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Original Research

Evidence for local sources and trophic biomagnification of bisphenols in the Arctic

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ABSTRACT

The Arctic, though remote, is exceptionally vulnerable to chemical contaminants that threaten its fragile ecosystems. Bisphenols (BPs), a class of endocrine-disrupting chemicals used in plastics and resins, are now detected across the Arctic, but the risks posed by their many analogues are poorly understood. Most studies have focused on documenting their presence, leaving a critical gap in our understanding of whether these compounds bioaccumulate in Arctic food webs and to what extent local, within-Arctic pollution contributes to the overall burden. Here we show, through a comprehensive analysis of 32 BPs in 134 samples from a Norwegian Arctic food web, that multiple BP analogues not only bioaccumulate but also biomagnify from plankton up to polar bears. We found that 5,5′-(1-methylethylidene)bis [(1,1′-biphenyl)-2-ol] (BPPH) exhibited the highest trophic magnification factor (a value of 2.3), and we documented total BP concentrations in polar bear tissues up to 1396 ng g^{-1} wet weight, orders of magnitude higher than in lower-trophic-level species. Furthermore, our analysis identified distinct local pollution sources, such as a firefighting training site releasing 2,4,6-trichlorophenol (2,4,6-TBP) and landfill leachate contributing other BPs to the local environment. These findings provide the first evidence of trophic magnification for multiple BPs in a polar food chain and underscore the urgent need to incorporate food-web dynamics and local source management into ecological risk assessments for the Arctic.

1. Introduction

Bisphenols (BPs) belong to a class of endocrine-disrupting chemicals (Supplementary Fig. S1). The term “bisphenols” usually refers to compounds containing two interconnected phenol rings [1]. Bisphenol A (BPA) is the most investigated BP compound

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worldwide [2]. It has been extensively applied in large volumes since 1957 as a plastic additive [3,4] and has been used in the production of polycarbonate and epoxy resins [5,6]. BPA production was reported at 7082 metric tons in 2022 and is expected to reach 12169 metric tons by 2032 [7], owing to its use in many daily-use items, such as epoxy resins and all types of plastic products [3,8–10]. Although BPA has many uses, it also has carcinogenic and teratogenic effects. In humans, the United States Environmental Protection Agency has established a safety limit of 50 μg of BPA per kg of body weight per day [11]. BPA has also been associated with diabetes and cardiovascular diseases in humans [12,13] and hormone levels in mammals [14] and birds [15]. In April 2023, the European Food Safety Authority reduced the tolerable daily intake for BPA from 4.0 μg per kg body weight per day to 0.2 ng per kg body weight per day, reflecting increased regulatory concern over BPA's health risks [16]. Due to the growing body of evidence of its hazardous effects, BPA is being replaced in commercial products by other additives with similar chemical structures and properties [17,18], such as bisphenol S (BPS) in thermal paper and food packaging, and bisphenol F (BPF) in epoxy resins and plastics [19]. These emerging BP analogues are characterized by versatile functional groups such as halogenated, sulfonated, and ether groups on the bisphenol basic structure (Supplementary Fig. S1) [20,21]. However, the toxicity of these BP analogues has not been sufficiently documented [22–26]. The inherent toxicological potential and the considerable lack of environmental data on BPs, particularly for Arctic environments, are the main motivations for the current study, which focuses on a representative Svalbard marine food web.

Previous studies have revealed the widespread global occurrence of BPs [2,27,28]. There are limited reports on BP pollution in the biota environment of Svalbard, Arctic. Nejumal et al. [29] reported bisphenol S (BPS) in the sediment of the Kongsfjorden (Svalbard, Ny-Ålesund area) at a concentration of around 0.2 ng g^{-1}. Ademollo et al. [30] reported that BPA concentrations ranged from lower than the limit of quantification (<LOQ) to 1.4 ng L^{-1} in the summer and from <LOQ to 0.9 ng L^{-1} in the winter, with mean values of 0.6 and 0.5 ng L^{-1}, respectively, measured in seawater collected from Kongsfjorden between 2016 and 2017. Several recent studies have revealed the presence of BPs in Arctic biota in Svalbard. Lucia et al. [31] surveyed for 20 bisphenols in Arctic biota and found that BPA was the most frequently detected compound. Elevated concentrations of bisphenol Z (BPZ) in Arctic char (*Salvelinus alpinus*) from Lake Erlingvatnet (Northwest Svalbard) were found with a maximum level of 142 ng g^{-1} wet weight (ww). Bisphenol G (BPG) levels of up to 94 ng g^{-1} ww were reported in Arctic char from Lake Ellasjøen (Bear Island). In 2018, Sørensen et al. [32] quantified levels of BPA in multiple biota, including copepods (*Calanus finmarchicus*, *C. glacialis*, and *C. hyperboreus*) (46 ± 55 ng g^{-1} ww), pelagic amphipods (*Themisto abyssorum* and *T. libellula*) (35 ± 10 ng g^{-1} ww), arrow worms (*Sagitta elegans*) (26.5 ng g^{-1} ww), krill (*Thysanoessa inermis*) (32 ± 2 ng g^{-1} ww), and benthic scavenging amphipods (*Onisimus* sp. and *Anonyx* sp.) (22 ± 20 ng g^{-1} ww), collected in Kongsfjorden in 2018. Considering the fragility of the Arctic ecosystem, it is imperative to investigate the exposure risks of Arctic biota to BPs, particularly from local sources of pollution. This will provide reliable information to help develop sustainable regulatory frameworks aimed at reducing BP contamination in the Arctic.

The present study utilized abiotic samples from well-defined local sources, and collected environmental samples and organisms to investigate the potential for BP emissions into nearby environments. BPs have the potential to undergo trophic transfer and bioaccumulate in higher trophic-level aquatic organisms [33,34], be transferred within matrices, or be bioaccumulated by local biota and potentially biomagnified in Arctic food chains. The following research goals guided this study:

(1) To determine the levels and composition of 32 emerging BP derivatives in 23 abiotic samples and 111 biotic samples across a broad range of matrices.
(2) To identify major local pollution sources and their impact on BP profiles in Longyearbyen, Svalbard.
(3) To assess the transfer potential of selected BPs from abiotic matrices in Svalbard to biota.
(4) To evaluate the bioaccumulation and ecological implications of BPs in the Arctic.

2. Materials and methods

2.1. Chemicals and reagents

All chemicals used in this study are provided in Supplementary Table S1 and Text S1.

2.2. Sample collection

A total of 134 samples, including 23 abiotic and 111 biotic samples, were collected in the vicinity of Longyearbyen, Svalbard Supplementary Table S2. Capture and handling of glaucous gulls (*Larus hyperboreus*) were done following the regulations of the Norwegian Animal Welfare Act and were approved by the Governor of Svalbard (Permits Nos. 16/00861–11 and 17/00414–6). We obtained abiotic samples consisting of one river surface water sample (collected from Longyear River), one landfill leachate sample, twelve surface marine sediment grab samples (collected from sampling stations 1–4 [ST1–ST4]), and nine soil grab samples (collected from different sites in Longyearbyen). ST4 is situated in Isfjord, approximately 10 km from any known local source (airport, landfill, or residential and sewage-related sources), and it was selected as a representative site of the anthropogenic background [35].

Biotic samples include pelagic amphipods (*Calanus* spp., $n = 12$), annelids ($n = 10$), and crabs (*Hyas araneus*, $n = 18$), as well as biological tissues from two local fish species—*Anarhichas lupus* ($n = 5$) and *Myoxocephalus scorpius* ($n = 35$)—glaucous gulls (*Larus hyperboreus*, $n = 20$), and a polar bear (*Ursus maritimus*). Liver and muscle samples were collected from each fish (muscle and liver weights listed in Supplementary Table S3). Information on the crabs (*Hyas araneus*) that were collected and analyzed individually is also shown in Supplementary Table S3. At each station, we sampled around 20 g of pelagic amphipods and 10 g of annelids. Biological data concerning the glaucous gulls from which liver samples were collected are provided in Supplementary Table S3.

We collected pelagic amphipods, annelids, crabs, and fish samples from each station (ST1 to ST4, Fig. 1), as described by Ali et al. [35]. Glaucous gull samples were collected at sea in Adventfjorden near the airport (78°140′ N, 15°300’ E), located off the coast between ST1 and ST2.

The polar bear tissue samples were collected from a male bear, found dead on April 15th, 2014, in Billefjord (78°22′48″ N, 16°19′12″ E). Solid phase extraction (SPE) and liquid–liquid extraction (LLE) (parameters shown in Supplementary Tables S4 and S5) were applied for environmental and biota samples. Detailed information on the extraction procedure is presented in Supplementary Text S2. The SPE was conducted at the Norwegian University of Life Sciences, and the extracts were shipped to the International Joint Research Center for Persistent Toxic Substances (IJRC-PTS) for analysis.

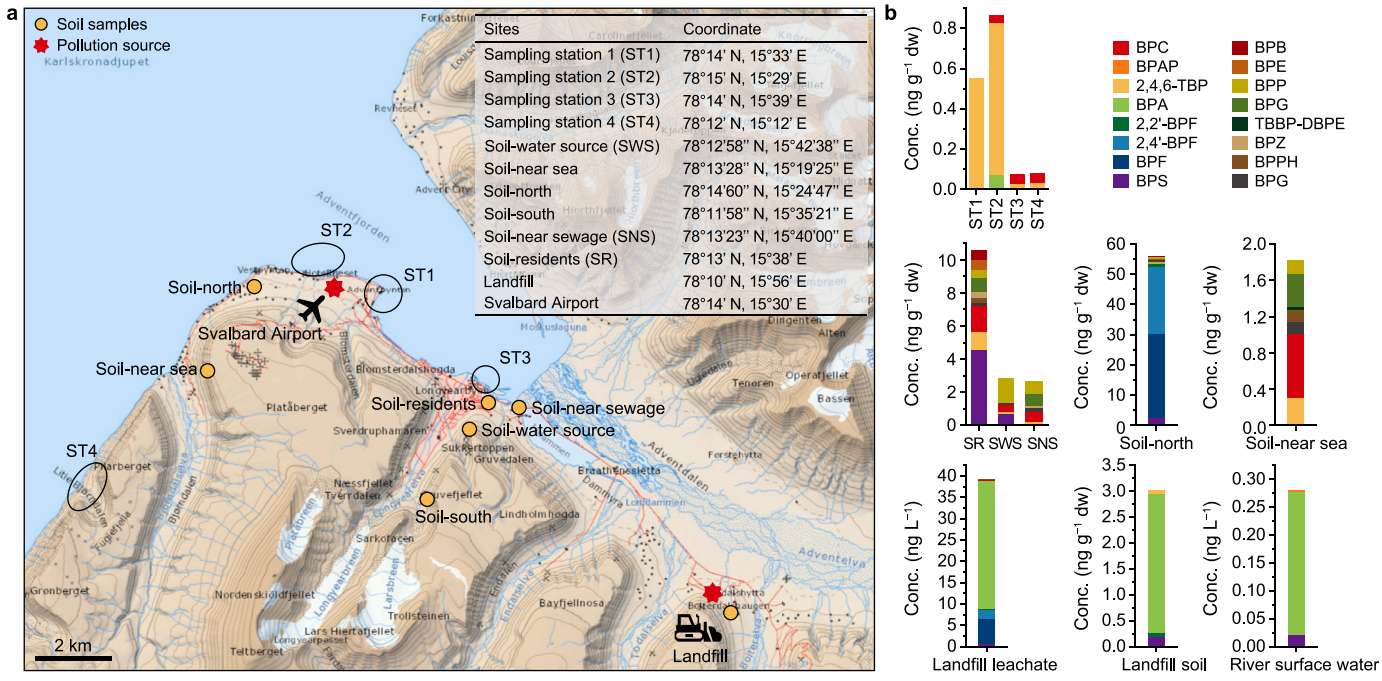

Fig. 1. **a**, Location of the sampling site in Svalbard for collecting abiotic samples. The map was obtained from https://toposvalbard.npolar.no/. The "Residents-soil" sample was collected near residential settlements, "Landfill soil" sample was collected near the landfill. The coordinates of these two samples are not provided. **b**, Total concentration (Conc.) of bisphenols in the abiotic environment. ST1–ST4 in the first line represent surface marine sediment samples, while the second line denotes soil samples from different sampling sites.

2.3. Quality assurance and quality control

All sampling materials and glassware used in the laboratory work were subjected to a strict cleaning procedure (detailed in Supplementary Text S3). The LOQ was calculated as a signal-to-noise ratio of 10 and ranged from 0.020 to 0.90 ng L^{-1} for water samples, 0.01–1.4 ng g^{-1} dry weight (dw) for sediment/soil samples, and 0.01–3.5 ng g^{-1} ww for biotic samples. For biotic samples, the average recovery of internal standards in all media was in the range of 41–85% (Supplementary Table S6) and in the range of 73–108% for abiotic samples. The BP compounds were analyzed at the IJRC-PTS. An Agilent 1290 Series Ultra-High Performance Liquid Chromatography (Agilent Technologies Inc., Palo Alto, California, United States) equipped with a 6340 triple quadrupole mass spectrometer with electrospray ionization operated in multiple reaction monitoring mode was used. The parameters are illustrated in Supplementary Text S4 and Table S4.

2.4. Statistical analysis

Data were not applied for statistical analysis when the measured level was lower than the LOQ. Nonparametric analysis of variance (Mann–Whitney *U* test) was applied to assess the differences in concentration values between different compounds, and Spearman correlation coefficients were treated as significant if their *p*-values were less than 0.05. The results were statistically analyzed using SPSS Statistics software (Version 26.0, IBM Corp., Armonk, NY, USA) [36] and Origin software (Version 2024, OriginLab Corporation, Northampton, MA, USA). The EPI Suite software (United States Environmental Protection Agency, Version 4.1) [37] was used to predict the physicochemical properties of the 32 target compounds. Data below the LOQ were excluded from the calculation of the mean and median. For other statistical analyses, values below the LOQ were substituted with LOQ/ $\sqrt{2}$ in order to enable statistical analysis and to avoid systematic overestimation or underestimation of concentrations.

To evaluate the biomagnification potential of BPs in the Arctic food chain, we used equations (1)–(3) to calculate the trophic magnification factor (T_{MF}).

$$T_{L,consumer} = 2 + \frac{\delta^{15}N_{consumer} - \delta^{15}N_{baseline}}{\Delta\delta^{15}N} \quad (1)$$

$$Log_{10}\, c = a + (b \times T_{L,consumer}) \quad (2)$$

$$T_{MF} = 10^{b} \quad (3)$$

The trophic level ($T_{L,consumer}$) was evaluated for each consumer based on the assumption that the baseline organism, the pelagic amphipod, has a $T_{L,consumer}$ of 2.0 [38]. $\delta^{15}N_{consumer}$ and $\delta^{15}N_{baseline}$ are stable isotope abundances ($\delta^{15}N$, ‰) for consumer and baseline organisms, which were referenced by literature reported for the adjacent area, where data are lacking in Svalbard, as compiled in Supplementary Table S7 [39–43]. The lowest $\delta^{15}N$ value for the pelagic amphipod illustrates that it is a baseline organism for species examined in this study, with a simple diet and relatively slower turnover of isotopes [44]. The value for the enrichment factor constant ($\Delta\delta^{15}N$) was set as 3.8 ‰, except for the bird, which was set as 2.4 ‰, as described by Ma et al. [45] and Xie et al. [38]. *c* refers to the concentration (ng g^{-1} dw) of the target BP compounds, *b* is the intercept, and *a* represents the slope of linearity applied to calculate T_{MF} based on equation (2).

To assess the bioaccumulation potential of BPs from sediments to benthic organisms, we calculated the biota-sediment accumulation factor (B_{SAF}) according to equation (4):

$$B_{SAF} = \frac{C_b}{C_s} \quad (4)$$

where C_b and C_s represent the BP concentrations in organisms (ng g^{-1} ww) and in sediment normalized by total organic carbon (TOC) (ng per g TOC dw), respectively [46,47]. Referring to available records on surface sediments in Isfjorden (78°20′02.4″ N, 15°18′39.6″ E) near Longyearbyen from 2019, we used a TOC value of 2.72 wt%, as described by Kim et al. [48].

3. Results and discussion

3.1. BP pollution in the abiotic environment

For the sampling sites (Fig. 1), out of 32 target BP compounds, 15 and 3 were detected in the soil and sediment, respectively. For soil samples, the concentrations of BPs varied considerably across different sites, with the lowest total concentration of 15 BP compounds (1.8 ng g^{-1} dw) found at the soil-near-sea sampling site and the highest of 56 ng g^{-1} dw collected near Longyearbyen airport (the sampling site is shown in Supplementary Table S2). BPF (28 ng g^{-1} dw) and 2,4-BPF (22 ng g^{-1} dw) in the soil-north were found to have the highest concentrations among all the BPs compounds detected in Longyearbyen soil, contributing 50% and 39%, respectively, to the $\sum_{15}$BPs concentrations (Supplementary Fig. S2).

BPA, 2,4,6-Tribromophenol (2,4,6-TBP), and 2,2-Bis(3-methyl-4-hydroxyphenyl)propane (BPC) were the BP compounds detected in sediments collected from ST1 to ST4, and the concentrations of Σ_3BPs in the sediment ranged from 0.070 to 0.86 ng g^{-1} dw. BPS (0.022 ng L^{-1}), BPA (0.25 ng L^{-1}), and BPAP (0.022 ng L^{-1}) were the predominant BP compounds detected in the Longyearbyen River (water sample) (78°130′ N, 15°38′ E). Overall, the concentrations of BPA and BPS in the Longyearbyen River were lower than those in the surface water situated in non-Arctic locations, usually found in the high ng L^{-1} or μg L^{-1} range in highly populated regions [49,50].

Nine BP compounds were detected in the leachate collected from the landfill, with total concentrations reaching 39 ng L^{-1}, which is considerably higher than the concentrations of BP compounds reported previously at other landfills [51–53].

3.2. Local source impact on BP in the abiotic environment

2,4,6-TBP was the only compound identified at ST1 (Supplementary Fig. S2), contributing 87% to the total Σ_3BPs at ST2. The local firefighting training site is located approximately 400 m southeast of theSvalbard airport near sites ST1 and ST2 [54–56]. Plastic-containing products are often used in supporting technologies for firefighting activities [57]. 2,4,6-TBP, a typical intermediate in the preparation of brominated flame retardants [58], may be generated during the process of applying 2,4,6-TBP-containing firefighting foam, which may have led to the subsequent discharge of the compounds in the environment close to ST1 and ST2.

Furthermore, BPC was the dominant compound in the sediment samples from ST3. BPC is a typical substitute for BPA in polymers used for consumer products, such as water bottles, food packaging, and textiles [59,60]. BPC was detected at 0.16 ng L^{-1} in the landfill leachate but not in the Longyear River, which flows downstream to the sediment monitoring site ST3. This suggests that leachate collected from the landfill may contribute to BPC at ST3 through the Adventdalen valley water flow. ST3 is also located near the Longyearbyen settlement, raising the possibility that BPC may also originate from residential activities and/or sewage discharge. Leachates have been recorded to contain a variety of chemicals, such as flame retardants, plasticizers, and phenols [61]. Hence, it is crucial to continue the screening of emissions from abandoned landfills as a potential local source of BP contamination. In addition, the presence of BPC in the soil near a sewage site (SNS) indicates that sewage discharge carried by the same water flow could also influence BPC levels at ST3.

Furthermore, distinct BP profile differences were observed between soils collected from the landfill and the residents (Supplementary Fig. S2). The main BP compounds in soils from residential areas (SR) in Longyearbyen—BPS in residents' soil and BPP in water-source soil—were different from those in the landfill (BPA). In addition, the predominant BP compound in marine sediments near ST3 (BPC) was also present at a low concentration level in the landfill (0.16 ng g^{-1} dw). BPA is the most prevalent compound in both landfill leachate (30 ng L^{-1}) and soil (2.7 ng g^{-1} dw) samples, constituting 76% and 89%, respectively. BPC, the main compound at ST3, was only present at low levels. This suggests that the landfill is unlikely to be the primary source of BPC, and residential or sewage-related sources may also contribute.

The spatial distribution of the median concentration for Σ_{13}BPs in Svalbard indicates that no significant difference among soil collected from different locations (Mann–Whitney U test, $p > 0.05$) (Supplementary Fig. S3b). Regarding the composition of BP compounds in the soil (Supplementary Fig. S2 and S3a), distinct BP patterns are identified in different soils, indicating that the sources contributing to BP pollution in Longyearbyen soil are complex. Please note that none of the collected soil samples resemble the landfill leachate profile, indicating that the landfill is not the direct source of soil contamination for the residential areas of Longyearbyen.

3.3. BP pollution in the biota environment

3.3.1. Concentration and levels

The sum of the target BPs detected in Svalbard biota indicates that. overall, the environmental levels for ΣBPs in different organs (fat, kidney, and spleen) of the apex predator, the polar bear, range from 216 to 1396 ng g^{-1} ww and are 1–5 orders of magnitude higher than those of other species at lower levels in the Svalbard marine ecosystem, including glaucous gulls (0.26 ng g^{-1} ww), sculpins (0.77–215 ng g^{-1} ww), wolffish (0.68–2.7 ng g^{-1} ww), crabs (5.3–11 ng g^{-1} ww), annelids (0.047–61 ng g^{-1} ww), and pelagic amphipods (0.17–4.8 ng g^{-1} ww). The spleen was the organ with the highest accumulation of BPs in the polar bear, with a total Σ_6BPs concentration of 1396 ng g^{-1} ww, followed by fat (936 ng g^{-1} ww) and the kidneys (805 ng g^{-1} ww). For fish samples, ΣBPs in the liver ranged from 2.7 to 215 ng g^{-1} ww, which was higher than that in the muscle (0.68–1.6 ng g^{-1} ww) (Fig. 3). Furthermore, PBP, 2,4,6-TBP, and BPA were considerably higher in fish livers than in fish muscle (Mann–Whitney U Test, $p < 0.01$) (Fig. 3). Moreover, BPF, 2,2-BPF, and BPA were significantly higher in fish livers than in crabs and pelagic amphipods (Mann-Whitney U Test, $p < 0.01$). Although the median concentrations for total BPs were slightly higher in annelids (7.9 ng g^{-1} ww) than in fish livers (3.2 ng g^{-1} ww), the difference was not statistically significant.

Comparable levels of ΣBPs concentration were found in glaucous gulls (Fig. 2) (relatively high trophic level) and in organisms belonging to lower trophic levels. The lowest BP levels of the entire biota sample set were reported in the glaucous gull samples (Σ_2BPs: 0.26 ng g^{-1} ww). This feature is different compared to the contaminant distributions of other pollutants (e.g., persistent organic pollutants) in glaucous gulls reported in previous studies. As an apex predatory species in the Arctic region [62–64], glaucous gulls are more susceptible to the bioaccumulation of chlorinated pesticides, such as hexachlorobenzene and hexachlorocyclohexanes, than species at lower trophic levels [65]. The

reported results indicate that BPs behave differently from classical persistent organic pollutants in birds.

Hence, the mechanisms of BP enrichment and uptake in birds and the potential bioaccumulation need to be further examined. Our results are supported by a previous investigation reported by Lucia et al. [31], who observed BPs in eggs of glaucous gulls collected in 2013–2014 at Kongsfjorden, Svalbard. The pollution profile of BPs in the livers of glaucous gulls is comparable to that found in their egg samples reported by Lucia et al. [31], where most BP compounds were not detected except for BPA, which had the highest concentration (8.8 ng g^{-1} ww). To the best of our understanding, to date, there are no reports related to BPs in the livers of glaucous gulls that are available for better comparison.

3.3.2. Distribution and pattern

The distribution of BPA and its substitute BP compounds in different Arctic species is further investigated. Overall, BPA is predominant in pelagic amphipods and fish muscle, contributing 55–100% and 75–96% of the total concentration, respectively (Supplementary Fig. S2). BPA is also highly abundant in the livers of the glaucous gulls (76%) and wolffish (52%). The less prevalent distribution of BPA in crabs, annelids, sculpin livers, and polar bear samples contrasts with the distinct patterns observed in these organisms, where BPF emerged as the predominant compound. BPF is a BPA analogue that usually replaces BPA in the production of epoxy resins or polycarbonate plastics [66]. The prevalence of BPF in fish is also an important feature pointing toward differences in uptake mechanisms and source strength. Wong et al. [27] illustrated that the species-dependent detection frequencies of BPF ranged from 100% for yellow seafins (*Acanthopagrus latus*) to 16.6% for spotted snakeheads. The predominance of BFP in fish (compared to BPA), such as snubnose pompano (*Trachinotus blochii*), bigeye (*Priacanthus macracanthus*) [27], and mullet (*Mugilidae*) [67], is also confirmed in other non-Arctic studies. Cardama et al. [67] have also provided data regarding the nondetection of BPA in crabs but with BPF in the range of < LOQ to 13.40 ng g^{-1} ww.

Moreover, the prevalence of Bis(3.5-dibromo-4 (2.3-dibromopropoxy) phenyl) sulfone (TBBP-DBPE) in the polar bear is a surprising feature. TBBP-DBPE is an emerging novel organic compound that has not been measured in Arctic animals before. Gauthier et al. [68] and Letcher et al. [69] revealed that a minor amount of TBBP-DBPE was detected in herring gull eggs (*Larus argentatus*) but in amounts below the limits of quantification. Even though the concentrations of this compound in herring gulls were below the detection limits, its high concentration in the polar bear (166–438 ng g^{-1} ww) can be associated with species-specific bioaccumulation or exposure to a specific point source. However, it is important to study food web-associated samples to elucidate bioaccumulation, identify species that are dependent on enrichment processes, and assess possible sources.

3.4. Trophic transfer of BPs in the arctic marine food chain

Trophic magnification factor is applied to study bioaccumulation in the prey-to-predator transfer of chemicals through food webs with complex predator–prey relationships [70]. This method is reliable for measuring biomagnification, as it is more conclusive than metrics derived from laboratory and chemical properties such as octanol–water partition coefficient (Log K_{ow}). This approach has already been applied in the Arctic to investigate the trophic transfer efficiency of contaminants [70]. The study design considers T_{MF} as a metric to quantify the actual bioaccumulation potential of BPs according to the trophic level–based inferred linear trophic structure, which can represent the general trophic hierarchy in the Arctic ecosystem in a practical method [71]. The calculated trophic levels were as follows: pelagic amphipods ($T_L = 2.0$), annelids ($T_L = 2.5$), crabs ($T_L = 2.9$), sculpins ($T_L = 3.6$), glaucous gulls ($T_L = 5.3$), and polar bear ($T_L = 5.1$). Contaminant transfer follows this pathway (Fig. 5). It should be noted that the stable nitrogen isotope values were collected from the literature and are hence not directly comparable. Nevertheless, the calculated trophic levels show the general trend of increasing trophic levels, with polar bears and glaucous gulls showing the highest levels. It is worth noting that both polar bears and glaucous gulls are top predators in the Arctic marine ecosystem, and their presence has been shown to influence the determination of T_{MF} within Arctic food chains [70]. Therefore, they were included in the Arctic food chain for the T_{MF} calculation in this study.

Most target BPs exhibited T_{MF} values exceeding 1, consistent with trophic magnification (Fig. 4a), including BPS (1.6), BPA (1.2), Pentabromophenol (PBP; 1.6), 1,1-dichloro-2,2-bis(4-hydroxy phenyl) ethylene (DCBPC; 1.4), BPC (1.4), and BPPH (2.3). Only 2,4,6-TBP showed a T_{MF} below 1 (0.75). The observed range (0.75–2.3) aligns with previous reports [72–74]. In addition, considerable variation was observed among different BPs, which aligns with earlier findings; for example, Franklin [75] reported large variability in the T_{MF} of emerging contaminants, such as per- and polyfluoroalkyl substances. T_{MF} greater than 1 is generally regarded as strong evidence of significant biomagnification potential [75]. Hence, these results illustrate that, in general, BPs exhibit trophic magnification within the Arctic food chain. Notably, BPPH showed the highest magnification potential ($T_{MF} = 2.4$). Considering that this compound possesses high fat solubility and endocrine-disrupting properties [76], its bioaccumulation in the Arctic food chain requires more attention. In contrast, the unlikely biomagnification of 2,4,6-TBP ($T_{MF} < 1$) may be due to its rapid metabolism, efficient excretion, and quick degradation in the environment.

3.5. Impact of the abiotic environment on biota

Biota-sediment accumulation factors are a suitable tool for evaluating the impact of sediment accumulation on bioaccumulation in the analyzed biota samples in this study. B_{SAF} can be used in nonequilibrium conditions based on criteria for the sedentary and benthic lifestyles of the tested species [47], which aligns well with the background of our case.

In general, the B_{SAF} of most BPs in sculpins were above 1, with the highest values found in sculpin liver among all benthic species (Supplementary Table S8). BPA showed B_{SAF} exceeding 1 in annelids, suggesting their role as a source for trophic transfer. Additionally, the B_{SAF} range of BPs in the Arctic (Svalbard) is consistent with that of flame retardants in Arctic marine food webs reported by Xiong et al. [77], ranging from 0.85 to 3.40 g TOC per g lipid.

The variation in B_{SAF} across the benthic biota was examined. An increasing trend in B_{SAF} was observed from pelagic amphipods ($T_L = 2.0$) to sculpins ($T_L = 3.6$) (Fig. 4b), indicating trophic magnification for most compounds, particularly BPA, BPC, and BPPH. Low B_{SAF} of 2,4,6-TBP and BPC in amphipods and annelids suggest limited accumulation through sediment contact, while the relatively higher B_{SAF} of BPA indicate a stronger influence of sediment-based exposure. However, bioaccumulation may be affected by multiple exposure pathways, including direct uptake from water, dietary transfer, and species-specific metabolism [78,79]. Further studies are needed to clarify the relative contributions of these pathways to BP accumulation in Arctic marine organisms.

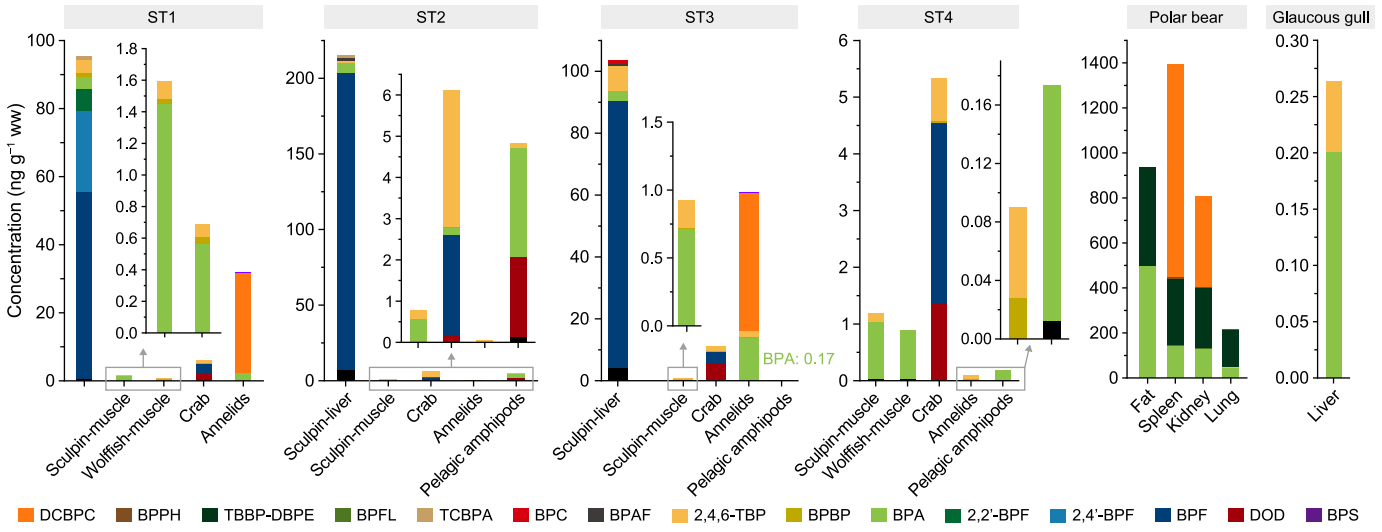

Fig. 2. The total concentration of bisphenols in the biota distributed in different sites. The data regarding detection frequencies of specific organisms below 50% at each location have not been provided. ST1–ST4: sampling stations 1–4.

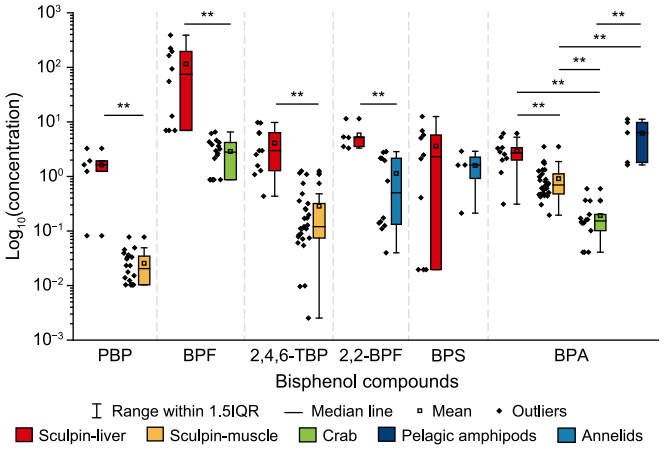

Fig. 3. Concentration (ng g^{-1} ww) of bisphenol compounds between different species in Svalbard. The data for organisms detected in less than 50% of the total samples in Svalbard have not been presented. The data for the polar bear were not included in the statistical comparison due to the limited sample size. $^{**}p < 0.01$. The box indicates the interquartile range (IQR, Q3–Q1), the line within the box represents the median, and the whiskers extend to the minimum and maximum values within 1.5IQR; values outside this range are considered outliers.

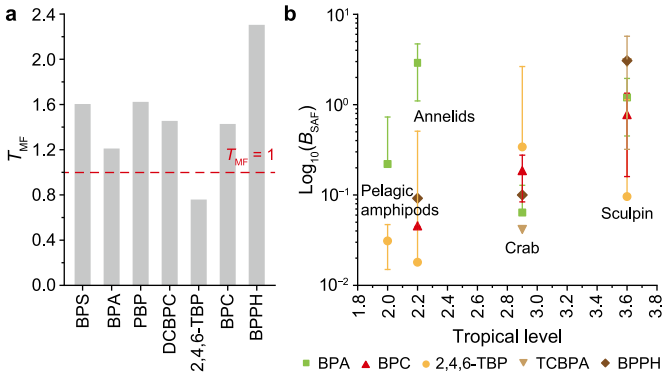

Fig. 4. a, Trophic magnification factors (T_{MF}) of bisphenol analogues in the Arctic marine food chain. **b**, Trophic level distribution of biota–sediment accumulation factors (B_{SAF}) for selected bisphenols across Arctic biota. Error bars indicate standard deviation.

4. Conclusion

We collected 134 samples near Longyearbyen (Svalbard), comprising 23 abiotic and 111 biotic samples. Total concentrations of Σ_{13}BPs in soils and Σ_3BPs in sediments were 1.8–56 and 0.073–0.86 ng g^{-1} dw, respectively. BPA is the most prevalent compound in both landfill leachate and soil. BP concentrations and profiles were elevated near the firefighting training site relative to other locations, implicating this site as a key source of 2,4,6-TBP, a common component of firefighting foams. In contrast, no evidence was found for the abandoned landfill as a direct source of BP contamination in the surrounding environment.

Overall, ΣBPs in different organs of the apex predator, the polar bear, are 1–5 orders of magnitude higher than in lower-trophic-level consumers. BPPH showed the highest magnification potential, suggesting the need for greater attention to its accumulation in Arctic food chains. Conversely, 2,4,6-TBP is less likely to biomagnify through the Arctic food chain. Elevated B_{SAF} values of BPA and other bisphenols in sculpin and annelids indicate effective sediment-to-biota transfer. Variation in B_{SAF} across trophic levels, from pelagic amphipods to sculpin, suggests a connection between sediment exposure and trophic magnification. In contrast, low B_{SAF} of compounds such as 2,4,6-TBP and BPC in lower trophic species imply limited accumulation due to exposure to the sediment environment.

5. Future perspectives

The general pollution of BPs in the vicinity of Longyearbyen (Svalbard) may also stem from other unidentified local sources. BP pollution in the investigated biota could originate from long-range transport and the subsequent deposition process. In addition, the $\delta^{15}N$ values used in this study were taken from Hobson et al. [39], who reported data from a high Arctic region that is ecologically similar to our study site. Barrow Strait–Lancaster Sound (Canadian Arctic) and Svalbard (European Arctic) share key ecological characteristics. Both represent high-latitude marine environments (75°–80° N) defined by polar climates and persistent or seasonal sea ice cover. In both regions, the marginal ice zone during

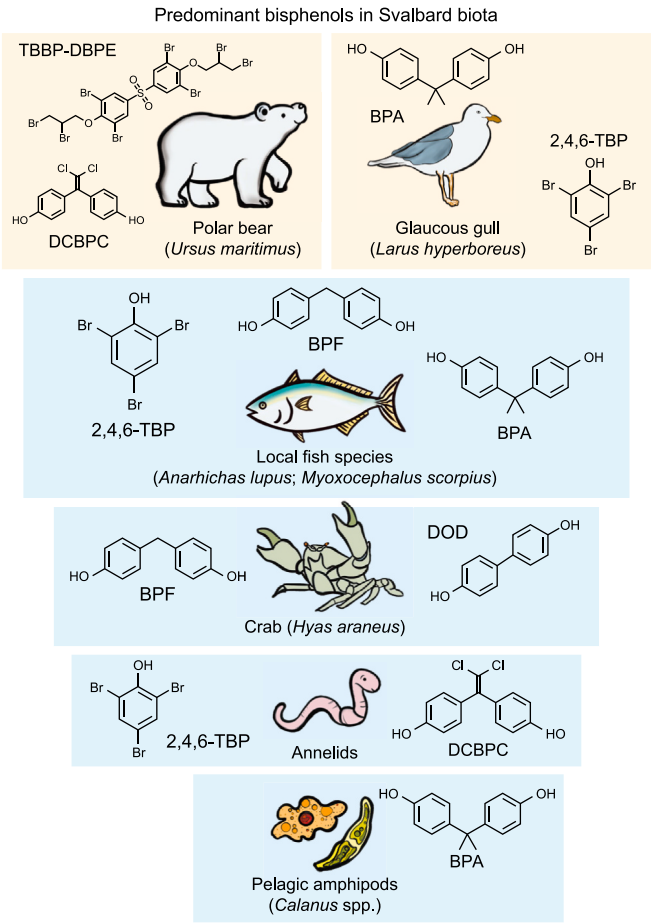

Fig. 5. Illustration of predominant bisphenol compounds in the Svalbard biota. Polar bears and glaucous gulls are identified as top predators in the Arctic marine ecosystem (highlighted with a light-yellow background), whereas species highlighted in blue represent relatively lower-trophic-level consumers.

summer retreat supports high primary production, with particulate organic matter largely derived from phytoplankton and ice algae. Zooplankton communities are similarly structured, dominated by *Calanus hyperboreus*, and the apex predator *Ursus maritimus* (polar bear) occurs in both systems. Moreover, Wold et al. [80] also demonstrated that T_L in seabirds from Svalbard, including glaucous gulls, are highly consistent with those reported by Hobson et al. [39] in the Canadian Arctic. Furthermore, Pedersen [81] documented a T_L of 5.1 in polar bears from the Barents Sea, which aligns closely with the T_L calculated in our study based on Hobson et al.'s $\delta^{15}N$ values. These consistent T_L estimates support using Hobson et al.'s $\delta^{15}N$ values as the $\delta^{15}N$ baseline for Svalbard.

Therefore, in the $\delta^{15}N$ data, it is considered acceptable to estimate T_L and calculate T_{MF} using $\delta^{15}N$ values from ecologically similar species or nearby Arctic regions. However, we still suggest further investigations of T_{MF} calculation due to the limitations of the research in referencing the $\delta^{15}N$ value from Arctic regions similar to Svalbard, where site-specific isotopic measurements are needed for future studies. Moreover, the linear food chain model based on T_L is a practical method, but it is a simplified approach in capturing complex ecosystems. Although T_L offers a valuable framework for the consideration of more probable diets and omnivorous behavior across multiple trophic levels, more studies are required.

CRediT authorship contribution statement

Xi-Ze Min: Writing - Original Draft, Methodology, Formal Analysis, Investigation, Visualization. **Fei Chen:** Investigation, Visualization. **Zhi-Zhong Zhang:** Methodology, Investigation. **Lu Wang:** Methodology, Investigation. **Aasim M. Ali:** Conceptualization, Methodology, Writing - Review & Editing. **Håkon A. Langberg:** Writing - Review & Editing, Resources, Validation. **Sarah E. Hale:** Writing - Review & Editing, Validation. **Gijsbert D. Breedveld:** Writing - Review & Editing, Conceptualization. **Bjørn Munro Jenssen:** Writing - Review & Editing, Methodology, Conceptualization. **Åse-Karen Mortensen:** Resources, Validation. **Tomasz Ciesielski:** Writing - Review & Editing, Resources, Validation. **Geir Wing Gabrielsen:** Writing - Review & Editing, Resources, Conceptualization. **Nan-Qi Ren:** Project administration. **Yi-Fan Li:** Writing - Review & Editing, Supervision, Funding acquisition, Project administration. **Zi-Feng Zhang:** Writing - Review & Editing, Supervision, Project administration, Methodology, Investigation, Formal Analysis, Conceptualization. **Roland Kallenborn:** Writing - Review & Editing, Validation, Supervision, Funding Acquisition, Project Administration.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2025.100627.

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