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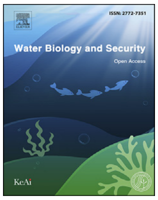

Plastic ingestion and associated additives in Faroe Islands chicks of the Northern Fulmar *Fulmarus glacialis*

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ABSTRACT

Northern Fulmars (*Fulmarus glacialis*) are a pelagic seabird species distributed at northern and polar latitudes. They are often used as an indicator of plastic pollution in the North Sea region, but data are lacking from higher latitudes, especially when it comes to chicks. Here, we investigated amounts of ingested plastic and their characteristics in fulmar chicks from the Faroe Islands. Plastic particles ($\geq$1 mm) in chicks of two age classes were searched using a digestion method with KOH. In addition, to evaluate if additive tissue burden reflects plastic ingestion, we measured liver tissue concentrations of two pollutant classes associated with plastic materials: polybrominated diphenyl ethers (PBDEs) and several dechloranes, using gas chromatography with high-resolution mass spectrometry. The most common shape was hard fragment (81%) and the most common polymer was polyethylene (73%). Plastic contamination did not differ between either age class, and we found no correlation between neither the amount and mass of plastic particles and the concentration of additives. After comparison with previous studies on adult fulmars, we do not recommend using chicks for biomonitoring adults because chicks seem to ingest more plastics than adults.

1. Introduction

Plastic pollution occurs in both abiotic and biotic compartments of ecosystems, even in remote regions such as the Arctic (Bergmann et al., 2022; Collard and Ask, 2021; Mishra et al., 2021) as determined by the Conservation of Arctic Flora and Fauna (CAFF, Irons et al., 2015). Data on plastics collected at the ocean's surface indicate that some of these plastics arrived in the Arctic after a long period at sea, and some studies have suggested that a significant, though unquantified, fraction came from sources located up to several thousands of kilometers away (Cózar et al., 2017; Lusher et al., 2015). Plastics in the Arctic can also originate from various marine and local activities such as discharges from fisheries, ship traffic, oil and gas exploration, aquaculture, or tourism (Grøsvik et al., 2018). Arctic organisms could become more exposed to plastic debris in the future because of the expected impacts of climate change in polar regions. For example, the Arctic sea ice contains microplastics ($\leq$5 mm, Arthur et al., 2009) and can act as a temporary sink for plastic (Obbard et al., 2014; Peeken et al., 2018) but higher temperatures will lead to further melting of Arctic sea ice, thereby releasing microplastics into sea water. In addition, the melting of the sea ice will open new routes for maritime traffic, likely releasing more plastic particles into the marine environment (e.g. Bergmann et al., 2022).

Plastics are assumed to enter the European Arctic from regions further south with marine currents through the passage between Scotland and Iceland (Cózar et al., 2017). In that passage, the Faroe Islands (hereafter the Faroes) are part of the connection between Arctic and Atlantic regions, and marine ecosystems around the Faroes could be more exposed to plastic pollution because of their location. In addition, there are major fisheries in Faroese waters (Taconet et al., 2019) and they are close to a major fishery around Iceland (Halsband and Herzke, 2019), which can generate vast amounts of plastic waste, as recorded in the Barents Sea (Grøsvik et al., 2018; Novikov et al., 2021). Given the geographic position of the Faroes between the Arctic and the Atlantic and the high exposure to plastic pollution organisms can undergo there, those islands

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constitute a useful area to study plastic pollution. Among those organisms, the fulmar is of particular interest because their fledglings are eaten by Faroese humans (Svanberg, 2021). Consequently, assessing plastic burdens and plastic additive levels in Faroese fulmars and understanding the role of plastic ingestion in the occurrence of those additives is of interest for fulmar and human health reasons. Given this, the Faroes constitute an area worthy of investigation in the frame of plastic pollution.

In the Arctic, the ingestion of plastic has been reported in several species ranging from the small amphipod *Gammarus setosus* to the large polar bear *Ursus maritimus* (Collard and Ask, 2021). Seabird species are particularly affected by marine debris and plastic pollution is a major threat for them, because larger loads of marine plastics in the gastro-intestinal tract can lead to gut obstruction and reduction of body condition and consequently to higher mortality rates (Roman et al., 2019; Wilcox et al., 2015). The frequency of occurrence of plastics can differ among seabirds in a given area. For example, in the Arctic, fulmars have a higher frequency of occurrence of ingested plastic pieces than Black-legged Kittiwakes (*Rissa tridactyla*), Thick-billed Murres (*Uria lomvia*) and Black Guillemots (*Cepphus grylle*) (Baak et al., 2020b). Two ecological and morphological features help explain why fulmars exhibit higher levels of ingested plastics than other species. (1) The opening between the proventriculus and the gizzard is narrow, preventing the fulmars from regurgitating the gizzard content where hard particles accumulate. (2) They feed at the sea surface, where floating plastics are found (Provencher et al., 2014). The first report of plastic ingestion by fulmars was made in Scotland (Furness, 1985) but studies about plastic ingestion by fulmars come mostly from Canada and the North Sea (e.g. Collard and Ask, 2021; Poon et al., 2017; van Franeker et al., 2021). In 2008, the fulmar was proposed as an indicator species of marine plastic debris by the Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) and a long-term threshold for the fulmar Ecological Quality Objective (EcoQO) in the North Sea was defined: “There should be less than 10% of northern fulmars (*Fulmarus glacialis*) having more than 0.1 g of plastic particles in the stomach of 50–100 beach-washed fulmars from each of 4–5 areas of the North Sea over a period of at least five years” (OSPAR, 2008; OSPAR Commission London, 2010). However, this EcoQO is not well-grounded scientifically because of a lack of data that can be used to determine a quantity at which negative effects can be observed for fulmars and other ecosystem components (van Franeker et al., 2011). A study on fulmars from the Faroes showed that 90% of the birds had plastic in their stomachs and 40% of those exceeded the EcoQO defined by van Franeker et al. (2021).

The consequences of plastic ingestion are not well known, especially in Arctic marine organisms (Halsband and Herzke, 2019). Regarding fulmars, both toxicological and physical impacts are suspected to occur. Because of their gizzard morphology, Procellariiformes have a higher risk of obstruction (Furness, 1985). Thus, dozens of plastic items trapped in the gizzard could affect digestion, although this has not been studied in wild seabirds (Collard and Ask, 2021). Plastics may have many embedded chemicals and there is evidence that they can adsorb toxic pollutants from the surrounding water, thus potentially enhancing the bioaccumulation of contaminants along the food web by ingestion (Teuten et al., 2007, 2009; Hale et al., 2010). Polybrominated diphenyl ethers (PBDEs) and dechloranes are two groups of organic pollutants used as flame retardants in several commonly-used products such as in textiles, electronic devices, or plastics among others (Betts et al., 2006; Chen and Hale, 2010; World Health Organization, 2006). PBDEs are found in all environmental compartments in Europe including the atmosphere, sediment and biota (Law et al., 2006). Birds, particularly, can be highly polluted by PBDEs, sometimes more than top predators (Chen and Hale, 2010). PBDEs are known to modify gene expression and alter thyroid functions and behavior (e.g. Guigueno and Fernie, 2017; Mortensen et al., 2022). In fulmars, PBDEs have been found in eggs, juveniles, and adults (Fängström et al., 2005). In addition, high plastic levels have been related to high levels of the congener BDE209 (Neumann et al., 2021). Dechlorane Plus (DP) and dechloranes 602, 603, 604 have been used since the 1978 ban of dechlorane in the United States because of its toxicity (Feo et al., 2012). As with PBDEs, dechloranes have been found in the environment (Sverko et al., 2011) and have also been detected in the Arctic biota, including seabirds (e.g. AMAP, 2017; Verreault et al., 2018). To our knowledge, only two field studies reported the occurrence of dechloranes in fulmars (Mortensen et al., 2022; Sühring et al., 2022), the first one suggesting an association between DP occurrence and physiological and hormonal alterations (Mortensen et al., 2022) and the second one showing non-detectable levels of DP isomers in the liver.

Although plastic ingestion by fulmars has been studied for decades in some regions, two important knowledge gaps remain. (1) What is the plastic burden in the intestine, particularly for early life stages? (2) What is the link between plastic burden and associated additives in liver tissue? Our main goal was to help fill those gaps in three ways. (1) Measure and report the quantity (number and mass) and relative frequency of occurrence of ingested plastics in fulmar chicks of two age classes. (2) Provide data for both the intestine and stomach contents, the former being usually ignored in similar studies. (3) Determine the correlation between plastic burden and both dechloranes and PBDEs concentrations in fulmar livers. Thus, our study provides new data on fulmar chicks for monitoring plastic pollution in northern regions and will help us understand the potential links between plastic ingestion and associated additives in a species consumed by humans.

2. Materials and methods

2.1. Bird specimens

In summer 2020, 10 living two-week old chicks and 10 living six-week old chicks (hereafter young and old chicks, respectively, Table 1 & Table S1) were collected in Stóra Dímun, Faroes (61.70°N; −6.75°E), and stored at −20 °C until further processing.

2.2. Fulmar dissection and extraction of plastic particles

All birds were dissected following van Franeker (2004) for monitoring plastic ingestion by fulmars, and the gastrointestinal tract was collected with its contents. The intestine and the stomach (proventriculus and gizzard) were then separated, and the contents from each was immersed in a solution of 10% KOH with a volume ratio 1:3 (tissue:KOH) (Rochman et al., 2015).

Samples were shaken using a low-profile laboratory shaker (IKA HS 501 digital, Staufen, Germany) at 100 rpm. After 2 days, the solutions were sieved (20 μm). The retained particles were rinsed with milliQ water and poured into a filtration unit. That mixture was then vacuum-filtered (5 μm acetate cellulose membrane). Only particles larger than 1 mm (OSPAR guidelines, OSPAR, 2008) were analyzed by spectroscopy and included in our study.

2.3. Identification of plastic polymers

All collected particles were analyzed except for gastrolith-like particles when the number per individual was >50. In this case, particles were

Table 1
Averaged biometric measurements of the collected fulmar chicks per age class, with standard deviation.

Age class	Body mass (g)	Wing length (cm)	Culmen length (cm)	Head + bill length (cm)	Gonys length (cm)
Young (*n* = 10)	291.7 ± 84.0	4.8 ± 0.9	2.5 ± 0.2	6.4 ± 0.6	1.1 ± 0.1
Old (*n* = 10)	869.8 ± 236.8	17.7 ± 4.0	3.4 ± 0.3	8.7 ± 0.7	1.4 ± 0.1
All (*n* = 20)	580.7 ± 339.3	11.3 ± 7.1	2.9 ± 0.5	7.5 ± 1.3	1.3 ± 0.2

pooled and a 10% subsample was randomly chosen for analysis. The polymer identification procedure was adapted from Neumann et al. (2021). Identifications were performed using the Fourier Transform Infrared (FTIR) Spectrometry technique (infrared spectrometer Cary 630 with Diamond Attenuated total reflectance (ATR), Agilent technology, Santa Clara, US) in the Norwegian Institute of Air Research (NILU). The windows for detection of spectra were set between 4000 and 650 cm^{-1} and resolution was set at 8 cm^{-1}. Between each particle analysis, the diamond crystal was cleaned and scans were collected to adjust for background noise. The obtained spectra were compared to a modified ATR Demo reference library at NILU. Matches were ranked from 0 to 1 (Hit Quality Index), a particle was identified if its score was $\geq$0.7. If a satisfying match could not be obtained, the particle was sliced and its spectrum was determined a second time. If the second match did not reach 0.7, the particle was classified as "Undetermined". Each particle was then classified as either plastic, gastrolith, or other.

2.4. *Characteristics of plastic particles*

The plastic particles were sorted using the 'Save the North Sea' protocol into industrial (pellet) and user (fragment, thread, sheet, foamed (van Franeker, 2004);). The particles were placed on a millimeter-gridded paper and photographed (Canon 500D, Tokyo, Japan) before their identification by FTIR. Size measurements of plastic particles were performed (using Image J: v1.52). As recommended by Hartmann et al. (2019), only the largest dimension was measured. Plastics were assigned to one of eight color groups recommended by Provencher et al. (2017): off/white–clear; grey–silver; black; blue–purple; green; orange–brown; red–pink, or yellow. The plastic particles were weighed per polymer and per individual. Industrial and user plastics were separately weighed. The gastroliths and other particles were weighed per individual (Quintix64-1S, Sartorius AG, Göttingen, Germany).

2.5. *Preventing and quantifying contamination by plastic particles*

Although our study was limited to particles visible with the naked eye -which are less prone to originate from the contamination of the working environment-our samples were treated with precaution from the perspective of investigating smaller particles (<1 mm) in the future. Therefore, each step, from the dissection of the birds until the selection of particles for identification, was performed to prevent any microplastic cross-contamination.

To reduce airborne contamination, all laboratory work was performed under a fume hood. Glassware and dissection tools were scrupulously washed using filtered milliQ water. Three times during the dissection period, procedural blanks were made for the two sample types (stomach and intestine). None of them contained any particle >1 mm. All the filtering membranes, including blanks, were retained for future studies of smaller microplastic particles.

2.6. *Associated additives*

We used methods for determining additives associated with plastics modified from Carlsson et al. (2014) and Herzke et al. (2016).

2.6.1. *Isotopic dilution*

Liver and plastic samples were spiked with an internal standard (IS) including ^{13}C labeled PBDEs −28, −47, −99, −153, −183, −197, −206 and −209 and ^{13}C labeled Dechlorane Plus syn and Dechlorane 602 prior to extraction (Cambridge Isotope Laboratory; CIL, Tewksbury, MA, USA).

2.6.2. *Liver samples*

Two grams of liver tissue were homogenized with pre-treated sodium sulphate (600C, 8h) (Merck, Darmstadt Germany) and extracted three times with 40 ml, 30 ml, and 30 ml cyclohexane: acetone mixtures (ratio 3:1) in an ultrasonic water bath for 10 min. The extract was concentrated in an RapidVap evaporation vacuum system (labconco, MO, USA) until they were dry and an aliquot of the extract was used for lipid determination. Samples were cleaned-up and fractionated using the EZprep 123 sample prep system (Fluid Management Systems; FMS, Billerica, MA, USA) and the prepacked 0.5 g fat removal kit with 6 g acidic silica column connected to a 4 g basic aluminum oxide column. The column set was washed with 20 ml of n-hexane and then samples were loaded with 10 ml of n-hexane and eluted with 150 ml of n-hexane. The basic aluminum oxide column was reversed and eluted with 50 ml dichloromethane, which was collected and evaporated. ^{13}C PCB159 was used as a recovery standard.

2.6.3. *Instrumental analysis*

Liver samples were analyzed for a suite of PBDEs (17, 28, 47, 49, 66, 71, 77, 85 99, 100, 119, 126, 138, 153, 154, 156, 183, 184, 191, 196, 197, 202 206, 207 and 209) (Wellington laboratories, Ontario, Canada and CIL, Andover, U.S.A.) and Dechlorane Plus (syn and anti) and Dechloranes 602, 603, 604 (CIL, MA, USA). For analyte detection, we used gas chromatography with high-resolution accurate mass spectrometry (GC-HRAM) (TRACE 1310-Q ExactiveTM GC OrbitrapTM, Thermo Fisher Scientific, Waltham, MA, USA). The GC-HRAM was equipped with a 15 m RTx 1614 MS column (0.25 μm id and 0.1 μm film thickness, Restek Corp, Bellefonte, PA, USA). Helium was used as a carrier gas at a flow rate of 1.6 mL/min. More information regarding the method can be found in Carlsson et al. (2014) and Herzke et al. (2016).

2.6.4. *Quality assurance*

All glassware was initially burnt at 450 °C for 8 h and rinsed with n-hexane and acetone. For each sample, new equipment was used to avoid cross-contamination. Laboratory tools were rinsed in acetone and cyclohexane in an ultrasonic water bath. In addition, sample preparation was carried out in a laminar flow clean cabinet (Bigneat Ltd. Waterlooville, Hampshire, UK).

For a batch of 10 liver samples, two laboratory blanks and standard reference materials (SRMs) were analyzed for quality control of the method. WMF-03 freeze-dried fish tissue (Wellington laboratories Inc., Ontario, Canada) was used as reference material.

The limit of detection (LOD) was set at average blank level + 3 x standard deviation for each congener and the limit of quantification (LOQ) was calculated as average blank level + 10 x standard deviation.

2.7. *Data analyses*

All data analyses were conducted with R statistical software (R Core Team, 2022; version 4.0.3). Data handling regarding plastic particles alone was performed using the «tidyverse » collection of libraries (Wickham et al., 2019). All means and standard deviations were calculated using the "summarySE" function from the "Rmisc" package (Hope, 2013). Assumption of normality was verified using the Shapiro-Wilk test. Neither the mass nor the number of plastic particles in each group were normally distributed. Therefore, Mann-Whitney tests were performed to compare the mass and number of plastic particles among groups. Data related to associated pollutants were checked for normality using the Shapiro-Wilk test. Correlations between plastic numbers or plastic mass, and all the dechlorane and PBDE congeners were tested with a Spearman's rank-order test. The PBDE and dechlorane congeners concentrations were compared between the two age classes by using a Mann-Whitney test. The threshold for statistical significance was set at 0.1 to reduce Type-2 statistical error.

3. Results

Plastic was found in 95% of all fulmar chicks. A total of 248 plastic particles were found in the stomach contents: 79 in the young chicks ($n = 10$) and 169 in the old chicks ($n = 10$). The only bird without plastic in either the stomach or the intestine was the smallest (youngest) individual. In contrast to the stomach contents, only one piece of plastic was found in the intestine contents. The difference between the two organs was significant ($p = 0.0051$; df = 19.01). We therefore focused only on stomach contents in the rest of our study.

3.1. Plastic burden & gastroliths

The average number of plastic particles per bird was 12.4 ± 17.5 (standard deviation, SD) and the average mass was 0.15 g per bird (Table 2). In young and old chicks, 8.0 ± 9.3 SD and 16.8 ± 22.7 SD plastic particles per bird were found on average, respectively. We determined no significant difference between the two groups, neither in number ($p = 0.24$, W = 66) nor in mass ($p = 0.43$, W = 61). Forty percent of the chicks exceeded the EcoQO threshold (0.1 g). Five of them were old chicks and three were young chicks (Table S2). The maximum mass of plastics found in a single bird was 872 mg, in a two-week old chick.

Besides plastic, gastroliths were another common hard particle found in the stomachs. On average, 6.8 ± 4.56 SD and 45.9 ± 53.53 SD gastroliths per bird, and 0.05 ± 0.05 mg and 0.51 ± 0.66 mg per bird were found in the young and the old chicks, respectively.

3.2. Plastic polymers

Four different plastic polymers were identified using FTIR spectroscopy: 181 particles of polyethylene (PE), 56 particles of polypropylene (PP), 8 particles of polystyrene (PS) and 3 particles of polyethylene terephthalate (PET) (Fig. 1A). The number of PE particles and their mass per bird was significantly higher than PS and PET ($p = 2.5 \times 10^{-6}$). The number of PP particles and their mass was significantly higher than PS and PET ($p = 0.0003$). The other differences were not significant. For each polymer, there was no significant difference in the number or mass between the two groups of chicks.

3.3. Shapes & colors

Combining both age classes, 201 fragments, 37 sheets, 6 threads, 2 pellets and 2 foamed particles were identified (Fig. 1B). Sheetlike particles were significantly more abundant in old chicks ($p = 0.049$) while the other types did not differ between the two age classes ($p > 0.1$).

Overall, 127 particles of plastic were classified as yellow, 62 as white, 24 as orange-brown, 12 as black, 8 as red-pink, 6 as green, 5 as blue-purple and 4 as grey (Fig. 1C). The number of yellow particles per bird was significantly higher than the others ($p < 0.1$) except white particles ($p = 0.546$). Black, blue-purple, green, grey and red-purple particles were less abundant and no statistically significant differences were detected among them ($p > 0.1$). All colors were represented in similar numbers in both age classes.

Table 2
Overview of the average number and mass of plastic per individual.

	Number of plastics	Mass of plastics (mg)
Young chicks		
Average (±SD)	8.0 ± 9.3	0.16 ± 0.26
Median	5	0.06
Minimum	0	0
Maximum	30	872
Old chicks		
Average (±SD)	16.8 ± 22.7	0.14 ± 0.15
Median	8	0.1
Minimum	2	5.8
Maximum	78	492
Total average (±SD)	12.4 ± 17.5	0.15 ± 0.21
Total median	7.5	0.08

3.4. Associated additives in liver

Among the 22 targeted PBDE congeners, five were not detected (BDE85, BDE138, BDE156, BDE184 and BDE191) and 4 were detected in each fulmar chick (BDE49, BDE119, BDE153 and BDE154). The lowest concentration of PBDE congeners was 0.0002 ng/g w.w. of BDE17 in an old chick and the highest was 2.065 ng/g w.w. of BDE209 in an old chick (Table S3). The congener BDE209 was above the limit of detection in five birds. No significant positive correlation between the concentration of each congener and the total level of PBDEs, and both plastic mass and plastic numbers could be found (Spearman test, $p > 0.1$). Significant differences between age classes were evident in the concentrations of several PBDE congeners. Younger chicks had significant higher levels of BDE153, 183, 202 (Mann-Whitney; W = 84, $p = 0.0089$; W = 76, $p = 0.049$; W = 79, $p = 0.0288$; respectively), and the summed levels of all PBDE congeners analyzed were also higher in younger chicks (Mann-Whitney; W = 79, $p = 0.0288$).

When considering all the targeted dechloranes, all birds had at least one of the dechloranes detected in their liver. Dec601 and Dec604 were not detected in any bird but both syn- and anti-DP were detected in 19 birds out of 20. As with PBDEs, we found no significant correlation between either the plastic mass or the plastic number and the concentration of each dechlorane congener separately or combined (Spearman test). Similarly to PBDEs, younger chicks showed significantly higher concentrations of dechloranes than older chicks (Dec602: Mann-Whitney test; W = 100, $p = 1.08 \times 10^{-5}$; Dec603: W = 92, $p = 0.0015$; anti-DP: W = 94, $p = 0.00032$ and syn-DP: W = 91, $p = 0.0022$). Consequently, the total concentration of all the dechlorane congeners analyzed was also significantly higher in young chicks (Mann-Whitney test; W = 100, $p = 1.08 \times 10^{-5}$; Table 3).

4. Discussion

Our study provides further evidence that young Northern Fulmar chicks ingest plastic debris. We also showed that two families of associated additives are detectable in all chicks sampled. We found no link between plastic numbers and masses, and the concentrations of those pollutants but our results supported that early life stages of fulmars are worth investigating. Indeed, young chicks had ingested as many or more plastics than older birds from the Faroes (Tanaka et al., 2019; van Franeker, 2012) and the levels of some PBDE congeners or dechloranes are as high as in other organisms (Vorkamp et al., 2015). In addition, there was an important difference between plastic burden in the stomachs and in the intestine, raising questions about the retention time of those particles in the stomachs and about the parameters influencing the transfer of plastics along the digestive tract. Our study provides answers on how much fulmar chicks are contaminated by plastic but also shows that the impacts and processing of those particles are poorly known.

4.1. Egestion of plastic pieces

Only one piece of plastic was found in an intestine, compared to the much higher plastic burdens found in the stomachs. To our knowledge, no studies provided information on plastic occurrence in the intestine of birds from the Faroes, but similar results have been reported in previous studies where adults were investigated (Furness, 1985; Terepocki et al., 2017). In stranded adult fulmars from the U.S.A., four out of 16 birds had one plastic piece in their intestine and one had two pieces (Terepocki et al., 2017). The fulmars from Scotland had no plastic piece in their intestine ($n = 13$, Furness, 1985). The minimal size of plastic was not mentioned by Furness (1985) but was also 1 mm in the study of Terepocki et al. (2017), making the comparison with the latter one more reliable. Although not quantified, plastics were more frequently found in the gizzard in our study, which is also supported by other studies (Mallory, 2008; Terepocki et al., 2017). Once ingested, a plastic piece passes the esophagus to reach the proventriculus, a large glandular stomach

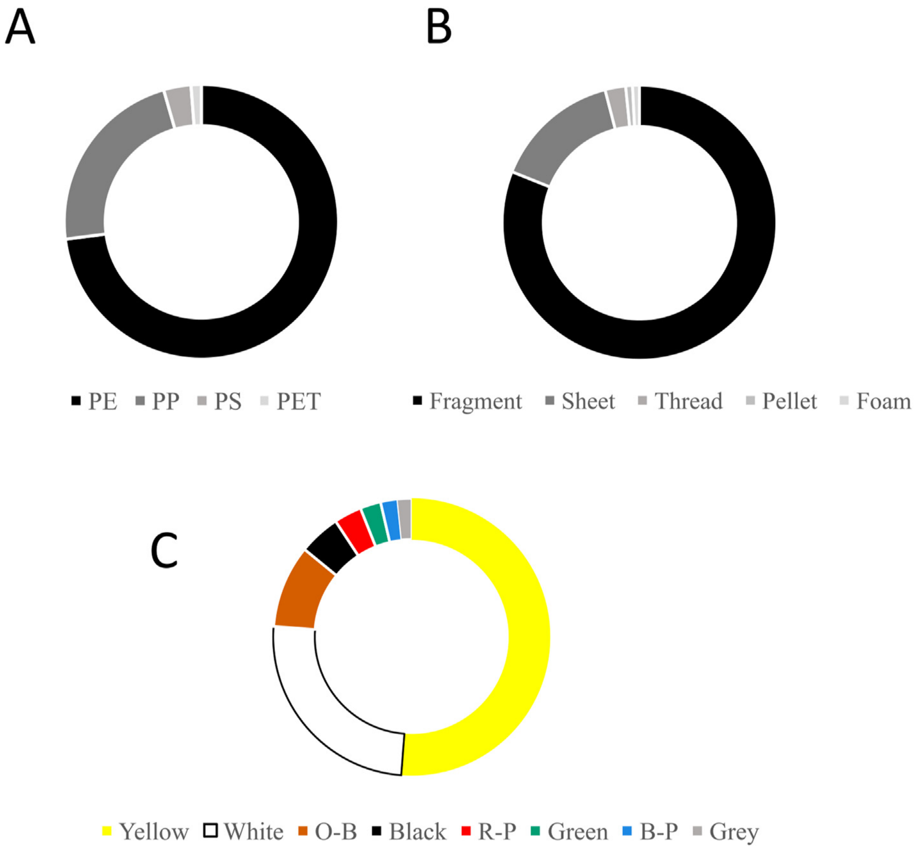

Fig. 1. Distribution of polymers (**A**), shapes (**B**) and colors (**C**) within all ingested plastic particles. B–P: blue-purple, O–B: orange-brown, PE: polyethylene, PET: polyethylene terephthalate, PP: polypropylene, PS: polystyrene.

Table 3
Averaged levels of BDE209, all PBDE congeners together and some dechloranes in both age classes, with standard deviations. All values are expressed in ng/g wet weight. Dec: dechlorane, anti-DP: anti isomer of dechlorane plus, syn-DP: syn isomer of dechlorane plus, PBDE: polybrominated diphenyl ether.

Age class	BDE209	All PBDEs	Dec-602	Dec-603	Syn-DP	Anti-DP	All dec
Young (*n* = 10)	0.744 ± 0.558	1.300 ± 0.693	0.357 ± 0.339	0.0059 ± 0.0027	0.015 ± 0.0055	0.071 ± 0.0386	0.449 ± 0.346
Old (*n* = 10)	0.476 ± 0.530	0.759 ± 0.605	0.058 ± 0.027	0.0016 ± 0.0014	0.007 ± 0.003	0.027 ± 0.0013	0.094 ± 0.038
All (*n* = 20)	0.610 ± 0.561	1.029 ± 0.704	0.207 ± 0.283	0.0038 ± 0.0031	0.011 ± 0.006	0.049 ± 0.036	0.271 ± 0.304

where digestion starts (van Franeker et al., 2005). After, the plastic piece reaches the muscular stomach, the gizzard, it is ground up before it reaches the intestine (Furness, 1985; Terepocki et al., 2017; van Franeker and Law, 2015). Therefore, plastics found in the gizzard are assumed to be too large to reach the intestine (van Franeker and Law, 2015) but are also assumed to be smaller than those found in the proventriculus (Terepocki et al., 2017). The single plastic piece found in the intestine in our study suggests that indeed some plastics can be egested after a few weeks. The great difference between the number of plastics found in the stomachs and in the intestine in both young and old chicks, might be explained by a slow grinding of plastic pieces in the gizzard, leading to a long retention time, in combination with a decreasing environmental exposure. That decreasing exposure also could be explained by the increasing foraging distance traveled by the parents (Weimerskirch et al., 2001). The retention time of plastic pieces in the fulmar digestive tract has been investigated in several studies with different results, going up to an estimated 1 year for a plastic to be egested (e.g. Ryan and Jackson, 1987; Terepocki et al., 2017). If plastic pieces can indeed stay in the gizzard for such a long time, first-year fulmars should be the most contaminated age class. They do not breed and therefore do not empty their proventriculus during the breeding season to feed their chicks. Moreover, there seems to be a gradual decrease in plastic burden from first-year to adult fulmars. This has been suggested by previous studies (van Franeker et al., 2022) and needs further investigation to be confirmed.

4.2. *The role of parental transfer*

The chicks used in our study were not fledged, hence all ingested plastic particles came either from parental regurgitation or were found by the chick itself in or around the nest. The plastic quantities recorded in our study are thought to result from feeding by both parents. The plastic pieces found in the stomachs in our study might also have come from the nest. Previous studies have shown that seabirds can use plastic when building their nests (e.g. Thompson et al., 2020; Votier et al., 2011). Northern Gannets *Morus bassanus* used preferably rope and nets in their nets (Votier et al., 2011) whereas the Herring Gull *Larus argentatus* mostly used sheetlike pieces in nests (Thompson et al., 2020). In our study, chicks ingested mostly hard fragments, sheet and thread-like particles representing only 17% of all ingested pieces. To our knowledge, no study reported the use of plastic in fulmar nests. Such a study would give an overview of the plastics directly available for the chicks in the nest, and help quantify the parental transfer of plastic particles.

4.3. Age class differences

Despite their consumption by humans, the high number of breeding pairs, the location of the islands and their year-round availability, there is a limited amount of data (Table 4) available for Faroese fulmars, and data are scattered across several age classes. In our study, the frequency of occurrence of ingested plastic debris was very high (95% of birds examined) despite the very young age of the birds. Another study that used samples from the Faroes also found similar frequencies of occurrence (91%, van Franeker, 2012). Data on plastics ingested by Faroese fulmars were collected in 1997 on 35 individuals with a relative occurrence of 51% but the bird ages are unknown (J F Provencher et al., 2014). Although plastic occurrence seemed to increase with chick age, the average mass of plastic reported per individual bird has been relatively stable across Faroese studies: 0.12 g and 0.21 g (van Franeker, 2012; van Franeker et al., 2005, respectively) and 0.15 in our study (Table 4).

However, both the average and median of ingested plastic particles per fulmar individual was highly variable. Another study focusing on fulmar chicks showed a result different than ours: in Ireland, only 29% of sampled chicks' regurgitates ($n = 14$) contained plastic (Acampora et al., 2017). Our results are more alarming and could be explained by differences in sample collection or chick age (which was not mentioned) or by the location of the Faroes making them more susceptible to plastic pollution. The bird age seems to be a factor influencing the levels of ingested plastics (van Franeker and Law, 2015), younger birds ingesting -or retaining-more plastics than older ones (van Franeker, 2012; van Franeker et al., 2022). As with other seabirds, when young fulmars are fledged, they could be less selective than adults when feeding as adults (Skórka and Wójcik, 2008; van Franeker, 2012). Also, the regurgitation of proventricular content while feeding chicks can explain that quantities of plastics are higher in chicks than in post-breeding adults which regularly unloaded their proventriculus to feed their chicks (Mallory, 2008; Van Franeker and Meijboom, 2002; van Franeker et al., 2005, 2011). Both points could explain why first year fulmars are the predominant age class displaying high plastic pollution levels (Tulatz, 2021; van Franeker et al., 2021). In our study, no significant differences—in terms of quantity or mass—were found between chick age categories. This may result from our small sample sizes, the short time between sampling young and old chicks, or the high variability in the amounts of plastic consumed. Also, studies compared here investigated different age classes, in different sampling years with different sample sizes. However, those studies involved older birds than in our study. This highlights first that despite their young age, chicks are highly contaminated by plastic from the first weeks of their life. Second, since fulmar chicks seem to have more plastics than adults in their stomach, they are inappropriate for biomonitoring adult plastic consumption. Using chicks could therefore lead to an overestimation of plastic levels in the marine environment. Chicks are fed by the parents through partial regurgitation of the stomach content, potentially unloading an amount of plastics that is not representative of the environmental contamination. Besides, chicks could ingest plastic present in or around the nest in addition to the food from the parents, biasing the assessment of plastic pollution in the surrounding marine environment. Also plastic ingestion by chicks is important because fledglings are consumed by Faroese humans and chick diets affect their morbidity and mortality rates as well as their fitness if they become adults.

4.4. Colors & polymers

The plastics collected in our study were mostly yellow and white (51.2% and 25.0% respectively). Light-colored plastics could be mistaken for food and light colors seem to be most common in floating marine debris, thus these frequencies seem to reflect the bioavailability of such items (Kühn et al., 2015). In fact, white and yellow were also the major colors of plastic found in Great Skua (*Stercorarius skua*) pellets from the Faroes (Hammer et al., 2016). Martí et al. (2020) included data from Cózar et al. (2017) where a prevalence of yellow-brown colors was found. Moreover, they observed an increase of white items along with an increasing distance from the land (Martí et al., 2020). In fact, PE, PP, PS and PET turn yellow as a result of environmental oxidation and weathering processes (Andrady, 2017), likely explaining the prevalence of yellow plastic particles in the marine environment, and consequently, in fulmars.

As previously observed in fulmars from the Faroes, PE, PP and PS were also the most ingested polymers in our study (Ask et al., 2020; Kühn and van Franeker, 2020; Tanaka et al., 2019, our study). This can be explained by their high production worldwide (Geyer et al., 2017), ubiquity in the environment, including in the Arctic (Halsband and Herzke, 2019; Hänninen et al., 2021) and low densities, which make them float at the sea surface, where fulmars feed.

4.5. Potential effects of plastic ingestion

Plastics are known to affect biota through the leaching of associated chemicals such as PBDEs (Neumann et al., 2021; Rochman et al., 2014; Tanaka et al., 2013, 2015). In our study, two families of plastic related additives were investigated. We detected BDE209 in only five birds, representing 25% of the birds collected, but this result is still quite alarming. Our sample sizes were low and thus poorly representative. Future work should be done, with more birds, to facilitate more accurate estimation. In the Arctic, several organisms were found with detectable levels of dechloranes (e.g. AMAP, 2017; Verreault et al., 2018) but to our knowledge, fulmars were investigated only twice and only adults were sampled (Mortensen et al., 2022; Sühring et al., 2022). Levels of dechloranes in our study are very similar to those found in other organisms (e.g. Vorkamp et al., 2015) despite the chicks young ages. However, it is challenging to draw any conclusion because other studies of Arctic species did not focus on fulmars, focused on other fulmar age classes (e.g. Schlabach et al., 2018, 2011; Vorkamp et al., 2015) or investigated only adults (Mortensen et al., 2022). We showed that early stages of an Arctic seabird were exposed to both PBDEs and dechloranes. They can be exposed during egg formation, during development in the egg, and by feeding by their parents. The long-term effects of exposure to plastic particles are unknown and require further studies. From a human health perspective, studying young fulmars is of interest because fledglings are the only age class consumed by the Faroese humans. Fledglings are 2–3 weeks older than the chicks that we sampled. Therefore, one could expect similar additive levels in fulmars consumed by humans, raising questions about fulmar meat as a source of pollutants.

4.6. Plastics & gastroliths

We showed that gizzards regularly contain gastroliths, as also shown by Matthews (1949). Gastroliths improve mechanical digestion by

Table 4
Available data on plastic ingestion by fulmars from the Faroes. FO: frequency of occurrence, NM: not mentioned.

Sampling year (n)	Age class	Limit of detection	FO (%)	Number/ind.	Mass (g/ind.)	Study
1997 (35)	Unknown	NM	51	1.7	NM	Provencher et al. (2014)
2002 (38)	Adults	1 mm	92	7	0.09	van Franeker et al., 2005
2005–2009 (371)	Fledgling to adult	NM	91	15	0.21	van Franeker, 2012
2010	Fledglings	NM	NM	16.5	NM	Tanaka et al. (2019)
2020 (20)	Chicks	1 mm	95	12.4	0.15	*Our study*

grinding “hard” food but have been poorly studied in seabirds (Downs et al., 2019). Some plastic pieces could also play a similar role. If confirmed, the occurrence of certain plastic polymers or shapes could then improve the processing of both food and other plastic items through the gizzard. The retention time of ingested plastic would then also depend on the plastics that act as gastroliths. Retention times are critical to estimate because they influence the leaching of pollutants into the tissues (e.g. Kühn and van Franeker, 2020).

4.7. Geographical comparison & OSPAR

In Europe, differences between EcoQ performances are quantified along OSPAR regions. Most recent data show that fulmars found in the English Channel and the North Sea are more contaminated than those found in the Faroes, Iceland, North of Norway and Svalbard (Kühn et al., 2021; Trevail et al., 2015). Those differences are assumed to be a consequence of different bioavailability of plastic in the foraging areas, despite long foraging distances (Edwards et al., 2013; Kühn and van Franeker, 2020). The levels of pollution are correlated with regions of intense human coastal and marine activities (Kühn and van Franeker, 2012). In addition to bioavailability of plastics in a region, the age of the bird plays a role. In the Faroes, young age classes ingest more plastics than adults and have as much plastic in their stomachs as adults from the more-polluted North Sea (van Franeker, 2012). Fulmars have a higher load of plastic than other sympatric species (Baak et al., 2020a; Furness, 1985). This can be explained by the fact that Procellariiformes, especially fulmars, forage at the sea surface where plastic pieces are more abundant, have a low degree of dietary specialization, and seldom regurgitate indigestible stomach contents (Ryan, 1987), unless provisioning their chicks. Those islands are of interest for several reasons: the availability of fulmars, fulmar consumption by the local human population, and their location. The Faroes are at the border of the Arctic and Atlantic Oceans and near where marine currents enter the Arctic with floating plastics from further south. They also have major fisheries in their waters, likely providing plastic waste from fishing equipment. These arguments points towards the need for an extension of the existing monitoring program in the North Sea (OSPAR, 2008) towards the Faroes region.

5. Conclusions

Our study showed that fulmar chicks are contaminated with both plastic particles and plastic additives. A high proportion of chicks had ingested plastics, most likely through parental transfer, with unknown consequences for their health, longevity and fitness. Chicks have higher plastic burdens in their stomachs than older life stages and could ingest plastic present in or around the nest in addition to the regurgitates from the parents, and are therefore not recommended in the frame of plastic pollution biomonitoring, as the data are not directly comparable with existing data sets for older birds. No correlation was found between the levels of any pollutant analyzed in our study and the current plastic load in the stomachs, indicating that those pollutants alone are not suitable substitutes for plastic monitoring. The link between ingested plastic and levels of associated chemicals in tissues requires further investigation, especially in early life stages. Understanding the physical and toxicological impacts of plastic ingestion in juveniles will help understanding the effects at both individual and the population levels. In addition, fledglings are consumed by Faroese humans, and therefore require more toxicological investigations.

Ethical statement

The anatomy of the fulmar digestive system precludes regurgitates as proxies of plastic burdens (Dehnhard et al., 2019). Besides, non-lethal methods are not yet sufficiently developed and cannot be used at the moment. Because of the remoteness of the study site and the age classes targeted, we could not collect stranded birds. We sampled 10 individuals of each age class as a compromise between the number of samples and the potential impact on the fulmar population. In the Faroes, year-round collections of unlimited numbers of fulmar eggs or birds are allowed because it is not protected. The collection of birds was performed by cervical dislocation by skilled and experienced staff on chosen nests according to their accessibility and the certainty of aging.

Author contributions

F.C.: Conceptualization, Methodology, Resources, Writing-Original Draft, Writing-Review & Editing, Supervision, Project Administration, Funding Acquisition, S.L.: Investigation, Data Curation & Analysis, Writing-Original Draft, Writing-Review & Editing, Visualization, J.D.: Resources, Writing-Review & Editing, C.H.: Resources, Writing-Review & Editing, D.H.: Resources, Experimental design, Writing-Review & Editing, M.H.: Investigation, Writing-Review & Editing, F.T.: Investigation, Writing-Review & Editing, G.W.G.: Resources, Writing-Review & Editing, A.T.: Resources, Writing-Review & Editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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