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Where does Arctic beach debris come from? Analyzing debris composition and provenance on Svalbard aided by citizen scientists

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Plastic debris is ubiquitous in all ecosystems and has even reached locations that humans will hardly reach such as the deep ocean floor and the atmosphere. Research has highlighted that plastic debris is now pervasive even in remote Arctic regions. While modeling projections indicated local sources and long-distance transport as causes, empirical data about its origin and sources are scarce. Data collected by citizen scientists can increase the scale of observations, especially in such remote regions. Here, we report abundance and composition data of marine debris collected by citizen scientists on 14 remote Arctic beaches on the Spitsbergen archipelago. In addition, citizen scientists collected three large, industrial sized canvas bags (hereafter: big packs), filled with beached debris, of which composition, sources and origin were determined. A total debris mass of 1,620 kg was collected on about 38,000 m² (total mean = 41.83 g m⁻², SEM = ± 31.62). In terms of abundance, 23,000 pieces of debris were collected on 25,500 m² (total mean = 0.37 items of debris m⁻², SEM = ± 0.17). Although most items were plastic in both abundance and mass, fisheries waste, such as nets, rope, and large containers, dominated in mass (87%), and general plastics, such as packaging and plastic articles, dominated in abundance (80%). Fisheries-related debris points to local sea-based sources from vessels operating in the Arctic and nearby. General plastics could point to both land- and ship based sources, as household items are also used on ships and debris can be transported to the north *via* the oceans current. Overall, 1% of the items (206 out of 14,707 pieces) collected in two big packs (2017 and 2021), bore imprints or labels allowing an analysis of their origin. If the categories 'global' and 'English language' were excluded, most of identifiable items originated from Arctic states (65%), especially from Russia (32%) and Norway (16%). But almost a third of the items (30%) was of European provenance, especially from Germany (8%). Five percent originated from more distant sources (e.g. USA, China, Korea, Brazil). Global measures such as an efficient and legally binding plastic treaty with improved upstream measures and waste management are urgently needed, to lower the amount of plastic entering our environments and in turn lifting the pressure on the Arctic region and its sensitive biota.

KEYWORDS

abandoned lost or otherwise discarded fishing gear, Arctic, beach debris, citizen science, derelict fishing gear, marine litter, plastic pollution, Polar Regions

1 Introduction

Recent research has highlighted that novel entities including plastic pollution already exceed the planetary boundary (Persson et al., 2022), as production and releases are increasing at a pace that surpasses the global capacity for assessment, monitoring and mitigation. This corresponds with the consensus that plastic debris has become ubiquitous in marine ecosystems including remote uninhabited Arctic beaches (Bergmann et al., 2017b). The Arctic is no longer seen as “one of the last unspoiled wildernesses” on Earth, but as an ecosystem that likely constitutes a sink for marine anthropogenic debris with increasing pollution levels over time (van Sebille et al., 2012; Parga Martínez et al., 2020; Bergmann et al., 2022b). This will be exacerbated by the growing global plastic production, which is projected to double by 2045 and reach 1.1 billion metric tons (Geyer, 2020), 11% of which enter aquatic environments (Borrelle et al., 2020). Furthermore, the formation of a sixth accumulation area has been predicted for the Nordic Seas (van Sebille et al., 2012; Onink et al., 2019). And with temperatures rising at a fourfold higher rate than the global average (Rantanen et al., 2022), the sea ice extent decreases giving plastic debris the chance to penetrate yet deeper into the Arctic Ocean (Bergmann and Klages, 2012). This exacerbates the pressure on sensitive Arctic biota, such as polar bears, reindeer, seals, and seabirds (Bergmann et al., 2017a). The consequences could be serious, as wildlife becomes entangled in nets or rope or ingests plastic debris (Bergmann et al., 2017b; Collard and Ask, 2021; Bergmann et al., 2022b). This is also observed on the Svalbard archipelagos, where most recorded waste was related to the fisheries (Bergmann et al., 2017a; Nashoug, 2017).

Although research has recently highlighted the presence of plastic debris in some compartments of the Fram Strait such as the sea surface, water column and the deep seafloor (Bergmann et al., 2016; Tekman et al., 2017; Grøsvik et al., 2018; Parga Martínez et al., 2020; Tekman et al., 2022a), such observations rarely allow identification of the provenance of debris. Modeling patterns indicate that a large part of debris drifts northwards with the Atlantic or originates from local sources (Pogojeva et al., 2021; Strand et al., 2021), however, empirical evidence is still limited. Beaches on remote uninhabited islands intercept prevailing water currents and the debris they carry (Lavers and Bond, 2017), therefore the collection of physical samples for analyzing the origin of the debris could be a good approach, especially as macroplastic on beaches was estimated to constitute 23% of the global ocean plastics (Isobe and Iwasaki, 2022). Similarly, a global meta-analysis of anthropogenic debris at the sea surface, on beaches and on the seafloor indicated highest quantities on beaches (Haarr et al., 2022).

Citizen science studies increasingly complement academic research as they expand the spatial and temporal scale of observations (Nelms et al., 2017; Walther et al., 2018), especially with regard to understudied remote ecosystems (Bergmann et al., 2017a) on a local, regional and international scale (Hidalgo-Ruz and Thiel, 2015). During the Covid-19 pandemic, where travel was limited and a surge of production, consumption and disposal of single use plastics occurred, the importance of citizen science became even more apparent, as travel restrictions hindered scientists from visiting specific survey sights and citizen scientists were able to retrieve samples since they were on site already (Ammendolia and Walker,

2022). Engaging citizens in science can also increase science and ocean literacy and thereby establish trust and motivate behavior changes (Nelms et al., 2017; Locritani et al., 2019).

Here, we present debris data from 14 Arctic beaches, and from three large, industrial-sized canvas bags (hereafter: big packs), filled with Arctic beach debris collected by citizen scientists on Svalbard. We quantified the debris mass and abundance per m² to determine current pollution levels and composition of Arctic beaches. These data were compared with those from the seafloor (Parga Martínez et al., 2020) and sea surface (Tekman et al., 2022a) in the region to delineate potential sinks of marine debris. The provenance of debris was determined to assess if items come from local or distant sources. Furthermore, debris items were inspected for date information to assess their age and the approximate time of pollution. In addition, we analyzed if items can be assigned to a certain sector, and in connection with that, what the debris entry points into the ocean could be: land-based or sea-based sources. Such knowledge is important to tailor solutions to reduce Arctic plastic pollution, and as baselines for future monitoring of the efficiency of upstream interventions such as a UN Plastics Treaty (Stokstad, 2022).

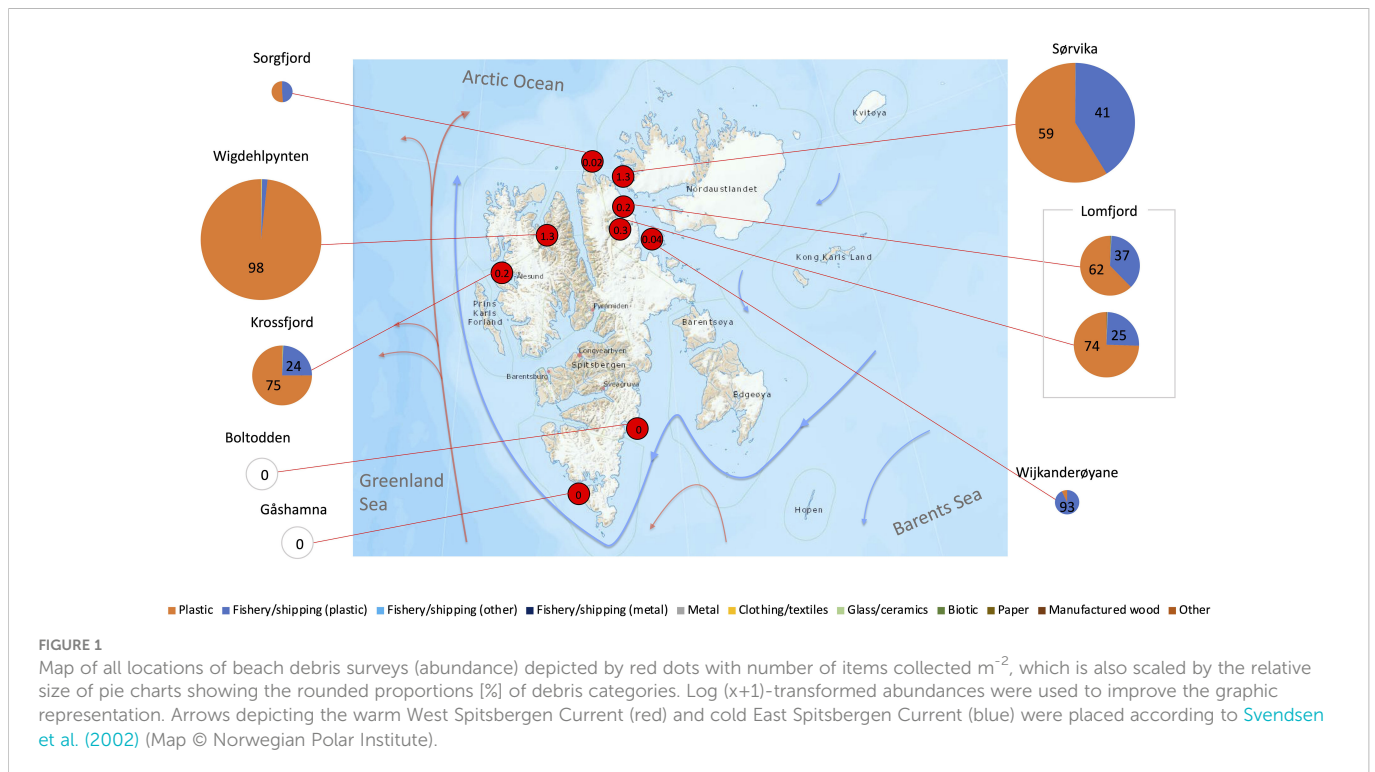
2 Material and Methods

All beach surveys were carried out by citizen scientists during tourist cruises between 2016 and 2021, which were organized and led by a tour guide and supported by the ship crew. This collaboration was sought by an experienced tour guide (Birgit Lutz) who already conducted cleanups during shore excursions and wished to support science after reading media reports on marine debris floating in Arctic waters prompted by the publication of Bergmann et al., 2016. A protocol for surveys was co-developed *via* video conferences to be feasible for visitor groups on Arctic beaches.

2.1 Study area

The sampling locations were located on the Spitzbergen archipelago in the eastern Arctic, which is influenced by several current systems that can be separated into warm- and cold-water currents (Figure 1). The West Spitsbergen Current (WSC) transports warmer waters from the Atlantic Ocean towards the north along the west side of Svalbard (Greenland Sea) (Przybylak et al., 2012). Cold waters are transported by the East Spitsbergen Current (ESC), which flows from the Arctic Ocean through the Nansen Basin past the east and along the southern part of Svalbard (Barents Sea), until it transports the water masses along the west (Greenland Sea) back towards the north pole (Wassmann et al., 2019). Another influence in this region are fisheries, especially in the Greenland Sea, off Svalbard and the Barents Sea (Garcia, 2007). The three main target species caught by Norwegian vessels in the Svalbard Fishery Protection Zone (1980 – 2013) include capelin (*Mallotus villosus*), cod (*Gadus morhua*) and shrimp (*Pandalus borealis*) (Misund et al., 2016).

The selection of survey locations depended on cruise schedule, weather, and sea conditions. Two numerical factors were recorded: area size and observer number.



2.2 Survey and sampling design

All citizen scientists were adults. Their number varied between 1 to 38 observers depending on the group size of the cruise (Tables 1–4). Overall, the citizen scientists did not have detailed prior knowledge but were given a presentation on Arctic plastic pollution beforehand, which also explained the procedure and protocol of the surveys (see 2.3.1) and use of the equipment provided (hand-held Global Positioning System device (Garmin eTrex 30 x), measuring band, spring balances (KERN 285-052; ≤ 5 kg and 285-502; ≤ 50 kg; $\pm 0.3\%$ accuracy)). All transects were laid out before taking samples and were of different sizes depending on the shoreline and terrain on site and ranged from 500 to ca. 5,500 m^2 . Using the GPS device, the geographic position of the corners of the transects, as well as their length and width were determined. The citizen scientists combed through this area for up to three hours and collected and sorted all anthropogenic items larger than 0.2 cm into different categories. Their weight and abundance were recorded along with beach properties and other metadata. Photographs were taken for a plausibility check and polar bear watches were held during all surveys. Participants were informed about the results *via* social media.

2.2.1 Sampling for provenance

In three of the transects, located in Hinlopen Strait, the collected debris was sent to AWI, for a more detailed analysis (Table 3). The first big pack (dimensions: 1.34 \times 1.20 \times 0.90 m; 1,443 m^3) was collected on a north-facing beach on Kiepertøya (Beach 2) in 2017, an island located in the south of the Hinlopen Strait. The transect area was calculated after sampling, as it was located around a bay. The second one was filled on Tommeløya (Beach 5), an island, which is part of the small archipelago of Tommeløyane, further north in the Hinlopen Strait. The sack was collected from an area of 600 m^2 . Here, the sides of the rectangle measured a = 20 m, b = 30 m, c = 28 m, and d = 8 m. The area was calculated using the

“Theorem of Pythagoras”. Debris for the third big pack was once more collected on Kiepertøya (Beach 3). However, this was a different beach, also facing north. The measuring tool from TopoSvalbard (Norwegian Polar Institute) helped calculate a length of 163 m between the coordinates. The width was determined on site with 15 m from the shoreline (= 2520 m^2). In the cases where the citizen scientists sampled for provenance, only pieces that did not fit in the big packs, where then documented on the survey forms and/or photographed.

2.3 Categorizing debris

2.3.1 Beach monitoring forms

The survey sheets, which were filled out by citizen scientists while on site and collecting debris, listed various debris types, such as fisheries-related debris (nets, ropes, floats) and other plastics, paper, glass/ceramics, biotic waste, etc. They were co-developed with the expedition leader, aiming for a simple, quick, and feasible design amenable to citizen science under cold Arctic conditions. Improvements, such as a slightly more distinguished categorization of debris have been made over time. In addition, the abundance of debris was recorded using a tally chart (since 2017). The survey sheets, including the information on weight, abundances and debris types were kept by Birgit Lutz (co-Author and expedition leader) and then forwarded to MB and ANM. To enable a retrospective harmonization of data, we added the code of Fleet et al. (2021) to our debris typology, which we had devised already in 2016 (Tables 1–3).

2.3.2 Big packs

In the absence of harsh Arctic conditions, the big packs could be analyzed in more detail at AWI. Each pack was inspected by different people, though all were executed or supervised by Melanie Bergmann.

TABLE 1 Details of beach surveys undertaken by citizen scientists on Svalbard.

	Boltodden	Wijkanderøyane	Lomfjord 1	Lomfjord 2	Sørvika 1	Sørvika 2	Wigdehlpynten	Krossfjord	Gåshamna	Total sum	Mean	SEM
Date	08.08.21	Jan 2019	07.08.17	06.08.18	23.08.17	11.08.21	17.09.17	15.08.21	07.08.21			
Longitude (°N)	77°30.048	79°20.391	79°32.88	79°25.50	79°57.334	79°56.491	79°23.991	79°09.452	76°56.395			
Latitude (°E)	018°12.525	019°28.430	018°02.10	017°46.03	018°37.941	016°43.378	013°58.632	011°38.303	015°48.593			
Distance to water [m]	0	0 - 2	1 - 30	0.5	0.5	0	7	0	0			
Substrate	Sand, rock	Rock	Pebble	Pebble	Pebble	Pebble	Sand, rock	Pebble	Sand, pebble			
Driftwood frequency	n.a.	None	None	Low	High	Medium	n.a.	Low	n.a.			
Exposure	Ocean	Strait	Fjord	Fjord	Strait	Fjord	Fjord	Fjord	Bay			
Marine region	Barents Sea	Barents Sea	Barents Sea	Barents Sea	Barents Sea	Greenland Sea	Greenland Sea	Greenland Sea	Greenland Sea			
Observer number	1	23	20	30	26	1	26	2	1			
Survey length × width [m]	100 × 10	65 × 24	n.a.	422 × 5	n.a.	112 × 15	179 × 15	130 × 15	50 × 10			
Transect area [m ²]	1,000	1,560	5,487*	2,110	2,048*	1,680	2,685	1,950	500	19,020	2,113	472.52
Fishery/shipping, p (pl_fi)		0.03	0.08	0.06	0.53	0.01	0.02	0.05	0	0.79	0.09	0.06
Plastic (pl)		0.003	0.14	0.19	0.76	0.01	1.24	0.16		2.51	0.28	0.14
Clothing/textiles (ct)							0.001			0.001	0.0002	0.0002
Fishery/shipping metal (me_fi)					0.0005					0.0005	0.0001	0.0001
Metal (me)			0.0002	0.0009	0.002		0.0007			0.003	0.0003	0.0001
Glass/ceramics (gc)			0.0009				0.001	0.001		0.003	0.0004	0.0002
Biotic (fw)				0.0005						0.0005	0.0001	0.0001
Manufactured wood (wo)			0.0007	0.0005	0.0005					0.002	0.0002	0.0001
Other (n.d.)								0.0005		0.001	0.0001	0.0001
Total sum	0	0.04	0.22	0.26	1.29	0.02	1.26	0.22	0	3.31	0.37	0.17

All debris abundances are given in count m⁻². N.a.: information not available. p: plastic, n.d.: not defined. (*) Area calculations based on GPS corner coordinates. The letters in brackets behind the debris types refer to the category levels used by Fleet et al. (2021) and enable a retrospective harmonization of data.

TABLE 2 Details of beach surveys undertaken by citizen scientists on Svalbard.

	Bol	Wij	Lom 1	Lom 2	Alp	Isf	Sør 1	Sør 2	Cro	Sor	Rei	Wig	Kro	Bru	Gås	Total sum	Mean	SEM
Date	08.08.21	Jan 2019	07.08.17	06.08.18	22.08.16	28.07.16	20.06.16	23.08.17	18.08.16	11.08.21	08.06.16	17.09.17	15.08.21	31.05.16	07.08.21			
Longitude (°N)	77° 30.048	79° 20.391	79° 32.88	79° 25.50	80° 20.568	80° 41.728	79° 57.334	79° 57.334	79°55.787	79°56.491	79°44.276	79°23.991	79°09.452	78°26.678	76° 56.395			
Latitude (°E)	018° 12.525	019° 28.430	018° 02.10	017° 46.03	024° 45.537	020° 54.782	018° 37.941	018° 37.941	016°54.151	016°43.378	013°51.042	013°58.632	011°38.303	011°49.231	015° 48.593			
Distance to water [m]	0	0 - 2	1 - 30	0.5	5.7 - 7	0.5	0.5	0.5	0.5 - 2	0	0.2	7	0	20	0			
Substrate	Sand, pebble	Rock	Pebble	Pebble	Sand	Rock	Pebble	Pebble	Sand, pebble	Pebble	Sand, pebble	Sand, rock	Pebble	Sand, pebble	Sand, pebble			
Driftwood frequency	n.a.	None	None	Low	Medium	High	High	High	Low	Medium	Low	n.a.	Low	Medium	n.a.			
Exposure	Ocean	Strait	Fjord	Fjord	Fjord	Bay	Strait	Strait	Fjord	Fjord	Fjord	Fjord	Fjord	Strait	Bay			
Marine region	Barents Sea	Barents Sea	Barents Sea	Barents Sea	Arctic Sea	Arctic Sea	Barents Sea	Barents Sea	Greenland Sea	Greenland Sea	Greenland Sea	Greenland Sea	Greenland Sea	Greenland Sea	Greenland Sea			
Observer number	1	23	20	30	30	15	38	26	28	1	18	26	2	26	1			
Survey length × width [m]	100 × 10	65 × 24	n.a.	422 × 5	100 × 52	90 × 20	n.a.	n.a.	90 × 20.5	112 × 15	120 × 14	179 × 15	130 × 15	90 × 20	50 × 10			
Transect area [m²]	1,000	1,560	5,487*	2,110	2,559	1,800	2,048*	2,048*	1,845	1,680	1,680	2,685	1,950	1,800	500	30,752	2,050	281.76
Fishery/shipping, p (pl_fi)		0.29	7.22	11.40	21.65	5.22	13.13	9.15		0.86	481.13	6.15	0.68	15.94		572.83	38.19	31.69
Plastic (pl)		0.01	1.28	5.13	2.08	5.78	6.84	2.71	3.21	0.21	0.83	4.67	1.43	7.33		41.51	2.77	0.67
Clothing/textiles (ct)						0.11						0.13		0.56		0.80	0.05	0.04
Fishery/shipping metal (me_fi)							0.98	3.79						0.72		5.49	0.37	0.26
Metal (me)			0.01	0.08	0.00	0.22		0.002				0.34		0.06		0.70	0.05	0.03
Glass/ceramics (gc)			0.30		0.31	0.44						0.82	0.03	2.67		4.57	0.30	0.18
Biotic (fw)				0.02												0.02	0.00	0.00

(Continued)

TABLE 2 Continued

	Bol	Wij	Lom 1	Lom 2	Alp	Isf	Sør 1	Sør 2	Cro	Sor	Rei	Wig	Kro	Bru	Gås	Total sum	Mean	SEM
Manufactured wood (wo)			0.01	0.02	0.002			0.002			1.43					1.46	0.10	0.10
Other (n.d.)													0.12			0.12	0.01	0.01
Total sum	0	0.30	8.82	16.65	24.04	11.78	19.98	12.84	7.01	1.07	483.39	12.10	2.26	27.28	0	627.51	41.83	31.62

All debris masses are shown in $g\ m^{-2}$. P: plastic, me: metal, n.d.: material not defined. N.a.: information not available. Abbreviations: Bol (Boltodden), Wij (Wijkanderøyane), Lom 1 (Lomfjord 1), Lom 2 (Lomfjord 2), Alp (Alpinøya), Isf (Isflakbukta), Sør 1 (Sørvika 1), Sør 2 (Sørvika 2), Cro (Crozierpynten), Sor (Sorgfjord), Rei (Reindiersodden), Wig (Wigdehlpnyten), Kro (Krossfjord), Bru (Brucebukta), Gås (Gåshamna). (*) Area calculations based on GPS corner coordinates. The letters in brackets behind the debris types refer to the category levels used by Fleet et al. (2021) and enable a retrospective harmonization of data.

TABLE 3 Summary of results of high-resolution analyses of beach debris in big packs.

	Kiepertøya 1	Tommelen	Kiepertøya 2	Total sum	Mean	SEM
Date	23/07/17	01/19	09/08/21			
Longitude (°N)	79°58.685	79°33.200	78°58.655			
Latitude (°E)	21°39.480	18°44.940	21°40.081			
Distance to water [m]	0.5	1 - 3	0			
Substrate	Sand, rock	Pebble	Sand, pebble			
Driftwood frequency	High	High	High			
Exposure	Strait	Strait	Strait			
Marine region	Barents Sea	Barents Sea	Barents Sea			
Observer number	30	10	13			
Length × width [m]	~200 × 20	n.a.	168 × 15**			
Transect area [m²]	3,999*	600*	2,250	6,849	2,283	981
Nets/ropes (pl_fi_net_/pl_fi_)	35	48	49	131	44	5

(Continued)

TABLE 3 Continued

	Kiepertøya 1	Tommelen	Kiepertøya 2	Total sum	Mean	SEM
Large containers (pl_fi_box_plbx)	10	7	7	25	8	1
Buoy/floats (pl_nn_flb)	3	2	5	9	3	1
Other		0.05	0.4	0.4	0.2	0.2
Fishery/shipping n.d., (pl_fi_ofi)	0.01			0.01	0.01	
Fishery/shipping metal (me_fi)	1			1	1	
Metal (me)	0.4	0.1	0.01	0.5	0.2	0.1
Strapping bands (pl_nn_stb)	5	1	0.3	6	2	1
Plastic foil (pl_nn)	0.4	3	0.3	3	1	1
Plastic article (pl)	2	2	0.2	4	1	1
Foam (p), (pl_nn_frg)	0.1	0.1	0.01	0.3	0.1	0.04
Plastic packaging (pl_fc)	1	19	1	21	7	6
Sanitary/medical waste	0.002			0.002	0.002	
Rubber (ru)	1	1	1	3	1	0.1
Unidentifiable plastics (pl)	3	12	2	17	6	3
Glass (gc)	0.01	1		1	0.4	0.4
Paper (pp)	0.05	0.1		0.1	0.1	0.003
Manufactured wood (wo)	0.003		0.01	0.01	0.01	0.003
Material n.d.		1		1	0.4	0.4
Total	62	97	66	225	75	11

All debris masses are presented in g m⁻². p: plastic, me: metal, n.d.: material not defined. (*) Area calculations based on GPS corner positions. (**) length determined with TopoSvalbard measuring tool (Norwegian Polar Institute). The letters in brackets behind the debris types refer to the category levels used by Fleet et al. (2021) and enable a retrospective harmonization of data.

Anna Natalie Meyer inspected the debris collected in 2021, forming the basis for the categorization of different types (Table 4), as well as going over some of the debris items collected in 2019. During the categorization process of all three big packs all items bearing markings, writing or imprints were put aside to determine their provenance.

All debris that could be, without a doubt, identified as items from the fishing/shipping industry, were categorized as such. Examples include rope and nets, fish boxes, baskets and crates. They were not categorized as other plastics, as vessels operating in waters near Svalbard are possible sources for marine debris found on the surveyed beaches. Less well-constrained items such as strapping bands and plastic foil were listed separately.

2.4 Determination of provenance and age

All items in the three big packs bearing marks, writing, labels, or imprints, were scrutinized to determine their age or country of origin (hereafter: provenance), which refers to the country that an item was likely produced in. Note, that this is currently the only way to narrow down its origin, but it does not necessarily reflect that this is where debris entered the ocean or environment. So, while these data indicate how far debris can potentially be transported, they have to be interpreted with care.

All items collected from Kiepertøya in 2021 with marks were weighed, photographed and the information transcribed and translated. If necessary, a magnifying glass or binocular was used for a closer examination of items collected in 2019 and 2021. In some cases, “Google Lens” was used, which can translate and find pictures of similar-looking or identical items online and more by hovering the camera over an item. This served as an overview for items or even

helped define what a piece was or what it had been used for. The provenance of items was determined based on the following criteria: (1) geographic information; (2) language (if multiple languages were shown, the language listed first was used); (3) company information (in some cases, inquiries were made regarding production country and date etc.) and (4) barcode. Items that are distributed at a global scale (e.g., Tetra Pak, Nestlé, Coca Cola) were classed as “Global”. The category “English language” was used for items with English writing, which cannot be assigned to the UK or US unambiguously. Figure 2 shows examples of items, classification and methods. Once the country of origin was determined, the debris was categorized according to Table 4. Year or date information was recorded.

2.5 Fourier transform infrared spectroscopy (FTIR)

The polymer type of all items collected in 2019 and 2021, for which the provenance could be determined and for which a physical item was still available, was determined by attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR; ALPHA II model by Bruker Optics). In addition, a small subsample of ropes and strapping bands was analyzed to confirm their polymer identity. Here, 12.5% of all ropes (82 ropes out of 657 in total) and 1% of all strapping bands (20 out of 1819) were randomly selected. Using the software OPUS, the spectra were compared to polymers in the database and a hit quality above 700 (0-1000) was deemed satisfactory. In addition, siMPle software (Primpke et al., 2020) was used whose hit quality range lies between 0.01 and 1 and a threshold of 0.7 was used for making the final decisions on the material types, as hit qualities were higher than in OPUS.

TABLE 4 Material and categorization of big pack debris, including examples (n.d. = not defined).

Material	Category	Examples
Plastic	Fishery/shipping plastic	Nets, rope, large containers (jerry cans, canisters, etc.), crates, fish boxes, floats
	Strapping bands	Plastic straps often used on pallets
	Foil	Foil often used to wrap fish
	Plastic article	Lighter, bullet casing, tape, canvas, toothbrush, toy, helmet, flashlight
	Foam	Styrofoam, other foam
	Plastic packaging	Bottles, caps, food containers
	Sanitary/medical waste	Syringes
	Rubber	Shoes, balloon parts, rubber gloves
	Unidentifiable plastics	Not identifiable plastics, fragments
Metal	Fishery/shipping metal	Metal buoy
	Metal	Shotgun cartridge, metal ring
Glass	Glass	Bottle
Paper	Paper	Cardboard
Wood	Manufactured wood	Cork, pieces of planks
n.d.	Other	Material of debris is not defined



FIGURE 2

Photographs of items for which the provenance was determined, thus (A) Global, (B) Germany, (C) Norway, (D) Russia, (E) Italy, (F) Global, (H) Sweden, (I) Denmark, (J) English language.

2.6 Statistical analysis

All survey data were converted to count or weight per square meter to enable comparisons. To analyze the data, we investigated two factors that could influence the abundance, weight, and composition of beach debris. The numerical factors “transect area size” and “number of observers” were recorded upon landing, although for some transects the size had to be calculated afterwards, using photos and digital measuring tools.

Analyses were run on data from all beaches, excluding the big pack beaches Kiepertøya 1 and 2 and Tommelen since elaborate methods used in the laboratory were not comparable with the beach surveys. The relationship between total mass or abundance and the

numerical factors “Transect area size” and “Number of observers”, was assessed using the Spearman rank order correlation and the Pearson correlation with Minitab 18.

3 Results

3.1 Arctic beach debris surveys

3.1.1 Abundance of beached debris

Overall, on all nine beaches, 8,299 pieces were collected on a total area of 19,000 m², resulting in 0.27 pieces of debris m⁻² (Figure 1).

However, the mean of all nine beaches was 0.37 items m⁻² (± SEM = 0.17). The most common material observed was plastic (99.6%), including both general (76.9%) and fisheries/shipping plastic (22.7%) (Figure 1).

The highest abundance was recorded at Sørvika and Wigdehlpynnten (1.3 items m⁻²) with general plastic dominating (Table 1). In contrast, no debris was found in transects on Boltodden and Gåshamna, the only two beaches that were only sampled by one (albeit very experienced) person. In addition, Boltodden was characterized as “open ocean”. The only location, where more fisheries/shipping plastic than general plastic was observed was Wijkanderøyane (93% versus 7%). Table 1 summarizes the characteristics, debris quantities and composition of all beaches.

The Spearman’s test for the number of debris items and our two numerical factors showed a significant positive correlation for “transect area size” (N = 9, rho = 0.76, p = 0.020) and “observer number” (N = 9, rho = 0.86, p = 0.003) indicating that a larger transect area or a higher helper number correlates with higher debris abundance.

3.1.2 Mass of beached debris

The citizen scientists collected a mass of 1,147 kg of debris on roughly 30,800 m² of transect area over the course of this study giving a total of 37 g m⁻². The mean of the mass recorded on the fifteen beaches was 41.83 ± 31.62 g m⁻², of which 98% were made of plastic overall (Figure 3). Fisheries-related plastic accounted for 90% of the plastics and general plastic for 8%. The highest mass was collected at Reindiersodden (483 g m⁻²), where a very heavy rope fender dominated the mass and resulted in nearly 100% fisheries/shipping plastic for this beach. The next highest masses were recorded at Brucebukta (27 g m⁻²) and Alpinioya (24 g m⁻²), again dominated by fisheries-related plastics (58% and 90%, respectively). On

Crozierpynten, Krossfjord and Isflakbukta fisheries-related plastic did not dominate. However, fisheries-related metal dominated (54%) at Crozierpynten, in the north, followed by the composition on Krossfjord, in the west, and Isflakbukta in the high north, where general plastic dominated (63% and 49%, respectively). A summary of all beach characteristics, debris mass and composition is given in Table 2.

The Spearman’s test suggests a significant positive relationship between the mass of debris and observer numbers (N = 15, rho = 0.659, p = 0.007), implying that a higher number of observers collects a greater debris mass. With a larger data set, a correction factor could be calculated to account for this source of variability. However, the restricted number of surveys undertaken, does not yet suffice to produce a robust correction factor. Executing the test without outliers, did not affect its outcome. There was no significant correlation between transect area size and debris mass.

3.2 High-resolution debris composition of three big packs

Since no data on the abundance of big pack 2 (Tommelen) were recorded, only the mass of all three big packs is described in the following section. The debris from the three big packs collected on Kiepertøya and Tommelen was examined more thoroughly than is possible on Arctic beaches. Some 240,000 g (62 g m⁻²) of debris were inspected from the first big pack (Kiepertøya, 2017). The second big pack (Tommelen, 2019) weighed ca. 60,000 g (97 g m⁻²) and the third (Kiepertøya, 2021) contained ca. 167,000 g of debris (66 g m⁻²) (Table 3).

“Plastic” dominated in all three samples (Figure 4). “Fisheries/shipping plastic” accounted for the greatest share. However, the big pack from Tommelen had a lower proportion of fisheries-related plastic (58%) compared to both Kiepertøya campaigns (78 and 92%).

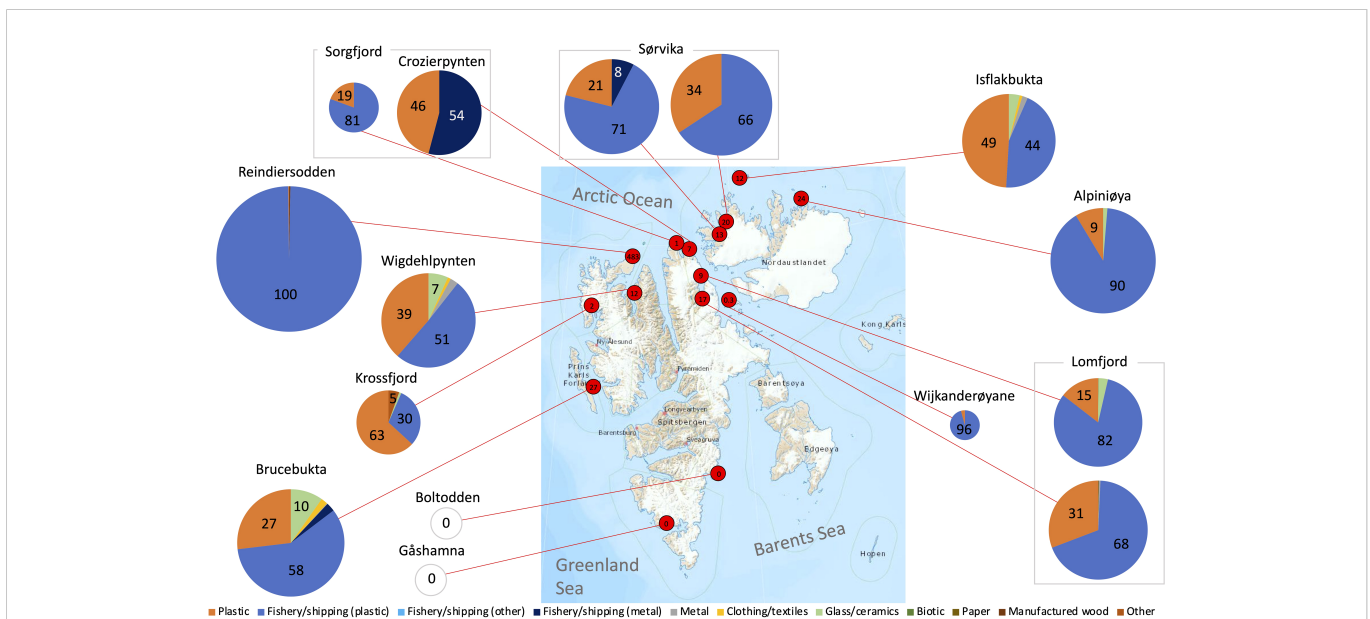


FIGURE 3 Map of all locations of beach debris surveys (mass) depicted by red dots with the mass in g m⁻², which is also scaled by the relative size of pie charts showing the rounded proportions [%] of debris categories. Log (x+1)-transformed mass was used to improve the graphic representation (Map © Norwegian Polar Institute).

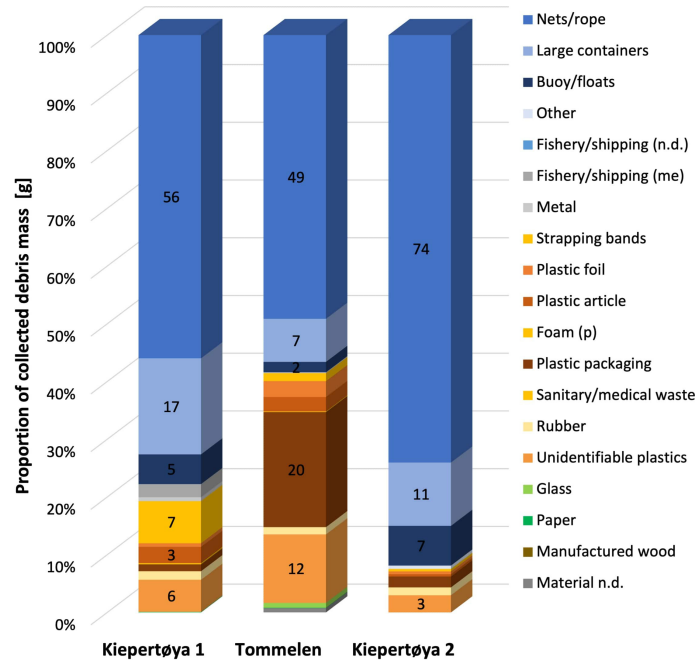


FIGURE 4 Detailed composition of beach debris categories (%) based on mass [g]. (n.d. = not defined, m = metal, p = plastic).

Nets and ropes were the most common items in this category, followed by large containers, such as buckets, canisters, and jerry cans.

The two big packs from Kiepertøya had a similar composition of debris. On Kiepertøya 1, besides fisheries waste, strapping bands (7%), unidentifiable plastics (6%) and plastic articles (3%), were categories that showed a higher proportion compared to others, such as rubber and foam. The second transect on Kiepertøya, where the highest mass of “Fisheries/shipping plastic” was recorded (92%), showed heavier amounts of unidentifiable plastics (3%) and plastic articles (2%). By contrast, the sample from Tommelen was characterized by plastic packaging (20%) and unidentifiable plastics (12%). This highlights unidentifiable plastics, strapping bands, and plastic packaging and articles as important debris categories. However, fisheries-related waste constituted still the largest portion of debris mass recorded.

3.3 Provenance of Arctic beach debris

3.3.1 Composition of provenance in three physical samples

The provenance was determined for 359 pieces from all three big packs (Figure 5). One percent of all items was identified out of the big packs from 2017 and 2021. The second big pack had to be omitted for this calculation as there were no overall abundance data available. Twenty-seven countries were identified in total, excluding the categories “English language” and “Global” (Table 5).

Regarding the pooled data of all big packs, the countries contributing the most were located closer to Svalbard (48%) such as Russia (23%), Norway (12%), and Denmark (9%). Note that

Greenland is associated to Denmark, which makes it difficult to determine from which location items originate unless specified. Although Sweden, Iceland and Finland are Arctic states and relatively close to Spitsbergen, their share was low (< 4%). Other European countries such as Germany (6%), the UK (4%), Spain (2%) and others accounted for 32% of the debris analyzed. This includes “English language” (9%), which is likely of UK provenance although this is not 100% certain. The category “Global” accounted for 18% and the remainder was of more distant provenance including American countries (2%) and Southeast Asia (2%). Combined they contributed 14 items to the whole of 359 pieces. While the USA and China had four debris pieces each, other countries classed as American and Asian only contributed one piece each. If the categories ‘global’ and ‘English language’ were excluded, most of the identifiable items originated from Arctic states (65%), especially from Russia (32%) and Norway (16%) (Figure 6). But almost a third of the items (30%) was of European provenance, especially from Germany (8%). Items of very distant provenance accounted for 5%.

3.3.2 Temporal trends regarding provenance of items

The proportion of the category “global” grew every year, from 6% in 2017 to 30% in 2021 (Figure 7). Interestingly, Norway (11-13%) and Denmark (7-13%) remained quite constant, whereas Russia (18-28%) showed a 10% increase over time. Norway and Russia register a slight decline in absolute numbers. The consistency in numbers also applies to Germany and the UK, where the debris quantities differ between 4-9% and 2-5%, respectively. While the decline also applies to the UK, it does not apply to Germany, where the numbers vary from sampling to sampling.



FIGURE 5
Items of determined provenance from 2017, 2019 (© M. Bergmann) and 2021 (© J. Hagemann).

More distant sources had a small but consistent share of debris over time (<5%). No statistical tests were done because of the small data set.

3.4 Date prints

Date prints were identified from 21 items out of 270 provenance items (8%) and ranged from 1960 to 2013. Ten pieces (48%) dated to the period between 2000 to 2013. The oldest piece found is a bottle fragment, which is likely from around 1960. [Supplementary Table 1](#) provides a list of all date prints and the articles provenance if applicable. Out of the 21 items with date prints, 71% (15 pieces) also bore signs of provenance and included Germany (27%), Norway (20%), Russia (Soviet Union), Denmark and the UK (13%), respectively, and the Netherlands (Holland) and Turkey (7%, respectively). The most recent production date which was estimated to be between 2012 - 2013, was from a German shoe. Other interesting finds included a helmet from the Soviet Union (1979) and a large container from Norway (1971).

3.5 Polymer composition of selected items

Out of 224 provenance-items for which physical samples from 2019 and 2021 were still available, 15 different polymer types could be identified. Polyethylene (PE) accounted for 61% of the items, 50% of which were high-density (HD) and 11% low-density (LD) PE. Polypropylene ranked second (31%). Poly(diallyl isophthalate) (0.4%) and polyurethane (0.4%) were less common. [Supplementary Table 2](#) provides a summary of the proportion of polymers recorded. All nets and ropes analyzed were synthetic (70% polyethylene, 30% polypropylene) and 95% of the strapping bands were made of polypropylene. The remainder consisted of HDPE.

4 Discussion

4.1 Citizen science data generated during beach clean-ups

This study relied on citizen scientists to generate reliable data during clean-ups on Arctic beaches, which expands our knowledge of plastic pollution in a remote and under-researched part of our Earth ([Bergmann et al., 2017a](#)). Citizens are often eager to contribute to environmental science, especially in terms of debris pollution, which is a tangible and topical issue, even for children ([Hartley et al., 2015](#)). While it has the potential to improve science and ocean literacy among participants, there is uncertainty regarding the data quality since no scientist was present during the surveys ([Aceves-Bueno et al., 2017](#)). Therefore, it is important to ensure reliable data collection *via* (1) preparation of clear protocols, (2) training of the leading guide, (3) on site supervision and (4) the revision of samples and data ([Hidalgo-Ruz and Thiel, 2015](#)). All of the above but (3) were followed during the work presented. In addition, beach surveys are particularly amenable to citizen scientists who can draw knowledge from their daily life for the recognition of debris items (>2 cm) requiring only little additional training. Nevertheless, in most beach clean-up scenarios, the beach or transect cannot be cleared of all debris, as it is buried in sediments ([Lavers and Bond, 2017](#)) or due to a lack of time. This could underestimate the debris on beaches such that the numbers can be considered as conservative estimates. Other benefits are the spatial and temporal coverage of under-sampled areas ([Nelms et al., 2017](#)). Indeed, this study would not have been possible or covered as many sampling locations without citizen scientists. [Kyllin \(2020\)](#) recorded 0.0011 items m⁻² on a beach in the Russian Arctic, which is a two-magnitude lower abundance compared to a similar beach (Krossfjord, 0.2 items m⁻²) from this study. If citizen science

TABLE 5 Summary of provenance identified (three big packs pooled) in order of proximity to Svalbard categorized into source regions.

Sources	Provenance	Quantity	Proportion [%]
Nearby/local 48%	Norway	43	12
	Russia	84	23
	Sweden	7	2
	Denmark	32	9
	Finland	1	0.3
	Iceland	4	1
	Faroes	1	0.3
	English language	31	9
Europe 22%	UK	13	4
	Germany	21	6
	Lithuania	1	0.3
	Poland	1	0.3
	Netherlands	7	2
	Belgium	2	1
	France	8	2
	Spain	6	2
	Italy	3	1
	Greece	1	0.3
	Bulgaria	14	4
	Turkey	1	0.3
Distant 3.9%	Canada	1	0.3
	USA	4	1
	Brazil	1	0.3
	Argentina	1	0.3
	Japan	1	0.3
	Korea	1	0.3
	China	4	1
	Philippines	1	0.3
	Global	64	18
Total		359	100

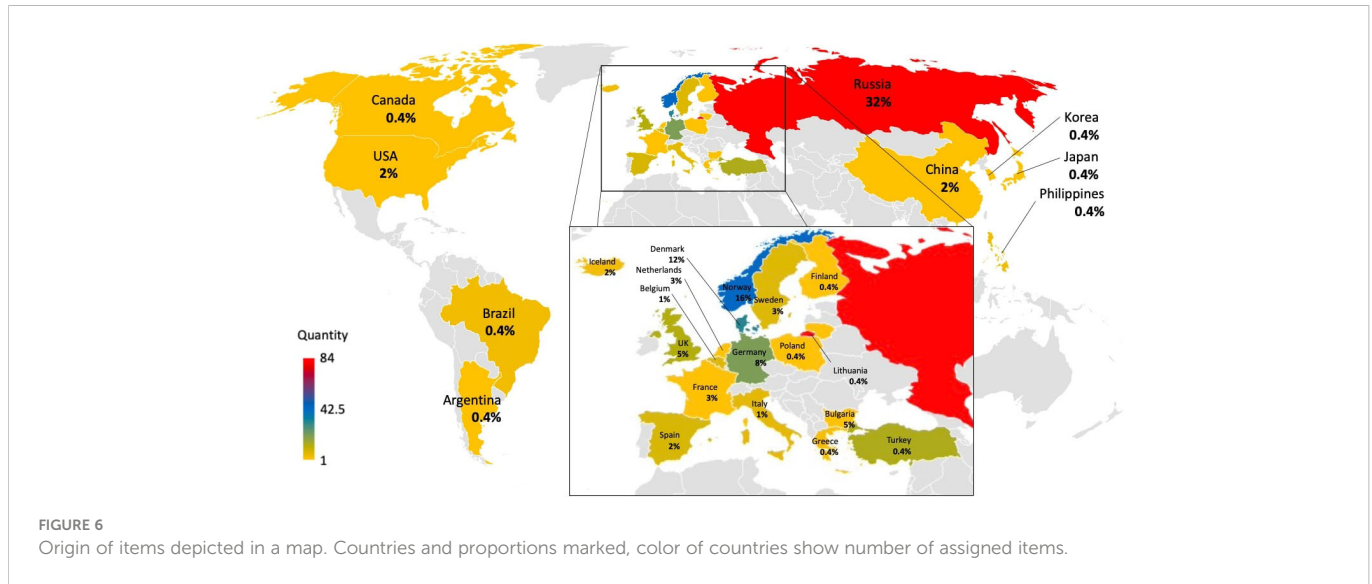
Absolute count and proportion [%] shown.

produced erroneous pollution levels, these would likely have been lower due to debris oversight rather than much higher numbers. However, it could also be argued that this form of data collection could be more reliable, when more observers are included that cover a larger area and reduce the risk of overlooking items as indicated by the positive correlations found between debris and observer numbers or area covered.

Nevertheless, beach clean-ups as such come with uncertainty, such as a lack of information on the retention of beaches (Onink et al., 2021) and if and when the beaches had been cleaned prior to surveys. Data from different beaches may thus not be comparable as recently also suggested by Provencher et al. (2021), who criticized a frequent lack of baseline knowledge. However, the beaches visited here are very

isolated such that some of them have probably never been cleaned. The oldest item identified was a bottle fragment from Norway, whose production likely dates back to the 1960's. While it is unclear when exactly this piece washed ashore, it still gives the indication, that this particular beach (Tommelen) had not been cleaned for some time as also indicated by a piece of a Soviet helmet.

When it came to sorting and determining the composition of the physical sample from 2021 inconsistencies emerged as the methods applied in 2017 and 2019 differed slightly. For example, since the categorization on survey forms for the citizen scientists was refined over the years, we categorized the big pack accordingly, for consistency. Items such as strapping bands and plastic sheeting had been assigned to "fisheries-related plastics" in the first year. While this



is likely true (Falk-Andersson, 2021), it is not 100% certain. So, in the following years they were listed separately, also when sorting the physical samples.

4.2 Arctic beach debris surveys

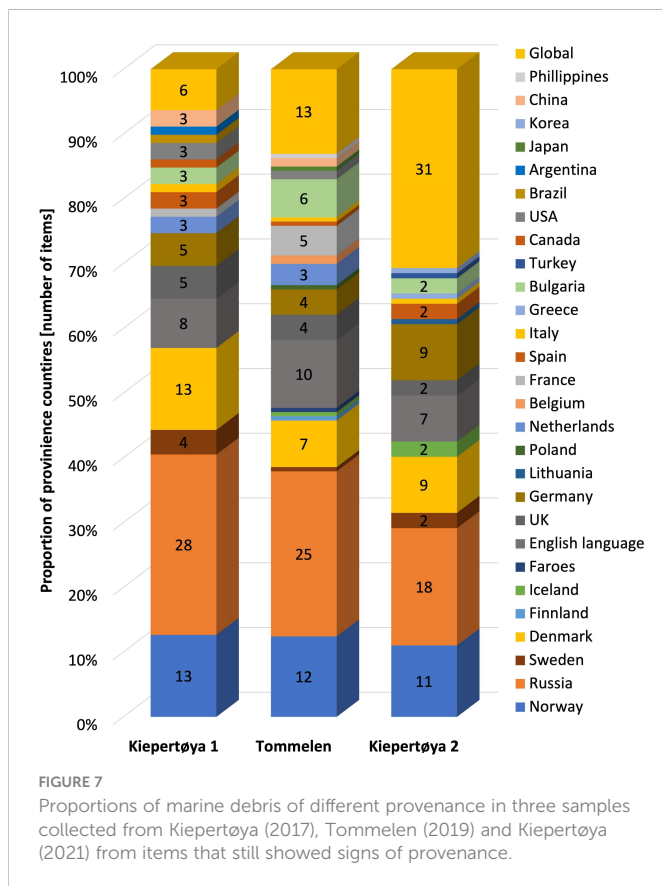
4.2.1 Debris mass

This study showed that plastic was present on most of the investigated beaches of Svalbard at a mean mass of 42 ± 32 SEM g

anthropogenic debris m^{-2} . This is high compared to a Bulgarian beach that harbored $2 g m^{-2}$ and was located near the third biggest town in Bulgaria (Panayotova et al., 2020). On New Zealand beaches, an overall mean weight of $9.17 \pm 2.91 g m^{-2}$ of marine debris was recorded, which could be low due to local stewardship and clean-ups by tourists (van Gool et al., 2021) similar to visited beaches on Svalbard. The pollution levels were assessed on two remote South Pacific islands. While the mass density of surface plastic debris was $571 \pm 197 g m^{-2}$ on the uninhabited Henderson Island (5200 km northeast of New Zealand), $3164 \pm 1989 g m^{-2}$ of plastic debris was recorded on Cocos Island (2750 km northwest of western Australia) (Lavers et al., 2021). Although these beaches are comparable to Svalbard, they had much higher amounts of debris compared to our data, which could be due to their proximity to the South Pacific Gyre, a known plastic accumulation zone. Although a debris accumulation zone has been projected for the Nordic Seas, too (van Sebille et al., 2012; Onink et al., 2019), the current stage of accumulation is uncertain.

The composition of the debris mass is dominated by fisheries-related debris (91%), 89% of these 91% being plastics, the rest being metal and other materials. This concurs with reports from Antarctica, where the shores of Bird Island and Signy Island saw 59% and 69% fisheries-related debris mass, respectively (Waluda et al., 2020). Likewise, in the North Pacific subtropical gyre, fisheries-related debris accounted for 90% of the mass (Lebreton et al., 2022). A common trait of remote and uninhabited areas could be that they harbor more sea-based debris than household-plastics, since recent estimates suggest that 2% of all fishing gear used globally could be emitted to the ocean every year (Richardson et al., 2022).

No debris was collected on Gåshamna and Boltodden, which could be a result of only one person surveying these beaches as supported by a positive correlation found between the number of observers and debris counts. Still, since these surveys were conducted by BL, who has organized clean-ups since 2016, this could be a coincidence. As both beaches happened to be located in the south of Svalbard it is conceivable that the currents carry debris further north, especially since Boltodden is exposed to the open ocean. All other beaches were located in fjords or bays, which might be more efficient



at trapping debris. A Polish research station near Gåshamna could also affect debris abundance, as scientists may clean up its surroundings (Weslawski and Kotwicki, 2018).

4.2.2 Debris counts

A mean debris abundance of 0.37 ± 0.17 SEM items m^{-2} was recorded on Svalbard's beaches, which classifies as “low polluted beaches” (Ansari and Farzadkia, 2022). Higher pollution levels were reported from beaches in Arctic Canada and West Greenland (1.4 ± 2.8 items m^{-2} , (Mallory et al., 2021), which could be due to the influence of human habitation within 5 km of most sampled areas. By contrast, Russian Arctic beaches had pollution levels that were more than a magnitude lower on a mainland (0.024 debris items m^{-2}) and island beach (0.011 debris items m^{-2}) (Kylín, 2020). A possible reason for the difference between the two beaches could be the fact that the mainland is ice-free for a longer period and more exposed to fishing activity, thus more debris can wash ashore (Kylín, 2020). The connection between the declining sea ice extent and increasing fishing vessel numbers operating in the Svalbard region has been made before (Stocker et al., 2020) as has been the link between high fishing activity in areas of low sea ice concentration (Fauchald et al., 2021). It could be argued that an increase in vessel activities of any kind (fishing, merchant, tourist or scientific) increases the accidental or deliberate release of plastic debris in the region, which could explain the higher number of debris items found in our surveys. This was also concluded for increasing debris quantities on the deep seafloor west of Svalbard (Tekman et al., 2017). A larger mean mass of debris was found on the more northern sites of Svalbard, though most surveys were done in the north compared with only two in the south. However, no firm conclusions can be drawn since more evenly distributed surveys would be needed for balanced comparisons. This highlights one limitation of our citizen science setup, where site selection could not be based on scientific criteria.

Comparison of debris quantities in different ecosystem compartments could help us to identify hidden sinks of plastic accumulation and to address the open question ‘Where is all the plastic?’ (Thompson et al., 2004). If the mean count is converted to items km^{-2} to enable a magnitude-scale comparison with data from the nearby Fram Strait obtained during the same time period, it is obvious that mean quantities are highest on beaches ($370,000$ items km^{-2}) followed by the seafloor ($3,485$ items km^{-2} (Parga Martínez et al., 2020)) and the sea surface (11 items km^{-2} , (Tekman et al., 2022a)). The two and five orders of magnitude differences support the realization that beaches are important accumulation areas of marine debris (Onink et al., 2021; Haarr et al., 2022; Isobe and Iwasaki, 2022; Tekman et al., 2022c).

Our data showed that most debris was plastic in terms of both abundance (99.6%) and mass (98%), when adding up all beached debris collected on the nine occasions where both abundance and mass was recorded. The dominance of plastic is not surprising since many studies have shown that plastic and artificial polymers form the majority of marine debris (Vesman et al., 2020; Mallory et al., 2021; Ansari and Farzadkia, 2022) and that most marine debris in the Eurasian Arctic is fisheries-related (Bergmann et al., 2017a; Nashoug, 2017; Jaskólski et al., 2018). Our mass percentage of 98% plastics is substantially higher than the global estimate for beaches, which is 76% but comprises both count and mass estimates (Tekman et al., 2022b) from more than 2,600 locations worldwide including urban regions

with a potentially higher diversity of debris sources. In addition, items from distant sources made of material such as paper and metal could degrade before reaching the Arctic.

The difference between mass and counts also transpires when comparing the debris composition of 14 Arctic beaches. The heaviest category is items from the fishing industry, which enter the environment at sea, a direct path of entry (local sea-based source) (Strand et al., 2021). The importance of local sea-based sources of Arctic debris is supported by reports of fast-sinking glass debris on the ocean floor (Bergmann et al., 2022b). Local debris emissions from increasing shipping activities could also act as a source of plastic pollution (Tekman et al., 2017; Tekman et al., 2020). In comparison, the category ‘general plastics’ accounts for the highest debris quantity recorded (80%) in terms of counts, pointing to land-based sources or also to ship waste since some items are universally used (e.g., cleaning agents, food packaging). Still, the presence of larger items, such as big food tubs point to ship galleys (Nashoug, 2017). Based on the date of manufacturing and provenance information, Ryan et al. (2019) concluded that most bottles collected on a remote beach in the South Atlantic stemmed from ships.

4.3 Comparing two physical samples

The difference between mass and abundance is particularly evident when comparing the compositions of two physical samples, where mass is dominated by fishery waste (80 – 92%) whereas general plastic dominated in terms of abundance (80 – 85%) (Figure 8). While the heaviest fishing net in our sample weighed 70 kg, it accounted only for one item, demonstrating why fisheries debris has such a high impact on mass composition. Similarly, in a study by Ryan et al. (2020), a small number of macro-debris items accounted for the greatest mass whereas “unidentifiable plastics” dominated in terms of abundance (41 – 50%), which is not surprising, as this category often comprises a high number of small, nearly mesoplastic-sized fragmenting items. Small, unidentifiable plastic debris and foam particles were also most abundant on the Western Black Sea coast (Topçu et al., 2013). Strapping bands (15 – 20%) came second highest in abundance, similar to observations in the Russian Far East (Jaskólski et al., 2018) and the Siberian Arctic (Vesman et al., 2020) and floating debris surveys in the Arctic and Northeast Atlantic (Tekman et al., 2022a).

4.4 Provenance of plastic items

Most debris that still bore signs of origin, seemed to have been produced in countries in close proximity to Svalbard, such as Arctic states including Russia, Norway and Denmark. This also corroborates the assumption, that much of the marine debris in the Norwegian continental shelf and Barents Sea is of regional provenance (Buhl-Mortensen and Buhl-Mortensen, 2017; Strand et al., 2021). However, almost a third of the items were of European provenance including countries bordering the North Sea or the North Atlantic such as Germany, UK, Netherlands, France and Spain. This is not surprising since particles drift northwards from the North Sea or East Atlantic towards the Norwegian, Barents and Greenland Seas in the time frame of more than a year from central Europe (Strand et al., 2021).

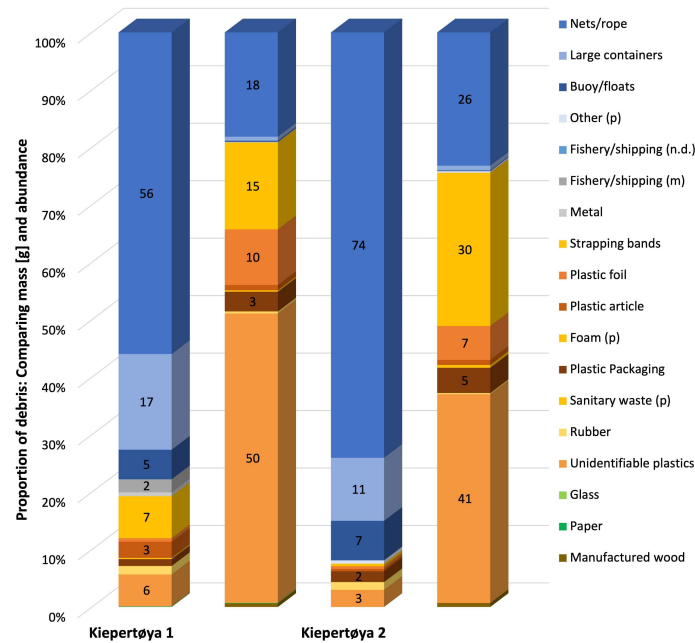


FIGURE 8

High-resolution proportion of two big packs. Two columns are shown per location: mass (left columns) and abundance (right columns). P = plastic, m = metal, n.d. = not defined.

The Atlantic circulation, which feeds the West Spitsbergen Current (Bergmann et al., 2016), transports the debris to the north where it washes ashore (Nashoug, 2017). However, debris items could also have entered the environment at a different point than their stated origin, especially those of a very distant provenance such as Korea, China, Brazil or Argentina. Interestingly, there were fewer items from very distant regions. If oceans currents carried items from those distant regions to the Arctic, transport could take a long time (van Sebille et al., 2012; Strand et al., 2021). However, these items could also have been bunkered in countries other than their imprinted provenance. They could stem from ships, that travel to the Arctic from which debris enters the ocean and then washes ashore (Ryan et al., 2021), from cruise ships that frequent both Polar Regions or from international ship crews.

4.4.1 Date prints

It is possible to interpret the age of debris from production or expiration date on them (Sander, 2016). The time period between production date and date of disposal is still highly variable in these cases (Sander, 2016) but can give an indication about where an item has been discarded. The age of bottles combined with information of a local or foreign provenance can make the distinction between ship debris and long-distance drift (Ryan et al., 2021). Since the most recent date found was from a German shoe from 2012/2013, this method was not useful in determining how the debris ended up on Svalbard, as the estimated transport time for items from Europe is 1-2 years (van Sebille et al., 2016; Strand et al., 2021). By contrast, a French bottle with an expiration dating back less than a year would unlikely have drifted from France to Svalbard in one year but stem from local ship-based sources.

5 Conclusion

Beached debris was collected on the great majority of locations illustrating widespread pollution on Svalbard's beaches. Citizen science thus helped to increase the temporal and spatial scale of observations in these remote under-researched regions. In terms of mass, most debris was related to fisheries, pointing to local sea-based sources and ship-related waste. In terms of debris counts, general plastic was most abundant, including packaging and plastic articles. They could stem from land- and sea-based sources alike. Comparison with data from the seafloor and sea surface indicates that Arctic beaches are accumulation areas for marine debris. The provenance of items indicated that 65% stem from nearby Arctic countries (local sources) and 30% from European sources. The effects of global heating, such as a decline in sea ice extent and shorter periods of sea ice coverage (Polasek et al., 2017), lead to a prolonged period for ships operating in the Arctic as well as ships extending their range higher north (Stocker et al., 2020; Bergmann et al., 2022b). Given projected growth trajectories in global plastic production (Geyer, 2020), a further increase of plastic pollution from both local and distant sources could be prevented through a legally binding global Plastics Treaty with upstream measures such as caps on global plastic production, improved waste management and harbor schemes (Bergmann et al., 2022a; Bergmann et al., 2022b). Adequate policing of waste management policies regarding fishing vessels and environmental education and awareness is important as well. This in turn would reduce the amount of debris entering the ocean and would lift the stress on Arctic biota, which are already threatened by the effects of temperatures rising four times faster than the global average (Rantanen et al., 2022).

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding author.

Author contributions

MB and BL contributed to conception and design of the study. BL executed taking samples, recording data and organized citizen scientists. AM and MB performed the statistical analysis. AM organized the database and wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2023.1092939/full#supplementary-material>

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