Marine Pollution Bulletin 211 (2025) 117409

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Characterization of plastic ingestion in urban gull chicks and its implications for their use as pollution sentinels in coastal cities

Ana Max[a], Victor Martín-Vélez[a,*], Joan Navarro[a], Asunción Borrell[b], Tomas Montalvo[c], Odei Garcia-Garin[a,b]

[a] Institut de Ciències del Mar (ICM), CSIC, Barcelona, Spain
[b] Department of Evolutionary Biology, Ecology and Environmental Sciences, and Biodiversity Research Institute (IRBio), Facultat de Biologia, Universitat de Barcelona, Barcelona, Spain
[c] Servei de Vigilància i Control de Plagues Urbanes, Agencia de Salud Pública de Barcelona, Pl. Lesseps, 1, 08023 Barcelona, Spain

ARTICLE INFO

Keywords:
Microplastics
Macroplastics
Yellow-legged Gull
Pollution
Bioindicator
Stable isotopes
Diet analysis

ABSTRACT

The increase of plastic pollution represents a significant ecological threat, particularly in human-impacted environments. However, the effects of plastic ingestion by urban wildlife are less understood. This study investigates the presence of microplastic (MPs; plastic <5 mm in size) and macroplastics (MaPs, plastic >5 mm in size) in yellow-legged gull (*Larus michahellis*) chicks inhabiting the urban marine ecosystem of Barcelona (northeastern Spain). The stomach contents of 56 gull chicks were analysed, revealing the presence of MPs in 100 % of the individuals and MaPs in 19.64 % of individuals. Additionally, trophic analysis, through stomach content and stable isotope determination, identified links between diet and plastic ingestion, with diet diversity associated with higher MaP abundance. These results highlight the high presence of plastics in the early stages of an urban-dwelling wildlife species and open the potential role of the use of urban gull chicks as sentinels of marine and terrestrial pollution in urban coastal areas. The findings suggest that chicks can serve as bioindicators of plastic pollution, emphasizing the urgent need to address the high levels of plastic contamination in urban environments.

1. Introduction

Plastic pollution has emerged a significant global problem in recent decades, affecting nearly every ecosystem worldwide (Essoufi et al., 2024) and being considered as a marker of the Anthropocene epoch (Geyer, 2020). Its widespread presence in the environment is driven by its high demand, low production cost, exceptional durability, and resistance to degradation (Geyer, 2020). The extensive use of packaged products, increasing levels of food waste, and ineffective plastic waste management contribute to the release of "user" plastics into the environment (Olmo-Gilabert et al., 2024; Provencher et al., 2017).

Although plastic pollution is present in all environments, it is particularly pronounced in coastal urbanized areas where marine and terrestrial ecosystems converge (Critchell et al., 2019; Deoniziak et al., 2022). Poorly managed urban and industrial waste, which is often improperly disposed of or inadequately contained, is classified as urban litter (Ballatore et al., 2022). Coastal cities face more severe challenges than inland areas, as urban litter— primarily composed of plastics—impacts both the terrestrial and marine environments, further exacerbating ocean pollution (Ballatore et al., 2022). This issue is especially critical when plastic waste undergoes fragmentation through various physical, biological, and chemical processes (Li et al., 2016), breaking down into microplastics (MPs) (Lusher et al., 2020).

Despite their small size, MPs and macroplastics (MaPs) persist in the environment for many years due to their durability and resistance to degradation, leading to their accumulation in wildlife (Li et al., 2016, Moreira-Mendieta et al., 2023). MPs have been observed entering trophic webs through inhalation or ingestion, raising concerns about potential adverse effects on wildlife and human health (Essoufi et al., 2024). Within wildlife, seabirds are considered a sensitive group of species because of plastic ingestion, as they are in the apex of the trophic web and directly associated to anthropogenic environments (Almeida et al., 2023). Previous studies already reported the presence and characterized the effects of plastic ingestion of several species of seabirds, focusing mainly on juvenile and adult individuals (Seif et al., 2018). Characterization of plastics is commonly related to pellets (Almeida

* Corresponding author.
E-mail address: victormartin@icm.csic.es (V. Martín-Vélez).

https://doi.org/10.1016/j.marpolbul.2024.117409
Received 11 October 2024; Received in revised form 2 December 2024; Accepted 2 December 2024
Available online 11 December 2024

et al., 2023, Lopes et al., 2021), as are easy to collect in the colonies or aggregation sites and are considered a non-invasive method (Martín-Vélez et al., 2024a, 2024b), and the food provided by parents are the main source of plastic transfer from adults to chicks (Almeida et al., 2023). However, studies relating the importance of plastic ingestion in avian chicks are scarcer (Collard et al., 2022), than the ones reported in adults (Acampora et al., 2017).

On the other hand, sentinel species can play a valuable role in monitoring plastic pollution in the environment. These species reflect the state of the environment and provide relevant data on the prevalence and impacts of environmental pollutants (Basu et al., 2007; Garcia-Garin et al., 2019). For these reasons, urban-dwelling wildlife may not only be affected by the presence of plastic pollution but also serve as effective sentinels of its presence. Among these, the opportunistic yellow-legged gull (*Larus michahellis*) is a potential candidate, both as an urban species impacted by plastic pollution and as a sentinel for coastal cities (Galimany et al., 2023). This is due to its plastic behaviour and its ability to exploit diverse habitats and resources, including urban and marine environments (Lopes et al., 2022; Martín-Vélez et al., 2024a; Méndez et al., 2020; Vez-Garzón et al., 2023).

The main objective of this study was to examine the ingestion of MPs and MaPs in urban yellow-legged gull chicks by quantifying their abundance, size, type, colour, and potential origin. The type of plastic was further analysed by identifying the polymers using micro-Fourier Transform Infrared (μFTIR) spectroscopy. Furthermore, to determine the potential origin of plastics, we investigated the relationship between plastic ingestion and the diet of chicks by analysing their stomach contents and stable isotopic markers in their feathers. Based on this new information, we evaluate if this species can serve as a sentinel for plastic pollution in coastal cities. To address this, we focused on the urban population of yellow-legged gulls inhabiting the dense populated city of Barcelona (Spain). We analysed the plastics found in the stomach contents and the diet of 56 chicks sampled across the city. Our main hypotheses were that yellow-legged gulls consume significant quantities of plastics derived from both marine and terrestrial resources, all originating from human waste and part of this plastic transferred from adults to chicks. Furthermore, due to their opportunistic feeding behaviour, which rely on multiple anthropogenic sources, these gulls are highly exposed to pollution hotspots (Nos et al., 2024). Additionally, we expected that the quantity of ingested plastics is related to diet composition (Lopes et al., 2021), with greater dietary diversity corresponding to higher plastic ingestion.

2. Material and methods

2.1. Study area and sample collection

Fifty-six gull chicks were sampled in May 2023 in different nest located on roofs within the city of Barcelona (Fig. 1), an overpopulated Mediterranean coastal city with a population of 1.600.000 inhabitants (Idescat, 2019). The urban population of this gull in Barcelona has increased in recent decades, with an estimated population of about 450–500 pairs in the city itself (Anton et al., 2017; Martín-Vélez et al., 2024a). All chicks were managed by the Public Health Agency of Barcelona (following Legislative Decree 2/2008, April 15, DOGC). After capture, biometric parameters were measured (body mass, tarsus, and beak length) (Table 1) and the new-growth body feathers of the chicks were collected. The individuals were then dissected to collect their stomachs, which were placed in plastic bags and frozen at −20 °C until analysis.

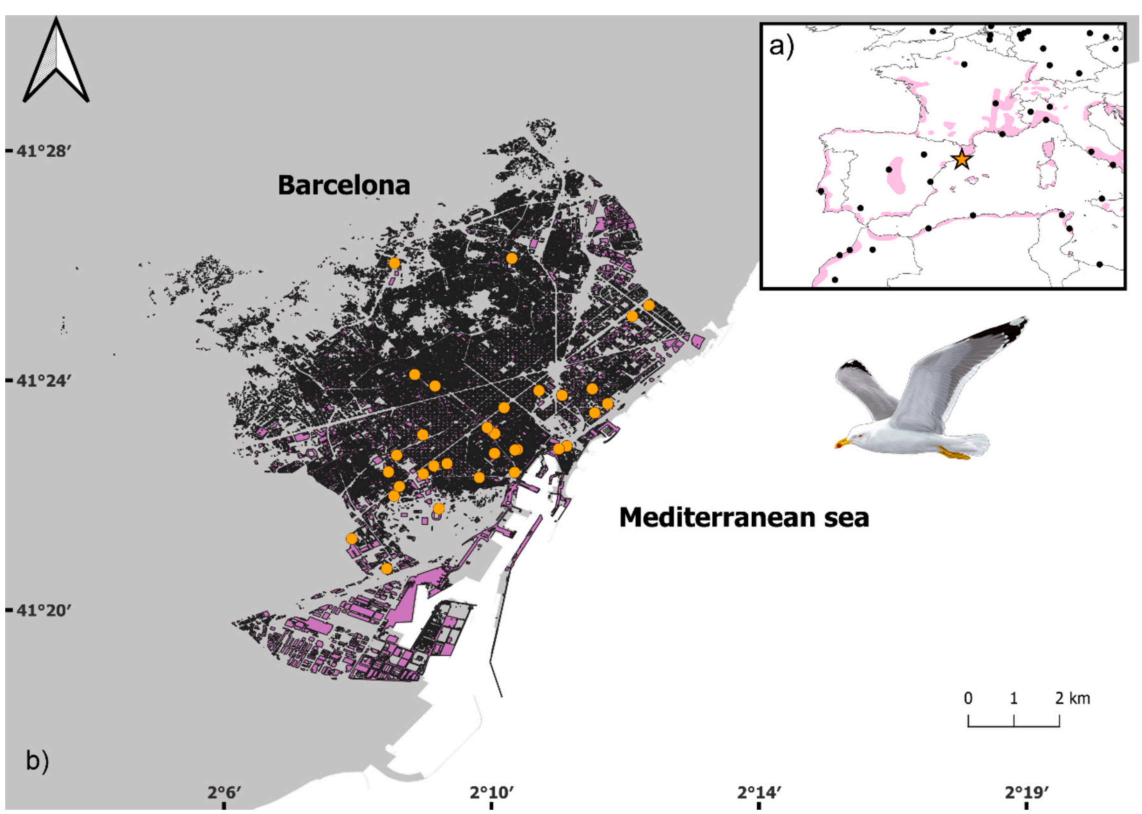

Fig. 1. (A) Location of Barcelona city in Europe (orange star point). Black points represent other cities with >500.000 inhabitants and pink shadow represent the breeding distribution of yellow-legged gull. (B) Distribution of the nests (orange dots) sampled in Barcelona during 2023. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Morphometric parameters (mean ± standard deviation, median and 95 % CI), plastic metrics (number of individuals with plastic, total number of items and frequency of occurrence) and abundance and size (mean ± standard deviation, median and 95 % CI) metrics of 56 yellow-legged gull chicks sampled in the city of Barcelona in 2023.

Morphometric parameters	Mean ± S.D.	Median	95 % CI
Body mass (g)	741.25 ± 172.3	735	694–787
Tarsus length (cm)	65.21 ± 5.22	66.32	63.8–66.6
Beak length (cm)	38.39 ± 4.81	38.07	37.09–39.69
Plastic metrics			
Chicks with MPs	56		
Total MP found	258		
FO% of MPs	100		
MPs per individual	4.61 ± 2.71	4	3.8–5.3
MP length (mm)	0.63 ± 0.86	0.31	0.41–0.52
Chicks with MaPs	11		
Total MaPs found	17		
FO% of MaPs	0.19		
MaPs per individual	0.3 ± 0.47	0	0.11–0.49
MaP length (mm)	10.55 ± 5.3	8.95	7.9–13.3

2.2. MP and MaP determination

The stomach dissection and identification of MPs were based on the protocol developed by Lusher and Hernandez-Milian (2018). Firstly, each stomach was weighted. After this, two nested metal sieves (5 mm and 1 mm) with a tray below were employed to separate the stomach contents to determine diet (see below) and to detect MPs and MaPs larger than 5 mm (Fig. 2A). Utilizing the sieve (inside the tray) as a support, the stomachs were individually opened using scissors. Subsequently, they were rinsed with Milli-Q water to cleanse the inner surface from partially digested food and potential MPs. The liquid that fell into a tray was then gathered in glass beakers and covered with aluminium foil. Depending on the volume of solution collected, either 50 or 100 mL of H_2O_2 16 % was promptly added to the solution. The beakers were subsequently incubated at 55 °C for a duration ranging from three to five days. H_2O_2 was added as necessary to digest all the organic matter present in the beakers until obtaining a transparent to slightly yellow solution containing water, H_2O_2, calcareous fragments, and candidate MPs. Once the solution had been digested, each sample was vacuum filtered using fiberglass filters (pore size 1.2 μm) and stored in Petri dishes sealed with Parafilm.

2.3. Diet determination

The diet of each individual was determined by analysing the prey found in the stomachs and by analysing the stable isotopes of N ($\delta^{15}N$) and C ($\delta^{13}C$) in the collected feathers. Regarding to the stomach content, the diet was analysed to the most specific taxonomic level possible and enumerated to the smallest possible quantity, classifying all the prey in three functional groups (marine prey, terrestrial prey and garbage) and other subgroups such as (demersal marine prey, pelagic marine prey and other marine prey). The otoliths found were stored dry and examined under a stereomicroscope. Species identification was performed using the AFORO database (Shape Analysis of Fish Otoliths) (http://aforo.cmima.csic.es, Lombarte et al., 2006) and the Otolith Atlas for the Western Mediterranean, North, and Central Eastern Atlantic (Tuset et al., 2008). Two trophic metrics were calculated to characterize the diet of yellow-legged gull based on stomach contents: FO% (frequency of occurrence =

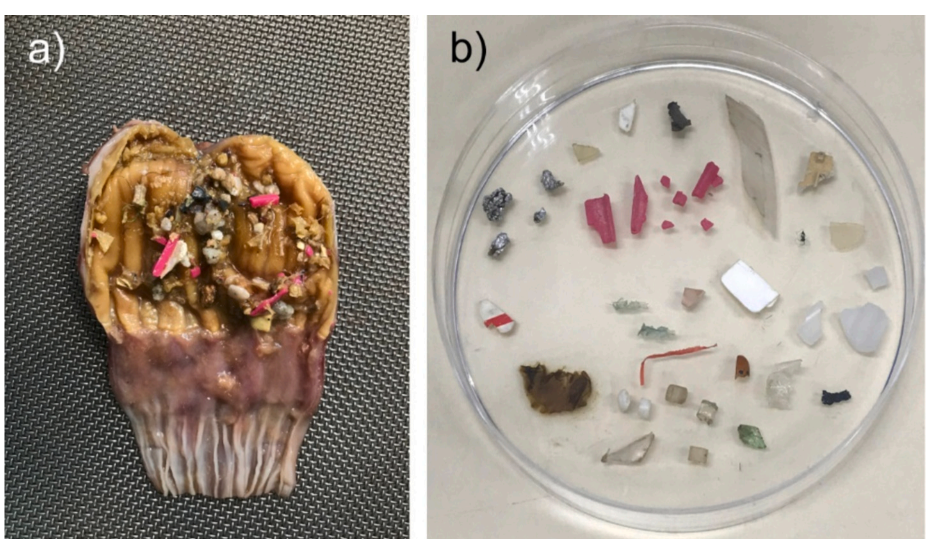

Fig. 2. a) Example of a dissected gull stomach with macroplastic and microplastic items; b) Examples of plastic items found in the stomachs of yellow-legged gull chicks based on size, shape, colour and type. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

number of occurrence samples / total amount of samples) and N% (contribution by number = number of occurrences of a specific type / total number of individuals counted) for each prey and the functional groups. The diversity of prey in the diet was evaluated by calculating the Shannon diversity index (H′) based on the abundance of prey found in the stomachs.

Regarding to the stable isotope markers, the $\delta^{15}N$ values infers individuals' trophic positions, with higher $\delta^{15}N$ values indicating higher trophic positions (Inger and Bearhop, 2008). Meanwhile, $\delta^{13}C$ analysis identifies feeding habitats: high values for coastal or shallow waters, low values for marine or oceanic habitats (Inger and Bearhop, 2008).

To determine the SIA values, all feathers were cleaned, dried, powdered and sent to the Stable Isotopes Lab of the Estación Biológica de Doñana (EBD-CSIC; www.ebd.csic.es/lie/index.html) for analysis of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes. The stable isotopic determination was performed with a Flash HT Plus elemental analyser connected to a Delta V Advantage mass spectrometer, following international standards. The ratios for stable isotopes are expressed in the standard δ-notation (‰) (see Vez-Garzón et al., 2023). Since the chicks were three to four weeks old, the isotope data from the feathers reflect their diet over their entire lives.

2.4. MP and MaP identification

Each sample was meticulously analysed using the LUPA program and a Stereo Microscope (Nikon SMZ1000). Each potential plastic was measured, photographed, characterized by colour, and classified into one of the following categories: fiber, fragment, sphere or film (Van Franeker et al., 2011; Fig. 2B). Additionally, classification was done to determine if they were MPs (< 5 mm) or MaPs (> 5 mm). Every candidate MP was transferred onto a calcium fluoride (CaF_2) slide and covered with another slide of the same material, for its chemical analysis through micro-Fourier Transform Infrared (μFT-IR) spectroscopy (spectrometer Thermo IN10MX). Each potential MaP was analysed through a Perkin Elmer Frontier Fourier transform infrared spectrometer. The analyses were carried out at the Scientific and Technological Centres of the Universitat de Barcelona (CCiTUB).

Infrared spectroscopy data was utilized to identify polymers using the OMNIC Picta software, which accesses fourteen reference libraries, including the Hummel Polymer Laminate Film and the Georgia State Crime Lab Sample Library. The match percentage measures the resemblance between the plastic spectrum and the item under analysis and each reference spectrum (the higher the match value, the closer the obtained spectrum is to the reference spectrum). In case of obtaining two polymers with the same percentage as a result, the correct one is verified by selecting different points of the MP for analysis. Once the polymers corresponding to each MP were identified, the proportion of MPs within the debris was recalculated. Of the polymers found in the stomachs, only those that matched the reference spectra by >50 % were accepted, and those MP that matched the reference spectra between 50 and 70 % were further evaluated by an experienced researcher. It was decided to choose this apparently low threshold because the candidate MPs, after having been previously digested and subjected to various processes, showed a considerably high rate of impurities in their surfaces.

2.5. Quality assurance/quality control (QA/QC) protocol

A comprehensive QA/QC protocol was rigorously adhered to throughout the isolation process of plastics, from the initial dissection to the final extraction from the glass filter. To monitor and mitigate potential environmental contamination with MPs during dissections, an open Petri dish containing filter paper was kept in place throughout the process. This dish was replaced after every 10 dissections, with each new dish properly labelled with the corresponding dissection number. Additionally, to control potential contamination from MPs potentially emanating from the heating apparatus, a separate beaker containing 200 mL of water (H_2O) and 50 mL of hydrogen peroxide (H_2O_2) was positioned within the heating unit. This control beaker was systematically replaced after every 10 incubation cycles. During the sample filtration process, an open Petri dish with a filter was consistently used to correct for potential bias from airborne MPs. This step was conducted within a positive laminar flow cabinet to further minimize the entry and exit of airborne contaminants or MPs into the samples. Furthermore, throughout the period when the glass filter plate was open for the identification of potential MPs, another Petri dish with an open filter was actively maintained to measure the concentration of ambient MPs. This dish was replaced after every 10 samples analysed to ensure continual accuracy in ambient contamination assessment. These measures were essential in minimizing contamination and ensuring the reliability of the study's findings on MP pollution.

2.6. Control correction

The blank samples underwent analysis, and the quantity of MPs identified and confirmed by μFTIR was as follows: dissection blanks ($\bar{x}$ = 0.66 particle per control), stove blanks ($\bar{x}$ = 0.87 particles per control), and stereomicroscope blanks ($\bar{x}$ = 1.25 particles per control).

In summary, it was determined that the potential error due to contamination was 0.95 MPs per 10 samples (0.095 MP per stomach). Given the small quantity of the control data, the bias was deemed insignificant and therefore negligible.

2.7. Statistical analyses

To test if the amounts of plastic (Total particles = TP; microplastic particles = MP and macroplastic particles = MaP) were related to diet, we carried out generalized linear models (GLMs) with Poisson distribution for count data (O'Hara and Kotze, 2010), through the function "glm" in the R package "lmerTest" (Kuznetsova et al., 2017). In the case of the number of MaPs, we corrected for over dispersion of the data by applying zero-inflated Poisson (ZIP) models to correct for multiple presence of zero values in the data (Campbell, 2021) through the function "zeroinfl" in the R package "pscl" (Jackman et al., 2015). Zero inflated models consist of two parts: (1) a zero inflated model that includes all values including zeros, which models the probability of

Table 2
Stomach content of yellow-legged gull chicks from the city of Barcelona in 2023. FO% = frequency of occurrence of each Prey. N% = contribution by number of each prey in the stomachs.

Prey	%FO	%N
MARINE PREY	67.86	68.14
Demersal prey	53.57	46.02
Microchirus variegatus	1.79	0.86
Diplodus vulgaris	3.57	1.77
Pagellus acarne	1.79	4.43
Micromesistius poutassou	1.79	1.77
Pomadasys incisus	1.79	1.77
Macrouridae	1.79	0.88
Boops boops	48.21	34.51
Pelagic prey	19.64	13.27
Trachurus sp.	12.5	8.85
Spicara smaris	3.57	1.77
Sparidae	1.79	0.88
Gadiculus argenteus	3.57	1.77
Other marine prey	12.5	7.05
Shell	1.79	0.88
Crustacean marine	10.71	5.31
Bivalve	1.79	0.86
Unidentified fish	3.57	1.77
TERRESTIAL PREY	57.14	30.1
Columba livia	57.14	28.32
Unidentified bird	1.79	0.89
Unidentified mammal	1.79	0.89
GARBAGE	3.57	1.77

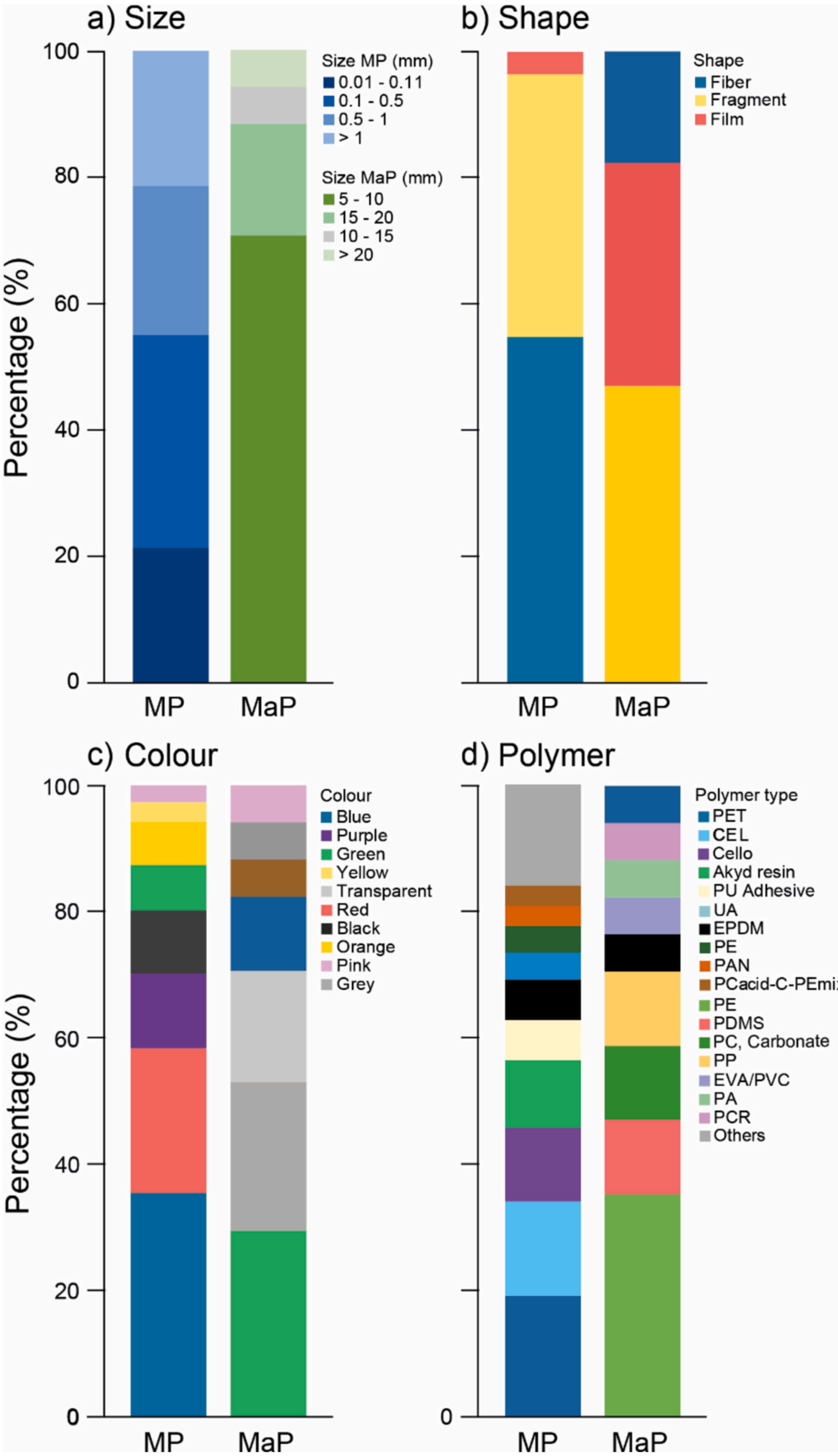

Fig. 3. Diversity in size (A), shape (B), colour (C), and type of polymer (D) of the microplastics (MP) and macroplastics (MaP) found in the stomachs of yellow-legged gulls chicks sampled in the city of Barcelona in 2023. Other polymers are reported in Table S1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

excessive zeros, and a (2) count model that excludes zero values, accounting for non-zero counts (Lambert, 1992; Loeys et al., 2012).

We included the following explanatory variables for plastic abundance: (1) body mass (BM), (2) diet diversity (DD), (3) $\delta^{13}C$ values and (4) $\delta^{15}N$ values. To assess the best combinations of predictors affecting plastic abundance we used a model comparison approach and used AIC for model selection (Chakrabarti and Ghosh, 2011; Table S2). We evaluated the goodness of the fit of the model using pseudo-R^2 and R^2 (Table S3) as recommended for ZIP and GLM models, respectively (Nakagawa and Schielzeth, 2013). All statistical analyses were performed in RStudio version 4.3.1.

3. Results

3.1. MPs and MaPs

We found MPs in all the 56 stomachs analysed (FO% = 100 %; total MP items = 258; mean ± standard deviation = 4.61 ± 2.71 MPs/stomach; median = 4; 95 % CI = 3.8–5.3) and MaPs in 11 (FO% = 19.64 %; total MaPs items = 17; mean ± standard deviation =0.31 ± 0.47 MaPs/stomach; median = 0; 95 % CI = 0.11–0.59) (Table 1).

Regarding MPs, out of the 403 potential MP particles initially selected, 258 (64.02 %) were confirmed as MPs, while 145 were discarded. Among those confirmed, their size ranged from 0.02 mm to 4.94 mm, with a mean ± standard deviation of 0.62 ± 0.86 mm (Table 2, Fig. 3A). All the different types of particles were secondary MPs, but they were unevenly distributed, with the proportion of fibres (54.65 %) and fragments (41.47 %) being more abundant than films (3.49 %) or spheres (0.4 %) (Fig. 3A). The overall colour distribution revealed a prevalence of blue (36.05 %), red (23.26 %), and purple (12.01 %) particles (Fig. 3A). Concerning MP polymer type, 22 different classes of synthetic materials were identified (Figs. 3A and S1). The most abundant polymers were polyethylene terephthalate (PET) (19.15 %), followed by cellulose (CEL), cellophane (Cello), and alkyd resins (14.89 % and 11.7 %, 10.64 % respectively). Other polymers found in the stomachs with a frequency below 10 % were polyurethane (PU) adhesive, urethane alkyd (UA), polyethylene propylenediene (EPDM), polyethylene (PE), poly(acrylonitrile), and polycarbonic acid, Carbonate, polyethylenemix (PC acid C PEmix).

Regarding MaPs, 39 potential MaP particles were initially detected. However, only 17 (43.59 %) were confirmed to be plastics. As shown in Fig. 3B, the most common size range for these MaPs was between 5 and 10 mm (70.59 %) (Fig. 3B). The shape distribution was quite varied, with fragments being the most prevalent (47.1 %), followed by films (35.29 %) and fibres (17.65 %). No spheres were found in this study (Fig. 3B). The most common colours observed were green (29.41 %), transparent (23.53 %), and black (17.65 %) (Fig. 3B). The most prominent polymers identified were poly(ethylene) (PE) (35.29 %), followed by poly(dimethylsiloxane) (PDMS), polycarbonic acid-carbonate-polyethylene (PC-Carbonate-PE), polypropylene (PP) (all with a frequency of 11.76 %). The rest of polymers, all of them with a frequency of 5.88 %, were poly(ethylene propylenediene) (EPDM), poly(ethylene:vinyl acetate+vinyl chloride) (EVA/PVC), polyamide (PA), polycarbonate resin (PCR), and PET (Fig. 3B).

3.2. Diet

Based on the stomach content we found that the 68.14 % were marine prey and 30.1 % were terrestrial prey, and other terrestrial resources, such as garbage and mammals, were found in very small quantities (Table 2). Bogue (*Boops boops*) was the main species, followed by urban birds, almost all of which were pigeons (*Columba livia)*. This variety in the frequency of occurrence and the total quantification of the diet is reflected through Shannon's entropy (H(FO) = 2.48; H(N) = 1.59). Stable isotope values of δ^{13}C ranged from −19.38 to −23.37 (mean ± standard deviation = −20.49 ± 0.77), while the δ^{15}N values ranged from 8.02 to 11.42 (mean ± standard deviation = 9.88 ± 0.59).

3.3. Relationships between plastic and diet

The zero-inflated model showed a significant effect of body mass, diet diversity and δ^{13}C values on MaP abundance (Fig. 4, Table S4). The coefficients of the zero-inflated model showed that the abundance of MaPs in the stomach decreased with increasing body mass and increased with diet diversity and δ^{13}C values. When zero values were excluded, δ^{13}C values remained significant for the count data (Table S4). In contrast, no significant relationships were found between these variables and the abundance of MPs and total plastics (TP) (Table S4).

4. Discussion

In this study, we examined MP and MaP ingestion by urban gull chicks in the city of Barcelona. MPs were detected in all gull stomachs, whereas MaPs were found in fewer cases. This discrepancy may be explained by the fragmentation of ingested MaPs into smaller particles through digestion or external physical and mechanical processes unrelated to the gulls, eventually transforming into secondary MPs (Cole et al., 2011). Additionally, gulls, like other seabirds, often regurgitate indigestible food as pellets, particularly when disturbed (Barrett et al., 2007; Yorio et al., 2020), but also when adults feed the chicks as in this case. Thus, the difference in the presence of MPs and MaPs may also be due to the regurgitation of plastics as indigestible material.

4.1. Plastic characteristics

Blue microfibers ranging from 0.1 to 0.5 mm were the most abundant MPs identified, while green and transparent fragments measuring 5 to 10 mm predominated among the MaPs. Several studies (Codina-García et al., 2013; Taurozzi and Scalici, 2024) on MPs in seabirds have found that fragments are the most common type of MP in a wide variety of environments. Taurozzi and Scalici (2024) suggested that the type of MP

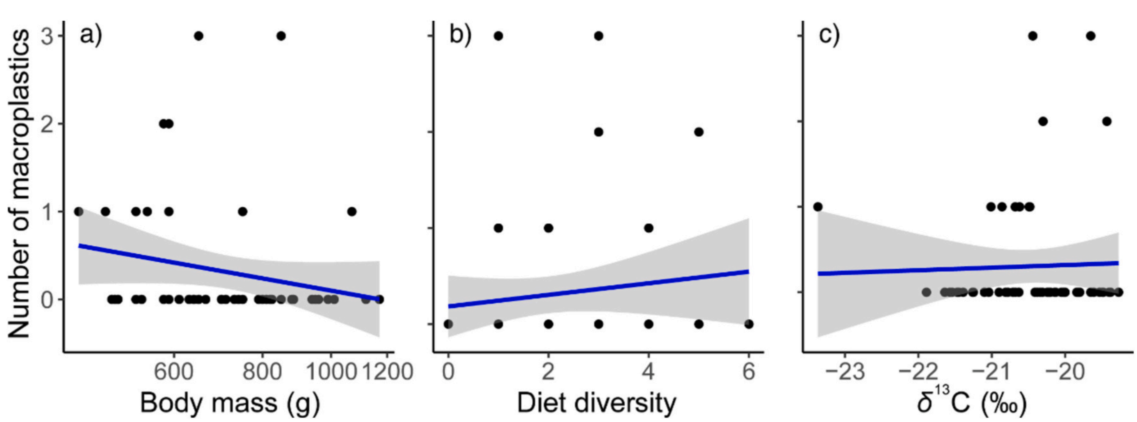

Fig. 4. Relationship between number of macroplastics and (A) body mass (g) in logarithmic scale, (B) diet diversity (number of prey) and (C) δ^{13}C values (‰). The black dots show the individual data, and the red line represents the trend fitted by linear regression. The grey shading around the red line indicates the 95 % confidence interval of the regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

detected might be biased depending on the method used for collection, being fibres more commonly found when analysing pellets, as their fine and flexible structure makes them more likely to be regurgitated by birds. However, our study contradicts this theory, as we found that fibres were the most common type of MP, despite employing stomach content analysis. This finding aligns with studies on yellow-legged gulls by Essoufi et al. (2024) and Lopes et al. (2021).

In terms of colour, the most abundant MPs identified in the present study were blue and red, while green and transparent were the predominant colours for MaPs. This characteristic varies considerably across different studies and does not appear to follow any specific pattern. However, our results, which indicate that blue is the most frequent colour, align with the findings of Gago et al. (2018), which noted that blue microfibers are the most common colour found in seawater (68 % of the diet had a marine origin). Furthermore, blue is widely used in various industries, such as textiles. Other studies indicate a clear predominance of dark MPs, leading to the hypothesis that they may be mistaken for natural elements present in the foraging areas exploited by seabirds (Codina-García et al., 2013; Essoufi et al., 2024). Specifically, as mentioned in Essoufi et al. (2024), the blue colour may resemble that of the water column, making it likely to be ingested when mistaken for food or nesting material (Lopes et al., 2020). It is also important to note that the MPs found could be secondary MPs, originally larger particles that have fragmented over time.

The most common polymer identified in this study was PET, which is widely used in the packaging industry, particularly for bottles and beverages (Nisticò, 2020). Balcells et al. (2023) revealed that the marine ecosystem close to Barcelona is severely polluted by plastics, particularly wet wipes, with an average concentration of 23.62 ± 6.49 kg km^{-2}. These wipes, often regarded as disposable despite being composed of PET fibres, are known to obstruct sewage treatment plants and systems. This obstruction results in the release of contaminated water directly into the sea without adequate filtration and purification, significantly contributing to persistent marine pollution from these materials (Pantoja Munoz et al., 2018; Morritt et al., 2014; Mitchell et al., 2017; Balcells et al., 2023). This finding may help explain the high concentration of PET fibres and polymers observed in our study. Cellulose and cellophane were the second and third most abundant polymers after PET, both of which are considered bioplastics (Steven et al., 2022). Cellulose, which is widely utilized for commercial purposes, is primarily sourced from cotton linters and wood pulp (Gilbert, 2017), particularly within the textile industry. Cellophane, a derivative of cellulose, is the predominant material used for food wrapping (Paunonen, 2013).

Regarding MaPs, the most prominent polymer identified was PE, which is the most produced plastic material by volume and has the highest tonnage among all plastics (Ronca, 2017). Its primary applications include packaging, films, bottles, bags, toys, and covering household appliances (Ghaffar et al., 2022). Other studies utilizing gulls as a model organism, such as those by Almeida et al. (2023, 2024), Martín-Vélez et al. (2024b) and Navarro et al. (2023), have also identified PE as the most prevalent polymer, accounting ranges from 45 %, to 70 % of the samples.

Given the high levels of plastics in the oceans mentioned earlier and the exposure of these birds to urban waste, this represents a significant indicator of plastic pollution in their feeding areas. Furthermore, this issue is particularly pronounced in Barcelona, where plastic pollution is increasing in urban areas (Galimany et al., 2023). Previous studies have demonstrated that the presence of plastics is closely related to human activity, with their abundance significantly increasing near coastal areas (Franco et al., 2019). Barcelona, a major contributor to plastic pollution in the Mediterranean (Liubartseva et al., 2018), ranks second among urban areas with a contribution of 1.8 %. Previous studies have revealed that 90 % of marine litter in Barcelona consists of plastic, with the city's port exhibiting the highest plastic density along the Catalan coast (Llorca et al., 2020; Liubartseva et al., 2018; Balcells et al., 2023). These findings underscore the significance of proximity in the accumulation of ocean debris and highlight the urgent need for more effective management of waste production and distribution in Barcelona.

4.2. Diet

The diet results indicate that yellow-legged gull chicks, like findings from the same population during the previous years (Méndez et al., 2020; Martín-Vélez et al., 2022; Vez-Garzón et al., 2023), were fed with a wide variety of prey, including both marine and terrestrial resources. Among specific prey, the most consumed was the fish bogue (N% = 34.51), followed by rock pigeon (N% = 28.32). One of the predictions of this study was that plastics primarily originate from the sea and coastal urban areas, which is supported by the dietary patterns we observed. The relationships between body mass and the abundance of MaPs suggest that the presence of MaPs may adversely affect the health of the chicks, leading to a decrease body size associated to potential damage originated by plastics (Charlton-Howard et al., 2023). On one hand, the correlation between δ^{13}C values and MaPs was positive, suggesting that a marine origin of the prey (reflected in higher δ^{13}C values, e.g. Diniz-Reis et al. (2022)) is associated with a higher presence of MaPs.

Regarding diet diversity, the results were consistent with other of our predictions: higher prey diversity is associated with a greater diversity of plastics. This suggests that MaPs may enter the food web indirectly through the consumption of prey with plastics by the adults and then transferred to chicks (with 80 % of the size smaller than 1 mm), although other fraction could be ingested accidentally when foraging. Previous studies already reported a high prevalence of MPs (fibres and fragments) in fish bogue *B. boops* (Garcia-Garin et al., 2019; Tsangaris et al., 2020; Bottari et al., 2022). However, no significant effects were found for MPs or total plastics, which was unexpected and may be attributed to a small sample size. Alternatively, other factors, such as the type of habitat used, the age of the breeding adults, or their foraging behaviour, which were not considered in this study, may influence the total amounts of these variables in gull stomachs.

5. Conclusions

Yellow-legged gull chicks have been confirmed to show a high prevalence of plastics and can act as potential sentinels of plastics, as their diet can be utilized to assess plastic pollution in coastal cities, mainly thanks to their position at the top of the food web, opportunistic behaviour, and omnivorous diet. Data on the accumulation of plastics in its stomach reveal the plastic pollution problem in Barcelona, confirming the yellow-legged gull's efficacy as a bioindicator for measuring plastic pollution in this urban marine ecosystem. However, the combination of other indicators (e.g. pellets, stomach content of adults, pollution sources) along with an increased sample size could be used for MaPs.

The presence of MPs and MaPs in the stomachs of the chicks could have harmful effects on their health, including body size reduction. The relationships observed between δ^{13}C values, the number of prey items, and MaPs suggest that the gull's diet is associated with the plastics present in their stomachs, potentially involving indirect ingestion via contaminated prey. As plastic pollution intensifies in coastal areas, gulls' exposure to anthropogenic materials correspondingly increases. This situation underscores the urgent need to reduce and improve waste management in coastal areas. To enhance understanding, further studies are needed to explore the origins of plastics and to obtain more representative data on the total diet of gulls, as well as to investigate the accumulation of plastics in these birds.

CRediT authorship contribution statement

Ana Max: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Victor Martín-Vélez:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Joan Navarro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Funding acquisition, Conceptualization. **Asunción Borrell:** Writing – review & editing, Funding acquisition. **Tomas Montalvo:** Writing – review & editing, Resources. **Odei Garcia-Garin:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Acknowledgements

This study is part of the Master thesis of AM, and is an output of the projects BCNGulls, Aliats and Intramural CSIC Project "Opportunistic gulls as sentinel species to monitor urban marine ecosystems". This study is a contribution of the ICM-TEF (Trophic Ecology Facility of the Institut de Ciències delMar—CSIC). VMV was supported by a Juan de la Cierva fellowship from the Spanish Government (JDC2022-049638-I). This work acknowledges the 'Severo Ochoa Centre of Excellence' accreditation (CEX2019-000928-S).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117409.

Data availability

Data will be made available on request.

References

Acampora, H., Newton, S., O'Connor, I., 2017. Opportunistic sampling to quantify plastics in the diet of unfledged black legged kittiwakes (Rissa tridactyla), northern fulmars (Fulmarus glacialis) and great cormorants (Phalacrocorax carbo). Mar. Pollut. Bull. 119 (2), 171–174.

Almeida, F.N., Leray, C., Boutry, J., Ter Halle, A., Vittecoq, M., Provencher, J.F., McCoy, K.D., 2023. Changes in plastic ingestion by yellow-legged gulls (*Larus michahellis*) over the breeding season. Mar. Pollut. Bull. 187, 114483.

Almeida, F.N., Leray, C., Souc, C., Scotto, S., Selmi, S., Hammouda, A., Ramos, R., ter Halle, A., McCoy, K.D., Vittecoq, M., 2024. Among-colony variation in plastic ingestion by yellow-legged gulls (*Larus michahellis*) across the western Mediterranean basin. Mar. Pollut. Bull. 204, 116508.

Anton, M., Vila, S.H., Garcia, D., Parareda, X.F., Cebrian, R. (Eds.), 2017. Atles dels ocells nidificants de Barcelona (Ajuntament de Barcelona / ICO / UB / Zoo).

Balcells, M., Blanco, M., Colmenero, A.I., Barría, C., Santos-Bethencourt, R., Nos, D., Lopez, C., Ribera, J., Sala, J., Garriga, M., Rojas, A., Galimany, E., 2023. Fishing for litter, accidental catch in bottom trawl nets along the Catalan coast, northwestern Mediterranean. Waste Manag. 166, 360–367.

Ballatore, A., Verhagen, T.J., Li, Z., Cucurachi, S., 2022. This city is not a bin: Crowdmapping the distribution of urban litter. J. Ind. Ecol. 26, 197–212.

Barrett, R.T., Camphuysen, K., Anker-Nilssen, T., Chardine, J.W., Furness, R.W., Garthe, S., Hüppop, O., Leopold, M.F., Montevecchi, W.A., Veit, R.R., 2007. Diet studies of seabirds: a review and recommendations. ICES J. Mar. Sci. 64, 1675–1691.

Basu, N., Scheuhammer, A.M., Bursian, S.J., Elliott, J., Rouvinen-Watt, K., Chan, H.M., 2007. Mink as a sentinel species in environmental health. Environ. Res. 103, 130–144.

Bottari, T., Mancuso, M., Pedà, C., De Domenico, F., Laface, F., Schirinzi, G.F., Romeo, T., 2022. Microplastics in the Bogue, Boops boops: a snapshot of the past from the southern Tyrrhenian Sea. J. Hazard. Mater. 424, 127669.

Campbell, H., 2021. The consequences of checking for zero-inflation and overdispersion in the analysis of count data. Methods Ecol. Evol. 12, 665–680.

Chakrabarti, A., Ghosh, J.K., 2011. AIC, BIC and recent advances in model selection. Philosophy of Statistics 583–605.

Charlton-Howard, H.S., Bond, A.L., Rivers-Auty, J., Lavers, J.L., 2023. 'Plasticosis': Characterising macro-and microplastic-associated fibrosis in seabird tissues. J. Hazard. Mater. 450, 131090.

Codina-García, M., Militão, T., Moreno, J., González-Solís, J., 2013. Plastic debris in Mediterranean seabirds. Mar. Pollut. Bull. 77, 220–226.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. MPs as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597.

Collard, F., Leconte, S., Danielsen, J., Halsband, C., Herzke, D., Harju, M., Tarroux, A., 2022. Plastic ingestion and associated additives in Faroe Islands chicks of the northern fulmar Fulmarus glacialis. Water Biology and Security 1 (4), 100079.

Critchell, K., Bauer-Civiello, A., Benham, C., Berry, K., Eagle, L., Hamann, M., Hussey, K., Ridgway, T., 2019. Plastic pollution in the coastal environment: current challenges and future solutions. Coasts and Estuaries 595–609.

Deoniziak, K., Cichowska, A., Niedźwiecki, S., Pol, W., 2022. Thrushes (Aves: Passeriformes) as indicators of microplastic pollution in terrestrial environments. Sci. Total Environ. 853, 158621.

Diniz-Reis, T.R., Augusto, F.G., Abdalla Filho, A.L., Araujo, M.G.D.S., Chaves, S.S.F., Almeida, R.F., Martinelli, L.A., 2022. SIA-BRA: a database of animal stable carbon and nitrogen isotope ratios of Brazil. Glob. Ecol. Biogeogr. 31 (4), 611–620.

Essoufi, C., Santini, S., Sforzi, L., Martellini, T., Chelazzi, D., Ayari, R., Hamdi, N., 2024. First evidence of MPs and their characterization in yellow-legged gull (*Larus michahellis michahellis*, Naumann, 1840) pellets collected from the Sfax salina, southeastern Tunisia. Mar. Pollut. Bull. 205, 116628.

Franco, J., Fort, J., García-Barón, I., Loubat, P., Louzao, M., Del Puerto, O., Zorita, I., 2019. Incidence of plastic ingestion in seabirds from the Bay of Biscay (southwestern Europe). Mar. Pollut. Bull. 146, 387–392.

Gago, J., Carretero, O., Filgueiras, A.V., Viñas, L., 2018. Synthetic microfibers in the marine environment: a review on their occurrence in seawater and sediments. Mar. Pollut. Bull. 127, 365–376.

Galimany, E., Navarro, J., Martino, I., Aymí, R., Cermeño, P., Montalvo, T., 2023. Gulls as potential sentinels for urban litter: combining nest and GPS-tracking information. Environ. Monit. Assess. 195, 521.

Garcia-Garin, O., Vighi, M., Aguilar, A., Tsangaris, C., Digka, N., Kaberi, H., Borrell, A., 2019. *Boops boops* as a bioindicator of microplastic pollution along the Spanish Catalan coast. Mar. Pollut. Bull. 149, 110648.

Geyer, R., 2020. Production, use, and fate of synthetic polymers. In: Plastic Waste and Recycling. Academic Press, pp. 13–32.

Ghaffar, I., Rashid, M., Akmal, M., Hussain, A., 2022. Plastics in the environment as potential threat to life: an overview. Environ. Sci. Pollut. Res. 29, 56928–56947.

Gilbert, M., 2017. Cellulose plastics. In: Brydson's Plastics Materials. Butterworth-Heinemann, pp. 617–630.

Idescat, 2019. Anuari estadístic de catalunya. In: *Pesca.* Institut d'Estadística de Catalunya. WorldCat, Barcelona. https://www.idescat.cat/pub/?id=aec&n=468.

Inger, R., Bearhop, S., 2008. Applications of stable isotope analyses to avian ecology. Ibis 150, 447–461.

Jackman, S., Tahk, A., Zeileis, A., Maimone, C., Fearon, J., Meers, Z., ... & Imports, M. A. S. S. (2015). Package 'pscl'. *Political Science Computational Laboratory*, *18* (04.2017).

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 8, 1–26.

Lambert, D., 1992. Zero-inflated Poisson regression, with an application to defects in manufacturing. Technometrics 34, 1–14.

Li, W.C., Tse, H.F., Fok, L., 2016. Plastic waste in the marine environment: a review of sources, occurrence and effects. Sci. Total Environ. 566, 333–349.

Liubartseva, S., Coppini, G., Lecci, R., Clementi, E., 2018. Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar. Pollut. Bull. 129, 151–162.

Llorca, M., Álvarez-Muñoz, D., Ábalos, M., Rodríguez-Mozaz, S., Santos, L.H., León, V.M., Farré, M., 2020. MPs in Mediterranean coastal area: toxicity and impact for the environment and human health. Trends in Environmental Analytical Chemistry 27, e00090.

Loeys, T., Moerkerke, B., De Smet, O., Buysse, A., 2012. The analysis of zero-inflated count data: beyond zero-inflated Poisson regression. Br. J. Math. Stat. Psychol. 65, 163–180.

Lombarte, A., Chic, Ò., Parisi-Baradad, V., Olivella, R., Piera, J., García-Ladona, E., 2006. A web-based environment for shape analysis of fish otoliths. The AFORO database. *Scientia Marina* 70, 147–152.

Lopes, C.S., de Faria, J.P., Paiva, V.H., Ramos, J.A., 2020. Characterization of anthropogenic materials on yellow-legged gull (*Larus michahellis*) nests breeding in natural and urban sites along the coast of Portugal. Environ. Sci. Pollut. Res. 27, 36954–36969.

Lopes, C.S., Paiva, V.H., Vaz, P.T., Pais de Faria, J., Calado, J.G., Pereira, J.M., Ramos, J. A., 2021. Ingestion of anthropogenic materials by yellow-legged gulls (*Larus michahellis*) in natural, urban, and landfill sites along Portugal in relation to diet composition. Environ. Sci. Pollut. Res. 28, 19046–19063.

Lopes, C.S., Antunes, R.C., Paiva, V.H., Gonçalves, A.M., Correia, J.J., Ramos, J.A., 2022. Fatty acids composition in yellow-legged (*Larus michahellis*) and lesser black-backed (*Larus fuscus*) gulls from natural and urban habitats in relation to the ingestion of anthropogenic materials. Sci. Total Environ. 809, 151093.

Lusher, A.L., Hernandez-Milian, G., 2018. Microplastic extraction from marine vertebrate digestive tracts Regurgitates and Scats: A Protocol for Researchers from All Experience Levels. Bio-protocol 8 (22).

Lusher, A.L., Bråte, I.L.N., Munno, K., Hurley, R.R., Welden, N.A., 2020. Is it or Isn't it: the importance of visual classification in microplastic characterization. Appl. Spectrosc. 74, 1139–1153.

Martín-Vélez, V., Montalvo, T., Afán, I., Sánchez-Márquez, A., Aymí, R., Figuerola, J., Navarro, J., 2022. Gulls living in cities as overlooked seed dispersers within and outside urban environments. Sci. Total Environ. 823, 153535.

Martín-Vélez, V., Domingo, J., Cardador, L., Montalvo, T., Navarro, J., 2024a. Unravelling urban nesting site selection in an opportunistic gull: an integrated analysis of micro-spatial habitat and litter quantification. Eur. J. Wildl. Res. 70, a69.

Martín-Vélez, V., Cano-Povedano, J., Canuelo-Jurado, B., López-Calderón, C., Céspedes, V., Ros, M., Sánchez, M.I., Shamoun-Baranes, J., Müller, W., Thaxter, C.B.,

Camphuysen, C.J., Cózar, A., Green, A.J., 2024b. Leakage of plastics and other debris from landfills to a highly protected lake by wintering gulls. Waste Manag. 177, 13–23.
Méndez, A., Montalvo, T., Aymí, R., Carmona, M., Figuerola, J., Navarro, J., 2020. Adapting to urban ecosystems: unravelling the foraging ecology of an opportunistic predator living in cities. Urban Ecosyst. 23, 1117–1126.
Mitchell, R.L., Thamsen, P.U., Gunkel, M., Waschnewski, J., 2017. Investigations into wastewater composition focusing on nonwoven wet wipes. Technical Transactions 114, 125–135.
Moreira-Mendieta, A., Garcia-Garin, O., Muñoz-Pérez, J.P., Urquía, D.O., Drago, M., Borrell, A., Páez-Rosas, D., 2023. Detection and quantification of microplastic pollution in the endangered Galapagos Sea lion. Sci. Total Environ. 896, 166223.
Morritt, D., Stefanoudis, P.V., Pearce, D., Crimmen, O.A., Clark, P.F., 2014. Plastic in the Thames: a river runs through it. Mar. Pollut. Bull. 78, 196–200.
Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution 4, 133–142.
Navarro, A., Luzardo, O.P., Gómez, M., Acosta-Dacal, A., Martínez, I., de la Rosa, J.F., Macías-Montes, A., Suárez-Pérez, A., Herrera, A., 2023. MPs ingestion and chemical pollutants in seabirds of gran Canaria (Canary Islands, Spain). Mar. Pollut. Bull. 186, 114434.
Nisticò, R., 2020. Polyethylene terephthalate (PET) in the packaging industry. Polym. Test. 90, 106707.
Nos, D., Montalvo, T., Cortés-Francisco, N., Figuerola, J., Aymí, R., Giménez, J., Solé, M., Navarro, J., 2024. Sources of persistent organic pollutants and their physiological effects on opportunistic urban gulls. J. Hazard. Mater. 465, 133129.
O'Hara, R., Kotze, J., 2010. Do not log-transform count data. Nature Precedings 1.
Olmo-Gilabert, R., Fagiano, V., Alomar, C., Rios-Fuster, B., Compa, M., Deudero, S., 2024. Plastic webs, the new food: dynamics of MPs in a Mediterranean food web, key species as pollution sources and receptors. Sci. Total Environ. 198, 170719.
Pantoja Munoz, L., Gonzalez Baez, A., McKinney, D., Garelick, H., 2018. Characterisation of "flushable" and "non-flushable" commercial wet wipes using microRaman, FTIR spectroscopy and fluorescence microscopy: to flush or not to flush. Environ. Sci. Pollut. Res. 25, 20268–20279.
Paunonen, S.I., 2013. Strength and Barrier Enhancements of Cellophane and Cellulose Derivative Films: A Review.
Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Rebolledo, E.L.B., Hammer, S., Van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods 9 (9), 1454–1469.
Ronca, S., 2017. Polyethylene. In: Brydson's Plastics Materials. Butterworth-Heinemann, pp. 247–278.
Seif, S., Provencher, J.F., Avery-Gomm, S., Daoust, P.Y., Mallory, M.L., Smith, P.A., 2018. Plastic and non-plastic debris ingestion in three gull species feeding in an urban landfill environment. Arch. Environ. Contam. Toxicol. 74 (3), 349–360.
Steven, S., Fauza, A.N., Mardiyati, Y., Santosa, S.P., Shoimah, S.M.A., 2022. Facile preparation of cellulose bioplastic from Cladophora sp. algae via hydrogel method. Polymers 14 (21), 4699.
Taurozzi, D., Scalici, M., 2024. Seabirds from the poles: MPs pollution sentinels. Front. Mar. Sci. 11, 1343617.
Tsangaris, C., Digka, N., Valente, T., Aguilar, A., Borrell, A., de Lucia, G.A., Gambaiani, D., Garcia-Garin, O., Kaberi, H., Martin, J., Mauriño, E., Miaud, C., Palazzo, L., del Olmo, A.P., Raga, J.A., Sbrana, A., Silvestri, C., Skylaki, E., Vighi, M., Matiddi, M., 2020. Using *Boops boops* (osteichthyes) to assess microplastic ingestion in the Mediterranean Sea. Mar. Pollut. Bull. 158, 111397. https://doi.org/10.1016/j.marpolbul.2020.111397.
Tuset, V.M., Lombarte, A., Assis, C.A., 2008. Otolith atlas for the western Mediterranean, north and central eastern Atlantic. Sci. Mar. 72, 7–198.
Van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Turner, D.M., 2011. Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea. Environ. Pollut. 159 (10), 2609–2615.
Vez-Garzón, M., Giménez, J., Sánchez-Márquez, A., Montalvo, T., Navarro, J., 2023. Changes in the feeding ecology of an opportunistic predator inhabiting urban environments in response to COVID-19 lockdown. R. Soc. Open Sci. 10, 221639.
Yorio, P., Marinao, C., Kasinsky, T., Ibarra, C., Suárez, N., 2020. Patterns of plastic ingestion in kelp Gull (*Larus dominicanus*) populations breeding in northern Patagonia. Argentina. Marine Pollution Bulletin 156, 111240.