Marine Pollution Bulletin 226 (2026) 119359

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Fingerprinting and modelling of the Toconao pellet spill in the Iberian Atlantic☆

Álvaro Cubas[a], Daura Vega-Moreno[b,*], Miriam N. Déniz-Martín[b], Ana Molina-Rodríguez[b], Cristina León-Santiago[b], Javier Hernández-Borges[c,d], Francisco Machín[a], Eugenio Fraile-Nuez[e]

[a] Oceanografía Física y Geofísica Aplicada (OFYGA), IU-ECOAQUA, University of Las Palmas de Gran Canaria, 35017, Spain
[b] OpenPLAS Group, Chemistry Department, University of Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, 35017, Spain
[c] Departamento de Química, Unidad Departamental de Química Analítica, Facultad de Ciencias, Universidad de La Laguna (ULL), Avda. Astrofísico Fco. Sánchez, s/n, 38206, San Cristóbal de La Laguna, Spain
[d] Instituto Universitario de Enfermedades Tropicales y Salud Pública de Canarias, Universidad de La Laguna (ULL), Avda. Astrofísico Fco. Sánchez, s/n, 38206, San Cristóbal de La Laguna, Spain
[e] Centro Oceanográfico de Canarias, Instituto Español de Oceanografía (IEO), Consejo Superior de Investigaciones Científicas (CSIC), Santa Cruz de Tenerife, 38180, Spain

ARTICLE INFO

Keywords:
Container loss
Environmental crisis
Transport
Trajectories
Marine litter

ABSTRACT

On December 8th, 2023, the cargo ship Toconao lost 6 containers, one of them carrying 1050 sacks, each containing 1.25 million plastic pellets, in Portuguese waters approximately 80 km off the coast of Viana do Castelo, in the Northwest Iberian Peninsula. Shortly after, pellets, broken and intact sacks were found on the Galician coast, triggering an environmental crisis that mobilized scientific advisory mechanisms to support crisis managers. This study combines chemical and morphological characterization with Lagrangian modelling to investigate the chemical fingerprint, physical transport and beaching of the spilled pellets. Spectral features of the attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) analysis agrees with previous studies indicating that the pellets are polyethylene-based masterbatch with a high additive content. The Toconao pellets exhibit irregular "top-hat" shapes and smaller sizes (2–3 mm). Particle transport was simulated with the TrackMPD and OpenDrift frameworks, considering the effect of ocean currents and windage. Results indicate that ~40% of the considered virtual particles reached the Galician coast within three weeks after the incident, while ~90% beached within five months, extending to the Bay of Biscay reaching the coasts of Western France. The integration of chemical and morphological fingerprints, and modelling, highlights the transport pathways and their potential long-term environmental effects.

1. Introduction

Until the early 1950s, it was generally believed that oceans were so extensive that they could absorb waste inputs indefinitely. Early concerns arose in response to events like the dumping of radioactive waste in the ocean and other globally recognizable events, such as mercury poisoning in Minamata Bay (Japan) and oil spill disasters from vessels such as the Torrey Canyon in Great Britain in 1967 (Reichelt-Brushett, 2023). Apart from oil spills and chemical substances, plastic debris has rapidly become one of the most pervasive and permanent pollutants in the oceans gaining considerable attention in recent years, with numerous initiatives and studies aimed at addressing the issue (Cole et al., 2011; van Sebille et al., 2020). The ubiquity of plastics, along with their additives and sorbed contaminants, pose long-term ecological and socioeconomic risks that make marine plastic pollution a high-priority research and policy concern (Geyer et al., 2017; Jambeck et al., 2015).

Incidents involving the loss of containers at sea or the accidental release of pellets during maritime transport can result in acute, highly localized environmental disasters. These are small, round-shaped plastic particles used as raw materials in the plastic industry, hence referred to as a type of primary microplastic. Evidence of pellet pollution associated with maritime activities has been documented for several decades. For instance, Abu-Hilal and Al-Najjar (2009) reported the widespread presence of plastic pellets along the beaches of the northern Gulf of

☆ This article is part of a Special issue entitled: 'Marine Processes and Humans MPB' published in Marine Pollution Bulletin.

* Corresponding author.
E-mail address: daura.vega@ulpgc.es (D. Vega-Moreno).

https://doi.org/10.1016/j.marpolbul.2026.119359
Received 22 September 2025; Received in revised form 12 January 2026; Accepted 29 January 2026
Available online 11 February 2026

Aqaba (Red Sea), pointing to accidental spillages related to cargo loss during maritime transport as well as emissions from local plastic manufacturing activities. Large-scale pellet spill accidents have further highlighted the acute impacts of such events on coastal environments. As an example, the fire and subsequent sinking of the M/V X Press Pearl off Sri Lanka in May 2021 released an estimated ~1680 t of plastic pellets. The pollution produced included both unburnt nurdles and thermally altered pyroplastic fragments that highly affected the west coast of Sri Lanka (De Vos et al., 2022a; Jayathilaka et al., 2022). More recently, Aswin et al. (2025) documented one of the most severe pellet spill events in Indian waters following the shipwreck of the MSC ELSA 3 in May 2025, identifying two hotspots with pellet burial in sediments indicating long-term retention. Nevertheless, this kind of events can be also associated with marine pollution in larger time scales. For example, plastic pellets with different sources have been documented to be present in the shores of the Atlantic Ocean since various decades (Baztan et al., 2014). Galgani and Rangel-Buitrago (2024) framed such recurring contamination events as “white tides”, underscoring the relevance of pellet pollution, sea transport risks and associated socioeconomic impacts.

A combined modelling and analytical approach is essential for understanding, predicting and managing pellet spills. Open-source Lagrangian particle-tracking frameworks (e.g., OpenDrift, Parcels, TrackMPD) permit the simulation of drift, susceptible coastal zones considering observed winds, waves and currents. These tools are routinely used in spill response and research to plan surveys and prioritize clean-up efforts. Complementary, laboratory and field analytical methods, notable attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy, enable identification of pellet polymer type and adsorbed chemicals. This allows the characterization of the chemical fingerprint of plastic and assessing whether they come from the same source which is critical both for assessing ecological risks and for legal/forensic attribution.

Under the above context, in this work we investigate the Toconao pellet spill incident that took place in the early hours of December 8th, 2023, when the cargo ship Toconao reported the loss of 6 containers in Portuguese waters due to a collision with a wave under rough sea conditions. The incident occurred at a latitude of 41°45′30″ N and a longitude of 9°50′24″ W, approximately 80 km from Viana do Castelo, Portugal (Northwest off the Iberian Peninsula). One of the lost containers transported 1050 sacks, each containing approximately 1.25 million pellets (25 kg), for a total of 1312.5 million plastic pellets (26.25 t).

The first chemical analysis confirmed the information of the product datasheet, indicating that these pellets consist mainly of polyethylene (PE) and are of the “Masterbatch” type, with the additive percentage around 10% instead of the usual 1% (Instituto Universitario de Medio Ambiente, 2024). The most concentrated additive was identified as Tinuvin 622, used as HALS (Hindered Amine Light Stabilizers) counting approximately 10% of the total composition (Instituto Universitario de Medio Ambiente, 2024). According to the European Chemicals Agency (ECHA), Tinuvin 622 is labelled as a harmful substance to aquatic life with long-lasting effects, but there is a lack of information about its toxicity (European Chemical Agency, 2023). Days after the incident, the arrival of these particles (including 60 intact sacks) was detected, especially on the shores of Galicia (Spain). Two months after the spill, the regional government announced that only 19% of the pellets have been collected from the environment (El País, 2024).

This incident has also been referenced by Scarrica et al. (2025), who used pellets collected after the event across the northwest of the Iberian Peninsula to explore alternative approaches for pellet identification and classification.

In this work, we combine FTIR analyses and Lagrangian transport modelling to (i) characterize the chemical and morphological properties of the spilled pellets, (ii) reconstruct their transport and coastal arrivals, and (iii) evaluate the potential environmental risks associated with this incident.

This multidisciplinary analysis was undertaken within the framework of the activation, in exercise mode, of the Spanish Research Council (CSIC) Disaster and Emergency Advisory Protocol (PADE) to support crisis managers during the Toconao incident.

2. Materials and methods

2.1. FTIR analysis

The pellets analysed in this study were supplied by the Accidental Marine Pollution Plan for Galicia (CAMGAL) of the regional government of Galicia, Spain. A total of 30 pellets were analysed, retrieved from an intact sack that was collected by the coastguard on the Galician coast a few days after the Toconao incident and subsequently delivered to the CAMGAL authorities. This guarantees that the analysed samples belonged to the Toconao pellet incident and not from any other source. The samples were analysed using a Cary 630 FTIR spectrometer (Agilent Technologies, California, USA), equipped with a single-reflection diamond ATR module. The equipment featured a ZnSe beamsplitter and a thermoelectrically cooled deuterated triglycine sulfate (dTGS) detector (1.3 mm diameter). Spectra were collected in the 4000–650 cm^{-1} range at a resolution of 8 cm^{-1}, with 32 scans averaged per sample. Polymer spectra were processed using Agilent MicroLab PC FTIR software, using the spectral libraries from Agilent.

2.2. Pellet spill simulations

To assess the distribution of the spilled pellets, two independent Lagrangian simulations were conducted using different modelling frameworks: a self-modified version of TrackMPD_v2.3 (Jalón-Rojas et al., 2019) and OpenDrift v1.14.2 (Dagestad et al., 2018). In both cases, particle trajectories were computed following Eq. (1) with a fourth-order Runge-Kutta integration scheme and a temporal resolution of 1 h.

$$\frac{d\vec{x}}{dt} = \vec{V}_{current} + \alpha \cdot \vec{V}_{wind} \quad (1)$$

where $\vec{x}$ denotes the position of every single particle, $d\vec{x}/dt$ represents its time derivative, $\vec{V}_{current}$ is the Eulerian ocean current velocity field, $\vec{V}_{wind}$ is the Eulerian wind speed field at 10 m height and α is the windage factor.

Stokes drift was not explicitly included in the trajectory calculations. Although wave-induced drift is known to influence the transport of floating debris in a complex manner (van Sebille et al., 2020), its operational implementation in Lagrangian models varies across studies. While some works directly include the full surface Stokes drift from wave models (e.g. Bosi et al., 2021; Durgadoo et al., 2021), others apply reduced or empirical fractions to account for the effective response of partially submerged objects (e.g. Pereiro et al., 2018; Röhrs et al., 2012; Breivik et al., 2016). Such approaches generally require additional assumptions or object-specific parameter choices. Moreover, Dagestad and Röhrs (2019) showed that, for wind-exposed drifters, which can behave similarly to pellets and sacks, the explicit inclusion of Stokes drift does not necessarily lead to improved trajectory predictions. For the sake of simplicity and to avoid more uncertainties within the modelling framework adopted here, windage was therefore used as an effective parameterization of wind- and wave-driven surface transport, although it presents its limitations.

In the OpenDrift simulation, 10000 particles were released, while 9996 particles were used in the TrackMPD run, since this framework recommends the number of particles to be a multiple of the available computing cores (28) for parallel computing. Particles were randomly seeded within a squared area (0.15° × 0.15°) centered at the reported container-loss position at the time of the incident (04:00 AM, December

8th, 2023). Their trajectories were subsequently tracked for approximately 150 days, until May 6th, 2024.

For the physical processes considered, $\overrightarrow{V}_{current}$ was obtained from the IBI Analysis and Forecast dataset, while $\overrightarrow{V}_{wind}$ was derived from the Global Ocean Hourly Sea Surface Wind and Stress from Scatterometer and Model product. Both datasets, available through the Copernicus Marine Service, were selected due to their open-access availability and their high spatial (0.028° and 0.125° respectively) and temporal resolution (15 min and 1 h respectively).

Regarding the windage factor, values of 2–4% are typically used for floating objects when Stokes drift is not included (Dagestad and Röhrs, 2019; Wagner et al., 2022). However, the simulations we carried out during the activation of the CSIC Disaster and Emergency Advisory Protocol in exercise mode in response to the Toconao pellet spill revealed that a value of approximately 2% provided good agreement with field observations. To account for the variability of the different elements observed during the event (individual pellets, intact sacks, and broken sacks), each particle in our simulations was therefore assigned a windage factor given by a normal distribution with a mean of 2.25% and a variance of 0.15%.

2.3. Spatiotemporal visualization for the simulation output

To analyse the spatiotemporal distribution of the virtual pellets spilled by the Toconao, we employed a series of spatial bivariate histograms. These histograms depict the daily density of elements within each pixel using a grid with a mesh size of 0.05°.

For visualization purposes, we computed the daily density of elements within each grid cell. This metric accounts for the fact that particle positions are recorded at an hourly temporal resolution. Here, a “particle position” refers to the position of a given particle recorded at a single model output time step.

Specifically, for each day, the number of particle observations falling within a given grid cell was accumulated over the 24-hourly outputs. This is then normalized by the total number of particle observations recorded over the entire domain during that day (Eq. (2)). As a result, the daily density represents the relative contribution of each grid cell to the total number of particle observations on that day, rather than the number of particles.

Because particle positions are saved every hour, the total daily number of particle observations (*TNPO*) is 24 times larger than the number of simulated particles. This normalization ensures that spatial patterns reflect particle presence and persistence within each cell.

The daily density of elements is therefore defined as:

$$DDE_{ij}(\%) = \frac{NPO_{ij}}{TNPO} \cdot 100 \quad (2)$$

where DDE_{ij} is the daily density of elements (%), NPO_{ij} is the number of particle observations in the pixel with coordinates (i,j) in the time step and *TNPO* is the total number of particle observations in the time step considered for this computation (24 h in this study).

3. Results

3.1. Chemical and morphological characterization

The Toconao pellets exhibit differences in comparison to other pellets with lower percentage of additive as they are a masterbatch. It is estimated that 10% of the weight of the pellets from this spill, corresponds to additives (Instituto Universitario de Medio Ambiente, 2024). Consequently, their chemical and physical properties also differ from those of pristine PE.

Infrared analyses displayed in Fig. 1 reveal the characteristic PE bands in both spectra: the asymmetric C—H stretching of the methylene group (—CH_2—) at 2914 cm^{-1}, the symmetric stretching at 2847 cm^{-1}, the CH_2 bending vibration at 1461 cm^{-1}, and the CH_2 rocking vibrations at 730 and 720 cm^{-1} (Smith, 2011). Nevertheless, several differences can be observed in the region between ~1800 and 500 cm^{-1} (Fig. 1).

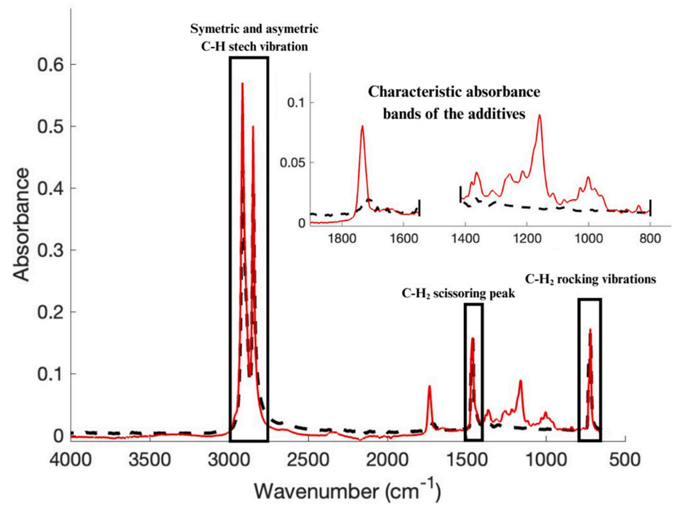

Fig. 1. ATR-FTIR spectra of pristine PE pellets (black dashed line) and Toconao masterbatch pellets (solid red line). The main characteristic absorption bands of PE are highlighted, including C—H stretching vibrations (2850–2960 cm^{-1}), CH_2 scissoring (1470 cm^{-1}), and CH_2 rocking (720 cm^{-1}). The superior plot represents the spectral differences in the region of 1800 and 500 cm^{-1} due to the presence of the additives. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These spectral variations reflect the influence of the additives present and suggest the presence of the Tinuvin 622 in the Toconao pellets featuring characteristic peaks of this additive such as C═O bond tension in the region between 1700 and 1750 cm^{-1}, intense bending bands of groups C—O—C in the spectral range of 1300–1050 cm^{-1}, flexion of primary O—H bonds between 1100 and 1050 cm^{-1} and tension C—N bonds also observed in the range of 1100–1050 cm^{-1}. This was further verified by thermal desorption coupled to gas chromatography–mass spectrometry (TD-GC–MS; Instituto Universitario de Medio Ambiente, 2024). In addition, the pellets in this spill had other additives such as Tinuvin 120, Tinuvin 123 and Sanol LS 770.

These nurdles have an irregular shape often resembling a top hat in comparison with the usual lentil shape, as shown in Fig. 2. Additionally, they are generally smaller in size, ranging from 2 to 3 mm instead of the 4–5 mm as Cocozza et al. (2025) already observed. The reported size range (2–3 mm) reflects minor variations associated with the irregular shape of the pellets rather than the presence of distinct size classes. All analysed pellets were collected from the same sack and exhibited a high degree of morphological and dimensional homogeneity, with no systematic variability observed within the sample set (n = 30).

3.2. Open ocean transport

The outputs of the simulations are presented in Fig. 3 through a composite of the daily density of elements. The results show that most of the particles experienced northward and eastward movements from the incident position, producing a “J” shape during the first month. Initially, the particles reached the northwestern coast of the Iberian Peninsula before continuing northward and spreading throughout the Bay of Biscay, with particles reaching the eastern coast (Western coast of France).

Moreover, the particles exhibit diverse movement patterns, including repeated offshore and inshore displacements (see the animations in Supplementary Data). Notably, mesoscale activity influences the distribution of particles, with a large amount of them becoming temporally trapped by eddies, particularly several anticyclonic eddies located north of the Iberian Peninsula.

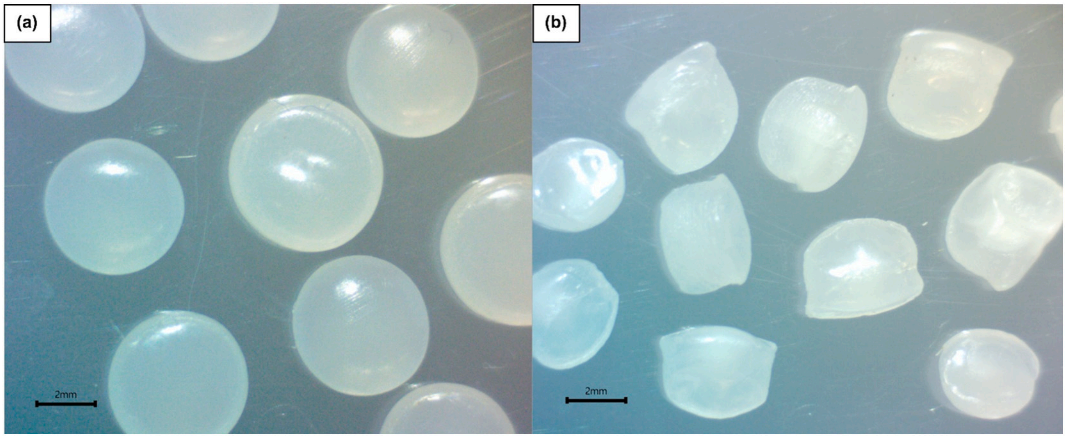

Fig. 2. Morphological comparison between (a) pristine PE pellets with lent shape and (b) Toconao pellets. Photos taken using an Euromez NexiusZoom EVO Stereo Microscope Trinocular Loup (model NZ.1703-S) with 0.65×, fitted with a Levenhuk M1400 PLUS-14Mpx digital camera with the Levenhuk Lite software (×54 version).

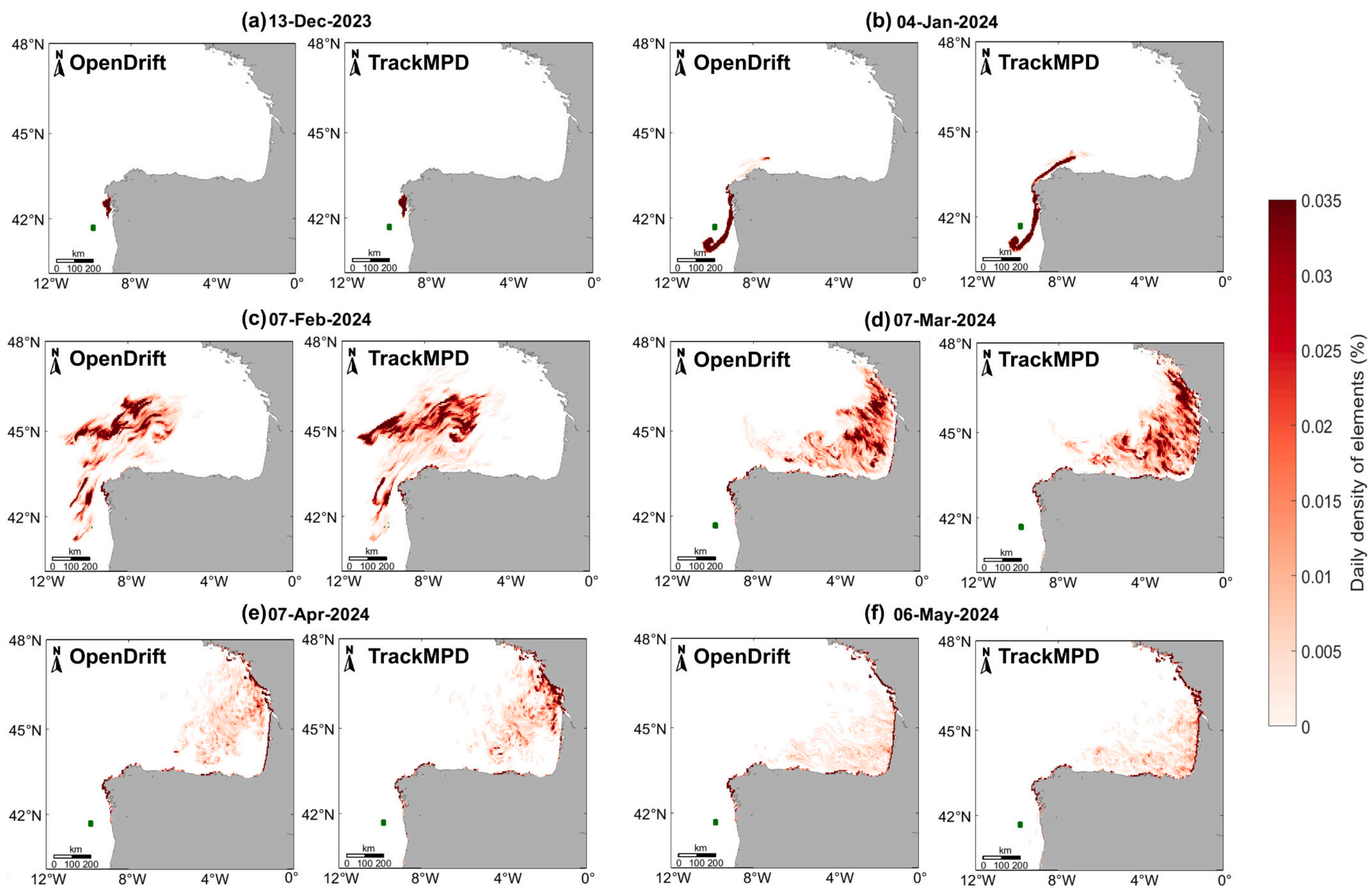

Fig. 3. Composite of selected snapshots showing the daily density of elements (%) associated with the Toconao pellet spill. Green pixels indicate the initial release locations of the virtual particles. The full daily animations are provided in the Supplementary Data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Coastal arrivals

An analysis about the timing and percentage of particles beaching on the coasts is presented in Fig. 4. Thus, a significant arrival of particles is observed in the Galician Rías on December 13th, 2023, and January 3rd, 2024, accounting for about 40% of the considered virtual particles (Figs. 4 and 5). Fig. 5 highlights the Ria de Muros y Noia as the most affected area, while southern Rías, such as Ría de Vigo, Ría de Pontevedra and Ría de Arousa, show a much lower density, resulting in fewer virtual particles reaching these areas. However, the coasts located North of Ría de Muros y Noia also show significant particle arrivals, especially near Cape Finisterre and the Rías de Ortigueira y Viveiro.

In the southern Bay of Biscay, the coast between Santander and Bilbao (Spain) is also affected by the arrival of virtual particles (Fig. 6). More significantly, particles also seem to reach the eastern coast of the bay (France), affecting the shores from southern Brittany to the areas

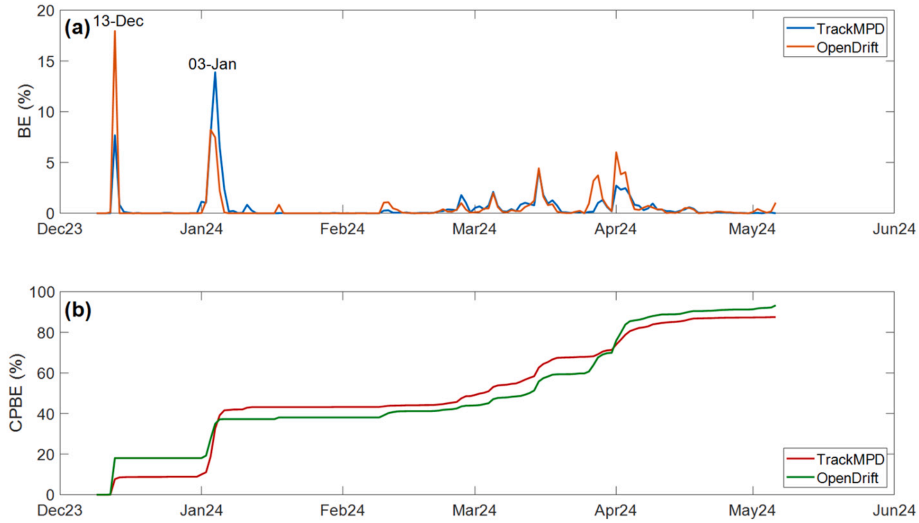

Fig. 4. (a) Temporal series of the number of daily Beached Elements (BE) highlighting the dates of the first two maxima. (b) Temporal series of the Cumulative Percentage of Beached Elements (CPBE). Both graphs include the results from the two Lagrangian frameworks used.

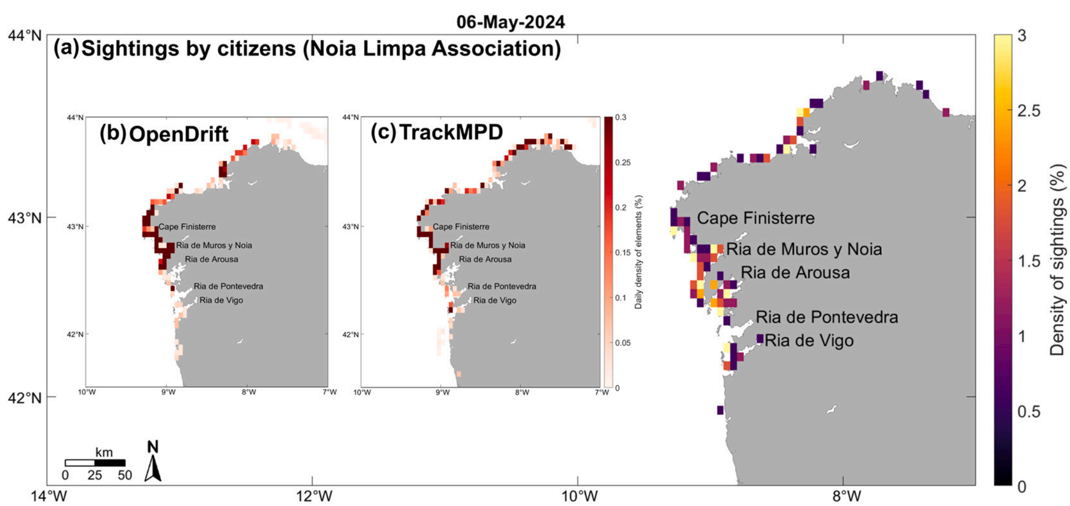

Fig. 5. (a) Density of sightings by citizens of potential pellets from the TOCONAO in Galicia (Spain) by May 6th, 2024. These sightings were compiled by the Noia Limpa Association and were publicly available on their website. (b) Daily density of particles (beached and active elements) in Galicia (Spain) by May 6th, 2024, from the OpenDrift simulation. (c) Same as (b) but with the results obtained using TrackMPD.

south of the Gironde Estuary (Fig. 6). These areas receive particles irregularly from late February 2024 to late April 2024 (Figs. 4 and 6). This second episode of arrivals is less pronounced but more prolonged over time, resulting in approximately 90% of the particles eventually reaching the coast after 6 months (Fig. 5b).

4. Discussion

This study combined chemical/morphological analyses and Lagrangian transport simulations to investigate the fate of the pellets released during the Toconao incident. The analytical results provide a fingerprint that could help to differentiate theses pellets from conventional PE nurdles, while the simulations offer insights into their dispersal and coastal arrivals. Together, these approaches allow for a comprehensive assessment of the environmental implications of the spill. In the following sections, we first discuss the chemical and morphological fingerprint of the Toconao pellets, then examine their modelled transport and distribution patterns, and finally address the reports of pellet arrivals in the Canary Islands.

4.1. *Chemical and morphological fingerprint*

The spectral differences observed in Toconao pellets are due to the additive-rich formulation which distinguishes them from pristine PE pellets as they are a masterbatch. Although FTIR detection of all Tinuvin 622 peaks is challenging due to its molecular structure with tris- and tetrasubstituted carbonyl groups that generate numerous closely spaced and poorly resolved bands, its presence has been evidenced by thermal desorption GC–MS (Instituto Universitario de Medio Ambiente, 2024). Beyond their chemical composition, Toconao pellets also differ morphologically as they are smaller in size and irregular in shape, similar to a top hat. While different sources of pellets may coexist in the same areas, as noted in previous studies (Baztan et al., 2014; Cocozza et al., 2025) the observed characteristics of this masterbatch could enhance the identification of origin of the masterbatch, nevertheless, further analysis would be needed to distinguish between high additive content pellets. Environmental impact will also be different from that of non-masterbatch PE pellets.

The high additive content of this masterbatch influences both its chemical and physical properties, and consequently its degradation

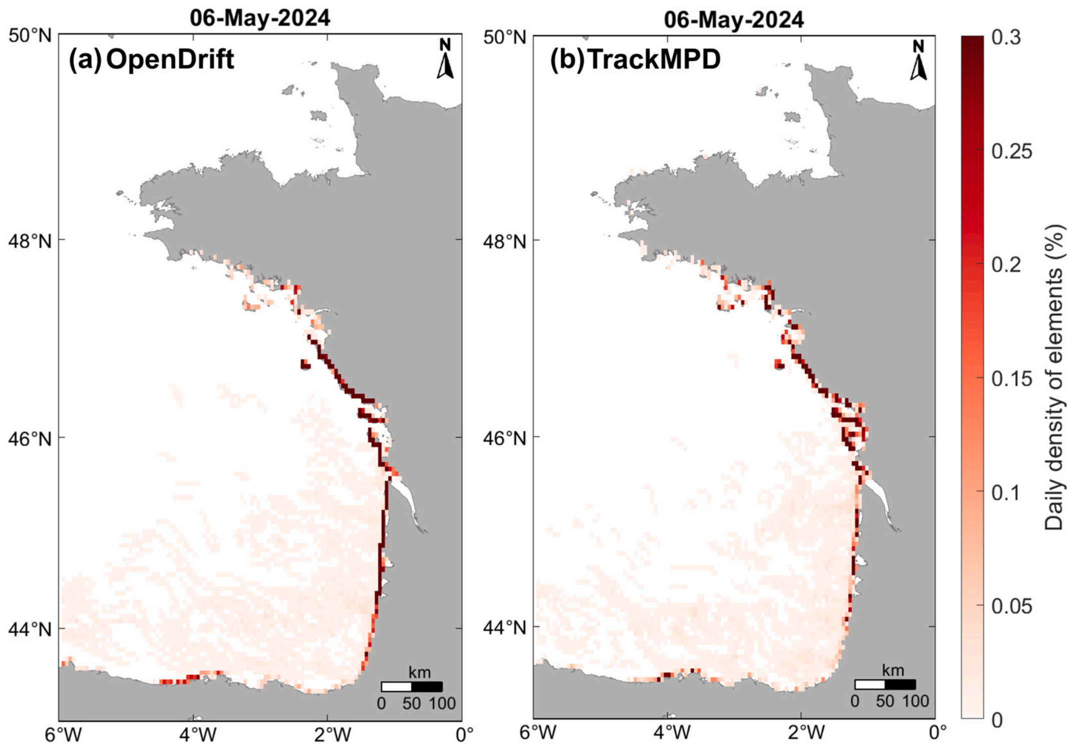

Fig. 6. (a) Daily density of particles (beached and active elements) on the eastern coast of the Bay of Biscay by May 6th, 2024, from the OpenDrift simulation. (b) Same as (a) but with the results obtained using TrackMPD.

behavior. Over time, these pellets are also expected to undergo weathering, during which new absorption bands may appear in the ATR-FTIR spectra. The most likely signals include hydroxyl groups (—OH) with broad peaks between 3500 and 3000 cm^{-1}, vinyl hydrogen (=C-H) within 3100–3000 cm^{-1}, carbonyl groups (—C=O) ranging from 1850 to 1650 cm^{-1}, and olefinic groups (C=C) within 1700–1600 cm^{-1}, among others (Aguiar et al., 2024; Andrady et al., 2022; Brandon et al., 2016). In parallel, environmental exposure is also expected to induce color changes over time. This effect, commonly referred to as yellowness, is mainly attributed to the formation of chromophores generated through oxidative processes in the polymer backbone (Marek et al., 2006). Nevertheless, given its specific chemical formulation, the degradation of this masterbatch may differ from that of conventional PE pellets and potentially occur over longer timescales. This makes it a relevant subject for future studies aimed at evaluating not only its environmental impact but also its degradation pathways.

4.2. Simulated transport and distribution

The results of the simulations are promising and relevant for the management of this environmental crisis as well as similar crises that may arise in the future. It is highlighted that, chronologically and geographically, the arrivals of virtual particles on December 13th, 2023 and January 3rd, 2024, are consistent with the reports of sacks and pellets on the Galician shores. Similarly, reports from the Noia Limpa Association regarding pellet sightings along the Galician coasts align well with our simulation. These reports indicate a higher number of sightings in the Ría de Muros y Noia, as well as in the Ría de Arousa and the northern coasts (Noia Limpa, 2024). The Government of Spain observed a similar pattern, reporting sightings near the municipality of Ribeira (Ría de Arousa) on December 13th, 2023, and in the municipality of Muros (Ría de Muros y Noia) on January 3rd, 2024, along with arrivals on January 6th and 7th, 2024 in northern Galicia and in the Ría de Vigo (Ministerio de Política Territorial y Memoria Democrática, 2024). This observed pattern is adequately mirrored in our simulation, which shows a greater impact on the Ría de Muros y Noia, significant impact on the northern coasts, and a lower impact in the Rías located south of Ría de Muros y Noia (Fig. 5). Nevertheless, it is important to interpret the pellet arrival reports with caution. Firstly, these reports are based on sightings, so the reported date does not necessarily coincide with the actual arrival date. Additionally, since most of these reports are based on citizen science, not all coasts have been systematically sampled every day. Furthermore, the pellets spotted by volunteers are not necessarily from the Toconao, as they can have multiple origins. The World Shipping Council indicates that between 2008 and 2022, an average annual loss of 1566 containers were reported (World Shipping Council, 2023), some of which could have transported pellets and caused spills similarly to the Toconao or the one in Sri Lanka in 2021 (de Vos et al., 2022b; Jayathilaka et al., 2022). In addition to the 1566 lost containers, unreported losses likely occurred, further increasing marine pollution levels in the marine environment. However, the combination of backward trajectories and the determination of the fingerprint of a pellet sample from a location, could be used as a technique to assess the origin and attribute the legal responsibility of unreported cases. However, for with this goal the used of detailed analytical analysis and accurate ocean modelling is imperative, and the uncertainty could still be considerable, thus more studies are needed.

Additionally, Cocozza et al. (2025) performed beach surveys in March 2024 along a coastal stretch of 633 km between Northern Portugal and Asturias (Spain). Their results exhibit a similar distribution, but it is remarkable that in the Ria de Muros y Noia they found low pellet pollution levels. Therefore, this discrepancy can be associated with the cleaning efforts made by volunteers, local communities and institutions (Vidal-Abad et al., 2024), indicating a high cleaning efficiency. Moreover, it should be noted that their results also consider pellets with different sources, as they already suggest. Consequently, the differences between the observed pellet pollution by Cocozza et al. (2025) and our simulation, can validate the hypothesis of multiple origins for the pellet pollution in the area following the pattern observed in other regions of the North Atlantic (Baztan et al., 2014). Regarding the movement of the particles (see the animations in Supplementary Data), it is notable that their transport is controlled by the characteristic dynamics of the area during the winter months, as expected. The northward and eastward movements are driven by the Iberian Polar Current and the transport associated with the Western Iberian Buoyant Plume, a low-salinity water layer that forms an inshore frontal region, promoting northward baroclinic transport all along the coast as a narrow band (Frouin et al., 1990; Peliz et al., 1999, 2002, 2005). The formation of this plume is attributed to buoyancy (freshwater) input from regional rivers and the Rías Baixas, a series of estuarine inlets (Peliz et al., 2002). Furthermore, the observed offshore and inshore displacements might be related to daily changes in the wind field, as well as oscillations associated with tides.

Once the particles have been dispersed across the Bay of Biscay, a northward and eastward movement is observed, driven by the typical circulation of the region in winter (Charria et al., 2013; Koutsikopoulos and Le Cann, 1996). This leads to the second episode of particles reaching the coasts, primarily the western coasts of France (Figs. 4 and 6). However, local media have not reported significant pellet arrivals, possibly because these microplastics have mixed with other marine debris elements.

It is important to consider that at the final time step of the simulation (May 6th, 2024, at 23:00), there are still particles present in the water domain (Fig. 6). During the spring and summer months northeasterly winds predominate in the Iberian basin (Bakun and Nelson, 1991; Wooster et al., 1976), generating the surface southward-flowing Portugal Coastal Current in contrast with the northward Iberian Poleward current observed in winter and autumn. Therefore, it is highly likely that these particles will eventually reach the northern coast of the Iberian Peninsula or even recirculate into the North Atlantic Subtropical Gyre. However, these still active particles represent a relatively small percentage of the total amount of elements (<10%). Also, the container may have drifted at the surface or at depth while releasing pellets and some sacks may have broken during its trajectory. Therefore, even though most of the virtual particles have been transported northwards, it is still possible that some pellets and sacks drifted differently. This interpretation is supported by Anfuso et al. (2024), who showed that windage strongly influences the drift of positively buoyant marine litter, with object size, exposed area to the wind, and degree of submergence playing a key role, even under low-energy conditions.

Both Lagrangian frameworks are largely consistent; however, some differences can be observed. Firstly, the acute episodes observed on December 13th, 2023, and January 3rd, 2024, have different intensities with TrackMPD (OpenDrift) producing a more pronounced arrival on January 3rd (December 13th, 2023). Moreover, slightly different spatial patterns can be observed in the particles presented in Figs. 5 and 6. This is likely attributed to differences in the beaching process considered in each frame. These versions of TrackMPD and OpenDrift consider the beaching of a particle when its trajectory encounters the polygon that define the land domain. As this polygon, the high-resolution GSHHS database (Wessel and Smith, 1996), is the same in both simulations, the differences observed must be related to how the software internally handles polygons, with TrackMPD implemented as a MATLAB toolbox and OpenDrift as a Python package.

Despite the overall consistency between both modelling frameworks, some limitations must be acknowledged. The simulations do not explicitly resolve coastal processes such as surf-zone dynamics or washing-off mechanisms, which can influence particle behavior once they reach the nearshore zone (Jalón-Rojas et al., 2024). In addition, the highly complex morphology of the northwestern Iberian coastline, particularly the Galician Rías, represents a challenging environment for the underlying ocean and wind velocity data and may increase uncertainty in coastal-scale predictions. Furthermore, the simulations do not consider finite-size particles and therefore do not account for inertial effects, which have been shown to influence the transport and accumulation of buoyant debris in the ocean (Beron-Vera, 2021). Despite these limitations, both modelling frameworks reproduce the main spatial and temporal patterns of observed pellet arrivals along the Galician coast.

Lastly, these findings not only contribute to the scientific understanding of pellet dispersal but also illustrate the operational value of rapid modelling tools within scientific emergency advisory mechanisms. In fact, the simulations presented here were conducted under the activation in exercise mode of the CSIC Disaster and Emergency Advisory Protocol, demonstrating how research infrastructures can provide timely evidence to support crisis managers during environmental emergencies.

4.3. Detection of pellets in the Canary Islands in January 2024

On January 10th, 2024, 33 days after the accident, the regional Government of the Canary Islands (∼2000 km south of the incident position) activated the Territorial Emergency Plan for Civil Protection of the Autonomous Community of the Canary Islands (PLATECA) due to the detection of a high concentration of plastic pellets on the coast of Bajamar, in Tenerife Island (Gobierno de Canarias, 2024).

Two days after, (January 12th, 2024) the alert condition was deactivated thanks to the scientific advisory we provided to the regional government. Firstly, the fingerprint of the observed pellets indicated a high degradation state which is inconsistent with a Toconao related origin. In addition, the shape of these pellets and their composition, despite some being PE pellets (polypropylene pellets were also observed), also indicated no relationship with the Toconao incident. Moreover, it was argued that regional ocean currents render impossible a direct link between the Toconao pellets and the nurdles observed in Tenerife at such time scales. The simulations presented here further support this interpretation, indicating that the pellets observed in Bajamar are more likely associated with multiple pollution events unrelated to the Toconao spill. However, these simulations also indicate that in a larger time scale (∼years) a small fraction of the lost pellets from the Toconao may arrive to the Canary Islands, but probably along with marine debris from different sources.

Therefore, the analysis performed here showcase a basis for the identification of pellets originated from the spill of the Toconao incident, with parameters that have been already used in the activation protocols to face environmental crisis.

4.4. Regulatory implications for pellet-loss and response management

Recent regulatory developments at the European level provide an important framework for interpreting the broader relevance of the present study. In November 2025, the European Union adopted Regulation (EU) 2025/2365, which establishes binding measures to prevent plastic pellet losses across the entire supply chain, including production, handling, storage, and maritime transport. Notably, the regulation explicitly refers to the Toconao case as a recent large-scale pellet loss incident, highlighting its relevance as a reference event in the development of the regulatory framework. Beyond preventive measures, the regulatory framework also addresses how accidental pellet losses should be managed once they occur. It promotes actions aimed at improving preparedness and response capacity, including environmentally sustainable cleanup practices, systematic documentation of loss incidents, and the collection and sharing of information on response actions and environmental impacts. In this context, Article 14 specifically focuses on accidental losses during handling or transport, underlining the importance of timely response measures and appropriate reporting mechanisms.

Within this framework, the approaches applied in this study directly support several of the regulation's objectives. Lagrangian transport simulations provide a quantitative basis to assess dispersal pathways and identify potentially affected coastal regions following accidental releases, while chemical and morphological fingerprinting contributes to distinguishing between different pellet sources. Together, these tools facilitate improved documentation of incidents, help interpret observed coastal pollution patterns, and support attribution efforts in scenarios where multiple pellet loss events may coexist in space and time. As such, this study illustrates how transport modelling and analytical approaches can complement regulatory efforts by strengthening response capacity and supporting informed decision-making in future pellet loss events.

5. Conclusions

Through an analytical and modelling approach, we evaluated the footprint of the pellets spilled during the Toconao incident and provided insights into their chemical composition, morphology and environmental distribution.

ATR-FTIR analyses suggest that the pellets are not pristine PE, but rather a masterbatch. Morphological observations further revealed a smaller size and irregular shape compared with typical lentil-shaped pellets in agreement with previous studies. These chemical and morphological features may help to create a fingerprint for their identification in future works. Additionally, this highlights the environmental implications of additive-rich plastics, which may present enhanced persistence and potential risks associated with additive release.

The simulations conducted suggest that within the first 3 weeks after the incident, approximately 40% of the particles reached the coast in two distinct arrivals. After 5 months, the percentage of beached particles gradually increased to 90%.

The most affected areas highlighted by the simulations are the western coast of France and the western coast of Galicia (Spain), particularly the Ria de Muros y Noia. This is aligned with reports issued by the media, governmental reports and citizen sightings. Although these reports must be treated with caution, they provide robustness for our results.

The comparison between the simulation outputs and a recent field work study suggest a high cleaning efficiency in the Ria de Muros y Noia which was detected as the most affected area.

The transport of the pellets is linked to the main oceanographic features of the region during winter. Additionally, the seasonality of the region can be attributed to a latter higher dispersion of a relative low percentage of the particles (<10%) across the Atlantic.

Finally, the combined analytical and modelling approach applied in this work demonstrates that the Toconao spill cannot be linked to the pellets detected on the Canary Islands in January 2024. This highlights the value of integrating chemical fingerprinting and particle-tracking simulations for clarifying sources of marine plastic pollution and guiding response strategies. Beyond its scientific contributions, this study also exemplifies how the activation in exercise mode of the CSIC Disaster and Emergency Advisory Protocol can help bridge scientific research with emergency management, ensuring rapid and evidence-based support during marine pollution crises. In this context, such integrated approaches are also directly relevant to the implementation of Regulation (EU) 2025/2365, supporting documentation and informed decision-making following accidental pellet loss events.

CRediT authorship contribution statement

Álvaro Cubas: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Daura Vega-Moreno:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Miriam N. Déniz-Martín:** Writing – original draft, Methodology, Investigation, Conceptualization. **Ana Molina-Rodríguez:** Validation, Investigation, Data curation, Conceptualization. **Cristina León-Santiago:** Investigation, Data curation. **Javier Hernández-Borges:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Francisco Machín:** Writing – review & editing, Validation, Supervision, Formal analysis, Data curation. **Eugenio Fraile-Nuez:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition.

Code availability

The TrackMPD framework is available in GitHub (https://github.com/IJalonRojas/TrackMPD) thanks to Jalón-Rojas et al. (2019). The modifications implemented by the authors include adapting the 2D horizontal mode of TrackMPD to utilize current data from IBI Ocean Physics Analysis and Forecasts. Additionally, windage and Stokes drift have been incorporated (the latter not used in the present study). For greater computational efficiency, instead of interpolating bathymetry data at every particle position, the nearest neighbour method is used. The OpenDrift framework is available in GitHub (https://opendrift.github.io/) thanks to Dagestad et al. (2018).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daura Vega-Moreno reports financial support was provided by Promotur Turismo Canarias (Next Generation EU Funds). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The first author acknowledges the support received through the *Ayudas para la Formación de Profesorado Universitario* (FPU24) programme funded by the Spanish Ministry of Science, Innovation and Universities (FPU2024/00618). This research was conducted within the framework of an exercise-mode activation of the CSIC Disaster and Emergency Advisory Protocol (PADE), which enabled the coordinated scientific response underpinning this study. Moreover, the authors would like to thank the Promotur Turismo Canarias Agreement for the joint implementation of initiatives aimed at intelligent management and the development of the Blue Tourism product. These efforts fall within the framework of the Recovery, Transformation, and Resilience Plan (Next Generation EU Funds) and align with Order No. 257/2023 issued by the Minister of Tourism and Employment, focused on the execution of cohesion actions in destinations as part of the Canary Islands Territorial Plan.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119359.

Data availability

Data will be made available on request.

References

Abu-Hilal, A.H., Al-Najjar, T.H., 2009. Plastic pellets on the beaches of the northern Gulf of Aqaba, Red Sea. Aquat. Ecosyst. Health Manag. 12 (4), 461–470. https://doi.org/10.1080/14634980903361200.

Aguiar, M.I.S., Sousa, A.F., Teixeira, G., Tavares, A.P.M., Ferreira, A.M., Coutinho, J.A.P., 2024. Enhancing plastic waste recycling: evaluating the impact of additives on the enzymatic polymer degradation. Catal. Today 429, 114492. https://doi.org/10.1016/j.cattod.2023.114492.

Andrady, A.L., Lavender Law, K., Donohue, J., Koongolla, B., 2022. Accelerated degradation of low-density polyethylene in air and in sea water. Sci. Total Environ. 811, 151368. https://doi.org/10.1016/j.scitotenv.2021.151368.

Anfuso, G., Álvarez, O., Dilauro, G., Sabato, G., Scardino, G., Sozio, A., Rizzo, A., 2024. A first attempt to describe the real-time behavior and fate of marine litter items in the nearshore and foreshore under low energetic marine conditions. Water 16 (3), 409. https://doi.org/10.3390/w16030409.

Aswin, A.P., Biju, A., Vincent, S.G.T., 2025. First rapid-response assessment of nurdle pollution along the southern coasts of India following the MSC ELSA 3 shipwreck. Reg. Stud. Mar. Sci. 92, 104643. https://doi.org/10.1016/j.rsma.2025.104643.

Bakun, A., Nelson, C.S., 1991. The seasonal cycle of wind-stress curl in subtropical eastern boundary current regions. J. Phys. Oceanogr. 21, 1815–1834. https://doi.org/10.1175/1520-0485(1991)021<1815:TSCOWS>2.0.CO;2.

Baztan, J., Carrasco, A., Chouinard, O., Cleaud, M., Gabaldon, J.E., Huck, T., Jaffrès, L., Jorgensen, B., Miguelez, A., Paillard, C., Vanderlinden, J.-P., 2014. Protected areas in the Atlantic facing the hazards of micro-plastic pollution: first diagnosis of three islands in the Canary Current. Mar. Pollut. Bull. 80, 302–311. https://doi.org/10.1016/j.marpolbul.2013.12.052.

Beron-Vera, F.J., 2021. Nonlinear dynamics of inertial particles in the ocean: from drifters and floats to marine debris and *Sargassum*. Nonlinear Dyn. 103 (1), 1–26. https://doi.org/10.1007/s11071-020-06053-z.

Bosi, S., Broström, G., Roquet, F., 2021. The role of Stokes drift in the dispersal of North Atlantic surface marine debris. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.697430.

Brandon, J., Goldstein, M., Ohman, M.D., 2016. Long-term aging and degradation of microplastic particles: comparing in situ oceanic and experimental weathering patterns. Mar. Pollut. Bull. 110, 299–308. https://doi.org/10.1016/j.marpolbul.2016.06.048.

Breivik, Ø., Bidlot, J.R., Janssen, P.A.E.M., 2016. A Stokes drift approximation based on the Phillips spectrum. Ocean Model 100, 49–56. https://doi.org/10.1016/J.OCEMOD.2016.01.005.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louazel, S., Batifoulier, F., Dumas, F., Pichon, A., Morel, Y., 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. J. Mar. Syst. 109–110, S60–S76. https://doi.org/10.1016/J.JMARSYS.2011.09.015.

Cocozza, P., Scarrica, V.M., Rizzo, A., Serranti, S., Staiano, A., Bonifazi, G., Anfuso, G., 2025. Microplastic pollution from pellet spillage: analysis of the Toconao ship accident along the Spanish and Portuguese coasts. Mar. Pollut. Bull. 211, 117430. https://doi.org/10.1016/j.marpolbul.2024.117430.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/J.MARPOLBUL.2011.09.025.

Dagestad, K.-F., Röhrs, J., 2019. Prediction of ocean surface trajectories using satellite derived vs. modeled ocean currents. Remote Sens. Environ. 223, 130–142. https://doi.org/10.1016/j.rse.2019.01.001.

Dagestad, K.-F., Röhrs, J., Breivik, Ø., Ådlandsvik, B., 2018. OpenDrift v1.0: a generic framework for trajectory modelling. Geosci. Model Dev. 11, 1405–1420. https://doi.org/10.5194/gmd-11-1405-2018.

De Vos, A., Aluwihare, L., Youngs, S., Dibenedetto, M.H., Ward, C.P., Michel, A.P.M., Colson, B.C., Mazzotta, M.G., Walsh, A.N., Nelson, R.K., Reddy, C.M., James, B.D., 2022a. The M/V X-press pearl nurdle spill: contamination of burnt plastic and unburnt nurdles along Sri Lanka's beaches. ACS Environ. Au 2, 128–135. https://doi.org/10.1021/ACSENVIRONAU.1C00031/SUPPL_FILE/VG1C00031_SI_001.PDF.

de Vos, M., Barnes, M., Biddle, L.C., Swart, S., Ramjukadh, C.L., Vichi, M., 2022b. Evaluating numerical and free-drift forecasts of sea ice drift during a Southern Ocean research expedition: an operational perspective. J. Oper. Oceanogr. 15, 187–203. https://doi.org/10.1080/1755876X.2021.1883293.

Durgadoo, J.v., Biastoch, A., New, A.L., Rühs, S., Nurser, A.J.G., Drillet, Y., Bidlot, J.-R., 2021. Strategies for simulating the drift of marine debris. J. Oper. Oceanogr. 14 (1), 1–12. https://doi.org/10.1080/1755876X.2019.1602102.

El País, 2024. Dos meses de la crisis de los 'pellets': Galicia contabiliza la recogida de menos del 20% de los microplásticos perdidos en el mar.

European Chemical Agency, 2023. Substance Information - Tinuvin 622 [WWW Document]. URL. https://echa.europa.eu/substance-information/-/substanceinfo/100.119.024. (Accessed 30 April 2024).

Frouin, R., Fiúza, A.F.G., Ambar, I., Boyd, T.J., 1990. Observations of a poleward surface current off the coasts of Portugal and Spain during winter. J. Geophys. Res. Oceans 95, 679–691. https://doi.org/10.1029/JC095IC01P00679.

Galgani, F., Rangel-Buitrago, N., 2024. White tides: the plastic nurdles problem. J. Hazard. Mater. 470, 134250. https://doi.org/10.1016/j.jhazmat.2024.134250.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782. https://doi.org/10.1126/SCIADV.1700782.

Gobierno de Canarias, 2024. Portal de Noticias del Gobierno de Canarias [WWW Document]. URL. https://www3.gobiernodecanarias.org/noticias/el-gobierno-de-canarias-activa-el-plateca-ante-la-deteccion-de-granulos-de-plastico-en-la-costa-norte-de-tenerife/. (Accessed 28 August 2025).

Instituto Universitario de Medio Ambiente, 2024. CARACTERIZACIÓN QUÍMICA DE "PELLETS" RECOGIDOS EN LA PLAYA DE NEMIÑA EN MUXÍA (A CORUÑA).

Jalón-Rojas, I., Wang, X.H., Fredj, E., 2019. A 3D numerical model to Track Marine Plastic Debris (TrackMPD): sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes. Mar. Pollut. Bull. 141, 256–272. https://doi.org/10.1016/J.MARPOLBUL.2019.02.052.

Jalón-Rojas, I., Defontaine, S., Bermúdez, M., Díez-Minguito, M., 2024. Transport of microplastic debris in estuaries. In: Treatise on Estuarine and Coastal Science, Second edition. Elsevier, pp. 368–409. https://doi.org/10.1016/B978-0-323-90798-9.00022-6.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352 (1979).

Jayathilaka, R.M.R.M., Weerakoon, W.R.W.M.A.P., Indika, K.W., Arulananthan, K., Kithsiri, H.M.P., 2022. Spatio-temporal variation of plastic pellets dispersion in the coastline of Sri Lanka: an assessment of pellets originated from the X-Press Pearl incident during the Southwest monsoon in 2021. Mar. Pollut. Bull. 184, 114145. https://doi.org/10.1016/J.MARPOLBUL.2022.114145.

Koutsikopoulos, C., Le Cann, B., 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Sci. Mar. 60, 9–19.

Marek, A., Kaprálková, L., Schmidt, P., Pfleger, J., Humlíček, J., Pospíšil, J., Pilař, J., 2006. Spatial resolution of degradation in stabilized polystyrene and polypropylene plaques exposed to accelerated photodegradation or heat aging. Polym. Degrad. Stab. 91, 444–458. https://doi.org/10.1016/j.polymdegradstab. 2005.01.048.

Ministerio de Política Territorial y Memoria Democrática, 2024. El Gobierno de España ofreció ayuda a la Xunta para limpiar los pellets de plástico de las playas.

Noia Limpa, 2024. Información pellets plástico galicia [WWW Document]. URL. https://www.noialimpa.org/es/informacion-pellets-plastico-galicia. (Accessed 22 May 2024).

Peliz, Á., Fiuza, A., Fiu, A., Za, Â., 1999. Temporal and spatial variability of CZCS-derived phytoplankton pigment concentrations off the western Iberian Peninsula. Int. J. Remote Sens. 20, 1363–1403. https://doi.org/10.1080/014311699212786.

Peliz, Á., Rosa, T.L., Santos, A.M.P., Pissarra, J.L., 2002. Fronts, jets, and counter-flows in the Western Iberian upwelling system. J. Mar. Syst. 35, 61–77. https://doi.org/10.1016/S0924-7963(02)00076-3.

Peliz, Á., Dubert, J., Santos, A.M.P., Oliveira, P.B., Le Cann, B., 2005. Winter upper ocean circulation in the Western Iberian Basin—Fronts, Eddies and Poleward Flows: an overview. Deep-Sea Res. I Oceanogr. Res. Pap. 52, 621–646. https://doi.org/10.1016/J.DSR.2004.11.005.

Pereiro, D., Souto, C., Gago, J., 2018. Calibration of a marine floating litter transport model. J. Oper. Oceanogr. 11 (2), 125–133. https://doi.org/10.1080/1755876X.2018.1470892.

Reichelt-Brushett, A., 2023. Marine pollution – monitoring, management and mitigation. In: Springer Textbooks in Earth Sciences, Geography and Environment. Springer Nature Switzerland, Cham. https://doi.org/10.1007/978-3-031-10127-4.

Röhrs, J., Christensen, K.H., Hole, L.R., Broström, G., Drivdal, M., Sundby, S., 2012. Observation-based evaluation of surface wave effects on currents and trajectory forecasts. Ocean Dyn. 62 (10–12), 1519–1533. https://doi.org/10.1007/S10236-012-0576-Y.

Scarrica, V.M., Cocozza, P., Anfuso, G., Staiano, A., Bonifazi, G., Rizzo, A., Serranti, S., 2025. Cost-effective approaches for microplastic pellets characterization using a machine learning tool. Ecol. Inform. 90, 103230. https://doi.org/10.1016/j.ecoinf.2025.103230.

Smith, B., 2011. Fundamentals of Fourier Transform Infrared Spectroscopy.

van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., Bergmann, M., Chapron, B., Chubarenko, I., Cózar, A., Delandmeter, P., Egger, M., Fox-Kemper, B., Garaba, S.P., Goddijn-Murphy, L., Hardesty, B.D., Hoffman, M.J., Isobe, A., Jongedijk, C.E., Kaandorp, M.L.A., Khatmullina, L., Koelmans, A.A., Kukulka, T., Laufkötter, C., Lebreton, L., Lobelle, D., Maes, C., Martinez-Vicente, V., Morales Maqueda, M.A., Poulain-Zarcos, M., Rodríguez, E., Ryan, P.G., Shanks, A.L., Shim, W.J., Suaria, G., Thiel, M., van den Bremer, T.S., Wichmann, D., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15, 023003. https://doi.org/10.1088/1748-9326/ab6d7d.

Vidal-Abad, A., Casal, M.A., Rey-Aguiño, J.M., Pichel-González, A., Solana-Muñoz, A., Poza-Nogueiras, V., Varela, Z., Galbán-Malagón, C., Ouro, P., Fernández-Sanlés, A., 2024. Case report of plastic nurdles pollution in Galicia (NW Atlantic) following the Toconao's spill in December 2023: the VIEIRA Collaborative. Mar. Pollut. Bull. 203, 116442. https://doi.org/10.1016/j.marpolbul.2024.116442.

Wagner, T.J.W., Eisenman, I., Ceroli, A.M., Constantinou, N.C., 2022. How winds and ocean currents influence the drift of floating objects. J. Phys. Oceanogr. 52, 907–916. https://doi.org/10.1175/JPO-D-20-0275.1.

Wessel, P., Smith, W.H.F., 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. J. Geophys. Res. 101.

Wooster, W.S., Bakun, A., Mclain, D.R., 1976. The seasonal upwelling cycle along the eastern boundary of the North Atlantic. J. Mar. Res. 34, 131–141.

World Shipping Council, 2023. World shipping council releases containers lost at sea report – 2023 update [WWW Document]. URL. https://www.worldshipping.org/news/world-shipping-council-releases-containers-lost-at-sea-report-2023-update. (Accessed 22 May 2024).