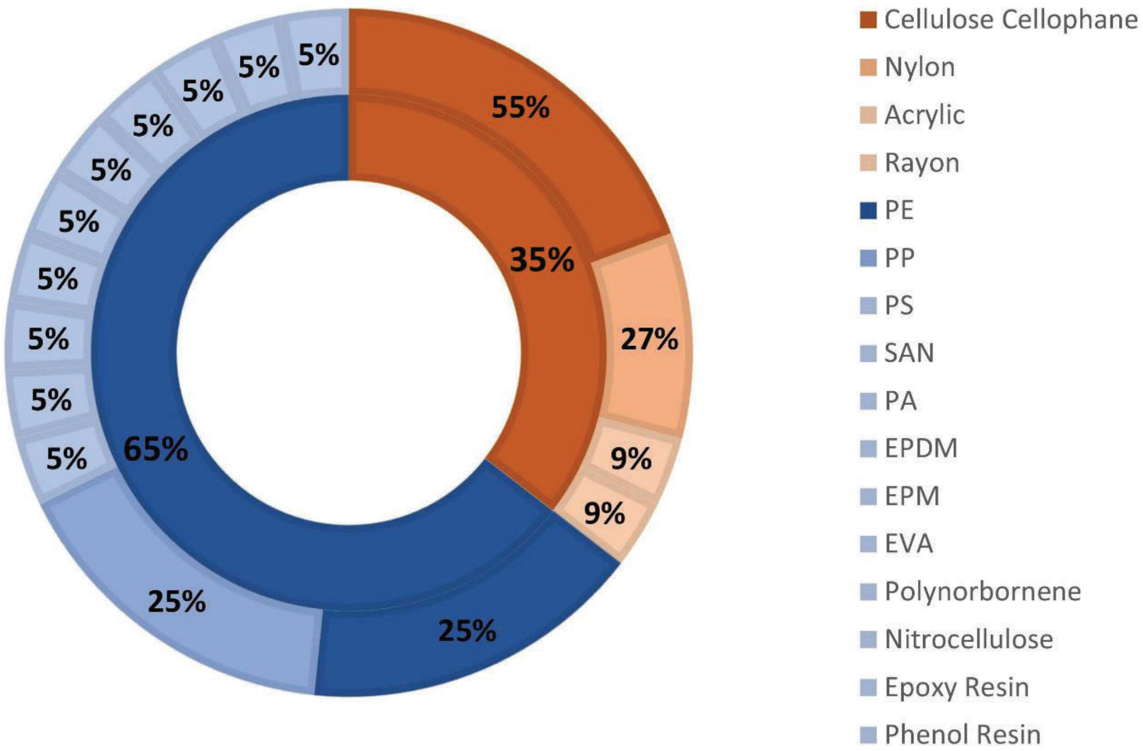

Fig. 17: Porcentaje de tipos de polímeros de partículas encontradas en los tractos gastrointestinales de las lubinas: Fibras están representadas por el compartimento rojo; los fragmentos están representados por el compartimento azul; Donut interior: Porcentaje de las formas de partículas; Donut exterior: Porcentaje de tipos de polímeros.

Capítulo III

Plastic pollution on eight beaches of Tenerife (Canary Island, Spain): An annual study

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Plastic pollution on eight beaches of Tenerife (Canary Islands, Spain): An annual study

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ABSTRACT

Stranded marine debris from eight beaches of Tenerife (Canary Islands, Spain) was analyzed.

Sampling was conducted along the high tide line every 35 m over the whole lengths in periods of 5 weeks for one year. Evaluated particles included all materials bigger than 2 mm, which were subdivided in Mesoparticles (2–10 mm) and Macroparticles (> 10 mm). There was a great variability of plastic abundance regarding the locations and the sampling dates. In contrast, the occurrence of debris along the beaches showed consistency and even zones of high and low accumulation. The most polluted beach was Poris, which is indeed infrequently visited, but highly affected by the main current.

Plastic particles were principally mesoparticles and white/transparent color. This study not only confirms, that the Canary Islands are highly affected by the marine plastic pollution, but also for the first time shows, that stranded plastic accumulates in restricted areas of sandy coastlines.

1. Introduction

Since the beginning of the use of plastic, the possibilities of its application grew constantly. Today these organic polymers are present all over and it became almost impossible to live a plastic-free life. The possibility of this wide range of use and cost-effective fabrication led to a worldwide production of 335 million tons of plastic in 2016, with an upwelling trend (PlasticsEurope, 2018). But what if the plastics after its use cannot be recycled properly and end up as waste in the environment?

Until 2015 humankind produced already 6300 million metric tons of plastic waste, of which approximately only 9% were recycled (Geyer et al., 2017). Around 60% of all ever produced plastics are accumulating in landfills or in the natural environment (Geyer et al., 2017). According to Barnes et al. (2009) the major release of plastics to the environment is the result of improper human behavior, e.g. littering. The litter can originate from domestic, agricultural and industrial activities (Koutsodendris et al., 2008). Randomly disposed waste in landscape can be easily wind-blown and thus reach any water body (Barnes et al., 2009). On the other hand, synthetic fibers of clothing discharged from washing machines as well as microbeads from personal care products can enter the aquatic environment via sewage treatment plants (Browne et al., 2011; Rochman et al., 2015a).

The most frequently definition of microplastics are particles > 5 mm as it was recommended by NOAA in 2008. Nevertheless a common definition for the size of plastic debris is still missing, but control of plastic emission will depend on an international agreed definition (GESAMP, 2015; Hartmann et al., 2019). Here we used the size classification for plastic debris based on the SI nomenclature as suggested by Hartmann et al. (2019).

Already since the early 70s it is known that plastic pollutes the oceans and is ingested by marine biota (Carpenter and Smith, 1972; Colton et al., 1974). At first mainly seen as an aesthetic problem and basically insignificant for research (Derraik, 2002), this subject gained relevance in recent years. Plastic is now considered the most common type of marine debris and represents a growing environmental problem (Barnes et al., 2009; Cole et al., 2011; Derraik, 2002; Moore, 2008; Thiel et al., 2013; Thompson et al., 2009) and aquatic pollution is reported from all over the world. Low density particles form garbage patches on the oceans' surface in the world's gyres (Eriksen et al., 2014, 2013; Law et al., 2010; Lebreton et al., 2018; Moore et al., 2001).Plastics with a higher density or because of fouling processes are reaching the deep sea (Van Cauwenberghe et al., 2013). Beaches of every continent have been reported to suffer plastic pollution of marine origin (Iñiguez et al., 2016; Li et al., 2016), even in the polar regions (Bergmann and Klages, 2012; Munari et al., 2017) or on remote islands

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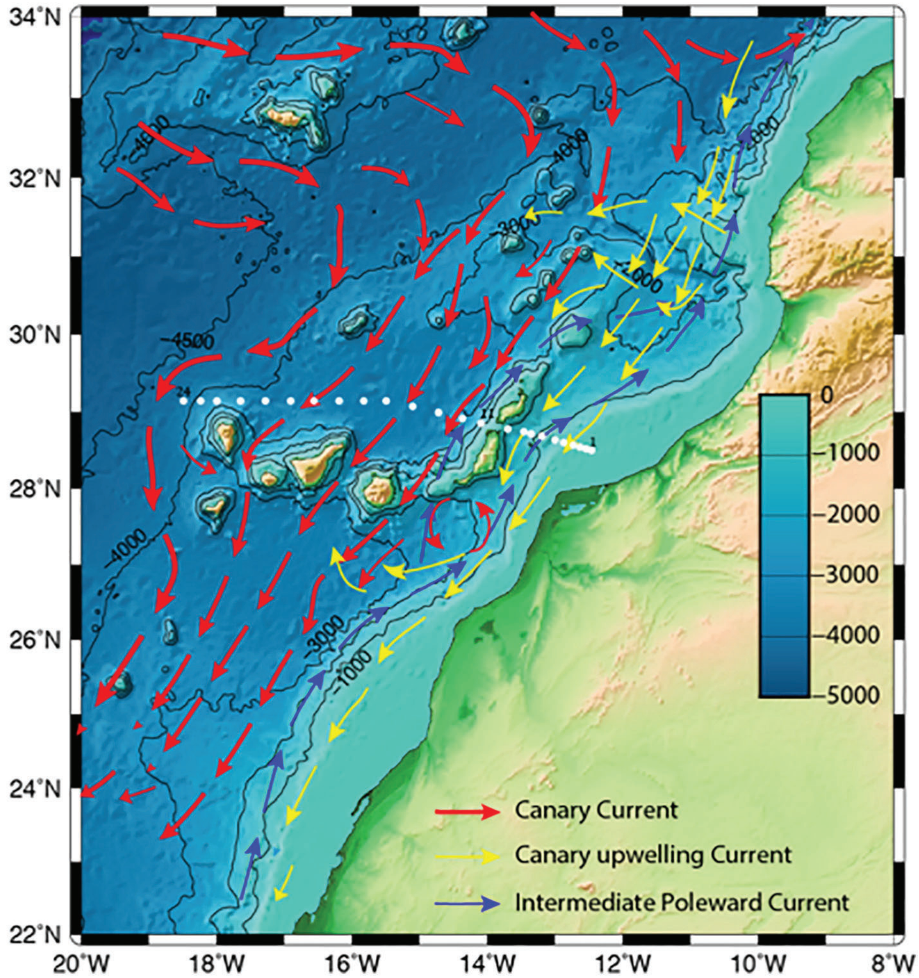

Fig. 1. Circulation scheme for the Canary Islands. Red arrows show the southward Canary Current coming from the North Atlantic Gyre. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: ICES Report on Ocean Climate 2018.

(Barnes, 2005; Monteiro et al., 2018). This shows that plastic has the potential to drift far away from the original entry point.

The North Atlantic Gyre shows a high concentration of plastic waste (Eriksen et al., 2010; Law et al., 2010) and its main current passing over the Azores and Portugal stream into the Canary stream brings plastic waste to the Canarian Archipelago (Fig. 1). This not only leads to pollution of the islands, but eventually biota, which is hitch-hiking on the plastic particles, can pose a threat as invasive species (Gregory, 2009). Another entry source is the trade winds, which can bring waste from the nearby African continent to the Canary Islands.

The Canary Islands, because of their volcanic origin, their location and the topography have a sensitive ecosystem, which among other things also includes some endemic species and can therefore easily been disturbed.

For the Canary Islands, plastic pollution has been reported along the beaches of Fuerteventura, Lanzarote and La Graciosa (Baztan et al., 2014; Edo et al., 2019; Herrera et al., 2018). For Tenerife, the largest and most visited island in the archipelago and, therefore potentially more susceptible to pollution, studies are very scarce (Álvarez-Hernández et al., 2019; Villanova Solano et al., 2018). Both studies suggested a very low occurrence of plastic particles, except for Playa Grande (Poris). Sampling was conducted only one time per beach, in February 2018 and in October, November and December 2018, respectively. While Álvarez-Hernández et al. (2019) sampled approximately every 10 m along the high tide line of every beach, Villanova Solano et al. (2018) sampled only in one spot of each beach.

This study was conducted in 2016/2017 and thus represents the first investigation about marine debris stranded on beaches of Tenerife. For the first time the evolution of plastic accumulation on eight strandlines of the island along one year was assessed. The main objective of the present study is the determination of beach pollution along the coastline of Tenerife. Therefore, the temporal variability of debris accumulation during one year was studied. Furthermore the study aimed to analyze the spatial variability, not only between sampling sites, but also alongside each beach. This information not only is necessary to establish future monitoring protocols, but also to expand the data network in Europe, which in turn is crucial to help advise policymakers in their decisions (Rochman et al., 2016). Hence it is possible to invoke positive changes to mitigate environmental accumulation of plastic (Rochman et al., 2016).

2. Materials and methods

2.1. Research area

A total of eight beaches of Tenerife were surveyed in intervals of five weeks between July 2016 and June 2017, two on the northern coastline and three on the southern and western coastline, respectively (Fig. 2). Strandlines hereafter were referred to as Almaciga, Arena, Cristianos, Gaviotas, Poris, Puertito, Socorro and Tejita. Beaches were chosen based on their accessibility, their orientation towards the main currents and their touristic pressure (Table 1).

Fig. 2. Map of Tenerife, indicating the sampling sites and total of samples taken from July 2016 to July 2017 on each location.

2.2. Sampling

Based on the methods of previous studies (Baztan et al., 2014; Galgani et al., 2013) quadrats were placed on the sand and particles within were surveyed.

Samples were consequently taken at the last high tide and quadrants were crossed by that line, to collect only the most recent deposited debris. Special care was taken, that between the accumulation of debris and the time of sampling no beach cleaning occurred.

The shorelines of every beach were sampled every 35 m by scraping the top layer of the sand from a 40 × 40 cm quadrat. This supernatant was put into a stainless steel sieve with a mesh size of 2 mm and then rinsed with clean seawater to absence the sand from the debris. Remaining particles were removed using tweezers and stored in aluminum foil for transportation to the laboratory.

Obtained samples were then oven-dried overnight at 70°, before they were classified in seven categories: Plastic, organic, mineral, metallic, paper, cigarettes and others. Plastic particles were separated into colors and further subdivided into meso- (2 mm–10 mm) and macro-particles (> 10 mm). The particles of each category were counted and weighed.

2.3. Statistical analysis

Statistical analyses and graphics were performed with R statistical software (R Core Team, 2017) and its extension, Rstudio. Data normality of plastic concentration was analyzed by the Shapiro Wilk test and the homoscedasticity was assessed graphically. Statistical differences between sampling sites and periods were tested using Kruskal-Wallis test and Conover posthoc test. The results were represented in boxplots.

3. Results

3.1. Total abundance

Overall, a total of 850 samples were obtained from eight locations throughout the months of July 2016 to July 2017. Depending on the length of every beach, most samples were taken on the strandlines of Tejita (280) and Cristianos (251), followed by Almaciga (63), Socorro (55), Gaviotas (46), Poris (44), Arena (40), and Puertito (30) (Fig. 2).

The total accumulation of plastic particles along the high tide line showed significant differences between locations (Kruskal-Wallis-Test, p-value $< 2.2e-16$) (Fig. 3). The amount of plastic particles was significantly higher in Poris than in all other beaches, except in Puertito. Puertito and Almaciga showed statistical difference to all other locations, but not among each other. The significantly lowest abundance of plastic debris was seen in Tejita.

Poris presented by far the highest plastic accumulation on the strandline regarding the mean and maximum values (Table 2). Puertito and Almaciga showed similar high average concentrations, but with Puertito reaching nearly the double amount in its highest concentration

Table 1
Summary of conditions at each sampling site.
Sources: [1a] Council of Santa Cruz de Tenerife; [1b] Council of Santiago del Teide; [1c] Council of Arona; [1d] Council of Arico; [1e] Council of Los Realejos; [1f] Council of Granadilla de Abona; [2] mobile app "GPS Test"; [3] Google Earth.

Location	Official beach name	Coordinates[2]	Length[3]	Orientation[3]	Esposure[3]	Sediment type	Hinterland	Seasonal changes	Touristic pressure	Cleaning
Almaciga	Playa de Almaciga[1a]	28°34′19.81″N 16°11′32.43″W	220	NNW	Open to NW	Sand stone	Natural hinterland with vegetation, on the bottom of a ravine, light traffic road alongside	Less sand in winter	Low	Manual cleaning (beach)/ emptying garbage (containers) twice a week[1a]
Arena	Playa de La Arena[1b]	28°13′46.94″N 16°50′27.28″W	150	W	Open to W, protected to N and S	Fine sand	In the center of an touristic nucleus (La Arena)	Steady	Medium (winter), very high (summer)	Manual cleaning (beach) daily by life guards[1b]
Cristianos	Playa Las Vistas[1c]	28°3′7.05″N 16°43′23.86″W	850	SSW	Open to SW, protected to W and S	Fine sand	In the center of an touristic nucleus (Los Cristianos)	Steady	Medium (winter), very high (summer)	Mecanic cleaning (sand)/ emptying garbage (containers) daily[1c]
Gaviotas	Playa de Las Gaviotas[1a]	28°30′48.16″N 16°10′33.16″W	220	SE	Open to SE	Sand stone	Natural hinterland, on the bottom of a cliff small urbanization nearby	Less sand in winter	Low (winter), high (summer)	Manual cleaning (beach)/ emptying garbage (containers) twice a week[1a]
Poris	Playa Grande[1d]	28°9′8.80″N 16°25′53.78″W	150	N	Open to N, protected to NE	Fine sand	Natural hinterland, small urbanization nearby	Steady	Low (winter), medium (summer)	Manual cleaning (beach)/ emptying garbage (containers) daily[1d]
Puertito	Playa del Puertito[1c]	28°6′48.88″N 16°46′5.38″W	70	SW	Open to SW, protected to W and S	Fine sand stone	Natural hinterland, small urbanization nearby	Steady	Low (winter), high (summer)	Twice a month[1c]
Socorro	Playa El Socorro[1e]	28°23′38.58″N 16°36′10.82″W	260	NNW	Open to NW, protected to NE	Sand stone	Natural hinterland, dead end road alongside	Less sand in winter	Low (winter), high (summer)	Manual cleaning (beach) daily by life guards[1e]
Tejita	Playa La Tejita[1f]	28°1′54.23″N 16°33′22.32″W	1100	S	Open to S, protected to NE	Fine sand	Natural hinterland, mountain (eastern end) small urbanization nearby (western end)	Steady	Low (winter), medium (summer)	No cleaning (beach)/emptying garbage bins (sunbed zones) daily[1f]

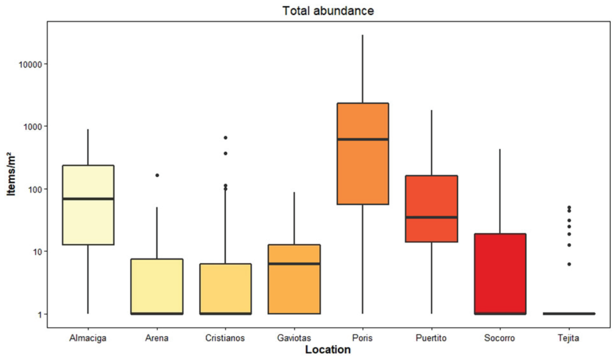

Fig. 3. Total plastic abundance in Items/m^2 by location collected from July 2016 to July 2017. The central thick line of each box designates the median, the box height shows the interquartile range; the whiskers indicate the lowest and the highest values and the circles point the values of outliers. Only for the graphical presentation in logarithmic scale values of 0 were replaced with values of 1.

compared to Almaciga. Less plastic debris was observed in the beaches of Gaviotas, Socorro, Cristianos and Arena. While Tejita indicated the lowest values in general, all beaches obtained at least one sample with no plastic particles during the year of sampling.

3.2. Temporal variability

There was no obvious pattern in seasonal changings for the total of all beaches. Moreover, peaks of plastic accumulation varied on every location during the sampling period.

Almaciga presented the peak mean value at 498.75 Items/m^2 (corresponding: 35.43 g/m^2) (December 2016) and the lowest mean value at 20.83 Items/m^2 (0.55 g/m^2) (April 2017) (Fig. 4a).

The maximum average accumulation in Arena was 53.13 Items/m^2 (1.07 g/m^2) in May 2017. Regarding the weight, highest values were obtained in April 2017 with 1.31 g/m^2 (20.31 Items/m^2). No plastic was found in September 2016 and June 2017. There was no significant difference between the sampling dates (Fig. 4b).

As for the beach of Cristianos, the highest mean value was 41.75 Items/m^2 (0.64 g/m^2) (May 2017), while the lowest mean value was 1.2 Items/m^2 (0.006 g/m^2) (March 2017). Plastic abundance in May 2017 and June 2017 was statistically different to the rest of the months, but not among each other (Fig. 4c).

Gaviotas showed the mean peaks at 40.63 Items/m^2 (0.43 g/m^2) in January 2017 and at 1.11 g/m^2 (15 Items/m^2) in November 2016. Only 1.25 Items/m^2 (0.003 g/m^2) in average were found in March 2017 (Fig. 4d).

The most polluted location was represented by Poris, with a maximum average of 15,135.94 Items/m^2 (411.96 g/m^2) in July 2017 and a minimum average of 18.75 Items/m^2 (0.1 g/m^2) in January 2017. In July 2016 the accumulation of plastic was statistically higher than in all other months, except for the sampling in November 2016 and March 2017. On the other hand, in January 2017 plastic abundance was significantly lower compared with the other sampling dates, except for the months February 2017 and May 2017 (Fig. 4e).

The second highest mean accumulation showed Puertito with 731.25 Items/m^2 (8.44 g/m^2) (June 2017). Even though the lowest mean value was 12.5 Items/m^2 (0.03 g/m^2) (April 2017), no statistical difference between months was observed (Fig. 4f).

As for Socorro, a high amount of plastic with an average of 155 Items/m^2 (9.63 g/m^2) was found in November 2016, while in October 2016, February 2017 and March 2017 no plastic at all was observed (Fig. 4g). This absence of plastic in these months was partially caused by seasonal changes and variations in the high tide line, which resulted in sampling spots with less sand, but rather stones or even massive rocks.

Tejita presented overall the lowest plastic abundance, with even 4 sampling dates without any plastic registered throughout the strandline. The maximum mean accumulation was 10.82 Items/m^2 (2.4 g/m^2) (August 2016) and this value was statistically highest (Fig. 4h).

3.3. Spatial variability

Plastic accumulation along the high tide line of each location was different, but the average amounts of the sampling positions throughout the year showed clear patterns for every beach.

The distribution of plastic across the strandline of Almaciga was mostly equal, with mean values from 160 Items/m^2 (9.84 g/m^2) (position 3) to 181.75 Items/m^2 (6.25 g/m^2) (position 6) (Fig. 5a). Only on the edges the average was lower: 110.94 Items/m^2 (4.11 g/m^2) at position 1 and 118.75 Items/m^2 (4.01 g/m^2) at position 7.

At the beach of Arena the mean accumulation of 30 Items/m^2 (0.61 g/m^2) at position 1 emerged, as the remaining positions showed all < 7 Items/m^2 (0.33 g/m^2) in average (Fig. 5b).

In general, Cristianos presented a low abundance of plastic at the representative points, except for the mean values of position 12 (120 Items/m^2, 1.42 g/m^2) (Fig. 5c). Besides, particles assembled more in the south-eastern part, whereas in the north-western part of the beach occurrence was less frequent.

Gaviotas showed average values from 16.25 Items/m^2 (0.27 g/m^2) (position 1) as a maximum to 5 Items/m^2 (0.13 g/m^2) (position 3) as a minimum (Fig. 5d). Plastic particles appeared rather on the extremes of the strandline than in the center.

The highest variation between the particular sampling positions was observed in Poris with the highest mean accumulation at 4591.88 Items/m^2 (100.31 g/m^2) (position 4) and a lowest at 85.94 Items/m^2 (1.45 g/m^2) (position 1) (Fig. 5e).

In the beaches of Poris and Puertito plastic particles assembled more in the center (Fig. 5f).

The mean amount of plastic debris at Socorro altered between the sampling points and reached the highest at position 5 with 43.13 Items/m^2 (1.49 g/m^2) (Fig. 5g).

Table 2
Mean values, standard deviation, median values and extreme values of the total plastic abundance at all sampling sites collected from July 2016 to July 2017. The results are presented as plastic particles per square meter (Items/m^2) and plastic weight per square meter (g/m^2).

Location	Values [Items/m^2]				Values [g/m^2]			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Gaviotas	11.68	17.41	0.00	87.50	0.31	0.68	0.00	3.81
Almaciga	154.66	192.70	0.00	893.75	7.06	13.54	0.00	77.44
Poris	2509.66	5078.28	0.00	28,218.75	66.87	130.29	0.00	578.08
Socorro	22.73	63.43	0.00	425.00	2.07	4.82	0.00	24.25
Tejita	1.50	5.69	0.00	50.00	0.27	2.51	0.00	38.94
Puertito	162.71	342.01	0.00	1781.25	2.71	4.50	0.00	18.02
Cristianos	12.38	49.93	0.00	650.00	0.19	0.84	0.00	9.19
Arena	10.47	27.71	0.00	162.50	0.27	0.79	0.00	3.64

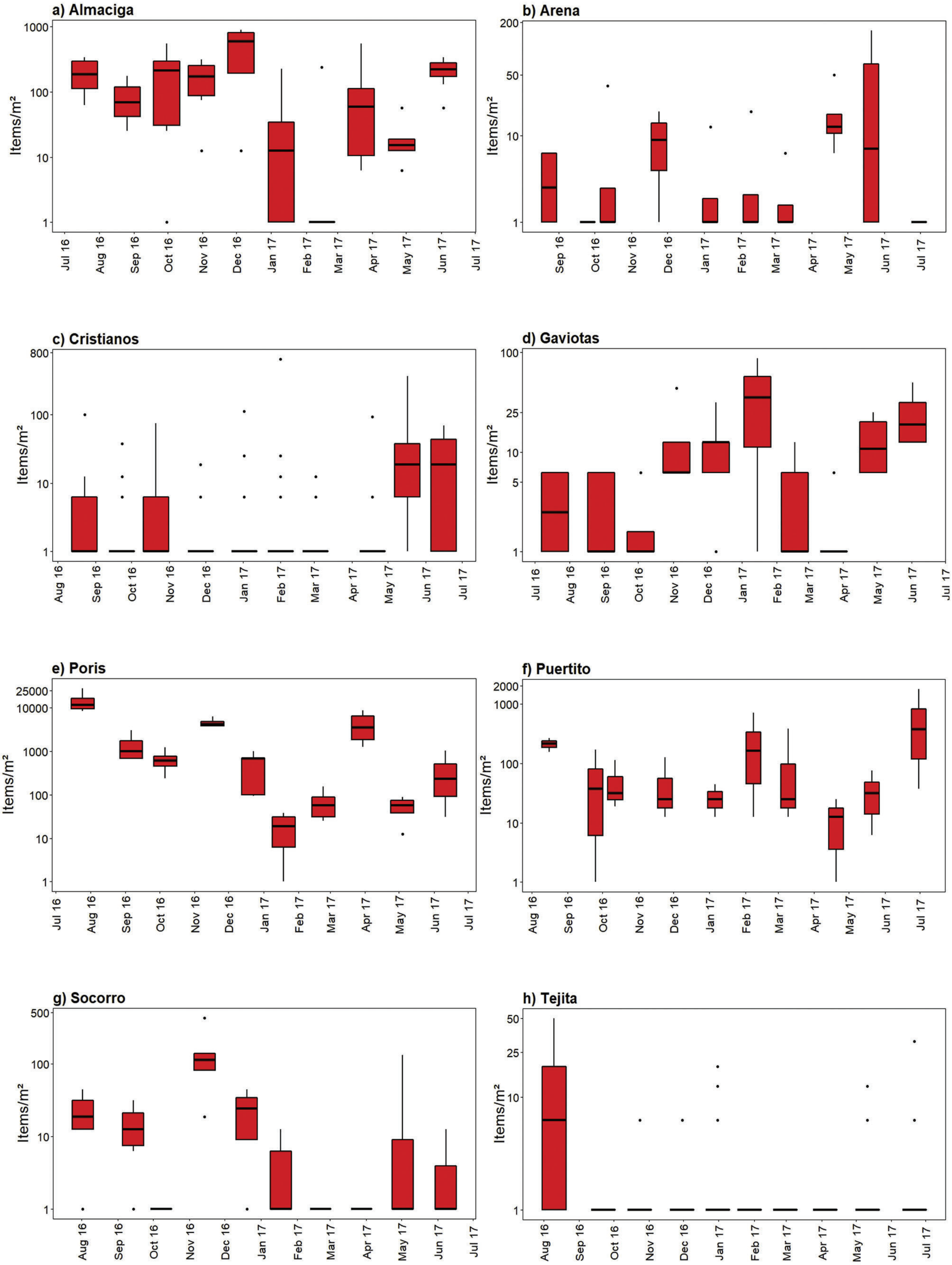

Fig. 4. Plastic abundance in Items/m^2 by sampling dates in a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita. The central thick line of each box designates the median, the box height shows the interquartile range; the whiskers indicate the lowest and the highest values and the circles point the values of outliers. Only for the graphical presentation in logarithmic scale values of 0 were replaced with values of 1.

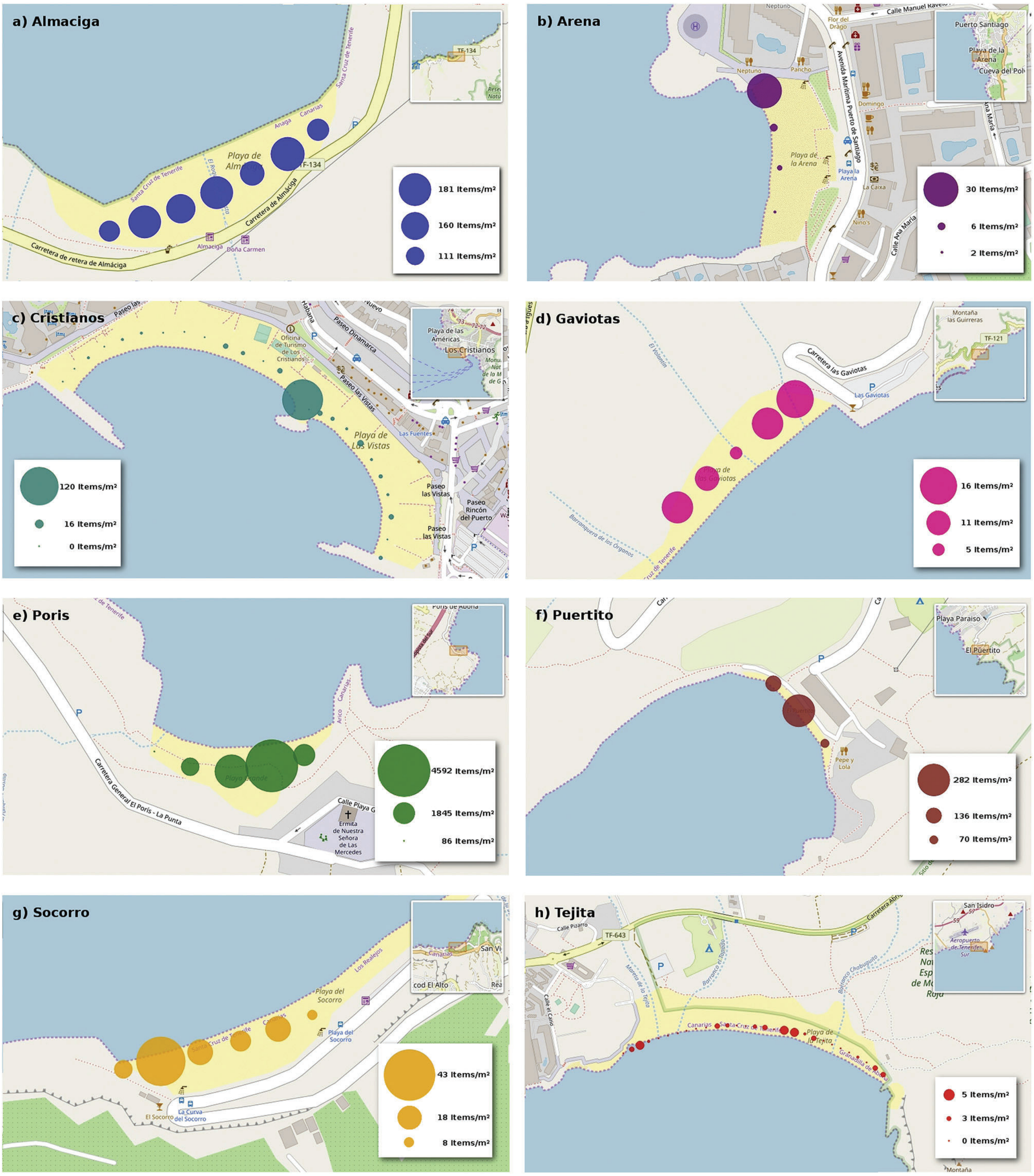

Fig. 5. Spatial variability of plastic abundance at a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita: Circles indicate mean abundance in Items/m^2 at each sampling point.

Particle accumulation at Tejita was very low and occurred only randomly (Fig. 5h). The highest mean value was 5 Items/m^2 (0.23 g/m^2) in the center of the strandline, but almost 25% of the representative points lacked plastic debris throughout the whole sampling period.

3.4. Types of debris and plastic colors and sizes

Overall, the most common particles throughout the sampling year were plastic debris (63%) of any color and organic materials (35%), which were mostly represented by algae, wooden pieces, seeds, leafs or other parts of plants (Fig. 6). < 0.5% was other anthropogenic debris, such as paper, cigarettes or metals. Around 2% of the debris remained undefined mostly because of the fragile material properties in dry condition. These particles were often assumed to be tar or wax, but correctness was not verified.

The 3 most abundant debris types were found on every location, whereat organics dominated on the majority of the beaches. The percentage of plastics was leading in Poris (80.48%) and Almaciga

Fig. 6. Composition of marine debris in total and at location a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita.

(49.71%), but in Cristianos (37.97%) and Puertito (34.03%) it was still represented with more than one-third of all debris. Less portion occurred in Socorro (15.14%), Arena (8.24%), Tejita (6.86%) and Gaviotas (5.90%). Other anthropogenic debris accounted < 2% at all locations.

The main color of the found plastic was white or transparent (64%), followed by yellow or orange particles (11%). These include pieces, that originally were white/transparent, but became yellowish or orange due to aging processes in the environment as well as yellow-dyed material (Fig. 7). The remaining categories counted with < 10% each and contained particles, which were actually dyed in the corresponding color. Although percentage of painted plastics varied among beaches, white/transparent was the dominating color at every location.

In general, mesoparticles (91%) were more abundant than macroparticles (9%), mostly represented by fragments or pellets (Fig. 8). Even though the ratio between particle size varied from beach to beach, the total amount of mesoparticles during the sampling year at each location never exceeded 24% of all plastic particles.

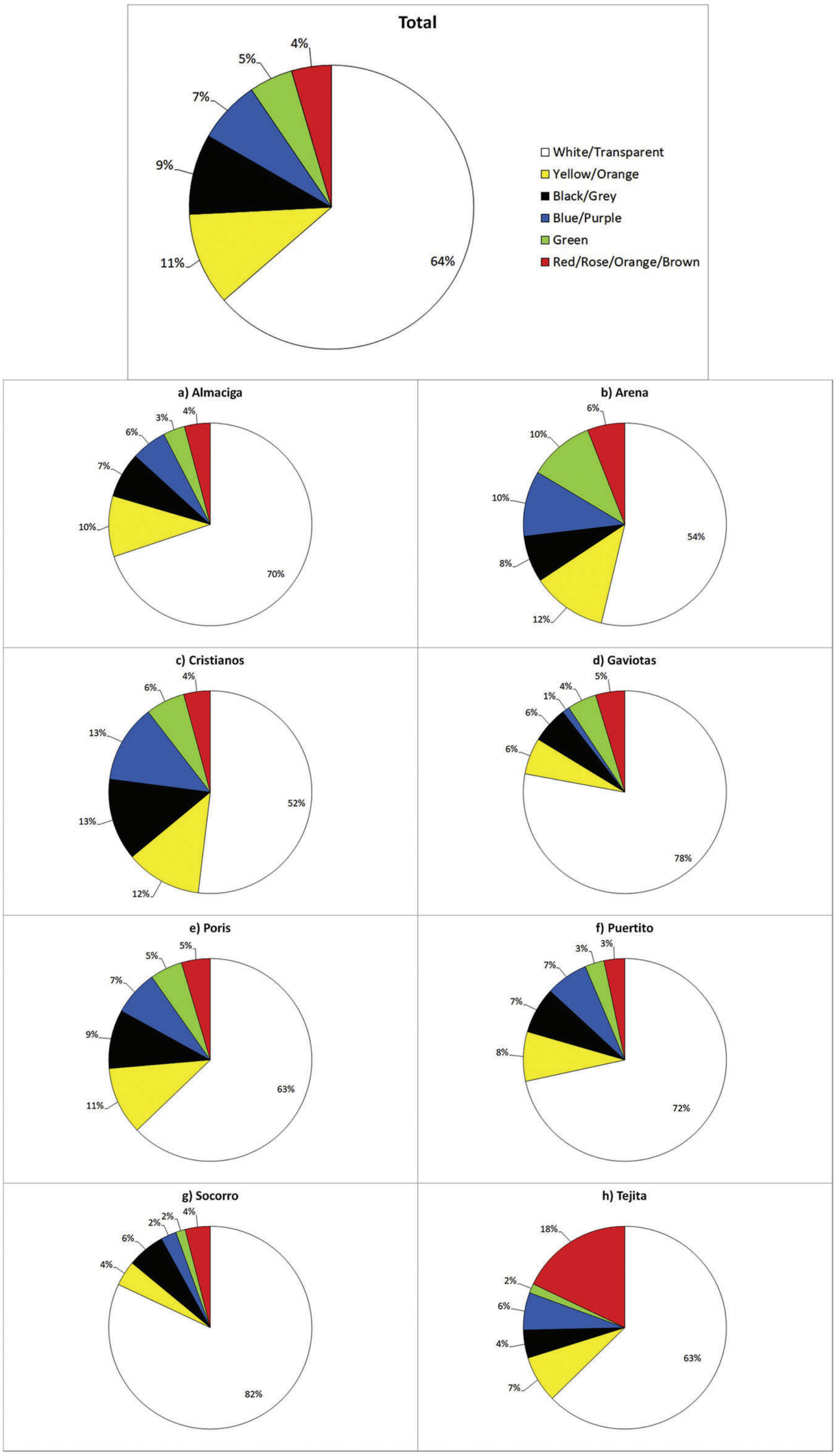

Fig. 7. Percentage of colors of plastic particles in total and at location a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita.

4. Discussion

The plastic pollution values found were very wide ranged, not only between locations but also between the sampling dates on every beach. Values of plastic weight mainly supported values of the amount of particles found on every location. Nevertheless they showed more variability as it can be seen in the temporal variability of Arena and Gaviotas, as well as on position 3 and 6 of Almaciga (spatial variability). This might be due to the different types of existing plastic and their densities. No evidence was found, that plastic accumulates more in areas of touristic pressure or near urban nucleus as it was assumed earlier (Ivar do Sul and Costa, 2007; Ryan et al., 2009; Thompson et al., 2009). Rather the beaches of Arena and Cristianos, which are located in tourist centers are very little affected by plastic pollution. On the other hand beaches of Poris, Puertito and Almaciga, which are very low populated and less visited showed a high accumulation of debris. This supports the suspicion that most of the stranded plastics originate from the open sea, rather than from local or population-related sources

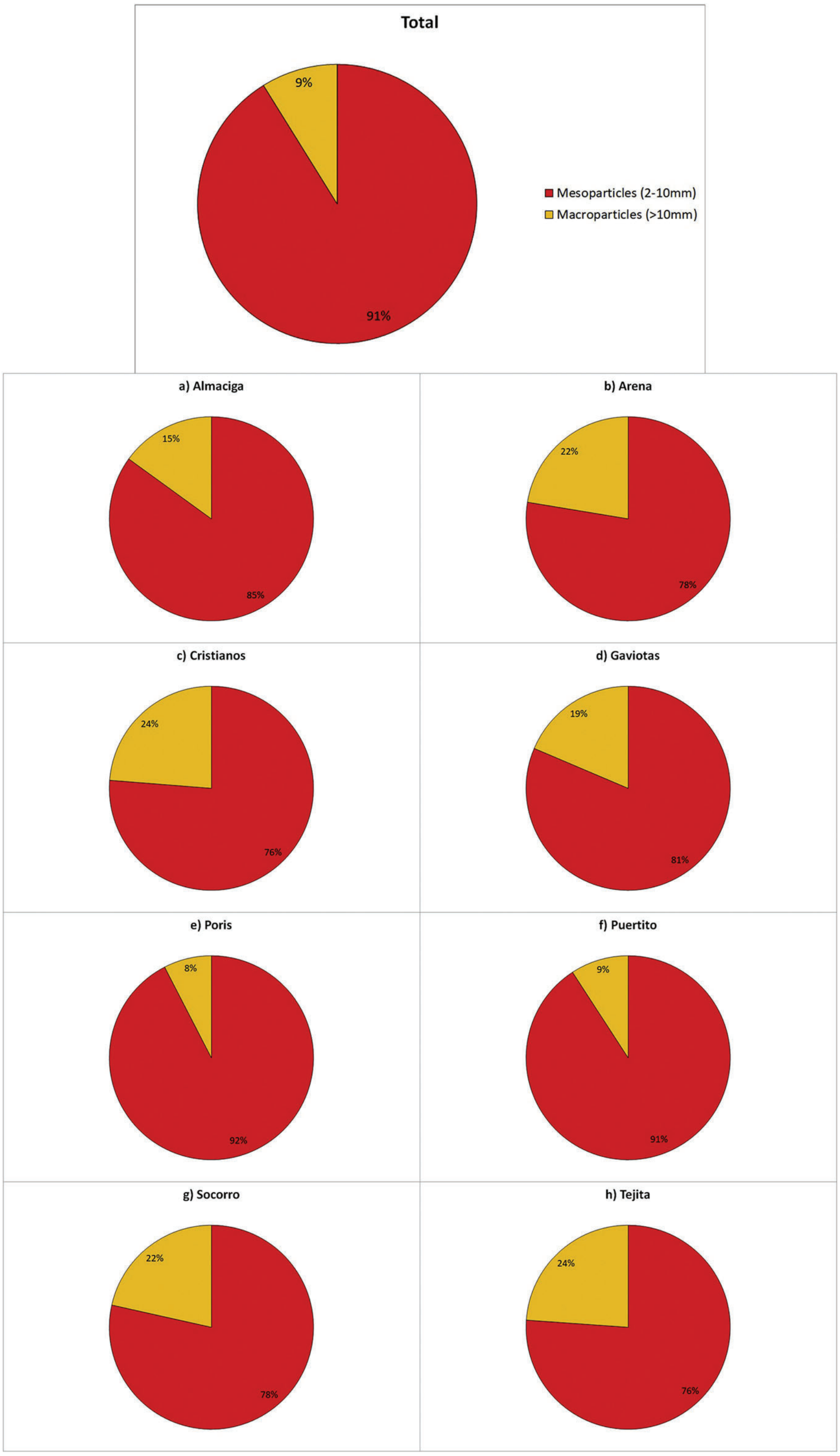

Fig. 8. Percentage of meso- and macroparticles in total and at location a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita.

(Baztan et al., 2014; Corcoran et al., 2009; Ivar do Sul et al., 2009). Moreover wave and wind driven origins seem to be the main priority for plastic accumulation on strandlines (Herrera et al., 2018; Ivar do Sul et al., 2009). The high pollution of Poris and Almaciga confirms this theory. Both beaches are widely open to the main currents, whereat other beaches situated on the northern and southern coastline are less exposed. The strandlines on the western side of Tenerife are all located in bays and therefore they are protected towards the main current. Nevertheless Puertito showed a high amount of debris, which might be due to two possible reasons: First, the bay represents a deeper inlet than Arona and Cristianos, which in turn can result in higher accumulation due to local currents and winds in the bay. Second, the beach receives far less attention in beach cleaning than the other two mentioned beaches. However, to determine the relation between plastic abundance on coastlines and current or wind directions more studies are needed. Also, the data showed no patterns for seasonal changes of plastic accumulation during the year, but the results of recent studies presented similar amount of plastic regarding the sampling months. The beaches of Gaviotas and Tejita demonstrated low plastic abundance in February 2018, as well as Socorro in October 2018 (Álvarez-Hernández et al., 2019; Villanova Solano et al., 2018). In contrast, on the strandline of Poris a high amount of plastic was found in October 2018 (Álvarez-Hernández et al., 2019). This coincidence might be due to the fact that in general the first two beaches are little polluted and the beach of Poris is highly polluted. As for Socorro, this study also shows low plastic abundance on days with less sand on the beach due to seasonal changes. Another explanation might be that the plastic accumulation on beaches is variable during one year, but show consistency throughout the months of every year. Further research is needed to investigate the long-term temporal variations of plastic accumulation on coastlines and its causes.

However, patterns had been seen for the distribution of plastic debris along the strandlines. The majority of the beaches accumulated particles in particular zones, which were mostly located in the center. Only Arena and Socorro accumulated at the edges. Tejita showed accumulation in the center and at one edge, which might be due the low pollution in general. For future investigations, it is therefore suggested to run preliminary sampling tests on the beaches of interest to determine zones and periods of minimum and maximum accumulation during the year. This information is essential for further diagnostics and monitoring. Besides, it can help local communities to improve their beach cleaning, as more attention can be paid to areas and periods of high accumulation.

Plastic seemed to be in general the most abundant debris on the coastline of Tenerife, but this proportioning results mostly from the high amount of particles found on Poris, Puertito and Almaciga. In case of Poris and Almaciga this high abundance can be explained by their exposed orientation towards dominant currents and winds. Furthermore, Poris is not only receiving debris from the open sea, but also from the south-eastern coastline of Tenerife, as the main current passes by closely. Therefore, the current can drag more anthropogenic debris from coastal urbanization, the capital and its harbor to this strandline. This might be an explanation for the high amount of plastic particles. Otherwise, Almaciga is exposed to the current coming from the open sea bringing all sort of debris, which results in a more balanced composition. Puertito, on the other hand, is located on the south-western side of the island and is therefore little affected by the main current. Nevertheless it is situated in a small bay, which is rarely cleaned, but is frequently visited by tourist boats and where it is common to have barbecues or celebrations on the weekends along the seafront. Local currents can be dominant and hence local debris can circulate and accumulate in the bay.

Of all plastic particles white and transparent is the most common color at all locations. These colors are commonly used for packaging like food containers, wrappers, films, bags and different kind of bottles. Packaging material is not only one of the main plastic demands, but rather is the most important market sector for the plastic production (PlasticsEurope, 2018). Furthermore particles between 2 and 10 mm were most abundant in all beaches, consisting mainly out of fragments or pellets. Pellets can be considered as primary microplastics and enter in the environment through accidental spillage during transport, inappropriate use as packing materials or direct out-flow from processing plants (Cole et al., 2011). Fragments, on the other hand, represent secondary microplastics and originate from larger plastic particles, which with time become brittle and consequently break down into smaller pieces due to degradation (e.g. biodegradation, photodegradation, thermooxidative degradation) and abrasion through wave action (Andrady, 2011; Barnes et al., 2009; Cole et al., 2011).

The fact that plastic represents one of the most found particles on the strandline reflects the magnitude of this kind of pollution in the environment. Not only that production raises continuously (PlasticsEurope, 2018), but also improper human behavior and lack of recycling leads to an ongoing contamination with plastic, which threatens environment and wildlife (Barnes et al., 2009). Plastic can contain chemical additives (e.g. colors, UV-filters, plasticizers, etc.), added at the time of manufacture and also has the property to absorb organic pollutants in aquatic environment (Bakir et al., 2014; Camacho et al., 2019; Lee et al., 2014; Moore et al., 2005; Ogata et al., 2009; Rios et al., 2010). Fragments are usually the result of a slow degradation processes, meaning that these plastic particles have been in the environment for a long time already.

This leads to two problems. First, level of sorbed organic pollutants rises in each particle with the decrease of the its size due to the increase of its surface-to-volume ratio. Plastic particles can reach a sorption equilibrium in seawater in 24 h and can desorb chemicals again in animal guts (Bakir et al., 2014; Tanaka et al., 2015; Teuten et al., 2007). Second, Invertebrates, fishes, sea birds, turtles up to marine mammals from all around the world are known to ingest plastic debris (Boerger et al., 2010; Bond et al., 2013; Bravo Rebolledo et al., 2013; Browne et al., 2008; Camedda et al., 2014; Campani et al., 2013; Choy and Drazen, 2013; Guebert-Bartholo et al., 2011; Herrera et al., 2019; Hoarau et al., 2014; Lusher et al., 2013; Mascarenhas et al., 2004; Possatto et al., 2011; Schuyler et al., 2013; Tanaka et al., 2013). In Tenerife, plastic was found in the gut contents from fledglings of Cory's shearwater (*Calonectris diomedea*) (Rodríguez et al., 2012). This shows that animals of the Canarian Islands are already affected and therefore endemic species of this sensitive ecosystem can be seriously endangered in the future. But not only wildlife is threatened by this marine debris, since plastic has been detected in various fish species and oysters sold for human consumption (Rochman et al., 2015b). However, as plastic is ingested by a wide range of animals, and pollutants can be sorbed to the tissue, these pollutants can enter into the food web (Browne et al., 2008; Rochman et al., 2013; Tanaka et al., 2013; Teuten et al., 2009), which ends in the human consumption and thus represents a serious threat for human health.

5. Conclusion

Tenerife presents plastic pollution on every studied beach. The plastic concentration was variable during the year and different for every sampling site. Furthermore, the amount of plastic showed high variability between strandlines in general, but especially on Poris, Puertito and Almaciga high levels of contamination were found. Along the year each beach presented a consistent spatial pattern of accumulation.

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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Author contributions

S.R. designed the experimental work, conducted the sampling, processed the samples in the laboratory, analyzed the data and wrote the manuscript. A.H. performed statistical analyzes and graphics with R. C.H. contributed to design the experimental work. All authors contributed to the acquisition of the data and edited the article.

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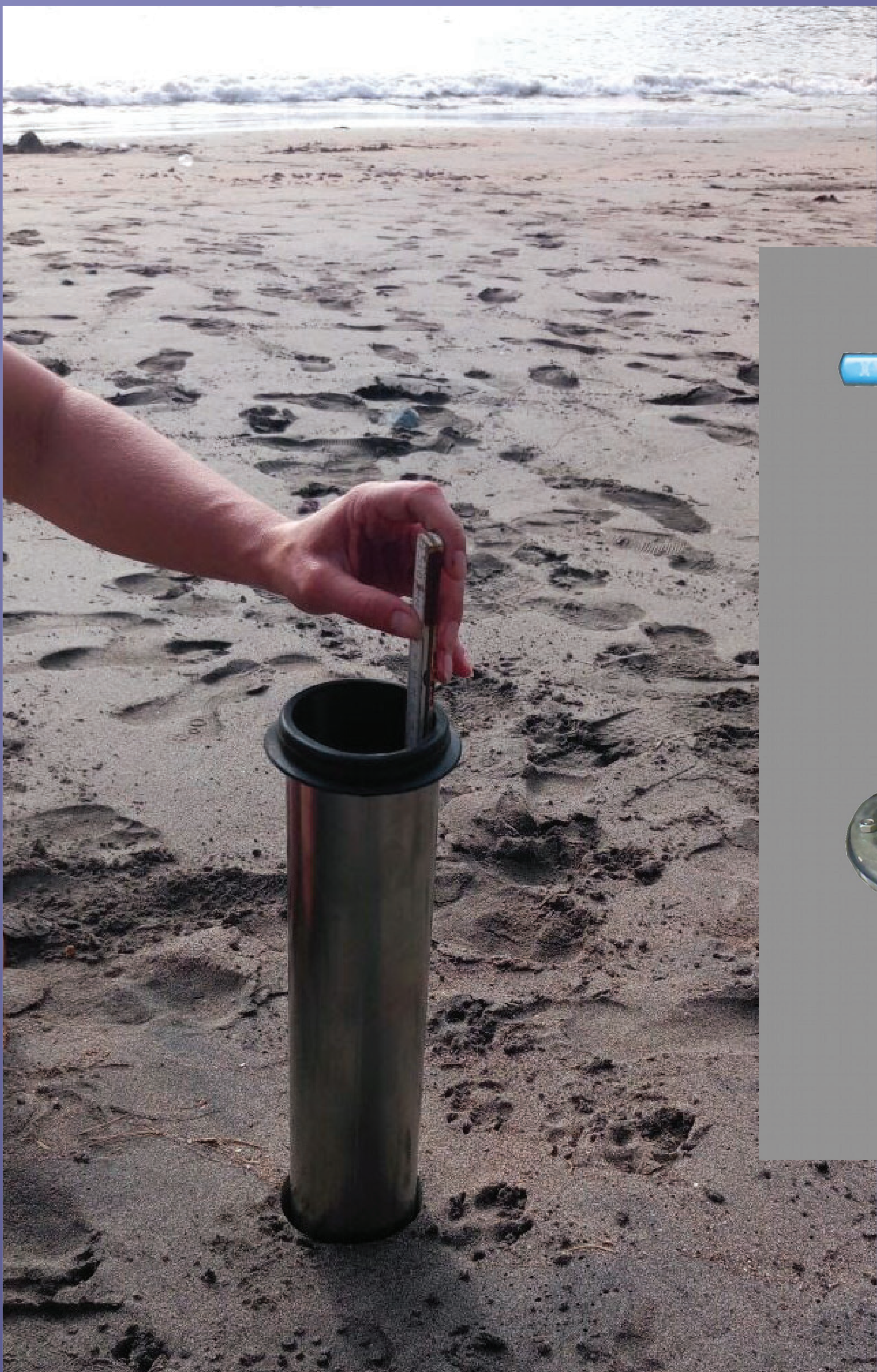
Capítulo IV

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



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An annual study on plastic accumulation in surface water and sediment cores from the coastline of Tenerife (Canary Island, 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 re search, 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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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 ≥ 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.

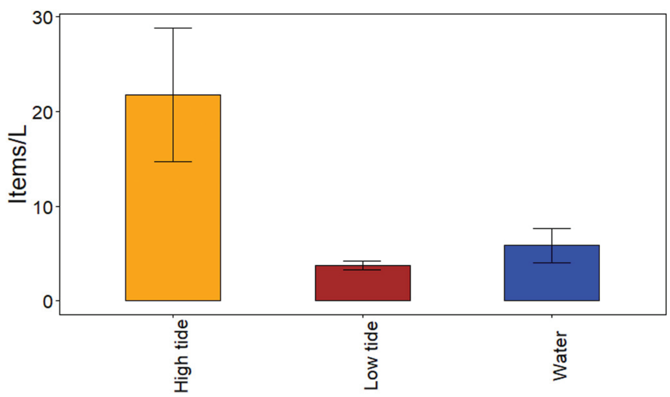

Fig. 2. Average particle abundance in items/L of each sampling zone collected from July 2016 to July 2017.

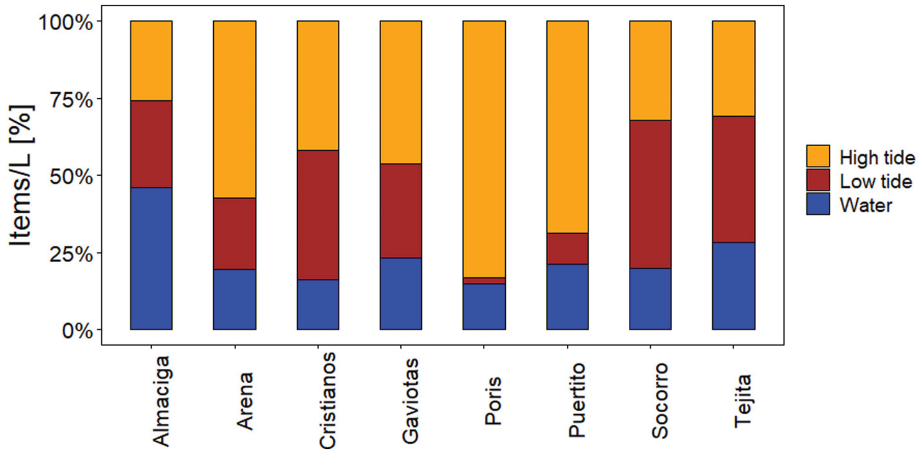

Fig. 3. Percental distribution of particles measured in items/L for each location in the three different sampling zones.

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		
	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
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
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

Location	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]
High tide	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	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	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

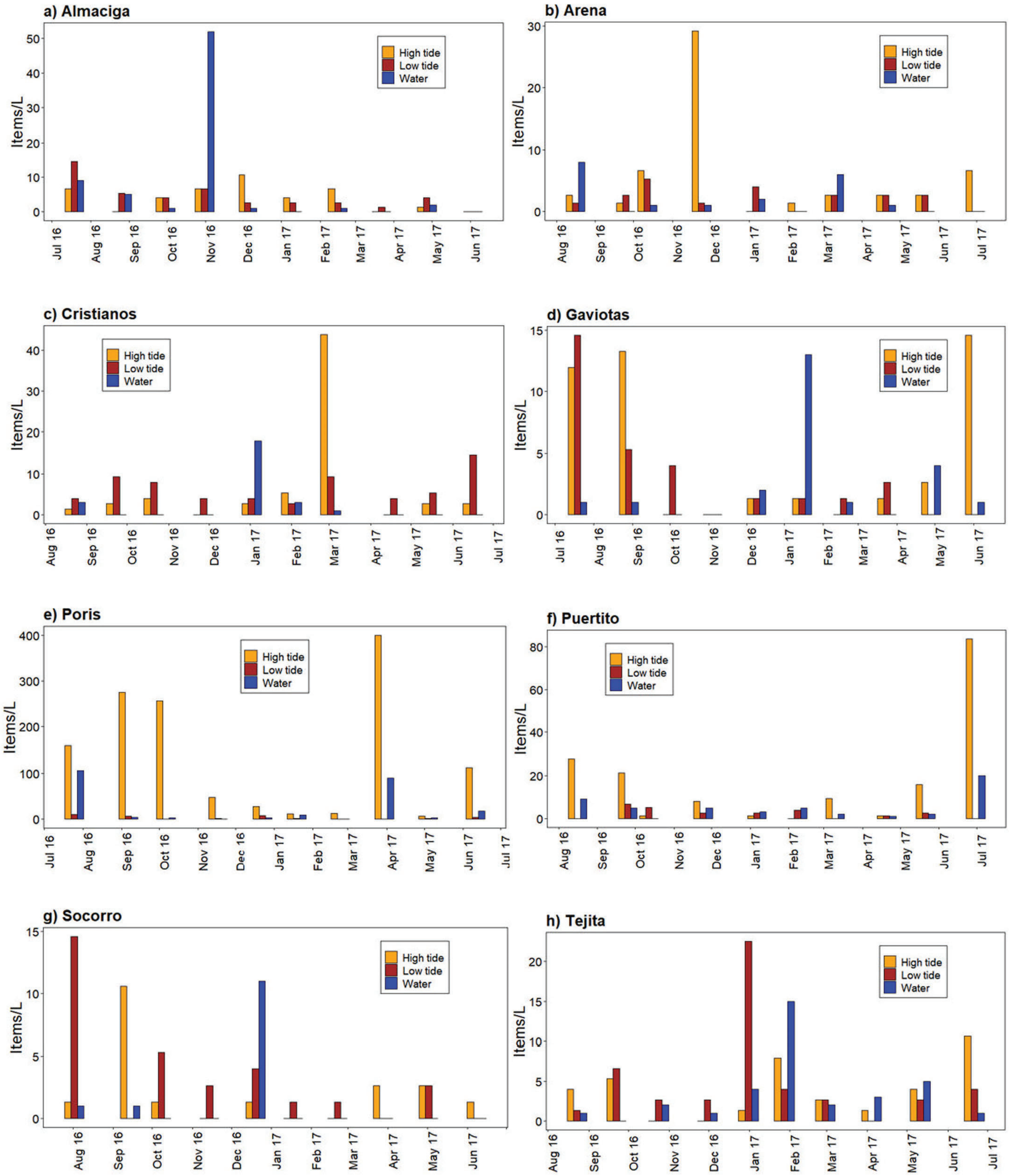

Fig. 4. Particle abundance in items/L in each sampling zone by sampling dates in a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita.

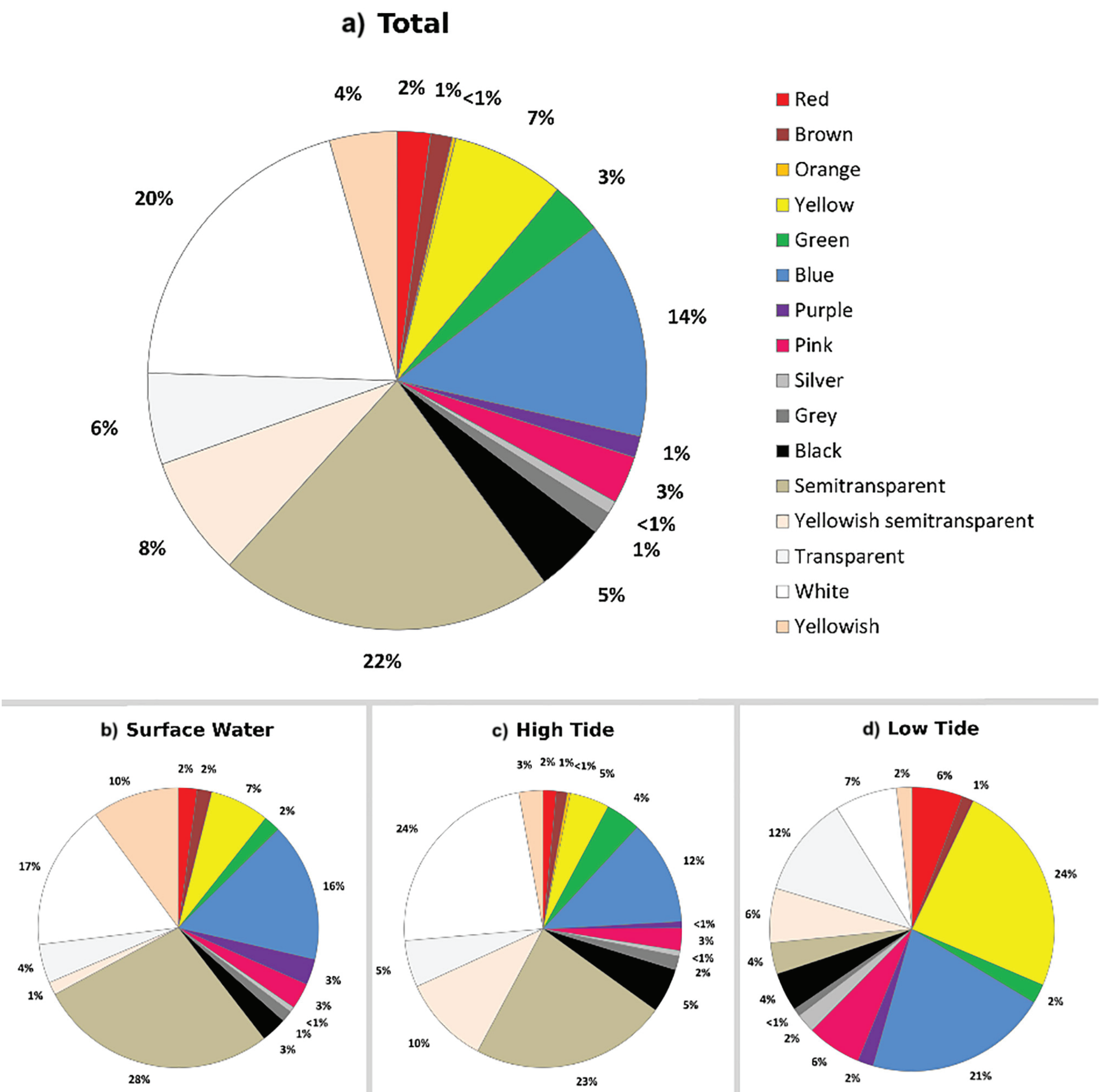

Fig. 5. Colour distribution of particles in total and from each sampling zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

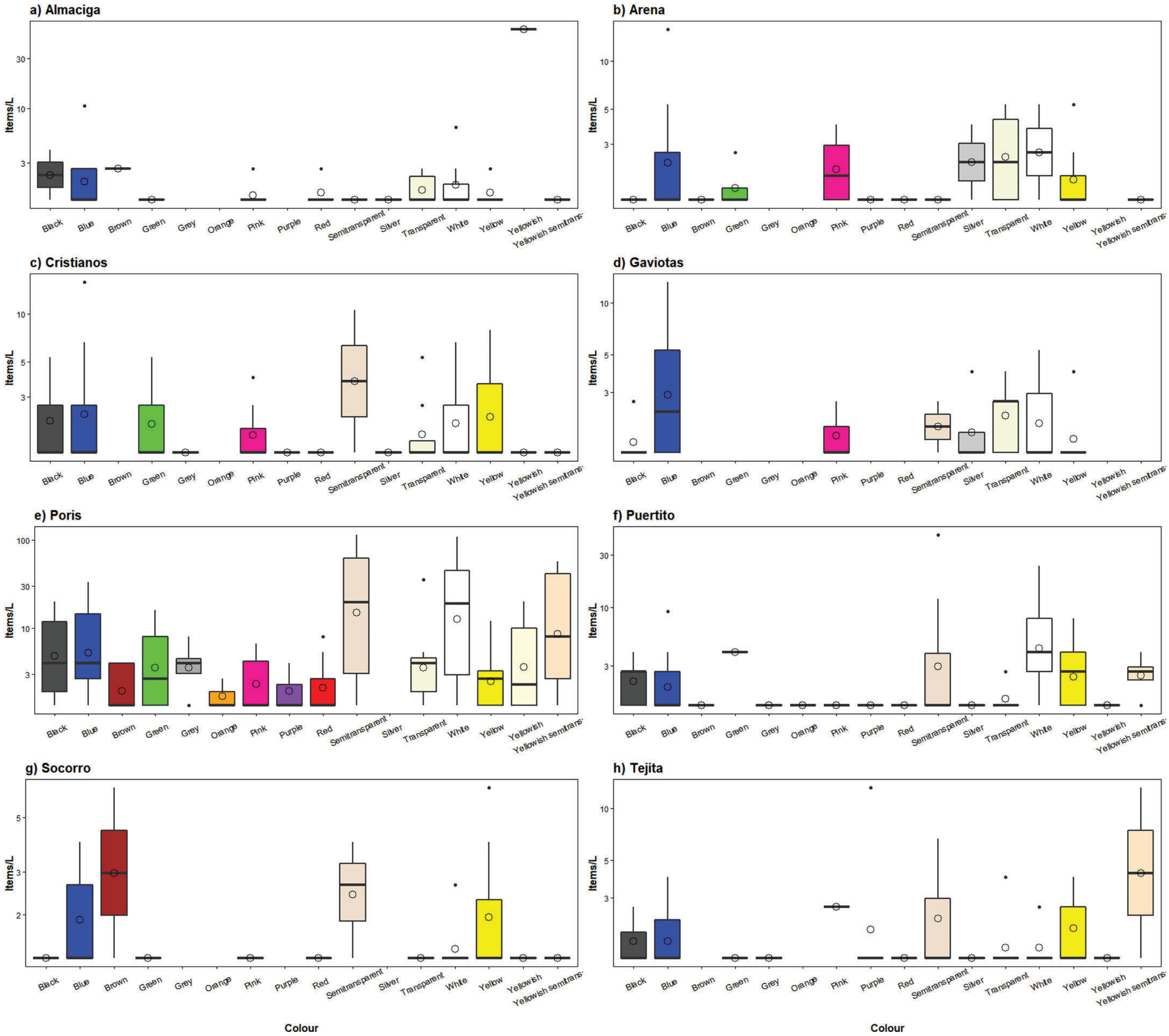

Fig. 6. Colour distribution of particles in Items/L by sampling dates in a) Almaciga, b) Arena, c) Cristianos, d) Gaviotas, e) Poris, f) Puertito, g) Socorro and h) Tejita. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile 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

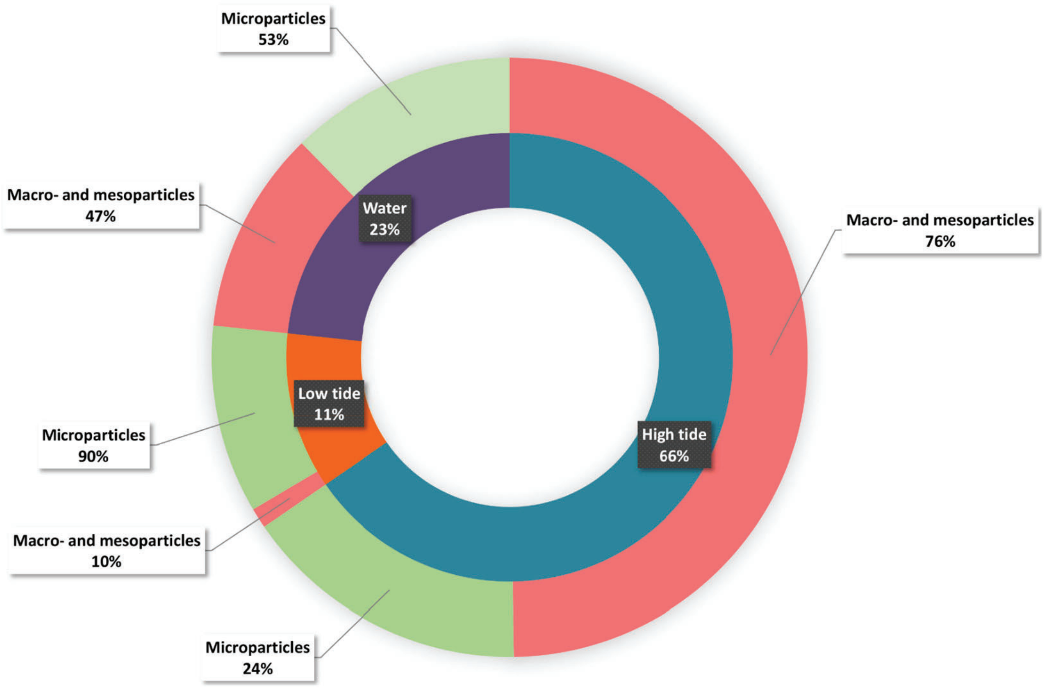

Fig. 7. Size distribution of particles: Inner donut: Particle amount in percentage at each sampling zone; outer donut: Percentage of macro- and mesoparticles (>1 mm) and of microparticles (<1 mm).

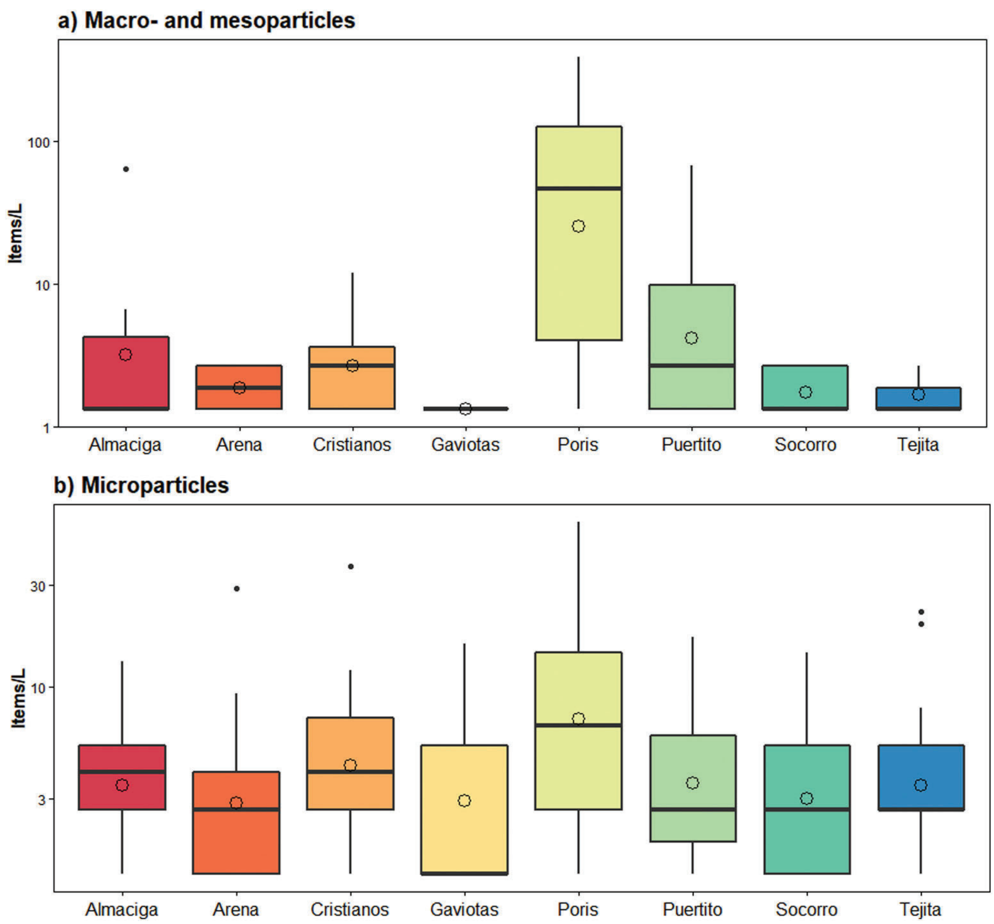

Fig. 8. Particle abundance in items/L of a) macro- and mesoparticles and b) microparticles by sampling location. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile range, the whiskers indicate the lowest and the highest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

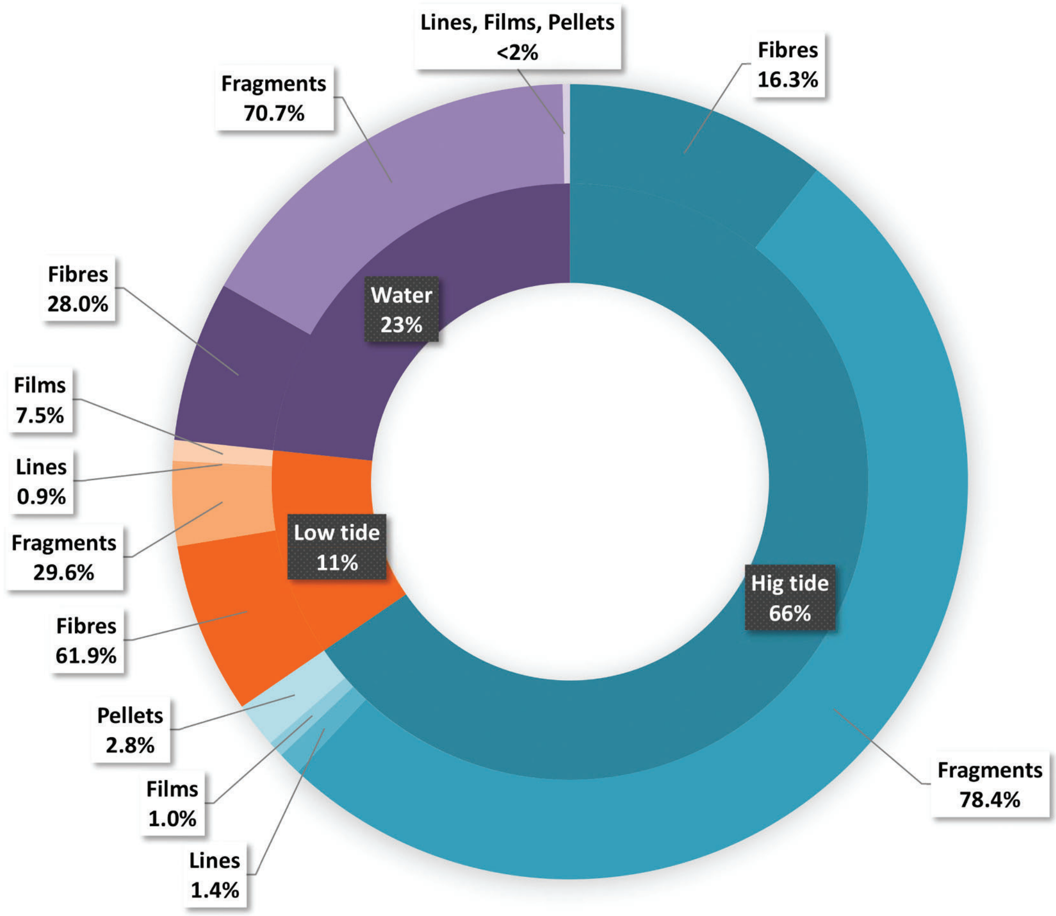

Fig. 9. Shape distribution of particles: Inner donut: Particle amount in percentage at each sampling zone; outer donut: Percentage of fibres, fragments, lines, films and pellets.

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

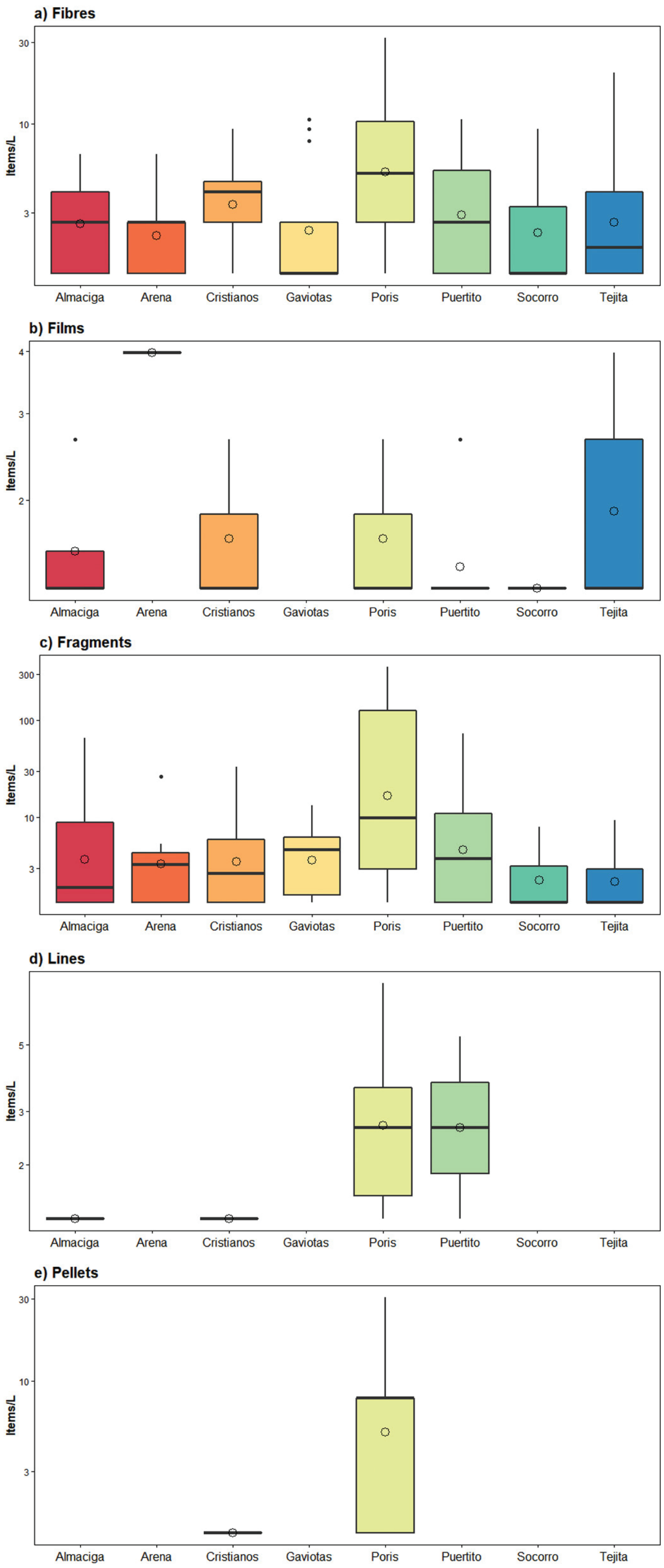

Fig. 10. Particle abundance in Items/L of a) fibres, b) films, c) fragments, d) lines and e) pellets by sampling location. The circle in each box represents the mean value and central thick line designates the median. The box height shows the interquartile range, the whiskers indicate the lowest and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

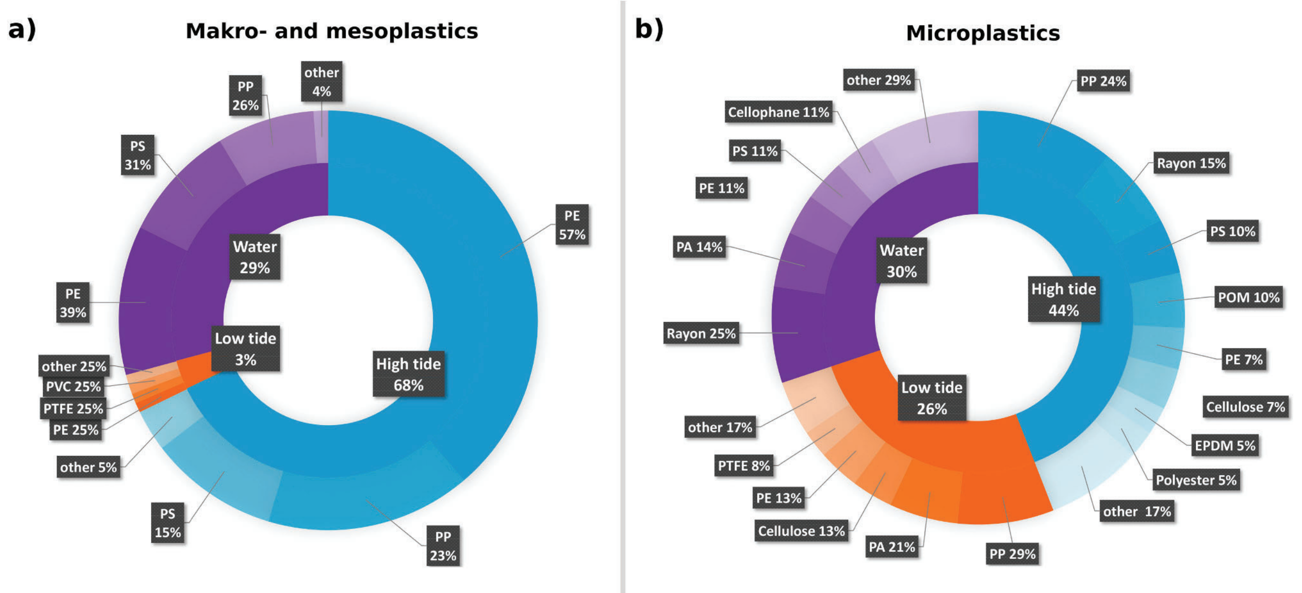

Fig. 11. Polymer types of plastics. Inner donuts: Particle amount in percentage at each sampling zone; outer donuts: Percentage of polymer types. a) Macro- and mesoplastics (>1 mm): "Other" identified polymers were: Cellulose, EPDM, ethylene/methacrylic acid ionomer, PA, PB, phenoxy resin, PP/PE copolymer, 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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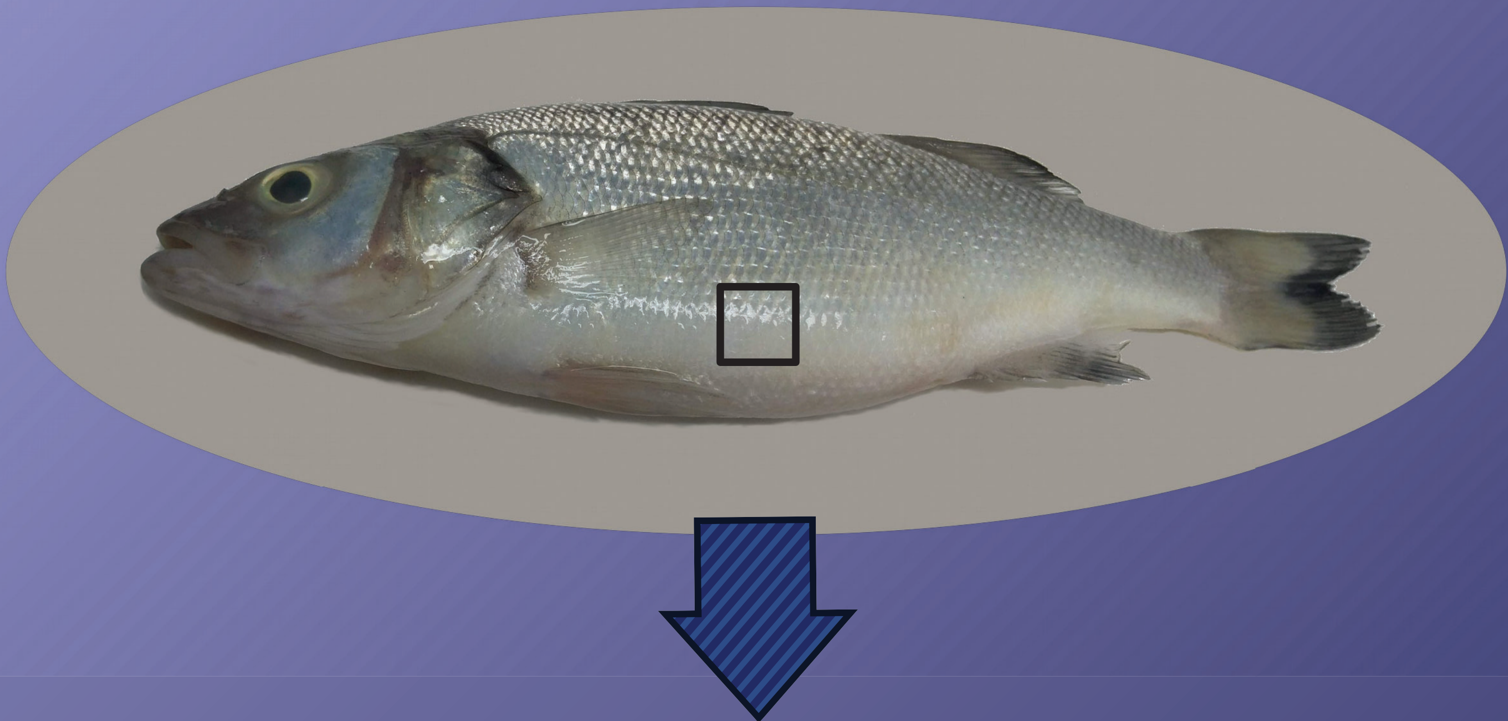
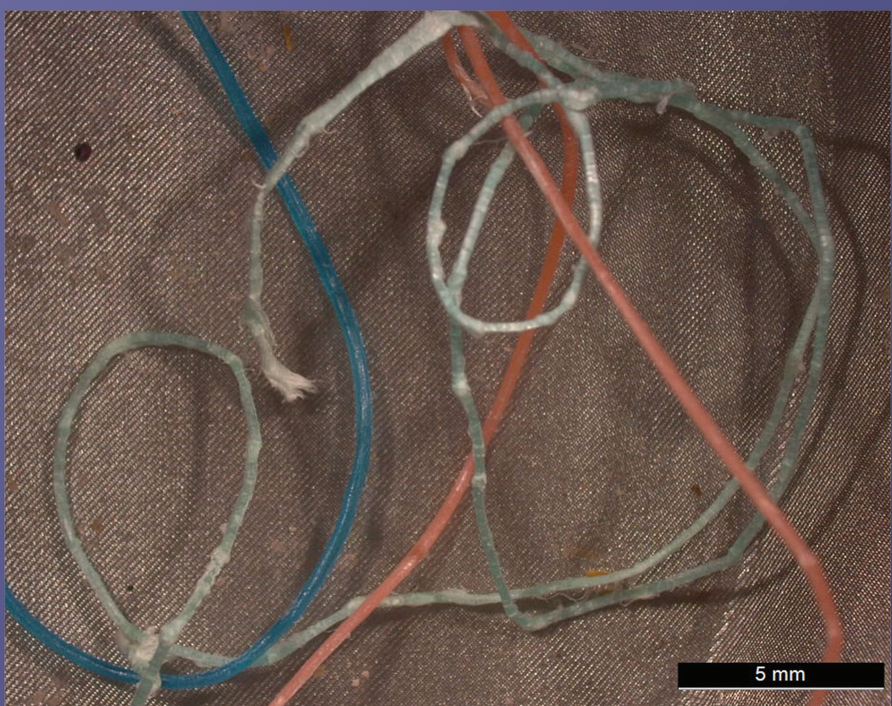
Capítulo V

Evidence of microplastic ingestion by cultured European sea bass (Dicentrarchus labrax)





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Evidence of microplastic ingestion by cultured European sea bass (*Dicentrarchus labrax*)

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ABSTRACT

The presence of microplastics (MPs) in the marine environment is a concerning topic due to the ecotoxicological effects and possible seafood contamination. Data is needed to evaluate human exposure and assess risks, in the context of a healthy and beneficial seafood consumption. While microplastic ingestion by wild fish has been reported since the early 70‘s, farmed fish are rarely investigated. Here, for the first time the presence of microplastics in fish cultivated in the coastal water of Tenerife (Canary Island, Spain) was evaluated. From 83 examined individuals, 65% displayed microplastics in their gastrointestinal tracts, with averages between 0.6 ± 0.8 (SD) and 2.7 ± 1.85 (SD) particles per fish. The total number of microplastics detected was 119. Fibres (81%) and fragments (12%) were the predominant shapes. FTIR analysis showed that fibres were mostly composed by Cellulose (55%) and Nylon (27%), whereas fragments by PE (25%) and PP (25%).

Since the beginning of the century, plastic pollution in the marine environment has continuously gained attention and has become a major problem worldwide (GESAMP, 2019; UNEP, 2016). Yearly increasing numbers of production (PlasticsEurope, 2016, 2018a, 2018b, 2019) and effects on marine wildlife due to entanglement, ingestion and even hitch-hiking of invasive species are of global concern (Gregory, 2009).

Ingestion of plastic by fish was first reported in the 1970's (Carpenter et al., 1972; Kartar et al., 1973). Carpenter et al. (1972) already suspected that the ingestion of plastic could cause intestinal blockage and therefore lead to major health problems and eventually death, but further investigations were sparse until 2010. Since then, the occurrence of plastic in fish and the resulting health threats have been well documented. Not only can ingestion of plastic lead to intestinal blockage, but it has also been directly linked to inflammatory responses of cells, alteration of gut microbiota, ulcerations, internal injuries and an increasing effect on mortality (Carpenter et al., 1972; Gall and Thompson, 2015; Hoss and Settle, 1990; Jabeen et al., 2018; Jin et al., 2018; Lu et al., 2016; Mazurais et al., 2015; Pedà et al., 2016; Wright et al., 2013). Studies have also shown that the ingested particles can travel within fish, as plastic was found in the liver, brain and even in the eggs (Avio et al., 2015; Chae et al., 2018; Collard et al., 2017; Ding et al., 2018; Pitt et al., 2018). Since plastic particles may also contain harmful chemicals, used as additives during plastic production or absorbed by the plastics in the water (Bakir et al., 2014; Camacho et al., 2019; Lee et al., 2014; Moore et al., 2005; Ogata et al., 2009; Rios et al., 2007; (Rochman et al., 2013a)), the combination of these chemicals and the plastic can cause a wide range of health problems such as liver toxicity, alteration of the endocrine system, neurotoxic effects, oxidative stress and even change of behaviour in fish (e.g. swimming behaviour, lethargy, predatory performance) (Barboza et al., 2018b(Barboza et al., 2018c); Chen et al., 2017; Luís et al., 2015; Oliveira et al., 2013; Rainieri et al., 2018; Rochman et al., 2013b; Rochman et al., 2014; Zhang et al., 2019).

The exposure of fish to microplastic is a matter of concern not only for fish health, but also for human health. Seafood is an important protein and polyunsaturated fatty acid source in human consumption and ingested microplastics were not only found in the gut, but also in muscle tissue (Abbasi et al., 2018; Garcia et al., 2020). Additionally, humans may be exposed to the harmful chemicals carried by microplastic that leached into animal guts (Bakir et al., 2014; Camacho et al.,

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2019; Engler, 2012; Lee et al., 2014; Moore et al., 2005; Ogata et al., 2009; Panio et al., 2020; Rios et al., 2007; (Rochman et al., 2013a); Saliu et al., 2020; Teuten et al., 2007). Currently, the magnitude of humans' exposure to plastic debris and attached chemicals through seafood is unclear, but concerns for human health rose (Lusher et al., 2017; Rochman, 2016; Seltenrich, 2015; Smith et al., 2018).

While the presence of microplastic in wild fish is well documented, studies on microplastic ingestion in captive fish are scarce (Cheung et al., 2018; Feng et al., 2019; Garcia et al., 2020; Wu et al., 2020). So far, there are only four studies available reporting the presence of plastic particles in the guts of farmed fish. Specifically, two of these studies investigated plastic ingestion by fish raised in cages in coastal waters (Feng et al., 2019; Wu et al., 2020). One study considered fish farms located in rivers (Garcia et al., 2020) and another study observed fish from fish ponds (Cheung et al., 2018). Moreover, only one study until now – focused on flathead grey mullets (*Mugil cephalus*) – has examined differences in the presence of microplastics between farmed and wild specimens, highlighting in this case lower contamination in the farmed specimens, which were raised in fish ponds.

Starting from this basis, in this work for the first time, the presence of microplastic in the European sea bass (*Dicentrarchus labrax*) cultivated in aquaculture facilities located in the coastal waters of Tenerife (Canary Islands, Spain) was investigated. This study has a value as baseline assessment not only for farmed fish, but also for the Canary Islands, since until now only one previous study has investigated the microplastic ingestion by fish from the archipelago (Herrera et al., 2019).

Fish samples were obtained between July 2016 and June 2017 from two different aquaculture companies: Punta Rasca Cultivos Marinos de Canarias, S.L. and Socat Canarias, S.L. Both companies were based in Tenerife, Canary Island (Spain) and cultivated – amongst other fish – European sea bass. Farming cages for growing purposes were made out of blue and black polyethylene (Punta Rasca Cultivos Marinos de Canarias, S.L.) or polyvinylchloride (Socat Canarias, S.L.). However, both companies used harvesting fishing nets made out of black and/or red nylon. Punta Rasca Cultivos Marinos de Canarias, S.L. used farming cages with a mesh size of 15 mm for adult animals, whereas Socat Canarias, S.L. used a mesh size of 24 mm. Both aquaculture facilities were located in the southern part of the West Coast of Tenerife close to the shoreline (Fig. 1). Adult fish were fed once a day with dry pellet food. Two sampling batches of 10 and 13 fish respectively were collected from a catch from Punta Rasca Cultivos Marinos de Canarias, S.L. The rest of the samples - batches of 10 individuals - were obtained from Socat Canarias, S.L.

Fish were obtained directly from the aquaculture companies after fish farm harvesting. Hence, fish did not pass any packaging process and therefore did not undergo any further contamination after being captured. Immediately after receiving the samples from the aquaculture companies, fish were stored in a clean new plastic bag to prevent air-born contamination. Subsequently, they were transported to the laboratory, where they were stored at −20° until further processing. For microplastic detection, fish were processed based on the method of Foekema et al. (2013) with minor adjustments. Length and weight of each individual fish was recorded before dissection. All viscera were removed and the digestion tracts from the oesophagus to the anus were carefully separated from the rest of the organs. Each tract was weighed and stored in clean glass jars. A 10% KOH solution was added, three

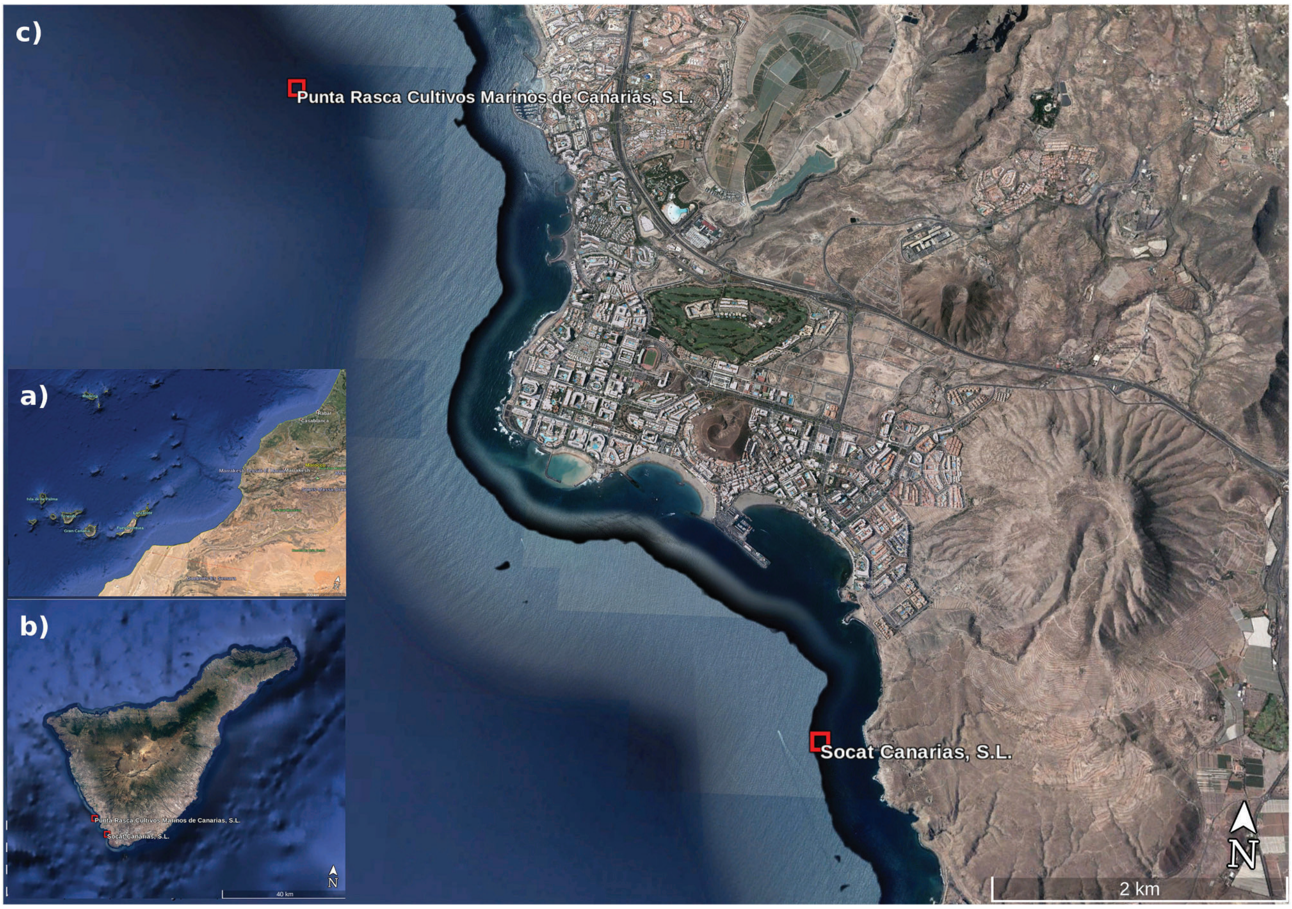

Fig. 1. Google Earth satellite images: a) Position of the Canary Island in the Atlantic Ocean; b) Location of the aquaculture sites in Tenerife; c) Location of the aquaculture sites according to the official data of the Canary Islands Government (Source: Google Earth Pro, ©2021 / Maxar Technologies, GRAFCAN, TerraMetrics, Landsat/Copernicus; Data SIO, NOAA, U.S. Navy, NGA, GEBCO).

times the amount of the organic material. Subsequently, the guts and their contents were left to digest at room temperature for at least 2 weeks before further processing. Once all of the biological material was dissolved, the supernatants were vacuum filtered over stainless steel filters with a mesh size of 25 μm. Hereafter, the filters were rinsed several times with pure water before being placed into a 10% EDTA solution for another day. EDTA was used to prevent possible salt formations on the steel gauze since it can sequester metal ions. After 24 h, filters were rinsed again with pure water, stored in petri dish bottoms, and left to dry in a desiccator. Finally, filters were covered and petri dishes were sealed with parafilm. All filtration processes were performed under a clean bench with filters covered at all times to avoid air born contamination. A Leica Microscope was used to visually analyse the stainless steel filter with the fish intestine contents. Particles on the gauze were counted and their colours and shapes were recorded. Due to the large amount of particles, only the content of 10% of all filters were further analysed via FTIR.

Larger particles (>200 μm) were analysed by using a Perkin Elmer Spectrum Two FTIR instrument, equipped with a deuterated triglycine sulfate (DTGS) detector and a diamond crystal ATR unit. Smaller particles (<200 μm) were analysed with a Spotlight 200i FTIR Microscopy System, equipped with a diamond coated μATR unit and a liquid nitrogen cooled mercury cadmium telluride (MCT) 100 * 100 μ single detector, displaying a 0.5 cm^{-1} spectral resolution and 40,000/1 RMS sensitivity for 2 min acquisition at 4 cm^{-1}. Spectra were recorded with a resolution of 4 cm^{-1} and 32 co-added scans in the wave-number range 400–4000 cm^{-1}. A point mode approach was applied to identify the particles and to collect the related spectra. A background spectrum was collected after every ten measurements. In the case of suspected cross contamination, analysis were repeated. Finally, patented COMPARE™ spectral comparison algorithm was used for spectral searching in commercially available library. A positive identification with the reference library was assigned for matches ≥75%.

Strict QA/QC procedures and measures to prevent contamination were followed throughout the entire sample manipulation. Specifically, a maximum of two persons were present in the laboratory during the dissection. Air circulation such as air conditioning, open window, etc. was minimized. White cotton lab coats and disposable latex gloves were used while manipulating the samples. All instruments, as well as the glass jars, were cleaned with alcohol and rinsed three times with pure water. KOH-Solution was filtered through a stainless steel filter (mesh size: 25 μm) prior to its use. Seven procedural blanks were run to determine background contamination and limit of quantitation (based the average of the blanks plus six times their standard deviation). An artificially contaminated sample with PE microparticles was used to determine the recoveries and validate the microplastics extraction and analysis procedure.

Finally, statistical analysis were performed with R statistical software (R Core Team, 2017) and its extension, Rstudio. Graphics were generated with Microsoft Excel (2013). Data normality of plastic concentration was analysed by the Shapiro Wilk test and the homoscedasticity was assessed graphically. Statistical differences between batches were tested using Kruskal-Wallis test.

The total accumulation of plastic particles in fish didn't show significant differences between batches (Kruskal-Wallis-Test, p-value = 0.1646) despite the higher abundance of plastic in fish from the first batch (Table 1).

Results showed, that 80 individuals (96%) within the 83 analysed fish had ingested material in their digestion tracts: 53 (65%) of all sampled fish displayed ingested anthropogenic debris (Table 1). 24 had ingested fine transparent fibres, detection of which was not feasible via FTIR due to their small diameter (less than 10 μm). They were not taken in further account for this study. The total number of items found in the digestive tracts equalled 119, where 97.5% of items were considered as microplastics (<5 mm). However, one individual had ingested three lines longer than 5 mm (Fig. 2), which should be accounted as mesoplastics. Fish from the first batch (Origin: Punta Rasca Cultivos Marinos de Canarias, S.L.) ingested the most amount of particles with an average of 2.7 ± 1.85 (SD) particles per fish. The lowest number of ingested items was presented in the fish from the third batch (origin: Socat Canarias, S.L.), with an average of only 0.6 ± 0.8 (SD) particles per fish. The highest amount of particles (n = 9) were found in an individual in the second batch. Overall, the portion of European sea bass that displayed the presence of microplastics in this study (65%) was considered very high compared to the contamination of fish species reported in other investigations (Barboza et al., 2018a; Herrera et al., 2019). Barboza et al. (2018a) reviewed 30 studies, which reported microplastic ingestion in fish. Investigations examined sample sizes from 1 to 566 individuals from a total of 70 different fish species. Only 23% of the sampled batches registered higher amounts of fish with ingested microplastic (66–100%). However, most of these batches (89%) consisted in a lower sample size (1–64) than the one of the present study (83). Recently, Herrera et al. (2019) conducted a literature review, complementing sources from Barboza et al. (2018a) with another additional 16 studies. In 6 of these studies a higher percentage of fish with ingested microplastic was reported, including the findings of Herrera et al. (2019), in which 78.3% of Atlantic chub mackerels (*Scomber colias*) caught around Gran Canaria and Lanzarote were detected with ingested microplastic. This study, together with our findings suggests that fish captured in the coastal waters of the Canary Islands may have a higher risk of contamination. This may be caused by a very high plastic contamination recently found washed ashore on the coastlines, as well as floating in the coastal waters of the Canary Islands (Herrera et al., 2020; Rapp et al., 2020; Reinold et al., 2020), reaching maximum amounts of 28,218.75 items/m^2 on the coastline of Poris (Tenerife) and 1,007,872 items/km^2 in the water near Las Canteras (Gran Canaria) (Herrera et al., 2020; Reinold et al., 2020). As farming cages in this study were situated close to urban cores with high touristic pressure, it needs to be considered, that the fish not only receive microplastic from the Canary current, but also from wind-blown litter nearby.

Compared to the only previous study regarding microplastic ingestion by European sea bass (Bessa et al., 2018) from the Mondego estuary

Table 1
General data of analysed fish organized by collecting date.

Date	Number of fish	Mean of length [cm]	SD of length	Mean of weight [g]	SD of weight	Mean of organ weight [g]	SD of organ weight	Percent of fish with ingested particles	Mean particles per fish	SD of particles per fish
05.07.2016	10	29.98	1.73	321.89	57.66	42.09	9.15	90	2.7	1.85
21.07.2016	13	33.03	2.29	424.77	92.26	55.93	16.7	62	1.5	2.29
10.08.2016	10	35	1.35	518.85	59.14	66.02	8.07	40	0.6	0.8
29.09.2016	10	37.06	2.75	607.18	141.74	64.76	20.1	40	0.9	1.22
19.01.2017	10	31.26	1.13	316.54	28.61	27.88	5.52	60	1.3	1.49
02.03.2017	10	27.78	2.12	221.87	56.86	17.66	7.61	70	1	0.77
25.04.2017	10	26.2	0.85	202.14	19.81	15.65	2.5	90	1.8	2.14
01.06.2017	10	29.75	0.9	282.84	28.58	26.29	4.72	70	1.5	1.5
Total	83	31.32	3.82	364.28	151.48	39.81	22.25	65	1.43	1.75

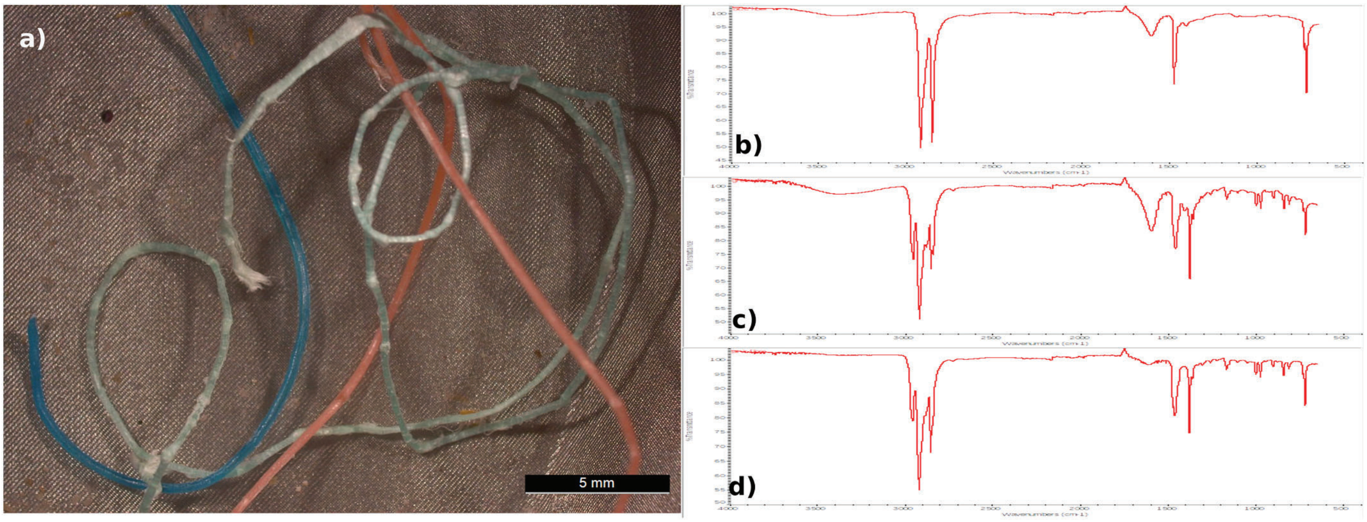

Fig. 2. a) Stomach content of a European sea bass from the 01.06.2017 b) FTIR spectra of the blue fibre – Polyethylene (PE) c) FTIR spectra of the green fibre – Polypropylene (PP) d) FTIR spectra of the red fibre – Polypropylene (PP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in Portugal, which considered both wild specimens, the fish in the present study displayed higher rates of ingested microplastic (65% vs 23%). Furthermore, higher averages of ingested particles (from a minimum of 0.6 particles to a maximum of 2.7 items/fish) were found compared to the wild sea bass (0.3 items/fish) This may lead to the suspicion that fish raised in aquaculture facilities may ingest more microplastic than wild fish, even if two different environment are considered.

Analysis of the items colours showed that 81% of all found microplastic were within the colour ranges of blue, yellow, black and transparent (Fig. 3). Blue (26%) and yellow (24%) particles alone made up half of all coloured material, but black (17%) and transparent (14%) particles were still present in considerable amounts. While blue, black and transparent have been reported dominating colours in other investigations, yellow items are normally found in lower rates (Abbasi et al., 2018; Azad et al., 2018; Bessa et al., 2018; Boerger et al., 2010; Herrera et al., 2019; Hipfner et al., 2018; Markic et al., 2018; McGoran et al., 2018; Pazos et al., 2017; Peters et al., 2017; Romeo et al., 2015; Rummel et al., 2016; Tanaka and Takada, 2016). However, yellow or orange plastic particles were found in fish of all feeding types (grazer, omnivore, planktivore, benthic predator, and pelagic predator), although predators seem to ingest a minor range of colours (Markic et al., 2018). Adult European sea bass are predators, which usually feed on invertebrates and other fish. Animals of the present study might have presented a wide range of coloured items, because they captured smaller fish of other feeding types (grazer, omnivores planktivores), which have been shown to be less selective regarding the colour of ingested particles (Markic et al., 2018). These fish could have passed through the cage mesh already containing coloured items in their guts. Differently, the higher amount of black and blue particles can be interpreted as fish nibbling on the cages or attacking fishing gear at the time of harvesting, as these were the predominant colours of the fishing equipment used by both companies. In addition, Carson (2013) claimed, that yellow and blue plastic particles presented significantly more bite marks than other colours. This justifies the vast amount of blue particles and also explains

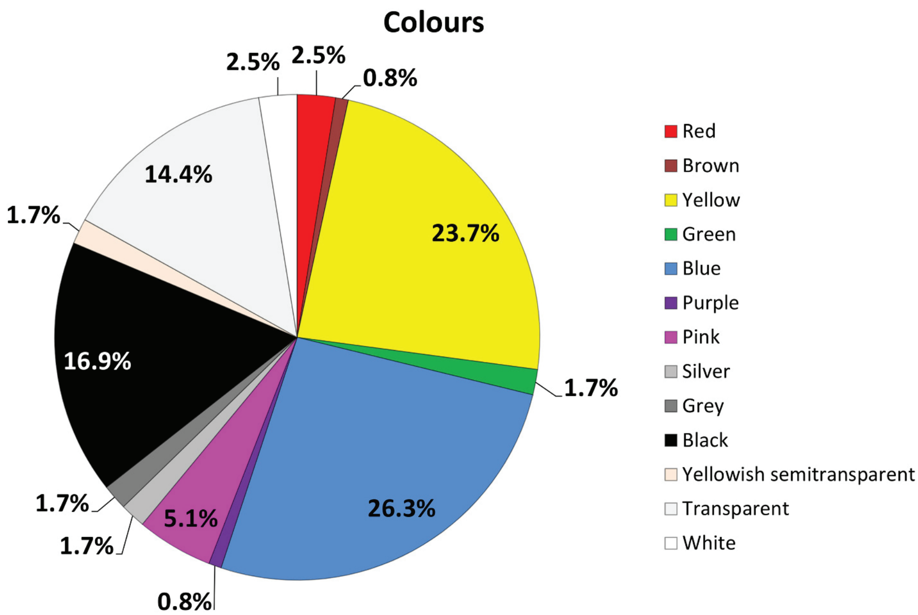

Fig. 3. Colours of particles ingested by fish.

the high percentage of yellow particles found in the fish guts. Animals might attack yellow objects in nature and even though they might not always swallow them, tiny pieces can end up in the digestion tracts of the fish. Furthermore, Wu et al. (2020) detected similar profiles of microplastic type between sediment and fish from fish farms. The wide range of colours as well as the excess of yellow particles could originate from the nearby urban areas. Although wind-blown litter, which enters the body of water, can reach farming cages by being dragged by the current, nearby sewage outflows can be a major source of microplastic in the coastal sediment. In the Canary Islands, wastewater is discharged directly into the sea after passing the wastewater treatment plants. 24 sewage outflows existed within a radius of 5 km around the aquaculture facilities, 10 of which were not authorized according to the official data of the Canary Islands Government (http://visor.grafcan.es/visorweb/) (GRAFCAN Cartográfica de Canarias IDE Canarias, 2018). Although it has been shown that wastewater treatment plants are very efficient and retain up to 99.9% of microplastics (Correia Prata, 2018), water from outflows is still found to discharge an average of 4.9 fibres/L, respectively 8.6 particles/L into the ocean (Talvitie et al., 2015). In urban areas, this amount can even reach 14–50 particles/L (Dris et al., 2015).

Microplastics were found in form of fibres, fragments, lines and films (Fig. 4). Fibres were the most common shape (81%), followed by fragments (12%). Films and lines accounted for less than 10%.

This result is consistent with the microplastic types reported in the majority of studies (Barboza et al., 2018a; Herrera et al., 2019). A recent study even determined, that smaller microplastics (0.01–1 mm) found on the shorelines of one of the Canary Islands only consisted of fibres (Rapp et al., 2020). It supports the suggestion that sewage outflows can act as a major source of fibre pollution in the marine environment. Browne et al. (2011) evaluated the amount of fibres being expulsed by washing machines and found that one single garment can shed more than 1900 fibres per wash. Accounting the number of washing runs and the amount of washed clothes in a densely populated area with additional touristic use, wastewater treatment plants can receive millions of litres every day. Hence, even miner wastewater treatment plants can discharge more than 52,000 particles (corresponding 0.004 particles/L) daily (Mason et al., 2016). Another important source of fibres, as well as lines in the ocean, comes from the fishing industry, as modern fishing gear is primarily made out of polyolefins and nylon (Andrady, 2011). Plastics from fishing nets and ropes used by the aquaculture companies can become brittle over time due to degradation processes and eventually break down into smaller pieces (Andrady, 2011; Barnes et al., 2009; Cole et al., 2011). As it has been proven that marine organisms attack plastic objects (Carson, 2013), captive *D. labrax* might have swallowed these microparticles accidentally by nibbling on the fishing gear. Furthermore, fish might have attacked fishing nets at the time of harvesting and therefore ingested small net pieces. Both sources, sewage outflows and plastic-based fishing gear, could explain the high amount of ingested fibres.

Finally, detection of plastic polymeric material was obtained by μFTIR. 8 analysed filters displayed 12 types of polymers and 2 types of resins (Fig. 5). Fibres (11) were identified either as cellulose/cellophane (55%), nylon (27%), rayon (9%) or as acrylic (9%). Particles (20) were mostly represented by PE (25%) and PP (25%). Other polymers were: PS (5%), SAN (5%), PA (5%), EPDM (5%), E/P (5%), EVA (5%), polynorbornene (5%), nitrocellulose (5%) as well as epoxy resin (5%) and phenolic resin (5%). Fig. 6 shows examples of the most popular polymer types found in this study.

Additionally, the three biggest particles found in a fish from the last batch, were identified as PP (67%) and PE (33%) (Fig. 2). Based on their shape they seemed to originate from fishing nets or ropes.

As recovered fibres consisted either of cellulose/cellophane, nylon, rayon or acrylic, results indicate that the presence of fibres may be related to local sewage outflows, since all of these polymers are commonly used in the textile industry and therefore are a fallout from washing clothes. The fact that cellulose and its derivates are the most represented polymers in this study is also in line with previous findings on cultured fish (Feng et al., 2019; Garcia et al., 2020; Wu et al., 2020). Differently, the detected nylon fibres could originate from textile as well as from fishing gear used in the local aquaculture facilities. Identified material of the fragment partition were rather diverse, but contained mostly polymers, which have been already reported to be ingested by fish in former studies (Table 2) such as PP and PE, which are commonly used in the fishing industry (Andrady, 2011). Finally two particles were assigned to pretty unusual polymers, which have not been reported so far in digestive tracts of fish: Polynorbornene and phenolic resin. Polynorbornenes are polymers that are characterized by high glass transition temperatures and high optical clarity. They are used in elastomers.

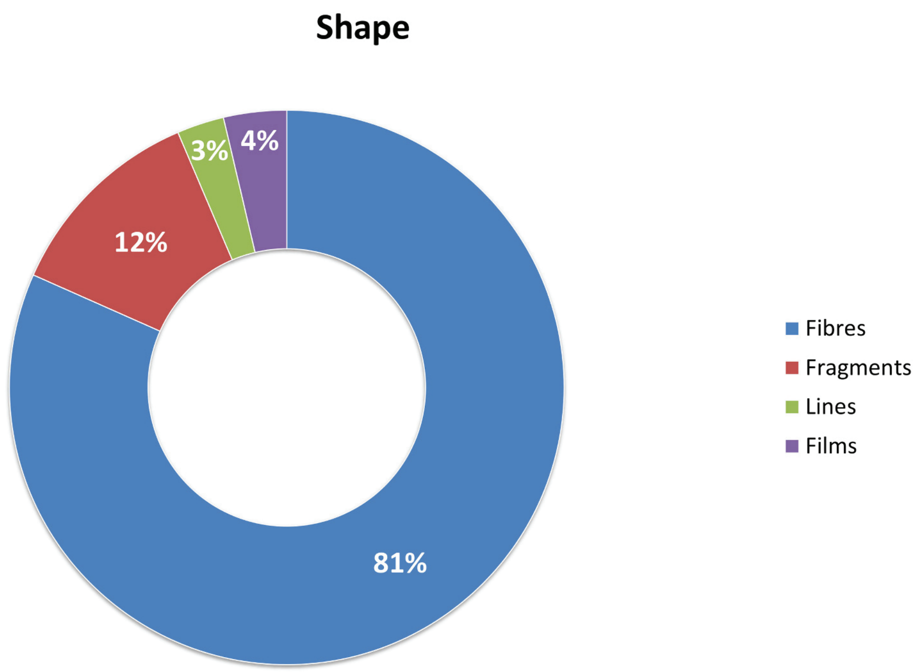

Fig. 4. Shapes of particles ingested by fish.

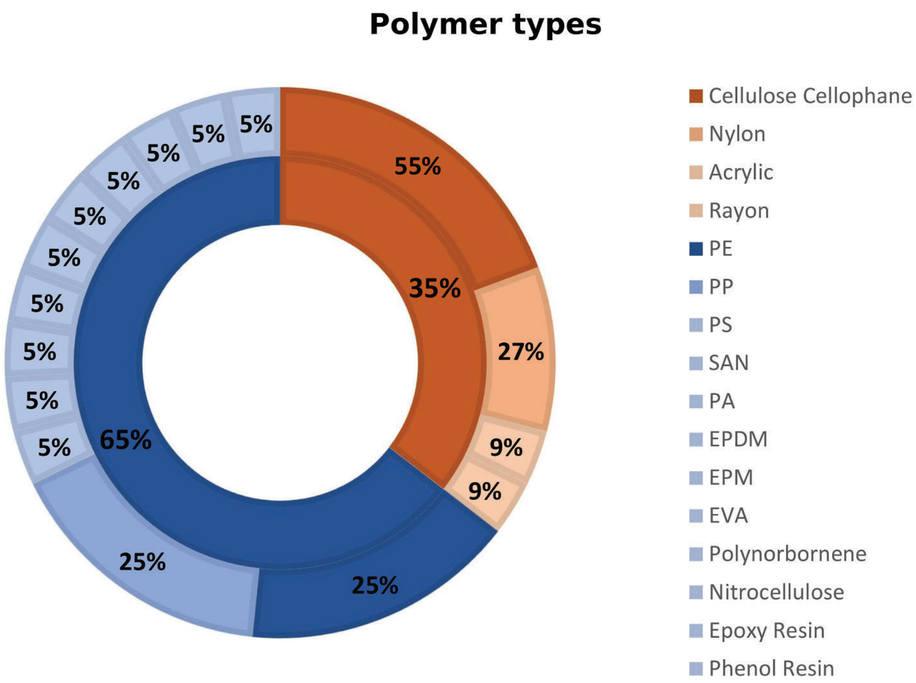

Fig. 5. Percentage of polymer types of ingested particles: Fibres are represented by the red compartment; Particles are represented by the blue compartment, Inner donut: Percentage of particle shape; Outer donut: Percentage of polymer types. Abbreviations: PE: Polyethylene, PP: Polypropylene, PS: Polystyrene, SAN: Styrene-Acrylonitrile-Copolymer, PA: Polyamide, EPDM: Ethylene-Propylene-Dien-Monomer, E/P: Ethylene-Propylene-Copolymer, EVA: Ethylene-Vinyl Acetate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

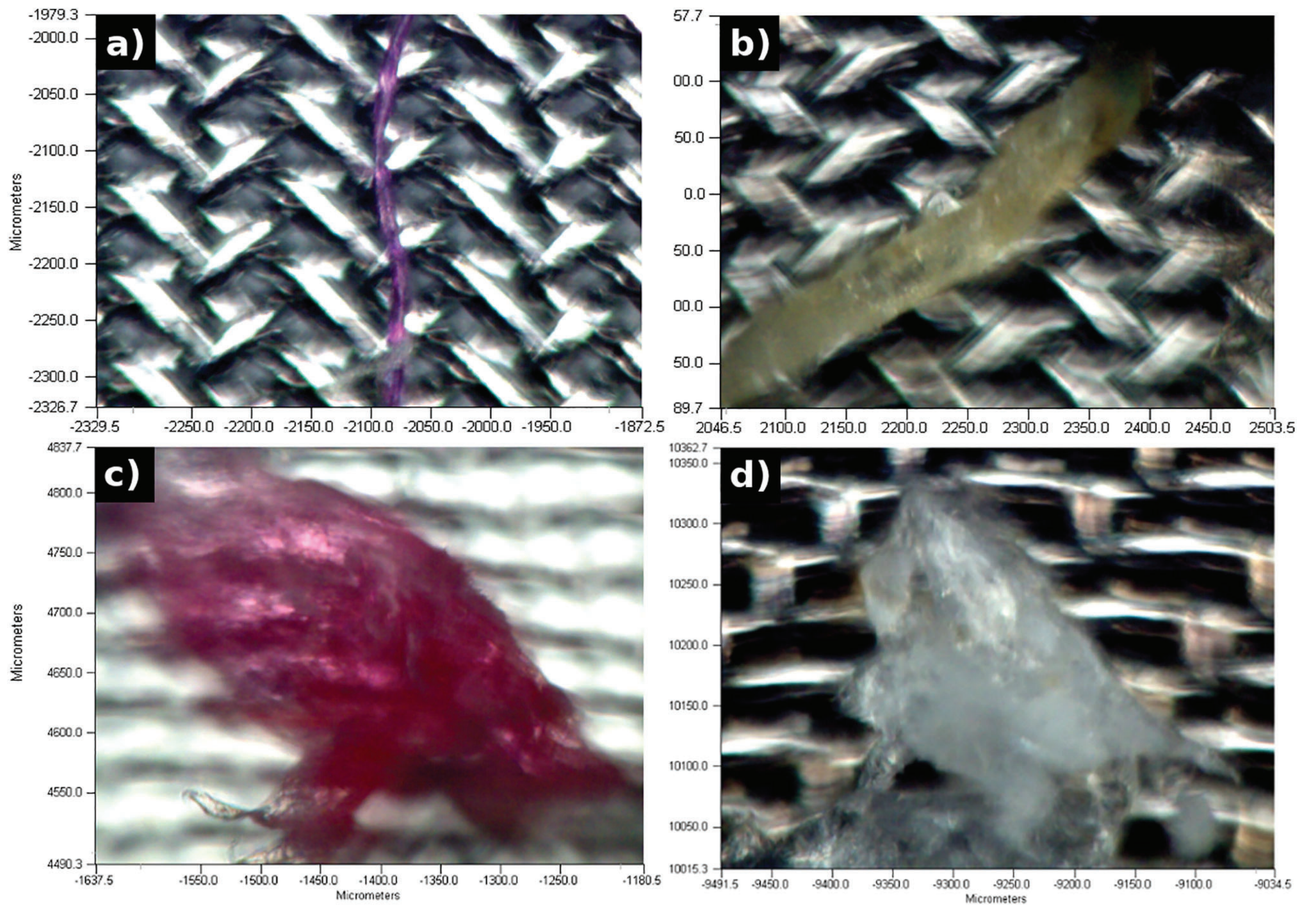

Fig. 6. µ-FTIR images of the 4 most common found polymer types: a) Cellulose/Cellophane b) Nylon c) Polyethylene (PE) d) Polypropylene (PP).

Phenolic resins have been widely used for moulded products, as well as in coatings and adhesives in the past, but today, epoxy resins have largely replaced them. This indicates, that plastics have the ability to travel in the ocean for a long time.

In summary, this study showed for the first time the presence of microplastic in the digestive tract of *D. labrax* from aquaculture facilities

Table 2
Polymer types ingested by fish; *including nylon and aramide.

Author	Ding et al., 2019	Nelms et al., 2018	Halstead et al., 2018		Rummel et al., 2016	Digka et al., 2018	Foekema et al., 2013	Cheung et al., 2018	Markic et al., 2018	Tanaka and Takada, 2016	(Jabeen, 2017)	Bråte et al., 2016	Morgana et al., 2018	Compa et al., 2018	Alomar et al., 2017	McGoran et al., 2018	Renzi et al., 2019		Murphy et al., 2017	Chagnon et al., 2018	Hipfner et al., 2018	Bessa et al., 2018	Baalkhuyur et al., 2018	Lusher et al., 2013	Peters et al., 2018
PP (Polypropylene)	0.54%	5.55%		10.42%	13%	27.7%	33.33%	42%	9%	43.3%		12.50%				15.00%	50.00%		5.00%		8.33%	14.00%	42.00%		
PE (Polyethylene)		22.22%			40%	55.5%	33.33%	25%	26%	52.0%		6.25%	17%	20.00%						27.27%		6.00%	42.00%	0.30%	
Polyester			17.50%	18.75%	4%			16%	28%		7.9%	37.50%	34%			33.00%				18.18%	41.67%	31.00%		5.10%	
PA (Polyamide)*		5.55%			22%			4%	4%			6.25%	21%	10.00%		20.00%	10.00%		77.00%			5.00%		35.60%	9.30%
PET (Polyethylene terephthalate)	33.87%	5.55%			4%	5.5%	16.67%	6%			10.6%			30.00%	36.36%			7.00%	17.00%						9.30%
PS (Polystyrene)	2.15%				9%	5.5%				2.0%		6.25%							1.00%				4.00%	0.90%	
Acrylic			0.00%	4.17%					3%				24%		15.15%				17.00%		25.00%			0.30%	
Rayon	48.92%		17.50%	14.58%					17%													30.00%		57.83%	
PTFE (Polytetrafluoroethylene)	4.84%					5.5%		3%				6.25%					10.00%								
PVC (Polyvinyl chloride)									7%			12.50%					30.00%	93.00%					8.00%		34.80%
PAN (Polyacrylonitrile)															12.12%							14.00%	4.00%		
Cellulose/Cellophane			15.00%	6.25%							49.1%			20.00%	30.30%										
EPDM (ethylene propylene diene monomer)		5.55%								0.7%															
E/P (Ethylene propylene)		27.78%								2.0%															
PAM (Polyacrylamid)		5.55%												20.00%											
PU (Polyurethane)					4%				3%																
Acrylic Polyester Blend			42.50%	37.50%																					
NBR (Nitrile rubber)		5.55%																							
rubber									2%																
Neoprene		11.11%																							
Alkyd															3.03%										
PBT (Polybutylene terephthalate)		5.55%																							
SAN (Styrene acrylonitrile resin)												6.25%													
Polystyrene acrilonitrile methyl methacrylate															3.03%										
SA (Styrene acrylate)							16.67%																		
PBMA (Poly(n-butyl methacrylate))												6.25%													
EVA (ethylene-vinyl acetate)													7%												
CPE (Chlorinated polyethylene)	9.68%																								
PVA (Poly(vinyl alcohol))																				54.55%					
Epoxy resin																									2.30%
Silicone																									2.30%
Amount of particles	186	18	66		23	N/A	6	79	128	150	227	16	30	10	N/A	1128	N/A		118	11	12	32	26	351	43

located in coastal waters. The number of fish, which had ingested plastic (85%), were found to be high and in line with previous findings regarding fish farmed in coastal waters (Wu et al. 2020; Feng et al. 2019. Although the precise origin of ingested microplastic could not be determined, the high amount of fibres and their composition indicate that local contamination plays an important role. Therefore, the regulations and management of the sewage outflows into the open sea needs to improve. Furthermore, it is recommended for aquaculture companies to choose facility locations away from urban and touristic nucleus to distance from sewage outflows. It is also proposed to limit the use of plastic materials in fishing gear used by aquaculture companies.

CRediT authorship contribution statement

S.R. designed the experimental work, conducted the sampling, processed the samples in the laboratory, analysed the data and wrote the manuscript. F.S. performed spectroscopical analyses via FTIR. C.H. contributed to design the experimental work. 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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Conclusiones

1. Tenerife presentó contaminación por plásticos en todas las playas estudiadas, tanto en sedimentos superficiales como profundos y en agua superficial de la orilla.

2. La cantidad de plástico mostró una alta variabilidad temporal como espacial, siendo Poris la playa más contaminada.

3. Cada playa presentó un patrón espacial de acumulación a lo largo de la línea de marea alta consistente durante el año.

4. En los sedimentos profundos se encontró una cantidad de plástico significativamente mayor que en muestras de agua superficial del litoral correspondiente, en el cual las cantidades de partículas son mayores en los sedimentos de la línea de marea alta que en los de la zona sumergida.

5. Las partículas mayores a 1 mm del color transparente/blanco fueron dominantes en las muestras de sedimentos superficiales. Los fragmentos y las fibras (>1 mm) del color transparente/blanco fueron las partículas más encontradas en los sedimentos profundos de la línea de marea alta y en el agua, mientras que los sedimentos profundos de la zona sumergida presentaron principalmente microplásticos azules y amarillos, compuestos más por fibras que por fragmentos.

6. Los tipos de polímeros de partículas mayores a 1 mm estaban representados básicamente por plásticos que se recuperan habitualmente en el medio marino, como PE, PP, PS, PTFE y PVC. Las partículas más pequeñas mostraron un espectro más amplio de tipos de polímeros, incluyendo en total 24 polímeros diferentes, siendo los más comunes PP, PA y rayón.

7. En el 65% de las lubinas (*Dicentrarchus labrax*) estudiados se encontraron microplásticos en los tractos digestivos.

8. Las fibras y fragmentos de color amarillo y azul resultaron ser las partículas más ingeridas por lubinas.

9. Las fibras ingeridas fueron identificadas principalmente como celulosa o nylon, mientras otras partículas fueron identificadas principalmente como PE o PP.

10. El estudio demuestra que tanto las playas como los animales alrededor de la isla se ven afectados por la contaminación marina por plástico. Las cantidades de plástico encontrados en las playas reflejan una dimensión de contaminación comparables con los lugares más contaminados a nivel global. En cuanto a los peces se ha visto una tasa de ingestión más alta que en lubinas salvajes de otros partes del mundo, pero similares a las encontradas en peces salvajes de otras especies en el área de Islas Canarias.

Conclusions

1. Tenerife had plastic pollution on all beaches surveyed, both in shallow and deep sediments and in shore surface water.

2. The amount of plastic showed a high temporal and spatial variability, with Poris being the most polluted beach.

3. Each beach showed a spatial pattern of accumulation along the high tide line that was consistent throughout the year.

4. Significantly more plastic was found in the deep sediments than in surface water samples from the corresponding shoreline, with particulate amounts being higher in the sediments at the high tide line than in the submerged zone.

5. Particles larger than 1 mm of transparent/white colour were dominant in the surface sediment samples. Fragments and fibres (>1 mm) of the transparent/white colour were the most common particles found in the deep sediments of the high tide line and in the water, while the deep sediments of the submerged zone showed mainly blue and yellow microplastics, composed more of fibres than fragments.

6. Particulate polymer types above 1 mm were mainly represented by plastics that are commonly recovered from the marine environment, such as PE, PP, PS, PTFE and PVC. Smaller particles showed a broader spectrum of polymer types, including in total 24 different polymers, the most common being PP, PA and rayon.

7. In 65% of the studied sea bass (*Dicentrarchus labrax*), microplastics were found in the digestive tracts.

8. Yellow and blue fibres and fragments were the most commonly ingested particles by sea bass.

9. Ingested fibres were mainly identified as cellulose or nylon, while other particles were mainly identified as PE or PP.

10. The study shows that both beaches and animals around the island are affected by marine plastic pollution. The amounts of plastic found on the beaches reflect a level of pollution comparable to the most polluted places globally. For fish, ingestion rates were found to be higher than in wild seabass from other regions, but comparable with wild fish of other species in the Canary Islands area.

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Appendix

Contribuciones científicas

Publicaciones

1. **Título:** Bioaccumulation of additives and chemical contaminants from environmental microplastics in European seabass (*Dicentrarchus labrax*)
   Autores: Alicia Herrera, Andrea Acosta-Dacal, Octavio Pérez Luzardo, Ico Martínez, Jorge Rapp, **Stefanie Reinold**, Sarah Montesdeoca-Esponda, Daniel Montero y May Gómez
   Revista: Science of The Total Environment
   Año: 2022

2. **Título:** An annual study on plastic accumulation in surface water and sediment cores from the coastline of Tenerife (Canary Island, Spain)
   Autores: **Stefanie Reinold**, Alicia Herrera, Nicolò Stile, Francesco Saliu, Carlos Hernández-González, Ico Martinez, Zaida Ortega, María Dolores Marrero, Marina Lasagni y May Gómez
   Revista: Marine Pollution Bulletin
   Año: 2021

3. **Título:** Evidence of microplastic ingestion by cultured European sea bass (*Dicentrarchus labrax*)
   Autores: Stefanie Reinold, Alicia Herrera, Francesco Saliu, Carlos Hernández-González, Ico Martinez, Marina Lasagni y May Gómez
   Revista: Marine Pollution Bulletin
   Año: 2021

4. **Título:** Microplastic ingestion in jellyfish *Pelagia noctiluca* (Forsskal, 1775) in the North Atlantic Ocean
   Autores: Jorge Rapp, Alicia Herrera, Daniel R. Bondyale-Juez, Miguel González-Pleiter, **Stefanie Reinold**, Maite Asensio, Ico Martínez y May Gómez
   Revista: Marine Pollution Bulletin
   Año: 2021

5. **Título:** Plastic pollution on eight beaches of Tenerife (Canary Islands, Spain): An annual study
   Autores: Stefanie Reinold, Alicia Herrera, Carlos Hernández-González y May Gómez
   Revista: Marine Pollution Bulletin
   Año: 2020

1. **Título:** Microplastic marine pollution in the Canary Islands and their effects in the food chain
   Autores: May Gómez, Ico Martínez, Jorge Rapp, **Stefanie Reinold**, Theodore T. Packard y Alicia Herrera
   Conferencia: 7th International Symposium on Marine Science
   Año: 2020

2. **Título:** An annual study of beach pollution on Tenerife (Canary Islands)
   Autores: Stefanie Reinold, Alicia Herrera, Carlos Hernández-González y May Gómez
   Conferencia: 7th International Symposium on Marine Science
   Año: 2020

3. **Título:** An annual study of beach pollution on Tenerife (Canary Islands)
   Autores: Stefanie Reinold, Alicia Herrera, Carlos Hernández-González y May Gómez
   Conferencia: International Conference for YOUNG Marine Researchers
   Año: 2020

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