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RESEARCH ARTICLE

Polymer types ingested by northern fulmars (*Fulmarus glacialis*) and southern hemisphere relatives

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Abstract
Although ingestion of plastic by tubenosed seabirds has been documented regularly, identification of the polymer composition of these plastics has rarely been described. Polymer assessment may assist in identifying sources and may indicate risks from additives occurring in specific types of polymers. Using known test materials, two identification methods Fourier transform infrared spectroscopy and near infrared spectroscopy (FTIR and NIR) were compared. Although both methods were found to be similarly suitable for identification of plastic polymers, a significant difference was observed in identification of natural materials. FTIR frequently misclassified natural materials as being a synthetic polymer. Within our results, an 80% match score threshold functioned best to distinguish between natural items and synthetics. Using NIR, the historical variability of plastics ingested by northern fulmars (*Fulmarus glacialis*) from the Dutch sector of the North Sea was analysed for three time periods since the 1980s. For the more recent decade, variability between fulmars from different regions in the northeast Atlantic was investigated. Regional variation was further explored by analysing plastics obtained from the stomachs of southern hemisphere relatives of the fulmar (southern fulmar, cape petrel, snow petrel) and Wilson's storm petrel. Results show that proportional abundance of polymer types in these seabirds is closely related to the plastic categories that they ingest (e.g. pellets, foam, fragments). The uptake of different plastic categories and related polymer types most likely reflects spatial and temporal variations in availability rather than ingestion preferences of the birds.

Keywords Marine plastic debris · Ingestion · Procellariiformes · Northern fulmar (*Fulmarus glacialis*) · Near infrared spectroscopy (NIR) · Fourier transform infrared spectroscopy (FTIR)

Introduction

Tubenosed seabirds (Procellariiformes) are known to ingest debris including plastics from the sea surface. At a global scale, 91 of 144 known procellariform seabird species have been recorded to ingest plastic (Kühn and van Franeker 2020). In many cases, ingestion may occur intentionally, but usually for unknown reasons. Resemblance to prey is often suggested, but Ryan (1987) linked plastic ingestion especially to seabird species with a less specialized diet. Ingestion of plastic might also occur accidentally. For example, albatrosses forage on strings of eggs of flying fish that are attached to pieces of floating plastic (Pettit et al. 1981). Finally, plastic ingestion will partly occur indirectly, e.g. by foraging on prey that ingested plastics itself (Hipfner et al. 2017). The effects of plastic on marine wildlife are largely unknown due to the many factors that might influence the level of harm. These factors include uptake, retention time, the digestion mode of different organisms and in particular the broad variety of polymers, shape and chemical burden of the plastics themselves. The retention time of plastic is difficult to determine in free-ranging seabirds. It depends on the shape and the size of the ingested plastic in relation to body size, the wearing process in the stomach and a threshold size that is needed to excrete the

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plastic (Ryan 2015). One study indicates a loss of 75% of the plastic load per month for fulmarine petrels (Van Franeker and Law 2015), while others suggest a complete loss of plastics in less than 2 months (Terepocki et al. 2017) or up to many months for a broader variety of species (Ryan and Jackson 1987; Ryan 2015).

Ingested plastics may cause mechanical disruptions and a false feeling of satiation (Kühn et al. 2015). Chemical additives added during the manufacturing process of different polymers and substances adsorbed from the marine environment are of concern, as potential toxic substances may harm marine organisms (Oehlmann et al. 2009; Teuten et al. 2009; Rochman 2015; Tanaka et al. 2015). Polymer assessments of plastics ingested by marine wildlife may be of value in relation to toxicity of specific polymers, their degradation products or specific additives used (Lithner et al. 2011).

Plastic ingestion by seabirds has been recorded from the 1960s onwards (Threlfall 1968; Kenyon and Kridler 1969), and an increasing body of publications proves that plastic and the ingestion of it by marine megafauna occur over all the world's oceans (Provencher et al. 2017). In recent years, research quantifying the abundance of plastics in organisms (frequency of occurrence, average number and sometimes average mass of plastic items) has been complemented by investigations of polymer types and related chemical burdens (Tanaka et al. 2013; Tanaka et al. 2019; Rizzi et al. 2019; Nelms et al. 2019; Avio et al. 2020). This development is related to the technical progress in analytical methods such as infrared and mass spectroscopy and to the focus on small-sized plastics that require advanced identification techniques. Studies investigating plastic ingestion by fish are relatively recent and frequently use Fourier transform infrared spectroscopy (FTIR) or Raman spectroscopy to identify polymer types (e.g. Löder and Gerdts 2015; Lusher et al. 2013; Rummel et al. 2016; Pellini et al. 2018; Wieczorek et al. 2018; Kühn et al. 2020). Several earlier studies (e.g. Yamashita et al. 2011; Amélineau et al. 2016; Avery-Gomm et al. 2016; Pham et al. 2017; Van Franeker et al. 2018; Tanaka et al. 2019; Rizzi et al. 2019) provided some information, but on the larger scale, the identification of plastic polymers in marine megafauna is still relatively scarce. Data on the composition of polymer types is needed to evaluate potential toxic consequences of plastic ingestion because different plastic types contain different types of additives, leaching behaviour and degradation products (Lithner et al. 2011). Spectroscopy produces light reflection or transmission spectra that can be compared with a library of known polymer spectra. The match between spectra is often expressed in percentages; however, the threshold of acceptance of the results, as being reliable, differs among studies.

Plastic ingestion by northern fulmars (*Fulmarus glacialis*) has been observed since the 1970s (Bourne 1976; Furness 1985; Van Franeker 1985). From 2002 onwards, this procellariform seabird has been used as a monitoring tool for marine debris for the Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in the North Sea. The fulmar is one of the most studied species with regard to the quantification of plastic pollution and has been proven to be a suitable monitoring tool to assess changes in abundance and types of plastic (Van Franeker et al. 2011; Van Franeker and Law 2015; OSPAR 2017; OSPAR 2019). Although single birds may undertake impressive foraging trips, 10 out of 12 fulmars tracked on trips lasting 4 to 15 days stayed within 100 km distance of the colony (Edwards et al. 2013). Similarly, the individual site foraging fidelity in northern gannets (*Morus bassanus*) tends to be within a scale of tens of kilometres (Wakefield et al. 2015), and behavioural traits suggest that wintering distributions show similar characteristics with birds staying within restricted areas known to them (Piper 2011). Boreal fulmars do not show seasonal migration patterns (Mallory et al. 2012). As a consequence of foraging site fidelity, the average amount of plastics in fulmar stomachs of larger sample sizes will reflect pollution patterns over restricted spatial scales over longer periods of time (Van Franeker et al. 2011). Research has been expanded from the Netherlands to the entire North Sea area and further to the North Atlantic, including the Faroe Islands (Van Franeker et al. 2011), Iceland (Kühn and Van Franeker 2012) and Svalbard (Trevail et al. 2015). Based on a common standardized protocol (Van Franeker 2004; Van Franeker et al. 2011; OSPAR 2015), these results are easily comparable with other studies and study regions, such as the Canadian (sub)Arctic (Mallory 2006; Mallory 2008; Provencher et al. 2009; Avery-Gomm et al. 2018) and the North Pacific Ocean (Donnelly-Greenan et al. 2014; Nevins et al. 2005; Avery-Gomm et al. 2012; Terepocki et al. 2017). The outcomes of these studies report the frequency of occurrence, average number of pieces and plastic mass. From these studies, it appears that ingested quantities of plastic by fulmars tend to decrease with increasing latitude (Mallory 2008; Van Franeker et al. 2011; Kühn and Van Franeker 2012; Baak et al. 2020). Recently, in fulmars from the Dutch coast, a decreasing trend in the mass of ingested plastic has been observed (Van Franeker and Kühn 2019).

NIR was used to evaluate potential differences in ingested polymers on a temporal and spatial scale. We used archived samples from long-term fulmar studies to analyse the polymer composition of ingested plastics from different time periods in the North Sea. To compare regional differences, the North Sea results were compared with the polymer composition of plastics from fulmars from other locations in the northeast Atlantic Ocean (Faroe Islands, Iceland and Svalbard) and to plastics obtained from a number of related species in the Southern Ocean. Temporal and spatial variation of plastic ingestion can be useful to detect changes in the composition of plastics and to monitor the effectiveness of certain mitigation measures. For example, Van Franeker and Law (2015) demonstrated that industrial plastic pellets have decreased in ocean gyres and in northern fulmars and linked this to the successful implementation of regulations to avoid loss of pellets during production and transportation. Comparable findings were made by Vliestra and Parga (2002) in the North Pacific Ocean and by Ryan (2008) in the South Atlantic Ocean. Seabirds are therefore seen as suitable sentinels to monitor changes in plastic pollution.

The starting point of our study aimed at identifying a suitable threshold level for the reliability of our near infrared spectroscopy (NIR) results in comparison with FTIR analyses for the same set of known polymer and natural particles. The second aim was to use NIR results to deepen the knowledge of plastics ingested by northern fulmars and related seabird species from the Southern Ocean.

Methods

IR method evaluation

FTIR analysis has been more regularly used than NIR for polymer identification of ingested plastics. For the current study however, NIR was available to analyse plastics from petrel stomachs. To detect potential differences in both techniques, a comparative experiment was prepared, applying NIR and FTIR on a large selection of known synthetics and natural items. Different threshold values for the reliability of the results were used. For each of these results, NIR and FTIR were compared to see whether the two methods delivered comparable and reliable results.

A total of 200 test items were prepared for both NIR and FTIR polymer assessments. These test items reflected a broad variety of items potentially encountered in stomachs of marine organisms, both natural prey (remains) and marine debris.

A total of 117 items were man-made materials, and 83 items were of natural origin (Table 1). Plastics covered a wide range of colours and plastic categories (24 raw industrial pellets and 66 consumer-type particles of categories as identified by Van Franeker et al. (2011), such as sheets, threads, foams and fragments). In this system, fibres from clothing were not considered. The details of each test item can be found in the Online Supplement Table 1.

In infrared spectroscopy, results of polymer identification are usually associated with a percentage match score. This score indicates the degree of overlap between the sample spectrum and the spectrum of the most similar substance from the IR library. For this study, the reliability of infrared spectroscopy plastic identification was tested at the thresholds of 70%, 80% and 90%. All items were analysed with both NIR (DTS-PHAZIR-1624 for 1600–2400 nm library details: Online Supplement Table 2) and FTIR (ATR-FTIR; Shimadzu Prestige 21, 10 Scans, Libraries: ATR Polymer 2, IRs Polymer 2, T-Polymer).

Results in either method were categorized as:

1) Correctly identified: for synthetic polymer test items above selected percentage and material correctly categorized; for natural items below selected percentage irrespective of chosen library substance.
2) Falsely identified: above selected percentage; but incorrectly categorized; for both synthetic polymers and natural items.
3) Not identified: for synthetic polymers below required percentage; note that natural materials with a match score below the chosen reliability percentage were considered as correctly classified, i.e. not being a known synthetic polymer. Spectra for natural items are often not available in the IR libraries. Therefore, a score lower than the intended match score was accepted as correct identification, meaning their identification as polymer was not successful.

Polymers identified by FTIR as HDPE and LDPE were grouped as PE, as the NIR library did not allow that distinction.

Seabird samples

For this study, we analysed plastics ingested by northern fulmars (*Fulmarus glacialis*) and three of its Southern Ocean close relatives (southern fulmar *Fulmarus glacialoides*, cape petrel *Daption capense* and snow petrel *Pagodroma nivea*) plus the Wilson's storm petrel (*Oceanites oceanicus*). For the temporal analysis of plastics from beached fulmars in the Netherlands, a selection of 129 birds covering three decennia (1980–2011) was used. For a regional comparison between fulmars from the North Atlantic, stomach contents of northern fulmars from the Netherlands were compared with samples from the Faroe Islands, Iceland and Svalbard. Samples from Antarctica were collected during research expeditions between 1984 and 1998 in the Windmill Islands area near the Australian Casey station (66° S, 110° E) in eastern Antarctica. Overall, we used plastics from stomachs of 317 individual birds, as specified in Table 2.

Dissection protocol

All birds were dissected according to guidelines by Van Franeker (2004) and OSPAR (2015). In short, external measurements (head, tarsus and wing length and bill length and depth) and details on moult (primary and secondary moult, down score) were recorded. Internally, the sex, age, organ health and condition were assessed, and the stomachs were removed. The stomach content was

Table 1 Numbers of man-made and natural items tested with FTIR and NIR, respectively

Category	Sub-category	*n* items
Man-made items (*n* = 117)	Synthetic polymers (22 different polymer types)	103
	Compostable bioplastics	8
	Balloon rubber	2
	Paraffin/palmfat	4
Natural items (*n* = 83)	Fish bones and otoliths, eye lenses of squid and fish, crab carapaces and shells of bivalves and insects, skin, bill structures and feathers of different seabirds, gastropods. Natural non-food items such as stones, wood, wool, seaweed and seeds	83

sieved on 1 mm mesh size, and all hard items were sorted under a stereomicroscope as either natural food or plastics. The plastic items were further split into plastic categories according to Van Franeker et al. (2011). Industrial pellets are small, often cylindric-shaped plastic granules, around 4 mm in diameter, and the raw material is used for the production of plastic products. Microbeads are much smaller, often spherical plastic granules usually 1 mm or less in diameter, which became known because they were used in many types of cosmetics but are actually used in many industrial applications. User plastics include sheets (e.g. plastic bags, agricultural foil), threads (ropes, nets, fishing line, etc.), foams (e.g. foamed polystyrene or polyurethane) and fragments (rigid items often broken of larger plastic objects). Plastic items such as balloons, cigarette filters and rubber are included in the category 'other'. All details regarding frequency of occurrence, average plastic number and mass were published within earlier publications (Van Franeker and Bell 1988; Van Franeker 1985; Van Franeker et al. 2011; Kühn and Van Franeker 2012; Trevail et al. 2015).

Table 2 Seabird species, location, year and sample number (n) of examined procellariform samples

Species	Country	Years	*n* birds
Northern fulmar	Netherlands	1982–2019	129
Northern fulmar	*NL1980-89*	*1980–1989*	*(58)*
Northern fulmar	*NL1909-99*	*1990–1999*	*(32)*
Northern fulmar	*NL2010-11*	*2010–2019*	*(39)*
Northern fulmar	Faroe Islands	2011	50
Northern fulmar	Iceland	2011	46
Northern fulmar	Svalbard	2013	35
Northern fulmar	Total	1982–2019	**260**
Wilsons storm petrel	Antarctica	1986–1998	45
Cape petrel	Antarctica	1985–1986	9
S. fulmar	Antarctica	1984	2
Snow petrel	Antarctica	1985	1
Antarctica	Total	1984–1998	**57**

Italics were used for sub categories (e.g. Netherlands per decennia). Bold was used for summarizing data

Sample analysis

All plastic items encountered in the seabird stomachs were individually weighed on a Sartorius electronic scale to an accuracy of 0.0001 g. NIR analysis was conducted using a handheld near infrared spectroscope with integrated spectrum library containing 28 different polymer types (for details see Online Supplement Table 2). Some samples from Svalbard were analysed using Agilent Technology 4500a portable FTIR (32 scans, Library: Aarhus University microplastics). Results were accepted based on the match score threshold level identified during the NIR/FTIR experiment. The 10 most occurring polymer types are given in full detail. Other polymer types had a very low occurrence throughout the total sample (< 15 particles, each type representing < 0.3%) and were combined in the category 'other'.

Data analysis

For visual impressions, graphs are presented as stacked columns either for numbers or mass. As mass of plastic is considered more important in terms of potential harm (Van Franeker et al. 2011; Provencher et al. 2019) and is used in the framework of monitoring of plastics in fulmars (OSPAR 2015), most graphs depict composition mass percentages. However, all underlying data (numbers and mass) are provided in Online Supplement Table 3.

Tests for statistical significance in polymer type proportions were conducted with https://epitools.ausvet.com.au/ as recommended by Provencher et al. (2017). We compared sample proportions of polymer types with 2-sample z test (two-tailed, significance level set at $p \leq 0.05$; https://epitools.ausvet.io/ztesttwo). This test compares proportional abundance by number of particles and does not consider mass.

Results

NIR and FTIR method evaluation

Detailed information on decisions for each test item can be found in Online Supplement Table 1. For synthetic samples,

Table 3 Number and percentage of items measured with FTIR and NIR with difference match score thresholds (A > 70%, B > 80%, C > 90%)

A					
Match score threshold > 70%		FTIR		NIR	
		n	%	*n*	%
Plastic (117)	Correct ID	*78*	66.67	*79*	67.52
	False ID	*32*	27.35	*23*	19.66
	No ID	*7*	5.98	*15*	12.82
Natural (83)	Correct ID	*10*	12.05	*68*	81.93
	False ID	*73*	87.95	*15*	18.07
	No ID	*0*	0.00	*0*	0.00
All (200)	Correct ID	*88*	44.00	*147*	73.50
	False ID	*105*	52.50	*38*	19.00
	No ID	*7*	3.50	*15*	7.50
B					
Match score threshold > 80%		FTIR		NIR	
		n	%	*n*	%
Plastic (117)	Correct ID	*79*	67.52	*74*	63.25
	False ID	*27*	23.08	*17*	14.53
	No ID	*11*	9.40	*26*	22.22
Natural (83)	Correct ID	*11*	13.25	*80*	96.39
	False ID	*72*	86.75	*3*	3.61
	No ID	*0*	0.00	*0*	0.00
All (200)	Correct ID	*90*	45.00	*154*	77.00
	False ID	*99*	49.50	*20*	10.00
	No ID	*11*	5.50	*26*	13.00
C					
Match score threshold > 90%		FTIR		NIR	
		n	%	*n*	%
Plastic (117)	Correct ID	*71*	60.68	*64*	54.70
	False ID	*11*	9.40	*5*	4.27
	No ID	*35*	29.91	*48*	41.03
Natural (83)	Correct ID	*41*	49.40	*83*	100.00
	False ID	*40*	48.19	*0*	0.00
	No ID	*2*	2.41	*0*	0.00
All (200)	Correct ID	*112*	56.00	*147*	73.50
	False ID	*51*	25.50	*5*	2.50
	No ID	*37*	18.50	*48*	24.00

Each category (synthetic, natural and the combination of both) is divided in items correctly identified, items falsely identified and items not identified

FTIR identified slightly more items correctly than NIR (FTIR: 78, 79, 71 items against NIR: 79, 74, 64 items for 70%, 80% and 90% thresholds respectively; Table 3). In contrast, FTIR failed regularly in distinguishing between plastic and natural items. Out of 83 natural items FTIR misidentified approximately one-half (40 items) even at the highest match score threshold level of 90%. When the threshold was set at 80% or 70%, half of the items were falsely identified as plastics (72 and 73 items, respectively). Falsely identified items include common prey remains such as bones, eye lenses, feathers, skin, crustacean carapaces, squid and polychaete jaws and insect shields. Most of these items were misidentified by FTIR as being polyamide (PA). NIR in general showed lower match scores for natural items, correctly classifying those as not being synthetic polymers. Only at the 70% match score threshold, 15 natural items were misidentified as being plastic, again mainly as PA. Yamashita et al. (2011) described difficulties with measuring dark items, when using NIR which is similar to our findings.

Our results indicate that a high match score threshold for FTIR is necessary to avoid misidentification of natural material (Table 3). At 80% match score threshold, almost half of all items were identified correctly (90/200 test items). For NIR, the match score does not have a significant influence on the reliability of the outcome of synthetic polymers ($p > 0.4$), but a strong influence on the recognition of natural materials. Almost all natural materials (80 out of 83 natural items) were identified as such when a threshold of > 80% match score was applied for NIR which is significantly higher than with a match score of 70% (68 out of 83 natural items; $p = 0.0027$).

Numbers for correct identification vary between the three thresholds. In weighing the potential misidentification of natural material against the successful identification of polymers in the synthetic material category, we have decided to set the threshold at > 80% in the further description of our results.

Plastic in procellariform seabirds

A total of 5303 plastic pieces with a combined mass of 60 g was analysed. To evaluate the impact of using the > 80% spectrum match, Fig. 1 shows results when no restriction is applied and when the 70%, 80% or 90% match thresholds are used. Polyethylene and polypropylene (PP) identification became more important when higher thresholds are applied, indicating that spectra for less common polymers show less similarity to those in the polymer library. Using > 80% spectra match threshold, 4155 of plastic pieces and 50 g of plastic mass were identified to a specific polymer type. Thus, 1148 plastic pieces (22% of items) with a combined mass of 10 g (17% of mass) remained below this threshold. Lacking an accepted identification, they are not included in the further analyses of plastic type proportions.

Plastic items belonged to seven categories (Table 4). As already experienced during the testing phase, NIR had difficulties with identifying foams. Of the 739 foam items measured, only 42.5% could be identified. Even though the identification of threads scored high in the testing phase (77% were correctly identified), in more than half of the threads measured in bird stomachs (53.8%), the polymer type remained unclear.

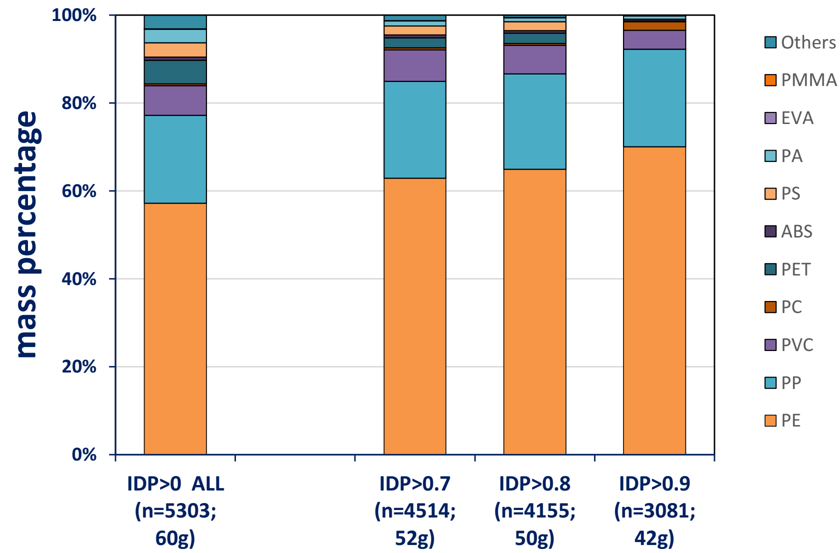

Fig. 1 Polymer identification with NIR, applying different match score thresholds of > 70, > 80 and > 90% (shown as identification probabilities (IDP)). Proportion percentages are shown in terms of mass for all plastic items encountered in all seabird samples

We present the number, mass and polymer composition of the plastic particles that were successfully identified and indicate a relationship of plastic category and polymer types (Fig. 2). Data shown in Fig. 2 clearly indicate a relationship of plastic category and polymer types. Pellets and fragments mainly consisted of PE (79 and 72% in terms of mass, respectively), while the other categories showed more variation. Threads, for example, consisted of 37% PE, 39% PP and 20% PVC. In contrast, microbeads were mainly made of PMMA (42%) and PS (37%), but due to their low abundance, they did not strongly influence overall results. Plastics with a high density, such as PVC, influenced the patterns and caused differences between numbers and mass (e.g. PVC in the 'other plastic' category (Fig. 2)).

As the variation between plastic categories was substantial, spatial and temporal, comparisons are presented separately per plastic category as well.

Temporal comparison

Plastics in fulmars from the Netherlands have been studied from the 1980s onwards. Here we compare plastics ingested by northern fulmars from three decennia. Pellets comprised the majority of mass (54%) during the 1980s (Fig. 3). In the 1990s, the mass of fragments, sheet and threads increased, and consequently the proportion of pellets decreased (20%). However, in the 2010s, pellets again gained relative importance (32%) together with

Table 4 Categories of marine debris items collected from all birds used in this study

Species	Country	*n* plastics	Fragment	Pellet	Sheet	Thread	Foam	Other	Bead
Northern fulmar	Netherlands	3439	1252	650	657	190	579	111	0
N. fulmar	*NL1980-89*	*(778)*	*(213)*	*(356)*	*(69)*	*(43)*	*(89)*	*(8)*	*(0)*
N. fulmar	*NL1990-99*	*(1129)*	*(389)*	*(94)*	*(378)*	*(83)*	*(97)*	*(88)*	*(0)*
N. fulmar	*NL2010-11*	*(1532)*	*(650)*	*(200)*	*(210)*	*(64)*	*(393)*	*(15)*	*(0)*
N. fulmar	Faroe Islands	536	361	36	49	35	50	4	1
N. fulmar	Iceland	342	199	14	39	25	55	1	9
N. fulmar	Svalbard	595	428	16	47	76	24	3	1
N. fulmar	Total	4912	2240	716	792	326	708	119	11
Wilson's storm petrel	Antarctica	342	194	110	14	2	20	0	2
Cape petrel	Antarctica	37	15	11	0	1	10	0	0
S. fulmar	Antarctica	11	10	1	0	0	0	0	0
Snow petrel	Antarctica	1	0	0	0	0	1	0	0
Antarctica	Total	391	219	122	14	3	31	0	2
All birds	Total	**5303**	**2459**	**838**	**806**	**329**	**739**	**119**	**13**

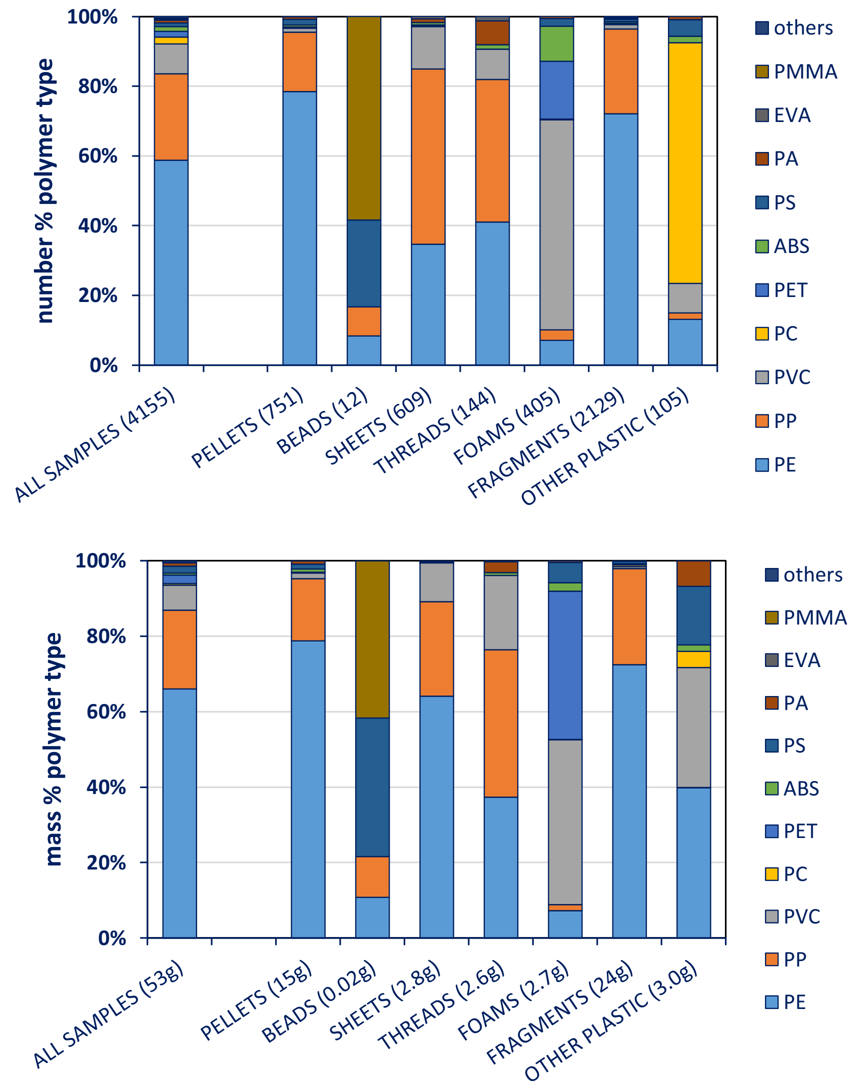

Fig. 2 Polymer type proportions of all items identified in this study, belonging to different plastic categories. Top: polymer type proportions in numbers. Bottom: polymer type proportions in gram. Graph is based on data shown in Online Supplement Table 3.2a

fragments (40%) and foam (13%), possibly influenced by a fulmar from 2010 with an unusual number of ingested pellets (n = 72). In the 1980s, 85% of the plastics were made of PE and 11% of PP, and only 4% were made of other polymer types (Fig. 3). In the 1990s, more diversity in plastic types was observed (14.4% of PVC and 2.9% polycarbonate (PC)). Polypropylene comprised almost half of the plastics (49%). In the most recent decennia, PE gained relative importance (53%), while PC almost disappeared (0.3%). Polyethylene terephthalate (PET) and polystyrene (PS) increased (9.4 and 7.9%, respectively). Numbers of PE differed significantly for all three decennia ($p < 0.0003$).

Regional comparison in the North Atlantic

Data for northern fulmars is available for four regions in the North Atlantic: the Netherlands, the Faroe Islands, Iceland and Svalbard (Table 4; Fig. 4). For the Netherlands, only data from the most recent decennia (2010–2019) was included, as data from the other regions were collected between 2011 and 2013. Fragments were the most dominant plastic category in all regions; for the Faroe Islands and Iceland, more than half of the plastic mass consisted of fragments (Fig. 4). Pellets were more common in the Netherlands but decreased with higher latitude. Threads were comparably abundant in Iceland and Svalbard. The highest variation of plastic types was found in the Netherlands. Polyethylene and PP comprised the majority of plastic mass in all regions and increased with latitude, with the exception of Svalbard, where the proportions of PE mass seemed closer to those of the Netherlands (Fig. 4). However, when testing for significant differences in PE numbers, the Netherlands had significantly less PE plastic items than all other locations ($p < 0.0001$). The Faroe Islands, Iceland and Svalbard did not show significant differences in the number of PE items ($p > 0.1$). Noticeably PVC comprised 13% of mass

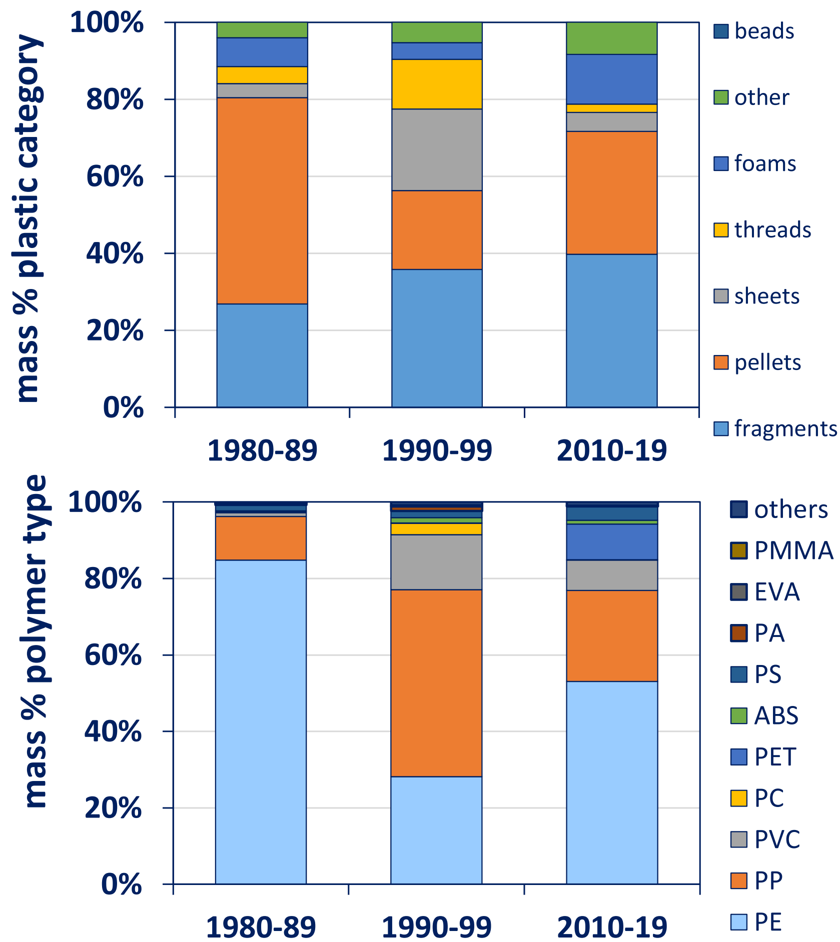

Fig. 3 Top: plastic categories ingested by northern fulmars in three decennia. Bottom: polymer categories of these plastics. Both graphs show proportions in terms of mass. Graph is based on data shown in Online Supplement Table 3.3a and b

on Svalbard but much lower proportions in the Netherlands, the Faroe Islands and Iceland (8%, 6% and 0%, respectively).

Global comparison

Sample numbers for the southern species were, except for the Wilsons's storm petrel, very low. There was one snow petrel available that had ingested one item (which could not be identified at > 80% match score). For northern fulmars, only data from the 1980s and 1990s were used to ensure comparability. Variation in plastic categories in northern fulmars was higher with sheets, thread and other plastics, while the Antarctic samples were dominated by fragments and pellets only. Polymer compositions (in mass) for the southern species separately and as a group are shown (Fig. 5). In terms of numbers, the polymer composition of the three remaining southern species did not differ significantly ($p > 0.73$) from each other, and therefore, these species were treated as one group. In southern species, PE mass is higher (81%) than in northern fulmars (64%) (Fig. 5). Also, the number of PE items was significantly higher in Antarctic birds than in northern fulmars ($p < 0.0001$).

Discussion

Infrared spectroscopy thresholds

FTIR analysis is a method increasingly used to identify plastics ingested by marine organisms. Currently, there is no common agreement on match score threshold levels in IR analysis. Literature research revealed 86 studies that have used either FTIR or NIR to determine the composition of plastics in seabirds, marine mammals, turtles and marine fish (Online Supplement Table 4). The threshold varied between 60 and 93%. Most studies that give details have varied in acceptance rate between 70 and 85% (Alomar and Deudero 2017; Bessa et al. 2018; Ory et al. 2017; Ory et al. 2018; Tanaka and Takada 2016). Unfortunately, a majority of studies using FTIR (n = 49; Online Supplement Table 4) did not provide any details on match score thresholds at all. Therefore, it is unclear whether they used a threshold or rather accepted any result displayed. For this study, a threshold level was established for the reliable identification of plastic items ingested by marine organisms, using either FTIR or NIR.

By testing both methods on a series of various natural and plastic items, we decided that in our case, a match score of

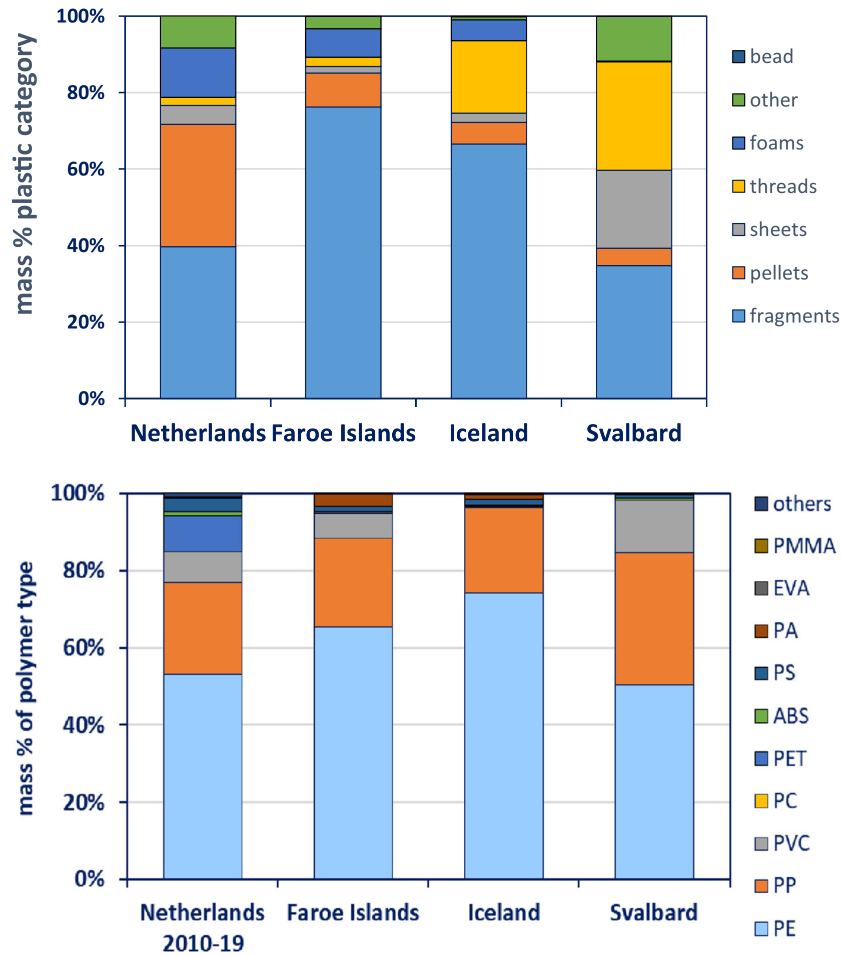

Fig. 4 Top: plastic categories ingested by northern fulmars from four North Atlantic regions. Bottom: polymer categories of these plastics. Both graphs show proportions in terms of mass. Graph is based on data shown in Online Supplement Table 3.4a and b

80% should be applied to document polymer composition of our samples. It is recommended that validity of match scores should be examined in each study.

The 80% represents a slightly higher threshold level than proposed by Lusher et al. (2017). These authors recommended the (often arbitrarily chosen) average threshold levels used in previous studies (70–75%) as a standard for plastics in fish and invertebrates that usually range in the size of micrometres.

Many different natural items such as fish and squid lenses, beaks, bones, skin and feathers were falsely identified by FTIR as being polymers. Precaution should be taken to avoid overestimation of plastics ingested by organisms, when solely relying on FTIR outcomes. Good background knowledge of typical natural food remains, occurring in the species studied, is highly recommended to avoid misidentification by FTIR. Identification of plastics is further complicated by the nature of plastics originating from biota samples. FTIR penetrates the surface of plastics for only a few micrometres (Renner et al. 2017); therefore, surface degradation and biofouling can cause high background noise in measurements, potentially contributing to the confusion of PA and natural keratin. Although NIR has shown to have difficulties with foams and dark colours, still both FTIR and NIR seem to be reliable and can be recommended for the identification of polymers.

Polymer types in seabirds

Infrared polymer analysis has not been applied to any of the species researched in this study. Although plastic is common in these species, the only crude polymer identification in Wilson's storm petrels and northern fulmars has been conducted by Moser and Lee (1992), using density separation. In both species the great majority of ingested plastic items were floating and, according to the authors, belonged to either PE or PP. This overlaps with the results from our findings, where PE and PP were the most common polymer types in both time and space.

Our data indicate that plastic categories determine polymer characteristics more than time and space scale. Fragments are predominantly made of PE (71%) and PP (27%). Characteristics of plastics ingested by birds, such as size and shape, have changed through time (Ryan 2008; Van Franeker and Law 2015). When fragment mass is high in birds, PE and PP are the most abundant polymer type as well. Many pellets in a sample increase the relative PE mass, e.g. in early data

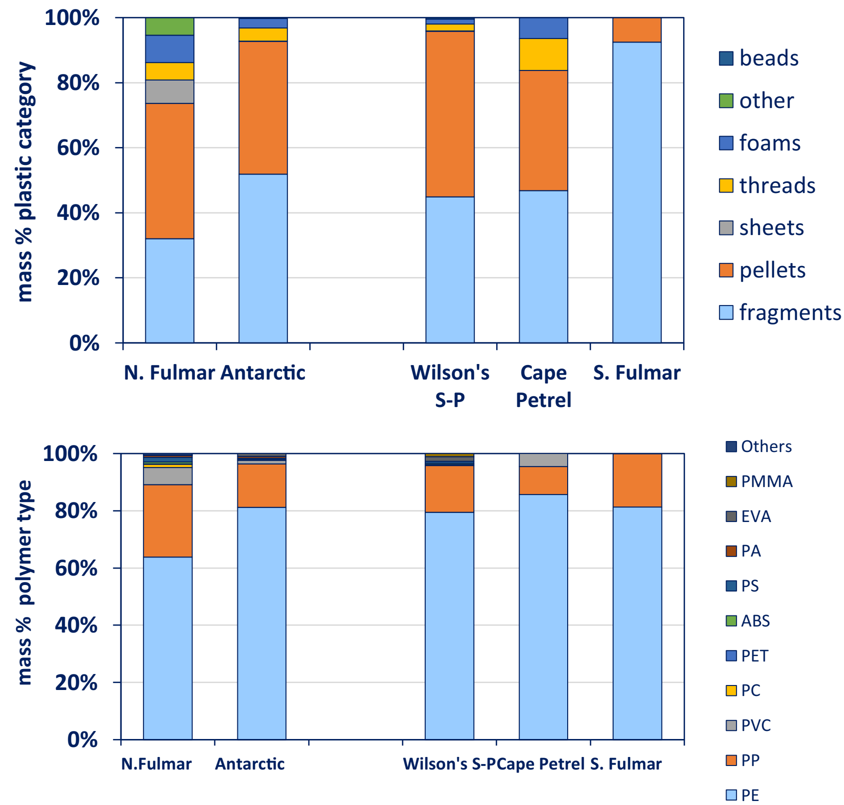

Fig. 5 Top: plastic categories ingested by northern fulmars from the 1980s to the 1990s and related seabird species from the Southern Ocean (all southern species combined and separately per species). Bottom: polymer categories of these plastics. Both graphs show proportions in terms of mass. Graph is based on data shown in Online Supplement Table 3.3a (N. fulmars) and 3.5a and b.

from the Netherlands (46%) and in Antarctic seabirds (31%). Since the 1990s, pellets decreased in northern fulmars, while mainly fragment mass increased (Van Franeker and Law 2015) and also PE mass decreased in the same time. Unfortunately no recent data of plastic ingestion by Antarctic seabirds is available that could confirm similar trends in the Southern Ocean. However, two recent studies from the Southern Ocean, investigating microplastics at the water surface, found PE and PP to be the dominant polymer types in non-fibrous plastics (Cincinelli et al. 2017; Isobe et al. 2017).

Threads were mainly found in Iceland and Svalbard, both remote places, where fishery-related plastic dominates the litter found on beaches (Bergmann et al. 2017; Falk-Andersson and Strietman 2019). The majority of threads (in terms of mass) ingested by all northern fulmars in the North Atlantic were made of PE (49%) and PP (21%). Only 3% of ingested threads comprised of PA (Online Supplement Table 3.3b), probably explained by the high density of PA, causing net and rope material made of PA to sink out of reach of surface-foraging seabirds. Soft materials such as sheets and foam are less abundant in birds from the Southern Ocean (Fig. 6). Seabirds migrate from their more polluted wintering areas to their breeding colonies in Antarctica (Van Franeker and Law 2015). Soft material digests quicker than hard pellets or fragments (Ryan 2015), and sheets and foam may therefore be excreted when arriving on their breeding locations on the continent. Soft plastic items may also disappear from the ocean's surface and therefore out of the reach of fulmarine petrels, before reaching the Southern Ocean (Suaria et al. 2020).

Foam in northern fulmar samples was identified as mainly being PVC (59% in terms of number, 42% of mass). PS comprised of only 5% in numbers and 2% of mass of foams found in the fulmar stomachs. A possible explanation might be the extremely low specific mass of PS foams, which may lead to rapid disappearance from open ocean environments where

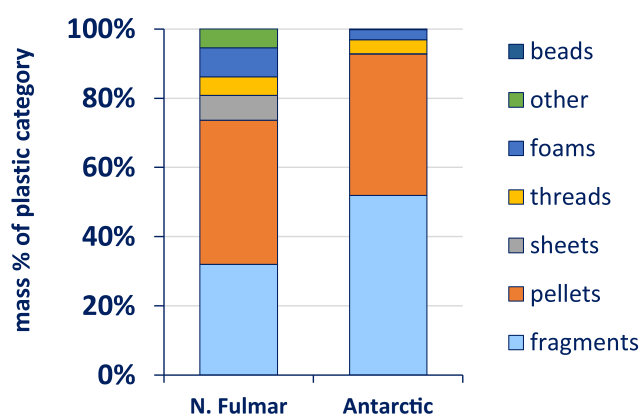

Fig. 6 Number of plastics in northern fulmars from the 1980s to the 1990s and procellariform seabirds from Antarctica per plastic category. Graph is based on data shown in Online Supplement Table 3.3a (N. fulmars) and 3.5a

fulmars forage. Different rates of processing on the materials in the bird's stomachs are another speculative interpretation. PVC was the predominant polymer type ingested by little auks (*Alle alle*) from the Arctic (Amélineau et al. 2016); however, almost all plastics (97.2%) the authors found were microfibres, a plastic category not considered in our study. PVC is a plastic type, usually containing high quantities of phthalate plasticizers (Hermabessiere et al. 2017). These substances are known for leaching from the plastics and for their endocrine disruptive characteristics (Oehlmann et al. 2009). PVC is the third most common plastic type in our seabird sample, and the associated risks of ingesting PVC should be of concern (Rochman 2015).

In seabirds, no polymer type specific preference has been reported. Plastic uptake by seabirds might simply reflect the background availability of plastics produced through the time and the distribution of marine plastic debris on the ocean surface. Polyethylene and PP are less dense than seawater, and almost all polymers, including those heavier than seawater, can be found in their expanded form as foam. This might explain the great availability of these polymers for the uptake by surface seizing seabirds. From the beginning of the industrial plastic production in the 1950s and onwards, PE and PP have always been the most commonly produced polymers over time (Geyer et al. 2017), resulting in widespread disposal.

Conclusion

FTIR has become a common identification method in plastic research. NIR has been used to a lesser extent; however, both methods are suitable for plastic ingestion studies. Caution should be given to the fact that especially FTIR tends to misidentify natural hard prey items as being plastic, mostly as synthetic polyamide. In order to reduce this type of error, we decided to use a reliability threshold of 80% with library matches. Basic knowledge of natural diet of the organism studied is valuable in order to evaluate the risk of small food fragments being misidentified as a synthetic polymer. Our results of plastic ingested by seabirds indicate a general predominance of PE and PP polymers, but the plastic category available at a specific location or in a specific time frame seems to be the driving factor of polymer proportions in seabirds, rather than variations in preference for different plastic types.

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Online Supplement to:

Global and temporal variation of polymer types ingested by the northern fulmar and southern hemisphere relatives

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Online Supplement Table 1: Details NIR and FTIR comparison

Plastics with polymer type and natural items analysed with FTIR and NIR. Details on plastic category and colour are given. For FTIR and NIR results are presented as ID match (plastic type with highest match score), the match score (0-100) with three different match score thresholds (>90%, >80% and >70%). All items were categorized as correct ID (correct polymer/natural type and match score higher than intended match score; No ID (lower match score than intended) and false ID (false polymer type but match score higher than intended match score).

Sample number	Polymer type	Object description	Category	Colour	Type	synthetic (1), natural (0)	FTIR ID	FTIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%	NIR ID	NIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%
CRT-TEST-001	PET	Water Bottle	fragment	light blue transparent	consumer plastic	1	PET	98.3	1	1	1							PET	97	1	1	1						
CRT-TEST-002		Chemical (Texel, July 2013; paraffine like)	other	white	paraffine	1	LDPE	95.5							1	1	1	PE	96							1	1	1
CRT-TEST-003	PVC	Waterpipe	fragment	grey	consumer plastic	1	PVC	95.2	1	1	1							PP	72				1	1				1
CRT-TEST-004		Chemical (Texel, July 2013; hard)	other	white	paraffine	1	Ionomer 2	84.7	1							1	1	PE	74	1	1							1
CRT-TEST-005		Fulmar foot web (skin)				0	PA6/66 GF FR	92.1							1	1	1	PA	67	1	1	1						
CRT-TEST-006	PS	Styrofoam	foam	whitish	consumer plastic	1	HIPS	97.7	1	1	1							ABS	89				1				1	1
CRT-TEST-007	SAN	School cup	fragment	colourprinted white	consumer plastic	1	PVC	77.6				1	1				1	ABS	90							1	1	1
CRT-TEST-008		plant - hard stem (reed like)				0	Arabic	86.9	1							1	1	PA	51	1	1	1						
CRT-TEST-009	PET	Food container	fragment	green	consumer plastic	1	LDPE	95.8							1	1	1	PET	88		1	1	1					
CRT-TEST-010	PE	Bag electric equipment	sheet	black printed transparent	consumer plastic	1	LDPE	93.9	1	1	1							PE	92	1	1	1						
CRT-TEST-011	PVC	vGansewinkel reference material	fragment	coloured	raw material	1	ABS	86.3				1				1	1	PVC	78			1	1	1				
CRT-TEST-012	PE	Bag	sheet	pink	consumer plastic	1	LDPE	94.8	1	1	1							PE	93	1	1	1						
CRT-TEST-013		Shellfish - Blue Mussel				0	PA HTN	91.5							1	1	1	PA	53	1	1	1						
CRT-TEST-014	PS	Meat tray	fragment	transparent	consumer plastic	1	PS	97.3	1	1	1							PS	93	1	1	1						
CRT-TEST-015	PLA	Compostable food container	fragment	transparent	bio-plastic	1	No result		1	1	1							PMMA	65	1	1	1						
CRT-TEST-016		Fish goby (small dried)				0	PA6/66 GF FR	89.5	1							1	1	PACC	58	1	1	1						
CRT-TEST-017	PET	Food container	fragment	dirty transparent	consumer plastic	1	PET	98	1	1	1							PET	97	1	1	1						

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CRT-TEST-018		Sprat fish bone				0	Arabic	88	1							1	1	PA	43	1	1	1						
CRT-TEST-019	PVC	vGansewinkel reference material	sheet	transparent	raw material	1	PVC	87.5		1	1	1						PVC	93	1	1	1						
CRT-TEST-020		Tomato skin				0	Arabic	88.3	1							1	1	PA	88	1							1	1
CRT-TEST-021	PP	CD box bottom	fragment	grey	consumer plastic	1	PP Homo	96.9	1	1	1							PP	96	1	1	1						
CRT-TEST-022		Fulmar feather 2				0	PA HTN	89.7	1							1	1	PA/ ABS	42	1	1	1						
CRT-TEST-023	7P0342	Compostable potato bag	sheet	lightly coloured	bio-plastic	1	PBT/PET GF	86.4	1							1	1	PVC	42	1	1	1						
CRT-TEST-024		Angler bone fragment				0	PA HTN	93							1	1	1	PA	53	1	1	1						
CRT-TEST-025	PC	Sample jar	fragment	transparent	consumer plastic	1	PC	99.6	1	1	1							PC	97	1	1	1						
CRT-TEST-026	Silica	Silica gel desiccant	pellet	transparent	consumer plastic	1	Silicon	88		1	1	1						PETG	37	1	1	1						
CRT-TEST-027	Cradonyl	Compostable pellet	pellet	white	bio-plastic	1	PA	80.2	1							1	1	CA	84				1				1	1
CRT-TEST-028	Century	Bioldegradable spoon	fragment	whitish	bio-plastic	1	Arabic	82.6		1	1	1						PA	83				1				1	1
CRT-TEST-029		Fish eyelens whiting				0	PA HTN	93.4							1	1	1	PA	70	1	1							1
CRT-TEST-030	PE	vGansewinkel reference material	fragment	blue	raw material	1	LDPE	93.7	1	1	1							PE	95	1	1	1						
CRT-TEST-031		Angler oogbol				0	PA HTN	86.4	1							1	1	PA	23	1	1	1						
CRT-TEST-032	PVC	Waterpipe	fragment	grey	consumer plastic	1	PVC	95.3	1	1	1							PP	64	1	1	1						
CRT-TEST-033		Crab, shield fragment				0	PA HTN	84.1	1							1	1	PA	41	1	1	1						
CRT-TEST-034	PE	vGansewinkel reference material	fragment	red	raw material	1	LDPE	91.9	1	1	1							PE	94	1	1	1						

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CRT-TEST-035		Fulmar toe nail				0	PA66	89	1							1	1	PA	38	1	1	1						
CRT-TEST-036	PE	vGansewinkel reference material	fragment	black	raw material	1	EMA	93	1	1	1							PS	13				1	1	1			
CRT-TEST-037	PP	Wrapper cellophane-like Post-it notes	sheet	orange printed transparent	consumer plastic	1	PMMA	88.2	1							1	1	PP	91	1	1	1						
CRT-TEST-038	Cradonyl	compostable fragment	fragment	redbrown	bio-plastic	1	Polyarylate	77.9	1	1							1	PMMA	81				1				1	1
CRT-TEST-039	PP	Wrapper dishwash tablet	sheet	printed transparent	consumer plastic	1	PA6	85.8	1							1	1	PP	89		1	1	1					
CRT-TEST-040	Cradonyl	ompostable fragment	fragment	whitish	bio-plastic	1	Arabic	80.3		1	1	1						PMMA	81				1				1	1
CRT-TEST-041		Harbour Seal hair				0	PA HTN	91.9							1	1	1	PA	60	1	1	1						
CRT-TEST-042	PET	vGansewinkel reference material	fragment	transparent	raw material	1	PET	97.4	1	1	1							PET	97	1	1	1						
CRT-TEST-043	PE	vGansewinkel reference material	sheet	transparent	raw material	1	LDPE	95.1	1	1	1							PE	92	1	1	1						
CRT-TEST-044	PA	SUIT fishing net	thread	dark green	consumer plastic	1	PA6 GF	94.6	1	1	1							PA	81		1	1	1					
CRT-TEST-045	PMMA	vGansewinkel reference material	fragment	white	raw material	1	PMMA	99.5	1	1	1							PMMA	92	1	1	1						
CRT-TEST-046	PC	vGansewinkel reference material	fragment	transparent	raw material	1	PC	99.7	1	1	1							PC	95	1	1	1						
CRT-TEST-047	PS	Food container	fragment	transparent	consumer plastic	1	HIPS	98.8	1	1	1							PS	95	1	1	1						
CRT-TEST-048		Shellfish - Oyster				0	Melamin	80.7	1							1	1	PA	11	1	1	1						
CRT-TEST-049	PP	vGansewinkel reference material	fragment	thick semitransparent sheet		1	PP Homo	98.2	1	1	1							PP	99	1	1	1						

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CRT-TEST-050		Fulmar feather 1				0	PA HTN	94.1							1	1	1	PA	55	1	1	1						
CRT-TEST-051	PS	Food container	fragment	transparent	consumer plastic	1	PS	98	1	1	1							PS	95	1	1	1						
CRT-TEST-052		Whelk eggs				0	Arabic	90.1							1	1	1	PA	48	1	1	1						
CRT-TEST-053	PVC	vGansewinkel reference material	fragment	Blue	raw material	1	ABS	87.7				1				1	1	PVC	76			1	1	1				
CRT-TEST-054		Crab, leg fragment				0	Aramid	87.3	1							1	1	PA	41	1	1	1						
CRT-TEST-055	PS	vGansewinkel reference material	fragment	brown	raw material	1	PS	98.5	1	1	1							PS	95	1	1	1						
CRT-TEST-056		Fulmar gizzard lining				0	PA HTN	90.8							1	1	1	PA	71	1	1							1
CRT-TEST-057	PET	PET - Sourcy Water Bottle	fragment	very light blue transparent	consumer plastic	1	PET	98.1	1	1	1							PET	96	1	1	1						
CRT-TEST-058	PP	PP - wrapper cellofaan like Post-it notes	sheet	transparent	consumer plastic	1	PMMA	89.4				1				1	1	PP	72			1	1	1				
CRT-TEST-059		Sheepwool natural from dyke				0	PA HTN	93.1							1	1	1	PA	56	1	1	1						
CRT-TEST-060	SAN	School cup	fragment	white	consumer plastic	1	SAN	94.6	1	1	1							ABS	91							1	1	1
CRT-TEST-061		wood - branch part				0	Arabic	90.7							1	1	1	PS	12	1	1	1						
CRT-TEST-062	PE	wrapper paper tissues	sheet	red	consumer plastic	1	LDPE	95.9	1	1	1							PE	92	1	1	1						
CRT-TEST-063		Fulmar bill 1				0	PA HTN	92.2							1	1	1	PA	72	1	1							1
CRT-TEST-064	PS	Coffee cup	fragment	white	consumer plastic	1	GPPS	97.3	1	1	1							PS	95	1	1	1						
CRT-TEST-065		Shellfish - Cockle				0	No result		1	1	1							POM	5	1	1	1						

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CRT-TEST-066	PP	Water can	fragment	green printed transparent	consumer plastic	1	PP Homo	99	1	1	1							PP	98	1	1	1						
CRT-TEST-067		Seaweed (Ulva)				0	Arabic	88.5	1							1	1	PA	48	1	1	1						
CRT-TEST-068	PVC	Dipped on cotton (offshore glove)	other	rubbery; blue	consumer plastic	1	PVC	86.9		1	1	1						PVC	95	1	1	1						
CRT-TEST-069		Cotton - inner part of SHOVA glove	thread	white		0	Arabic	87.3	1							1	1	PA	25	1	1	1						
CRT-TEST-070		Shelfish - Ensis old				0	No result		1	1	1							PA	32	1	1	1						
CRT-TEST-071	Polyester	Blue woven band	thread	dark blue	consumer plastic	1	PET GF	98.3							1	1	1	PET	79				1	1				1
CRT-TEST-072		jellyfish (dried)				0	Skin	77.5		1	1	1						PA	31	1	1	1						
CRT-TEST-073	PA	Tie-wrap	fragment	milky	consumer plastic	1	PA66	98.6	1	1	1							PA	94	1	1	1						
CRT-TEST-074		Shellfish (slipper shell)				0	Skin	90.3		1	1	1						PA	33	1	1	1						
CRT-TEST-075	Acryl	Acryl Sun sail	thread	Red	consumer plastic	1	No result					1	1	1				POM	41				1	1	1			
CRT-TEST-076		Angler cartilage				0	Arabic	87	1							1	1	PA	57	1	1	1						
CRT-TEST-077	PA	Fishing line (knotted)	thread	yellow	consumer plastic	1	PP Block	96.2							1	1	1	PP	87				1				1	1
CRT-TEST-078		Shrimp (dried carapax head)				0	Aramid	86.7	1							1	1	PA	65	1	1	1						
CRT-TEST-079		Angler tooth				0	Arabic	81.6	1							1	1	PA	52	1	1	1						
CRT-TEST-080	PVC	Outdoor chair cover	rubber	whitish	consumer plastic	1	PET GF	80.4				1				1	1	PVC	85		1	1	1					
CRT-TEST-081		Shellfish - Ensis young				0	No result		1	1	1							PA	17	1	1	1						
CRT-TEST-082	PVC	Isolation tape	sheet	blue	consumer plastic	1	PVC	82.5		1	1	1						PVC	92	1	1	1						

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CRT-TEST-083		wood - old				0	Arabic	97.2							1	1	1	PA	37	1	1	1						
CRT-TEST-084	PP	Sisal rope imitation	thread	brown	consumer plastic	1	PP	97.8	1	1	1							PP	55				1	1	1			
CRT-TEST-085		Sepia shield				0	No result		1	1	1							PA	11	1	1	1						
CRT-TEST-086	PA	nylon bolting Rings	fragment	whitish	consumer plastic	1	PA66	99.2	1	1	1							PA	97	1	1	1						
CRT-TEST-087		Fulmar bill 2				0	PA HTN	93.2							1	1	1	PA	75	1	1							1
CRT-TEST-088	PP	Food container	fragment	white	consumer plastic	1	PP Homo	98.4	1	1	1							PP	97	1	1	1						
CRT-TEST-089		fishbones from Fulmar stomach				0	Arabic	88.1	1							1	1	PA	51	1	1	1						
CRT-TEST-090	PVC	Cabrion Roof cover	rubber	black	consumer plastic	1	PMMA	94.8							1	1	1	PS	13				1	1	1			
CRT-TEST-091		Seaweed				0	Arabic	94.1							1	1	1	PA	52	1	1	1						
CRT-TEST-092	PP	Flag line	thread	white	consumer plastic	1	PP Block	93.6	1	1	1							PP	84		1	1	1					
CRT-TEST-093		tomato seed				0	Arabic	95.8							1	1	1	IONOMER	68	1	1	1						
CRT-TEST-094	Polyester	sailing band woven	thread	white	consumer plastic	1	PET	96.2							1	1	1	PET	72			1	1	1				
CRT-TEST-095	Arabic	Balloon	rubber	green	consumer plastic	1	Arabic	89.8		1	1	1						PET	81				1				1	1
CRT-TEST-096	PVC	PVC coated on Polyester	sheet	white	consumer plastic	1	ABS	89.8		1	1	1						PVC	77			1	1	1				
CRT-TEST-097	PET	Packaging container of a lamp	fragment	transparent	consumer plastic	1	PET	97.3	1	1	1							PET	96	1	1	1						
CRT-TEST-098	CA	Cigarette filter (used; beach)	other	whitish	from beach	1	PVDC	80.9				1				1	1	PA	62				1	1	1			
CRT-TEST-099		Bird bone (sternum Woodcock)				0	Arabic	92.1							1	1	1	PA	50	1	1	1						

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CRT-TEST-100	PA	Almega sportfishing line 0.5mm	thread	transparent	consumer plastic	1	PA6	98.8	1	1	1							PA	84		1	1	1					
CRT-TEST-101	PVC	Stair profile	rubber	brown	consumer plastic	1	No result					1	1	1				PET	40				1	1	1			
CRT-TEST-102	PE	Twisted rope	thread	orange	consumer plastic	1	LDPE	91.6	1	1	1							PE	97	1	1	1						
CRT-TEST-103		fossil shark tooth				0	PVDC	84.5	1							1	1	PS	16	1	1	1						
CRT-TEST-104	PA	Silvery white rope	thread	white	consumer plastic	1	PET GF	97.3							1	1	1	PET	84				1				1	1
CRT-TEST-105	?	Compostable Greenpen Mater-Bi	fragment	green	bio-plastic	1	Polyarylate	78.3	1	1							1	PA	87				1				1	1
CRT-TEST-106		Feathershaft Woodcock				0	PA HTN	93.9	1	1	1							PA	53	1	1	1						
CRT-TEST-107		Seaweed Laminaria				0	Arabic	93.6							1	1	1	PA	43	1	1	1						
CRT-TEST-108		Small melon seed				0	Arabic	92.9							1	1	1	CA	28	1	1	1						
CRT-TEST-109		Ray egg skin from Ducth coast				0	PA HTN	89.8							1	1	1	PA	62	1	1	1						
CRT-TEST-110		Nereis jaw from Fulmar stomach				0	PA HTN	90.6							1	1	1	PS	19	1	1	1						
CRT-TEST-111	PVC	Stair profile	rubber	black	consumer plastic	1	No result					1	1	1				PPO	18				1	1	1			
CRT-TEST-112	PE	Jar screw cap	fragment	yellow	consumer plastic	1	LDPE	91.4	1	1	1							PE	96	1	1	1						
CRT-TEST-113	PP	Rope	thread	brown	consumer plastic	1	PP Random	97.8	1	1	1							PP	89		1	1	1					
CRT-TEST-114		fish eyelens from Fulmar stomach				0	PA66 GF FR	90.6							1	1	1	PA	72	1	1							1
CRT-TEST-115		Wingshield from insect from fulmar stomach				0	PA6/66 GF FR	89.4	1							1	1	PA	67	1	1	1						

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CRT-TEST-116		Melon seeds from Fulmar stomach				0	Arabic	94.2							1	1	1	PA	66	1	1	1						
CRT-TEST-117		whelk egg from Fulmar stomach				0	PA HTN	92.4							1	1	1	PA	63	1	1	1						
CRT-TEST-118		squid jaw part from fulmar stomach				0	PA6/66 GF FR	93.8							1	1	1	POM	20	1	1	1						
CRT-TEST-119		squid eyelens from Fulmar stomach				0	PA6	88.4							1	1	1	PA	74	1	1							1
CRT-TEST-120	PA	Bolting ring	fragment	white	consumer plastic	1	PA6	99.5	1	1	1							PA	97	1	1	1						
CRT-TEST-121	PVC	Botaflex rubber	rubber	red	consumer plastic	1	Arabic	88.8				1				1	1	PVC	73			1	1	1				
CRT-TEST-122	PE	Plastic bag of postal magazine	sheet	transparent	consumer plastic	1	LDPE	95.4	1	1	1							PE	92	1	1	1						
CRT-TEST-123	PP	Rope multifibre	thread	orange	consumer plastic	1	PP	97.3	1	1	1							PP	81		1	1	1					
CRT-TEST-124	PA	woven safety band textile	thread	white	consumer plastic	1	PET	93.9							1	1	1	PET	74				1	1				1
CRT-TEST-125		fishbone from Fulmar stomach				0	Arabic	85.8	1							1	1	PA	48	1	1	1						
CRT-TEST-126		fish eyelens very small from Fulmar stomach				0	Aramid	91.3							1	1	1	PS	22	1	1	1						
CRT-TEST-127		Nereis jaw from Fulmar stomach				0	PA6/66 GF FR	91.4							1	1	1	PA	66	1	1	1						
CRT-TEST-128		otolith Whiting from Fulmar stomach				0	No result		1	1	1							PA	32	1	1	1						
CRT-TEST-129	SBS rubber	door stop	rubber	brown	consumer plastic	1	SBS	84.2		1	1	1						PP	13				1	1	1			
CRT-TEST-130	SIS rubber	door stop	rubber	white	consumer plastic	1	SIS	87.8		1	1	1						PVC	88				1				1	1

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CRT-TEST-131		Elastic Natural Rubber band broad	rubber	brown		0	Arabic	89	1							1	1	PVC	86	1							1	1
CRT-TEST-132		Elastic Natural Rubber band narrow	rubber	brown		0	Arabic	88.3	1							1	1	PET	87	1							1	1
CRT-TEST-133	PE	Beamtrawl net	thread	green	consumer plastic	1	PVDC	77.9				1	1				1	PE	92	1	1	1						
CRT-TEST-134	7P0204	Compostable banana bag; crispy	sheet	transparent	bio-plastic	1	No result		1	1	1							PMMA	69	1	1	1						
CRT-TEST-135		Manilla natural rope	thread	brown		0	Arabic	93.6							1	1	1	PA	57	1	1	1						
CRT-TEST-136		Parasitic copepod tubing				0	PA6/66 GF FR	89.4	1							1	1	PA	73	1	1							1
CRT-TEST-137		Vertebra fish from Fulmar stomach				0	Arabic	80.7	1							1	1	PA	56	1	1	1						
CRT-TEST-138	PS	vGansewinkel reference material	fragment	greyish white	raw material	1	PS	97.3	1	1	1							PS	94	1	1	1						
CRT-TEST-139	PS	vGansewinkel reference material	fragment	white	raw material	1	Urethan	79.5				1	1				1	ABS	93							1	1	1
CRT-TEST-140	PE	vGansewinkel reference material	fragment	blue	raw material	1	LDPE	91.8	1	1	1							PE	97	1	1	1						
CRT-TEST-141	PE	vGansewinkel reference material	fragment	grey	raw material	1	LDPE	92.1	1	1	1							PE	91	1	1	1						
CRT-TEST-142	PE	vGansewinkel reference material	fragment	green	raw material	1	LDPE	92.2	1	1	1							PE	88		1	1	1					
CRT-TEST-143	PE	vGansewinkel reference material	fragment	black	raw material	1	LDPE	92.4	1	1	1							PS	10				1	1	1			

Sample number	Polymer type	Object description	Category	Colour	Type	synthetic (1), natural (0)	FTIR ID	FTIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%	NIR ID	NIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%
CRT-TEST-144		Operculum whelk from Fulmar stomach				0	PA6/66 GF FR	92.4							1	1	1	PA	75	1	1							1
CRT-TEST-145		Onion skin from Fulmar stomach				0	Arabic	92.8							1	1	1	PA	48	1	1	1						
CRT-TEST-146		Fishbone from Fulmar stomach				0	Arabic	87.1	1							1	1	PA	58	1	1	1						
CRT-TEST-147	Silica	Silica gel desiccant spherules	other	purple	consumer plastic	1	Cellopha	89.4				1				1	1	PM MA	7	1	1	1						
CRT-TEST-148		Fishbone from Fulmar stomach				0	Arabic	81.9	1							1	1	POM	30	1	1	1						
CRT-TEST-149		Ray egg skin from Dutch coast				0	PA6/66 GF FR	88.5	1							1	1	PA	20	1	1	1						
CRT-TEST-150	PE	vGansewinkel reference material	fragment	black	raw material	1	LDPE	90.5	1	1	1							PP	18				1	1	1			
CRT-TEST-151	Arabic	Balloon rubber	other	mint green	consumer plastic	1	Arabic	78			1	1	1					PVC	83				1				1	1
CRT-TEST-152		Seaweed dried; Sacharina				0	Arabic	86.3	1							1	1	PA	41	1	1	1						
CRT-TEST-153		squid jaw part from Fulmar stomach				0	PA6/66 GF FR	92.4							1	1	1	PA	70	1	1							1
CRT-TEST-154	PE	vGansewinkel reference material	fragment	red	raw material	1	LDPE	91.8	1	1	1							PE	98	1	1	1						
CRT-TEST-155	ABS	vGansewinkel reference material	fragment	black	raw material	1	No result					1	1	1				PS	14				1	1	1			
CRT-TEST-156		Bulbous seed unknown				0	Arabic	92.9							1	1	1	PA	53	1	1	1						
CRT-TEST-157		Wool; sheep; painted blue				0	PA6/66 GF FR	90.6							1	1	1	PA	68	1	1	1						
CRT-TEST-158		Seal whisker				0	Aramid	87.6	1							1	1	PA	68	1	1	1						

Sample number	Polymer type	Object description	Category	Colour	Type	synthetic (1), natural (0)	FTIR ID	FTIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%	NIR ID	NIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%
CRT-TEST-159	ABS	vGansewinkel reference material	fragment	grey	raw material	1	ABS	97.2	1	1	1							ABS	92	1	1	1						
CRT-TEST-160		Bird bill outer layer (keratin) Eiderduck				0	Arabic	90.7							1	1	1	PA	70	1	1							1
CRT-TEST-161	ABS	vGansewinkel reference material	fragment	grey-white	raw material	1	ABS	82.9		1	1	1						PPO	78				1	1				1
CRT-TEST-162		Feathershaft Eiderduck				0	PA6/66 GF FR	93.8							1	1	1	PA	73	1	1							1
CRT-TEST-163	ABS	vGansewinkel reference material	fragment	green-transparent	raw material	1	ABS	93.8	1	1	1							ABS	94	1	1	1						
CRT-TEST-164	Silica	Silica gel desiccant spherules	other	transparent	consumer plastic	1	Arabic	86				1				1	1	PM MA	5	1	1	1						
CRT-TEST-165	ABS	vGansewinkel reference material	fragment	milky-transparent	raw material	1	PA612	96.5							1	1	1	PA/ ABS	69				1	1	1			
CRT-TEST-166		Bone bird Eiderduck sternum				0	Arabic	89.9	1							1	1	PA	55	1	1	1						
CRT-TEST-167		Footweb skin Eiderduck				0	PA6/66 GF FR	90							1	1	1	PA	67	1	1	1						
CRT-TEST-168	PE	Industrial pellet; beach	pellet	green	from beach	1	No result					1	1	1				PE	90	1	1	1						
CRT-TEST-169	PE	Industrial pellet; beach	pellet	transparent	from beach	1	No result					1	1	1				PE	94	1	1	1						
CRT-TEST-170	PE	Industrial pellet; beach	pellet	white	from beach	1	Silicon	80.2				1				1	1	PE	96	1	1	1						
CRT-TEST-171		Insect wing of fly				0	Aramid	90.1							1	1	1	ABS	24	1	1	1						
CRT-TEST-172	NBR rubber	Industrial pellet; beach	pellet	black	from beach	1	NBR	81.1		1	1	1						PS	30				1	1	1			
CRT-TEST-173		Seaweed Ulva				0	Arabic	92.2							1	1	1	PA	46	1	1	1						

Sample number	Polymer type	Object description	Category	Colour	Type	synthetic (1), natural (0)	FTIR ID	FTIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%	NIR ID	NIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%
CRT-TEST-174	PP	Industrial pellet; beach	pellet	white	from beach	1	No result					1	1	1				PP	85		1	1	1					
CRT-TEST-175		Barnacle parts				0	Melamin	77.9	1	1							1	PA	23	1	1	1						
CRT-TEST-176	PE	Plastic bag heavy sheet	sheet	transparent	consumer plastic	1	LDPE	95.8	1	1	1							PE	95	1	1	1						
CRT-TEST-177	PS	Black underside of CD box	fragment	black	consumer plastic	1	PS	98.6	1	1	1							PS	8				1	1	1			
CRT-TEST-178	PS	Transparent upperside of CD box	fragment	transparent	consumer plastic	1	PS	98	1	1	1							PS	95	1	1	1						
CRT-TEST-179		Crab carapax				0	Melamin	83.1	1							1	1	PA	38	1	1	1						
CRT-TEST-180		Clay-pellet hydrokorrel				0	Silicon	84.6	1							1	1	PS	17	1	1	1						
CRT-TEST-181	PE	Soft-foamed sheet for packaging	foam	white	consumer plastic	1	LDPE	95.7	1	1	1							PE	58				1	1	1			
CRT-TEST-182	PE	Bubble wrap	sheet	transparent	consumer plastic	1	LDPE	93.9	1	1	1							PE	86		1	1	1					
CRT-TEST-183		Stone from Fulmar stomach				0	No result		1	1	1							PA	22	1	1	1						
CRT-TEST-184	PE	soft airgun bullet	other	yellow	from beach	1	Ionomer	84.7				1				1	1	PE	98	1	1	1						
CRT-TEST-185	PS	Piepschuim - Polysterene foam cell	foam	white	consumer plastic	1	HIPS	94.3	1	1	1							ABS	70				1	1				1
CRT-TEST-186	PE	cap of jerrycan from beach	fragment	red	from beach	1	LDPE	91.5	1	1	1							PE	98	1	1	1						
CRT-TEST-187	PE	Bottle cap - from beach	fragment	blue dark	from beach	1	Ionomer	89.1				1				1	1	PE	97	1	1	1						
CRT-TEST-188		chemical? palmfat?	other		paraffine	1	LDPE	91.8							1	1	1	PE	91							1	1	1
CRT-TEST-189		seaweed blaasjeswier				0	Arabic	95.7							1	1	1	PI	7	1	1	1						
CRT-TEST-190	PE	Water bottle cap; beach	fragment	blue	from beach	1	LDPE	93.8	1	1	1							PE	98	1	1	1						

Sample number	Polymer type	Object description	Category	Colour	Type	synthetic (1), natural (0)	FTIR ID	FTIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%	NIR ID	NIR match score	Correct ID >90%	Correct ID >80%	Correct ID >70%	No ID >90%	No ID >80%	No ID >70%	False ID >90%	False ID >80%	False ID >70%
CRT-TEST-191	PVC	heavy type of bag in which a shirt was packed	sheet	transparent	consumer plastic	1	PVC	86.6		1	1	1						PVC	96	1	1	1						
CRT-TEST-192		Shellfish Oyster				0	No result		1	1	1							PA	16	1	1	1						
CRT-TEST-193	PP	plant pot; beach	fragment	brown	from beach	1	PP	95	1	1	1							PP	95	1	1	1						
CRT-TEST-194	PE	plug on airvalve of jerrycan; beach	fragment	transparent	from beach	1	LDPE	95.9	1	1	1							PE	98	1	1	1						
CRT-TEST-195		Toenail Eiderduck				0	PA66 GF FR	87.6	1							1	1	PA	67	1	1	1						
CRT-TEST-196	PET	softdrink bottle; beach	fragment	transparent	from beach	1	PET	96.2	1	1	1							PET	97	1	1	1						
CRT-TEST-197	PET	mineral water bottle; beach	fragment	bluish transparent	from beach	1	PET	96.7	1	1	1							PET	97	1	1	1						
CRT-TEST-198		chemical? Paraffin?	other	white	paraffine	1	LDPE	93.9							1	1	1	PE	82	1							1	1
CRT-TEST-199	PP	ice box	fragment	white	consumer plastic	1	PP	97.3	1	1	1							PP	96	1	1	1						
CRT-TEST-200		Squid eyelens from Fulmar stomach				0	PA6/66 GF FR	92.4							1	1	1	PA	76	1	1							1

Online Supplement Table 2 Polymer type abbreviations

ABBREVIATION	NAME
ABS*	Acrylonitrile butadiene styrene
CA*	Cellulose acetate
EMA	Copolymer of polyethylene
EST*	Elastomer
EVA*	Ethylene-vinyl acetate
HDPE	High density polyethylene
HIPS	High impact polystyrene
ION*	Ionmer
LDPE	Low density polyethylene
NABS*	Nylon/ABSblend
PA*	Nylon (polyamide)
PB*	Polybutylene
PBT*	Polybutylene terephthalate
PC*	Polycarbonate
PE*	Polyethylene
PET*	Polyethylene terephthalate
PETG*	Polyethylene terephthalate glycol
PI*	Polyimide
PMMA*	Polymethyl metacrylate
PMP*	Polymethyl pentane
POM*	Acetal (Polyoxymethylene)
PP*	Polypropylene
PPO*	Polyphenylene oxide
PPS*	Polyphenolyne sulfide
PS*	Polystyrene
PSO*	Polysulfone
PTT*	Polytrimethylene terephthalate
PUR*	Polyurethane
PVC*	Polyvinyl chloride
PVCD	Polyvinylidene chloride
SAN*	Styrene acrylonitrile
STP*	Styrenic terpolymer
TPV*	Thermoplastic elastomer

*Integrated in Phazir NIR library

Online Supplement Table 3: Details on plastic categories and polymer types found in this study

Table OS 3.1. Details of plastic categories found in seabirds. Per species, region and decennia, the number and percentage of each plastic category are given.

Species	Country	years	n birds	n plastics	fragment	pellet	sheet	thread	foam	other	bead	% fragmen	% pellet	% sheet	% thread	% foam	% other	% bead
Northern Fulmar	Netherlands	1982-2011	129	3439	1252	650	657	190	579	111	0	36%	19%	19%	6%	17%	3%	0%
Northern Fulmar	*NL1980-89*	*1980-89*	*(58)*	*(778)*	*213*	*356*	*69*	*43*	*89*	*8*	*0*	27%	46%	9%	6%	11%	1%	0%
Northern Fulmar	*NL1909-99*	*1990-99*	*(32)*	*(1129)*	*389*	*94*	*378*	*83*	*97*	*88*	*0*	34%	8%	33%	7%	9%	8%	0%
Northern Fulmar	*NL2010-11*	*2010-19*	*(39)*	*(1532)*	*650*	*200*	*210*	*64*	*393*	*15*	*0*	42%	13%	14%	4%	26%	1%	0%
Northern Fulmar	Faroe_Islands	2011	50	536	361	36	49	35	50	4	1	67%	7%	9%	7%	9%	1%	0%
Northern Fulmar	Iceland	2011	46	342	199	14	39	25	55	1	9	58%	4%	11%	7%	16%	0%	3%
Northern Fulmar	Svalbard	2013	35	595	428	16	47	76	24	3	1	72%	3%	8%	13%	4%	1%	0%
Northern Fulmar	**TOTAL**	**1982-2013**	**260**	**4912**	**2240**	**716**	**792**	**326**	**708**	**119**	**11**	46%	15%	16%	7%	14%	2%	0%
Wilsons Storm-pe	Antarctica	1986-98	45	342	194	110	14	2	20	0	2	57%	32%	4%	1%	6%	0%	1%
Cape Petrel	Antarctica	1985-86	9	37	15	11	0	1	10	0	0	41%	30%	0%	3%	27%	0%	0%
S. Fulmar	Antarctica	1984	2	11	10	1	0	0	0	0	0	91%	9%	0%	0%	0%	0%	0%
Snow Petrel	Antarctica	1985	1	1		0	0	0	1	0	0	0%	0%	0%	0%	100%	0%	0%
	ANTARCTICA total	**1984-98**	57	391	219	122	14	3	31	0	2	56%	31%	4%	1%	8%	0%	1%
		TOTAL	**317**	**5303**	**2459**	**838**	**806**	**329**	**739**	**119**	**13**	**46%**	**16%**	**15%**	**6%**	**14%**	**2%**	**0%**

Table OS 3.2a. Plastic categories and polymer types in all birds. Number and mass of plastic categories with associated percentages. Included are plastics ingested by all birds (all species, all years, all locations).

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	n items	n items	n items	n items	n items	n items	n items	n items
PE	2402	587	1	214	50	28	1508	14
PP	1043	130	1	300	63	12	535	2
PVC	371	9	0	76	14	239	28	5
PC	84	0	0	1	0	1	8	74
PET	72	2	0	2	0	66	2	0
ABS	61	5	0	4	2	40	8	2
PS	45	12	3	0	0	9	16	5
PA	35	5	0	7	11	2	9	1
EVA	15	1	0	4	2	0	8	0
PMMA	8	0	7	0	0	0	1	0
others	19	0	0	1	2	8	6	2
SUM	4155	751	12	609	144	405	2129	105

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	gram	gram	gram	gram	gram	gram	gram	gram
PE	32.2264	11.561	0.0022	1.6709	0.5838	0.1936	16.9788	1.2359
PP	10.7673	2.4694	0.0022	0.7657	1.2297	0.0423	6.2537	0.0043
PVC	3.2389	0.2102	0	0.3283	0.6225	1.1628	0.1533	0.7618
PC	0.2268	0	0	0.0028	0	0.0016	0.0911	0.1313
PET	1.1751	0.044	0	0.0037	0	1.0473	0.0801	*0*
ABS	0.2830	0.1212	0	0.008	0.0253	0.0596	0.0155	0.0534
PS	0.9735	0.1906	0.0075	0	0	0.142	0.1482	0.4852
PA	0.4480	0.1255	0	0.0007	0.0907	0.0117	0.0101	0.2093
EVA	0.0466	0.0085	0	0.0045	0.0073	0	0.0263	*0*
PMMA	0.0108	0	0.0085	0	0	0	0.0023	*0*
others	0.2476	0	0	0.0036	0.0135	0.0814	0.0317	0.9327
SUM	49.644	14.731	0.0204	2.7882	2.5728	2.7423	23.7911	3.8139

Polymer	ALL SAMPLES (4155)	PELLETS (751)	BEADS (12)	SHEETS (609)	THREADS (144)	FOAMS (405)	FRAGMENTS (2129)	OTHER PLASTIC (105)
	% of n	% of n	% of n	% of n	% of n	% of n	% of n	% of n
PE	58.8%	78.4%	8.3%	34.7%	41.0%	7.0%	72.1%	13.1%
PP	24.8%	17.1%	8.3%	50.3%	41.0%	3.0%	24.3%	1.9%
PVC	8.6%	1.2%	0.0%	12.1%	8.7%	60.3%	1.2%	8.4%
PC	1.9%	0.0%	0.0%	0.2%	0.0%	0.3%	0.4%	69.2%
PET	1.7%	0.3%	0.0%	0.3%	0.0%	16.6%	0.1%	0.0%
ABS	1.4%	0.7%	0.0%	0.6%	1.2%	10.1%	0.4%	1.9%
PS	1.0%	1.6%	25.0%	0.0%	0.0%	2.3%	0.7%	4.7%
PA	0.8%	0.7%	0.0%	1.1%	6.8%	0.5%	0.4%	0.9%
EVA	0.3%	0.1%	0.0%	0.6%	1.2%	0.0%	0.4%	0.0%
PMMA	0.2%	0.0%	58.3%	0.0%	0.0%	0.0%	0.0%	0.0%
others	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Polymer	ALL SAMPLES (53g)	PELLETS (15g)	BEADS (0.02g)	SHEETS (2.8g)	THREADS (2.6g)	FOAMS (2.7g)	FRAGMENTS (24g)	OTHER PLASTIC (3.0g)
	% of g	% of g	% of g	% of g	% of g	% of g	% of g	% of g
PE	66.0%	78.7%	10.8%	64.1%	37.4%	7.3%	72.5%	39.8%
PP	20.9%	16.6%	10.8%	25.0%	39.0%	1.6%	25.4%	0.1%
PVC	6.6%	1.4%	0.0%	10.2%	19.7%	43.7%	0.6%	31.8%
PC	0.4%	0.0%	0.0%	0.1%	0.0%	0.1%	0.4%	4.2%
PET	2.2%	0.3%	0.0%	0.1%	0.0%	39.4%	0.3%	0.0%
ABS	0.5%	0.8%	0.0%	0.2%	0.8%	2.2%	0.1%	1.7%
PS	1.9%	1.3%	36.8%	0.0%	0.0%	5.3%	0.6%	15.6%
PA	0.9%	0.8%	0.0%	0.0%	2.9%	0.4%	0.0%	6.7%
EVA	0.1%	0.1%	0.0%	0.1%	0.2%	0.0%	0.1%	0.0%
PMMA	0.0%	0.0%	41.7%	0.0%	0.0%	0.0%	0.0%	0.0%
others	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table OS 3.2b. Plastic categories and polymer types in northern fulmars. Number and mass of plastic categories with associated percentages. Included are plastics ingested by all northern fulmars (all years, all northern hemisphere locations).

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	n items	n items	n items	n items	n items	n items	n items	n items
PE	2118	489		202	49	28	1336	14
PP	990	107		300	62	12	507	2
PVC	368	9		76	14	237	27	5
PC	84			1		1	8	74
PET	72	2		2		66	2	
ABS	57	5		4	2	38	6	2
PS	40	12	3			7	13	5
PA	34	5		7	10	2	9	1
EVA	10			4	2		4	
PMMA	8		7				1	
Other polymers	18	0	0	1	2	8	5	2
SUM	3799	629	10	597	141	399	1918	105

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	gram	gram	gram	gram	gram	gram	gram	gram
PE	30.8189	10.9233		1.669	0.5289	0.1936	16.2682	1.2359
PP	10.5048	2.3321		0.7657	1.2194	0.0423	6.141	0.0043
PVC	3.2165	0.2102		0.3283	0.6225	1.1445	0.1492	0.7618
PC	0.2268			0.0028		0.0016	0.0911	0.1313
PET	1.1751	0.044		0.0037		1.0473	0.0801	
ABS	0.2786	0.1212		0.008	0.0253	0.0589	0.0118	0.0534
PS	0.9659	0.1906	0.0075			0.1399	0.1427	0.4852
PA	0.4357	0.1255		0.0007	0.0784	0.0117	0.0101	0.2093
EVA	0.0293			0.0045	0.0073		0.0175	
PMMA	0.0108		0.0085				0.0023	
Other polymers	0.2475	0	0	0.0036	0.0135	0.0814	0.0316	0.1174
SUM	47.9099	13.9469	0.0160	2.7863	2.4953	2.7212	22.9456	2.9986

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	% of n	% of n	% of n	% of n	% of n	% of n	% of n	% of n
PE	55.8%	77.7%	0.0%	33.8%	34.8%	7.0%	69.7%	13.3%
PP	26.1%	17.0%	0.0%	50.3%	44.0%	3.0%	26.4%	1.9%
PVC	9.7%	1.4%	0.0%	12.7%	9.9%	59.4%	1.4%	4.8%
PC	2.2%	0.0%	0.0%	0.2%	0.0%	0.3%	0.4%	70.5%
PET	1.9%	0.3%	0.0%	0.3%	0.0%	16.5%	0.1%	0.0%
ABS	1.5%	0.8%	0.0%	0.7%	1.4%	9.5%	0.3%	1.9%
PS	1.1%	1.9%	30.0%	0.0%	0.0%	1.8%	0.7%	4.8%
PA	0.9%	0.8%	0.0%	1.2%	7.1%	0.5%	0.5%	1.0%
EVA	0.3%	0.0%	0.0%	0.7%	1.4%	0.0%	0.2%	0.0%
PMMA	0.2%	0.0%	70.0%	0.0%	0.0%	0.0%	0.1%	0.0%
Other polymers	0.5%	0.0%	0.0%	0.2%	1.4%	2.0%	0.3%	1.9%
SUM	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Polymer	ALL SAMPLES	PELLETS	BEADS	SHEETS	THREADS	FOAMS	FRAGMENTS	OTHER PLASTIC
	% of g	% of g	% of g	% of g	% of g	% of g	% of g	% of g
PE	64.3%	78.3%	0.0%	59.9%	21.2%	7.1%	70.9%	41.2%
PP	21.9%	16.7%	0.0%	27.5%	48.9%	1.6%	26.8%	0.1%
PVC	6.7%	1.5%	0.0%	11.8%	24.9%	42.1%	0.7%	25.4%
PC	0.5%	0.0%	0.0%	0.1%	0.0%	0.1%	0.4%	4.4%
PET	2.5%	0.3%	0.0%	0.1%	0.0%	38.5%	0.3%	0.0%
ABS	0.6%	0.9%	0.0%	0.3%	1.0%	2.2%	0.1%	1.8%
PS	2.0%	1.4%	46.9%	0.0%	0.0%	5.1%	0.6%	16.2%
PA	0.9%	0.9%	0.0%	0.0%	3.1%	0.4%	0.0%	7.0%
EVA	0.1%	0.0%	0.0%	0.2%	0.3%	0.0%	0.1%	0.0%
PMMA	0.0%	0.0%	53.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Other polymers	0.5%	0.0%	0.0%	0.1%	0.5%	3.0%	0.1%	3.9%
SUM	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table OS 3.3a. Temporal comparison. Number and mass of plastics ingested by northern fulmars from the Netherlands during three decennia with associated percentages.

Fulmar Netherlands particle numbers				
Plastic	all years	1980-89	1990-99	2010-19
Subcategory	n particle	n particle	n particle	n particle
pellets	650	356	94	200
beads	0	0	0	0
sheets	657	69	378	210
threads	190	43	83	64
foams	579	89	97	393
fragments	1252	213	389	650
other	111	8	88	15
Industrial	650	356	94	200
User	2789	422	1035	1332
Total	3439	778	1129	1532

Fulmar Netherlands particle sizes *(mass per particle)*				
Plastic	all years	1980-89	1990-99	2010-19
Subcategory	*g/particle*	*g/particle*	*g/particle*	*g/particle*
pellets	0.022	0.022	0.022	0.023
beads	0.000	0.000	0.000	0.000
sheets	0.005	0.008	0.006	0.003
threads	0.012	0.015	0.015	0.005
foams	0.006	0.012	0.004	0.005
fragments	0.011	0.019	0.009	0.009
other	0.021	0.074	0.006	0.082
Industrial	0.022	0.022	0.022	0.023
User	0.009	0.016	0.008	0.007
Total	0.011	0.019	0.009	0.010

Fulmar Netherlands plastic category %'s in numbers				
Subcategory	all years	1980-89	1990-99	2010-19
	% of n	% of n	% of n	% of n
pellets	19%	46%	8%	13%
beads	0%	0%	0%	0%
sheets	19%	9%	33%	14%
threads	6%	6%	7%	4%
foams	17%	11%	9%	26%
fragments	36%	27%	34%	42%
other	3%	1%	8%	1%
Industrial	19%	46%	8%	13%
User	81%	54%	92%	87%
Total	100%	100%	100%	100%

Fulmar Netherlands plastic category %'s in mass				
Subcategory	all years	1980-89	1990-99	2010-19
	% of mass	% of mass	% of mass	% of mass
pellets	37%	54%	20%	32%
beads	0%	0%	0%	0%
sheets	9%	4%	21%	5%
threads	6%	4%	13%	2%
foams	9%	8%	4%	13%
fragments	34%	27%	36%	40%
other	6%	4%	5%	8%
Industrial	37%	54%	20%	32%
User	63%	46%	80%	68%
Total	100%	100%	100%	100%

Table OS 3.3b. Temporal comparison. Number and mass per polymer type of plastics ingested by northern fulmars from the Netherlands during three decennia with associated percentages. Match score threshold is set at >80%.

Polymer	n	mass	n	mass	n	mass
	1980-89	1980-89	1990-99	1990-99	2010-19	2010-19
PE	523	10.7566	339	2.1032	537	6.2497
PP	83	1.4436	328	3.6485	295	2.8065
PVC	9	0.1357	101	1.0759	226	0.9306
PC			81	0.2182	3	0.0086
PET	2	0.0275	3	0.0045	51	1.1019
ABS	6	0.028	12	0.1045	20	0.1127
PS	10	0.2024	8	0.1304	10	0.4297
PA	4	0.0431	10	0.088	7	0.0166
EVA	1	0.0019	6	0.0209	3	0.0065
PMMA	1	0.0023				
others	4	0.0439	6	0.0673	3	0.1126
SUM	643	12.685	894	7.4614	1155	11.7754

Polymer	% n	% mass	n	mass	n	mass
	1980-89	1980-89	1990-99	1990-99	2010-19	2010-19
PE	81%	85%	38%	28%	46%	53%
PP	13%	11%	37%	49%	26%	24%
PVC	1%	1%	11%	14%	20%	8%
PC	0%	0%	9%	3%	0%	0%
PET	0%	0%	0%	0%	4%	9%
ABS	1%	0%	1%	1%	2%	1%
PS	2%	2%	1%	2%	1%	4%
PA	1%	0%	1%	1%	1%	0%
EVA	0%	0%	1%	0%	0%	0%
PMMA	0%	0%	0%	0%	0%	0%
others	1%	0%	1%	1%	0%	1%
SUM	100%	100%	100%	100%	100%	100%

Table OS 3.4a. Regional comparison. Number and mass of plastics ingested by northern fulmars from the Netherlands (2010-2019), the Faroe Islands, Iceland and Svalbard with associated percentages.

Fulmar plastic category in numbers				
Subcategory	NETH	Faroe I	Iceland	Svalbard
	n	n	n	n
pellets	200	36	14	16
bead	0	1	9	1
sheets	210	49	39	47
threads	64	35	25	76
foams	393	50	55	24
fragments	650	361	199	428
other	15	4	1	3
Industrial	200	37	23	17
User	1332	499	319	578
Total	1532	536	342	595

Fulmar particle *mass per particle*				
Subcategory	NETH	Faroe I	Iceland	Svalbard
	g/particle	*g/particle*	*g/particle*	*g/particle*
pellets	0.023	0.020	0.024	0.015
beads	0.000	0.000	0.000	0.000
sheets	0.003	0.003	0.004	0.024
threads	0.005	0.006	0.045	0.020
foams	0.005	0.012	0.006	0.000
fragments	0.009	0.017	0.020	0.004
other	0.082	0.066	0.048	0.212
Industrial	0.023	0.019	0.015	0.015
User	0.007	0.015	0.017	0.009
Total	0.010	0.015	0.017	0.009

Fulmar plastic category %'s in numbers				
	NETH	Faroe I	Iceland	Svalbard
Subcategory	% of n	% of n	% of n	% of n
pellets	13%	7%	4%	3%
bead	0%	0%	3%	0%
sheets	14%	9%	11%	8%
threads	4%	7%	7%	13%
foams	26%	9%	16%	4%
fragments	42%	67%	58%	72%
other	1%	1%	0%	1%
Industrial	13%	7%	7%	3%
User	87%	93%	93%	97%
Total	100%	100%	100%	100%

Fulmar plastic category %'s in mass				
	NETH	Faroe I	Iceland	Svalbard
Subcategory	% of mass	% of mass	% of mass	% of mass
pellets	32%	9%	6%	4%
bead	0%	0%	0%	0%
sheets	5%	2%	2%	20%
threads	2%	2%	19%	28%
foams	13%	7%	5%	0%
fragments	40%	76%	67%	35%
other	8%	3%	1%	12%
Industrial	32%	9%	6%	5%
User	68%	91%	94%	95%
Total	100%	100%	100%	100%

Table OS 3.4b. Regional comparison. Number and mass per polymer type of plastics ingested by northern fulmars from the Netherlands, the Faroe Islands, Iceland and Svalbard with associated percentages. Match score threshold is set at >080%.

Polymer	Netherlands	Netherlands	Faroe I	Faroe I	Iceland	Iceland	Svalbard	Svalbard
	n	mass	n	mass	n	mass	n	mass
PE	537	6.2497	293	4.7069	157	3.202	280	2.2552
PP	295	2.8065	109	1.6724	58	0.954	106	1.5251
PVC	226	0.9306	15	0.4583	6	0.0143	11	0.6017
PC	3	0.0086						
PET	51	1.1019	10	0.0288	5	0.0043	1	0.0081
ABS	20	0.1127	2	0.005	16	0.0086	1	0.0198
PS	10	0.4297	6	0.1035	3	0.0653	3	0.0346
PA	7	0.0166	5	0.2236	2	0.048	6	0.0164
EVA	3	0.0065						
PMMA					7	0.0085		
others	*0.9887446*	*0.988476*	*0.98194*	*0.9674*	*0.9608*	*0.9851*	*0.98289*	*0.99541*
SUM	1152.9887	12.651276	440.982	8.16587	254.961	5.29007	408.983	5.45631

Polymer	Netherlands	Netherlands	Faroe I	Faroe I	Iceland	Iceland	Svalbard	Svalbard
	%n	%mass	%n	%mass	%n	%mass	%n	%mass
PE	46%	53%	66%	65%	62%	74%	68%	51%
PP	26%	24%	25%	23%	23%	22%	26%	34%
PVC	20%	8%	3%	6%	2%	0%	3%	13%
PC	0%	0%	0%	0%	0%	0%	0%	0%
PET	4%	9%	2%	0%	2%	0%	0%	0%
ABS	2%	1%	0%	0%	6%	0%	0%	0%
PS	1%	4%	1%	1%	1%	2%	1%	1%
PA	1%	0%	1%	3%	1%	1%	1%	0%
EVA	0%	0%	0%	0%	0%	0%	0%	0%
PMMA	0%	0%	0%	0%	3%	0%	0%	0%
others	0%	1%	1%	0%	0%	0%	0%	0%
SUM	100%	100%	100%	100%	100%	100%	100%	100%

Table OS 3.5a. Global comparison. Number of plastics ingested by seabird species from Antarctica, with associated percentages.

Species	n plastics	fragment	pellet	sheet	thread	foam	other	bead	% fragment	% pellet	% sheet	% thread	% foam	% other	% bead
Wilsons Storm-petrel	342	194	110	14	2	20	0	2	57%	32%	4%	1%	6%	0%	1%
Cape Petrel	37	15	11	0	1	10	0	0	41%	30%	0%	3%	27%	0%	0%
S. Fulmar	11	10	1	0	0	0	0	0	91%	9%	0%	0%	0%	0%	0%
Snow Petrel	1		0	0	0	1	0	0	0%	0%	0%	0%	100%	0%	0%
SUM	**391**	**219**	**122**	**14**	**3**	**31**	**0**	**2**	**56%**	**31%**	**4%**	**1%**	**8%**	**0%**	**1%**

Table OS 3.5b. Global comparison. Number and mass per polymer type of plastics ingested by seabird species from Antarctica, with associated percentages. Match score threshold is set at >80%.

	All ANTARCTIC spp			
Polymer	Antarctic	Antarctic	Antarctic	Antarctic
	n items	gram	% of n	% of g
PE	284	1.4075	80%	81%
PP	53	0.2625	15%	15%
PVC	3	0.0224	1%	1%
PC			0%	0%
PET			0%	0%
ABS	4	0.0044	1%	0%
PS	5	0.0076	1%	0%
PA	1	0.0123	0%	1%
EVA	5	0.0173	1%	1%
PMMA			0%	0%
others	*1*	*0.0001*	0%	0%
SUM	**356**	**1.7**	**100%**	**100%**

	All Wilson's Storm-petrel			
Polymer	WSP	WSP	WSP	WSP
	n items	gram	% of n	% of g
PE	252	0.8558	79%	79%
PP	50	0.1754	16%	16%
PVC	1	0.0041	0.3%	0.4%
PC			0%	0%
PET			0%	0%
ABS	4	0.0044	1.3%	0.4%
PS	5	0.0076	1.6%	0.7%
PA			0%	0%
EVA	5	0.01730	1.6%	1.6%
PA	1	0.01230	0.3%	1.1%
others	*1*	*0.00010*	0.3%	0.0%
SUM	**319**	**1.1**	**100%**	**100%**

	All Cape Petrel			
Polymer	DAP	DAP	DAP	DAP
	n items	gram	% of n	% of g
PE	22	0.3411	81%	86%
PP	2	0.0386	7%	10%
PVC	2	0.0183	7.4%	4.6%
others	*1*	*0.00010*	3.7%	0.0%
SUM	**27**	**0.4**	**100%**	**100%**

	All Southern Fulmar			
Polymer	FGO	FGO	FGO	FGO
	n items	gram	% of n	% of g
PE	10	0.2106	83%	81%
PP	1	0.0485	8%	19%
others	*1*	*0.00010*	8.3%	0.04%
SUM	**12**	**0.3**	**100%**	**100%**

Snow Petrel (1 foam PPO with IDP<0.8)		
Polymer	n	mass
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PPO	0	0

Online Supplement Table 4. Details on polymer identification methods using infrared spectroscopy and match score thresholds applied in different studies.

Search ended in March 2020.

Group	**Threshold level >%**	**References**
Seabirds	80%	Leopold et al. 2019; this study*
	75%	Amélineau et al. 2016; Le Guen et al. 2020
	60-85%	Avery-Gomm et al. 2016
	No details	Álvarez et al. 2018; Bessa et al. 2019; Lenzi et al. 2016; Nicastro et al. 2018; Yamashita et al. 2011*; Zhu et al. 2019a
Marine mammals	80%	Moore et al. 2019; Van Franeker et al. 2018
	70%	Hudak & Sette 2019; Nelms et al. 2019; Caron et al. 2018
	60%	Lusher et al. 2015
	No details	Besseling et al. 2015; Bravo Rebolledo & van Franeker 2015; Eriksson & Burton 2003; Perez-Venegas et al. 2020; Zhu et al. 2019b
Turtles	No details	Pham et al. 2017; Rizzi et al. 2019
Marine fish	93%	Savoca et al. 2019
	85%	Bessa et al. 2018; Capillo et al. 2020; Ory et al. 2017
	80%	Bernardini et al. 2018; Digka et al. 2018; Garcia-Garin et al. 2019; Karthik et al. 2018
	70%	Akoueson et al. 2020; Alomar et al. 2017; Bour et al. 2018; Goswami et al. 2020; Lefebvre et al. 2019; Morgana et al. 2018; Nelms et al. 2018; Ogonowski et al. 2019; Ory et al. 2018; Su et al. 2019; Tanaka & Takada 2016; Zhang et al. 2019
	75%	Kühn et al. 2020
	60%	Avio et al. 2015; Avio et al. 2020; Bucol et al. 2020; Kroon et al. 2018; Lusher et al. 2013; Markic et al. 2018
	No details	Al-Salem et al. 2020; Alomar & Deudero 2017; Baalkhuyur et al. 2020; Bianchi et al. 2020; Bråte et al. 2016; Cannon et al. 2016; Chagnon et al. 2018; Chan et al. 2019; Cheung et al. 2018; Compa et al. 2018; Fernández & Anastasopoulou 2019; Foekema et al. 2013; Giani et al. 2019; Güven et al. 2017; Halstead et al. 2018; Hermsen et al. 2017; Herrera et al. 2019; Jabeen et al. 2017; Karlsson et al. 2017; Karuppasamy et al. 2020; Kühn et al. 2018; Kumar et al. 2018; McGoran et al. 2017; Murphy et al. 2017; Neves et al. 2015; Pegado et al. 2018; Pellini et al. 2018; Pozo et al. 2019; Renzi et al. 2019; Rummel et al. 2016; Sbrana et al. 2020; Steer et al. 2017; Welden et al. 2018; Wesch et al. 2016; Wieczorek et al. 2018; Zhu et al. 2019c
*NIR was used		

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