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The importance of wastewater as a local source of POPs and CEACs in the Arctic environment

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Persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) are problematic due to their presence in Arctic ecosystems and their biomagnification in the Arctic food chain. Long-range environmental transport is believed to be the dominant source of POPs and CEACs in the Arctic, but wastewater is gaining increasing attention as a potential significant local contributor. Here, we present comprehensive information about the presence of POPs and CEACs in Arctic wastewater treatment systems collected through a review of scientific and grey literature. Many compounds have never or rarely been analyzed in Arctic wastewater treatment systems and data from the region are unevenly represented in time and space. For the POPs, sparse but consistent data indicate that wastewater is not a significant local source of polychlorinated biphenyls, hexachlorocyclohexanes, or current use pesticides to the Arctic environment. Less consistent but more abundant information indicates that wastewater may be a significant source of per- and polyfluoroalkyl substances to the Arctic environment but that other equally important sources exist. In contrast, insufficiently treated wastewater appears to be a significant source of polybrominated diphenyl ethers, organophosphate flame retardants and benzotriazole ultraviolet stabilizers, as well as several of the CEAC listed groups of chemicals: phenols, polycyclic aromatic hydrocarbons, pharmaceuticals and personal care products, phthalates, siloxanes and microplastics in the Arctic. We advise improved wastewater treatment to be implemented to reduce the load of these and similar compounds to the Arctic environment. We further advise investigations to be initiated to substantiate our conclusions by improving the geographical coverage, the representation of chemical compounds and the range of wastewater treatment technologies. In particular, we recommend a focus on closing major knowledge gaps by assessing systems with (a) discharge of untreated wastewater, (b) recipients of wastewater from Indigenous communities, (c) recipients of wastewater from major Arctic cities, (d) recipients of industrial wastewater, (e) freshwater recipients and (f) surface run off. Where treatment produces sludge, an evaluation of sludge deposits as a source of exposure should be included. Finally, we advise that the sites which have previously been intensively monitored be used for the evaluation of time-trends.

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Environmental significance

Persistent Organic Pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs) are widely detected in Arctic ecosystems, where they bioaccumulate and pose risks to wildlife and human health. Historically, these contaminants have been attributed mainly to long-range environmental transport from lower latitudes. This review, however, demonstrates that Arctic wastewater systems discharge a diverse suite of POPs and CEACs, including pharmaceuticals, PFASs, phthalates, and microplastics, with an estimated annual load of more than 6 tonnes of chemical contaminants to the Arctic environment. Our findings underscore the need for improved wastewater management and monitoring in Arctic communities to mitigate local contamination and protect vulnerable ecosystems and food chains.

1 Introduction

Persistent organic pollutants (POPs) are defined as the persistent, bioaccumulative, and toxic chemicals that can undergo long-range environmental transport (LRET) and are banned or restricted by United Nations Stockholm Convention Annex A due to their extensive presence in the circumpolar Arctic.[1,2] LRET refers to the movement of chemical substances over vast geographic distances *via* the atmosphere, oceans and river systems, delivering contaminants to remote regions such as the Arctic, far from their original sources of emission.[1] In addition to POPs, the group of chemicals defined as chemicals of emerging Arctic concern (CEACs),[3] predominantly including chemicals with industrial and consumer uses, are gaining increased awareness in the Arctic despite having shorter lifespans than POPs,[3] due to their slower breakdown at low temperatures and reduced sunlight.[3]

While many POPs are related to activities uncommon within the Arctic region, such as pesticides for agricultural use, others, such as polychlorinated biphenyls (PCBs), have more widespread industrial and consumer uses that would generate emissions locally in Arctic communities.[1] CEACs have been observed at elevated levels near Arctic towns and villages, indicating that human settlements may serve as point sources that increase local exposure.[3] The use of personal care products, such as cleaning agents, detergents, and hair and skin care agents, often leads to direct discharge to sewers. Pharmaceuticals enter the sewer system *via* human excreta: around 60% of tetracycline antibiotic dosages are excreted *via* urine and feces,[4] which is in the lower range of the generally recognized 60–80% of consumed drugs being flushed down the toilet untransformed.[5] In addition, chemical metabolites, which may be equally environmentally harmful, are also excreted. Chemicals with completely different purposes may also appear in wastewater (WW), such as chemicals used for the impregnation of textiles, including per- and polyfluoroalkyl substances (PFASs),[6] siloxanes and phthalates,[3] or microplastics with their chemical additives (*e.g.* UV-stabilizers), which enter sewage predominantly *via* laundering of synthetic clothes,[7–10] and flame retardants. Where sewer systems combine domestic WW and surface water run-off from roads and buildings, chemicals associated with their construction, use and maintenance, including those that are released *via* incomplete burning, such as polycyclic aromatic hydrocarbons (PAHs), may appear.[11] Even where separate sewers are used, surface run-off may contribute such chemicals to recipients.[12] Finally, industrial effluents are a well-known historical source of chemicals in the environment, as they may carry industrial chemicals if insufficiently treated.

Globally, the presence of micropollutants (MPs), including many POPs and CEACs, in municipal WW and the efficacy of wastewater treatment (WWT) systems in removing them have received significant research attention, with 10 000+ studies published in the past two decades.[13] Numerous comprehensive global reviews have been produced,[13–17] reporting a diverse suite of chemicals routinely being present in municipal sewage and that in- and outlet concentrations vary widely regionally, and according to WWT methods.[6,13–15,18–23] For example, the concentrations of most MPs in untreated WWT plant (WWTP) influents in the Asian region tend to be higher than those in European and North American countries.[14] Information about MPs in Arctic WW treatment systems (WWTSs) is, however, absent from the available reviews,[6,13–23] and information from the more southern parts of the globe cannot be assumed to mirror the situation in the Arctic, as consumption patterns, industries, WWT systems and infrastructure differ significantly.

In the Arctic region, advanced WWT is uncommon. About 20% of Arctic domestic WW is discharged without any treatment, and a secondary treatment level or higher is accomplished for as little as 19%,[24] which is significantly less than the 86% reported for Europe and North America overall.[25] Inadequately treated WW in the Arctic region is, thus, a likely source of MPs in the Arctic region, where emissions to local recipients used for the harvest of seafood for human consumption could constitute a direct exposure route beyond what would be expected by LRET alone.[3] In addition, WWTP sludge in the Arctic region is generally landfilled or used as landfill coverage, and only a minor fraction is treated beyond dewatering.[24] Due to the slow/absent degradation of persistent compounds trapped in sludge in cold environments, surface deposits of sludge may also lead to environmental/human exposure of POPs and CEACs.

As part of a larger AMAP-initiated (Arctic Monitoring and Assessment Program) review on the importance of local sources *versus* long-range environmental transport of contaminants to the Arctic,[1] this review serves to improve the understanding of the importance of WW as a source of POPs and CEACs to the Arctic environment.

We reviewed scientific and grey literature focusing on the presence of POPs and CEACs in Arctic domestic and industrial WWT systems, including untreated influents and effluents, treated effluents, recipient waters and sediments, to (a) understand the concentration ranges of POPs and CEACs in Arctic WW and relate them to WW from other regions, (b) search for evidence of the efficiency of Arctic WW treatment systems in the removal of POPs and CEACs, (c) estimate the mass-fluxes of the

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most frequently monitored POPs and CEACs from Arctic WWT systems to the Arctic environment, and (d) discuss the importance of WW as a source of POPs and CEACs to the Arctic environment by reviewing literature evaluating concentration gradients in local recipients.

2 Methods

2.1 Literature review

Data on the presence and concentration of contaminants in Arctic (as defined by AMAP)[26] WW, WW sludge and WW recipients' waters and sediments were collected by reviewing scientific literature found using the search tools Web of Science, Google Scholar, and Scopus and through the retrieval of reports from local authorities (including those in local languages). The list of chemicals included is equivalent to the list included in the study by de Wit *et al.* (2026).[1] The completeness of our search was verified by confirming that all relevant studies in the database "Pharmaceuticals in the Environment" had been identified and included, alongside any additional studies.[27]

Global reviews of POP and CEAC concentrations in WW influents and effluents of non-Arctic WWTPs were compiled using the same search tools to compare with Arctic systems. For chemicals with no global review paper available, papers that reported country-wide monitoring were referred to. No comparative global values were included when no global reviews were available.

2.2 Calculations

For the concentration of POPs and CEACs in each Arctic WWTP, we compiled published measures of central tendency (median, mean, or measured value – if only one measurement was available) of the POPs and CEACs in influent and/or effluent (SI S1) (Fig. 1–5). We also identified Arctic country-specific maximum detected concentrations in untreated WW (influent and untreated WW) and treated effluent (data in SI S2) that we used in our comparison to non-Arctic WW. These maximum WW concentrations represent a conservative measure of wastewater contamination. For non-Arctic WWTPs, minimum and maximum concentrations across all studies were compiled. In all non-Arctic cases the minimum concentrations were below the detection limit (DL), with the exception of caffeine. For the use in estimates of the maximum annual loads, 75th percentile concentrations were calculated. To do this, concentrations that were not detected (ND, *i.e.*, the result was below the detection limit of the method) were substituted with the detection limit. As a result, in situations of low detection frequency, the calculated 75th percentile is higher than it would have been if, for example, the values of zero or 0.5 times the DL had been used.

A worst-case estimate of the annual load of the most frequently monitored POPs and CEACs entering the Arctic environment due to domestic WW discharge was then calculated. The load estimation methodology consisted of the following steps:

(1) Estimation of total wastewater discharge volume: the total annual wastewater discharge volume in the Arctic was estimated based on a population equivalent (PE) of 5.2 million inhabitants, a per capita wastewater generation rate of 145 L per person per day and a factor of 365 days per year.

(2) Distribution according to the wastewater treatment level: the total wastewater volume was distributed according to the regional wastewater treatment status reported by Jensen *et al.*[24] (20% untreated/unknown, 61% preliminary or primary treatment, and 19% secondary treatment or higher).

(3) 75th percentile concentrations for each treatment category in each Arctic region were calculated (S2) as conservative estimates of average values. Based on these, overall Arctic-wide average 75th percentile concentrations were then calculated for each treatment category.

(4) Calculation of annual contaminant loads: annual discharge loads for each compound and treatment category were estimated by multiplying the average Arctic 75th percentile concentration by the respective wastewater discharge volume.

(5) Calculation of total annual loads: finally, the total annual load was estimated by summing the loads calculated for all compounds and treatment categories.

3 Fate of POPs and CEACs in wastewater treatment systems

By default, conventional WWT systems are designed to remove readily biodegradable organic compounds, macro-nutrients (N and P), and microorganisms, with the main intention of preventing the eutrophication of local recipients and human exposure to pathogens.[28] Presently, they are not designed to remove anthropogenic chemical substances such as POPs and CEACs.[29] In WWT systems applying treatment beyond primary, however, easily degradable organic or volatile chemicals are removed *via* (bio)degradation or volatilization.[14,18,29] Hydrophobic pollutants, including most legacy and new POPs and some CEACs, are also predominantly removed (>70%) *via* sorption to particulate organic matter, such as biosolids in the activated sludge process of secondary treatment.[18,29] However, poorly-to-moderately biodegradable hydrophilic pollutants, such as many PPCPs, pesticides, and household chemicals, including corrosion inhibitors, sweeteners, chelating agents, and phosphorus flame retardants (OPFRs), are only minimally removed through conventional treatment.[18,30] Advanced (quaternary) physicochemical treatment processes, such as advanced oxidation processes, activated carbon filters, or membrane-based technologies, are required to effectively remove these types of contaminants from WW.[16,29–31] As most WWTPs do not apply such advanced treatments, they are considered to be the primary pathways of many CEACs.[30,32,33] In addition, some chemicals appear to be formed during WWT.[6,14,34] This could be due to a variety of factors, such as transformation from unmonitored precursors to target analytes, as commonly observed for PFASs.[6]

Although the presence of POPs and CEACs in municipal WWTP effluents has been thoroughly documented and their impacts on receiving water systems increasingly are recognized,[18,35,36] the establishment of regulatory criteria has only

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recently been forthcoming. Hitherto, the only country in the world that had established criteria for MPs in municipal WWTP effluents was Switzerland,[20,30] where regulation led to the wide implementation of quaternary treatment processes for municipal WW. In January 2025, however, a revision to the EU's Urban Wastewater Directive[37] was adopted, requiring the implementation of quaternary treatment by urban WWTPs in the EU serving ≥150 000 PE as well as WWTPs for >10 000 PE discharging to a sensitive recipient. The regulation will be implemented in steps, prioritizing larger plants, with full implementation set for 2045. Treatment efficiency will be monitored *via* a list of indicator pharmaceutical substances whose concentrations must be reduced by 80%. The revised directive will influence Arctic urban/centralized systems in the EU member states of Finland and Sweden, as well as the EU affiliate Norway. However, as in the Arctic region small WWT systems prevail, and only 3% of the WW discharged to the Arctic environment is currently subject to tertiary treatment,[24] a *de facto* prerequisite for advanced treatments to function,[31] the implementation of quaternary treatment can be expected for a minimal fraction of Arctic WW, only. Nature-based solutions (NBSs) such as ponds, lagoons, wetlands, and infiltration systems, which account for 5% of Arctic WWT,[24] constitute another attractive treatment option for MPs.[31] However, the functioning of Arctic NBSs was shown to be highly variable and only meet the treatment-level for which they were designed a fraction of the time.[38] In no case was the tertiary treatment level achieved, making them unlikely to be as effective for MP removal as more southern NBSs.[31]

4 POPs and CEACs in Arctic domestic wastewater

Altogether, we identified and included data from 32 sources reporting the concentrations of the target POPs and CEACs listed by de Wit *et al.*[1] in WW in the Arctic region: 13 scientific papers,[39–51] 10 reports,[52–61] two theses,[62,63] one conference proceeding,[64] and three internal analytical reports from WWTPs.[65–67] For perspective, we related the Arctic WW POP and CEAC concentrations to concentrations reported in 12 global reviews,[6,14,18–23,68–71] eight comprehensive national investigations and one corrigendum.[71–78] A summary of the results can be found in Table 1, with detailed data in the SI (S1). Compounds without any observations in Arctic WW were omitted from Table 1 and were not investigated further in non-Arctic WW but remain listed in S1.

The most studied contaminant classes in Arctic WW were PPCPs[41,42,45–50,55,58,62,63] and PFASs[39,40,42–44,48,52,56,58,65,67] of which many were sampled and analyzed on more than 20 occasions at different Arctic locations (Tables 1 and S1). WWTPs in the Arctic region of the Scandinavian countries (the Faroe Islands,[39,45,52–54,56] Finland,[57,58,66,67] Greenland,[39,45,52,56,79] Iceland,[39,44,45,52,53,56,59,60,65] and Norway[42,46,49–52,55,61,63]) were studied the most, followed by Canada[40,41,43,47,48] (S1). To our knowledge, there have only been two WWTPs studied in Alaska (United States) concerning the target contaminants,[62] and no data are available for POPs or CEACs from WWTPs in the Arctic region of either Russia or Sweden (S1). The sampling years represented are stated in the SI (S2). The first observations were from 2003 and the last observations were from 2022; however, there are only two studies after 2018, likely due to the logistical challenges of travelling to and sampling at remote northern communities during the COVID 19 pandemic.

Overall, the variability in contaminant concentrations in effluents between Arctic WWTPs was large (Table 1), even within the same country (S1). This variability is likely due to a variety of factors, including treatment type, time of sampling (hour, year, and season), differences in water consumption per capita and lifestyle, and possibly also differences in WW collection methods, as well as sampling and analytical methods.

The factors which could lead to more concentrated Arctic WWTP influent and untreated effluent are

(1) Water consumption tending to be lower in remote Arctic communities compared to more populated areas due to lack of water and/or piping.[38,43,80,81]

(2) Infiltration of groundwater and surface run-off into Arctic sewer systems being less likely due to

(a) The lack of sewer networks (*e.g.* the Canadian Arctic relies on truck services and in small communities in Alaska and Greenland, black WW is hauled in plastic bags to discharge points).[82,83]

(b) Sewers above ground due to permafrost.

(c) No or limited groundwater flows due to permafrost.[84]

(d) Small communities with less extensive sewer networks in comparison to non-Arctic regions.[84]

(e) Surface water run off separately *via* natural streams or open ditches, as opposed to combined sewers.

On the other hand, the absence of significant industrial production and less abundant consumption of modern convenience products such as PPCPs in rural Indigenous Arctic communities might lead to lower concentrations of MPs in Arctic WW compared to non-Arctic. Also, in Iceland and the Faroe Islands, in contrast to the rest of the Arctic region, water consumption is high,[85] leading to less concentrated WW.

Apart from a few target contaminants, the concentrations in Arctic untreated WW (influents and untreated WW) fell within the ranges measured in non-Arctic untreated WW, and most compounds were observed at much lower maximum concentrations than those found in non-Arctic untreated WW (Tables 1 and S1). The contaminants, which had higher maximum values in untreated Arctic WW compared to global data, were the sum of PBDEs, which was found to be extremely high in the influents in four Canadian lagoon treatment systems,[43] and the PAHs acenaphthylene, acenaphthene, fluorene and phenanthrene, of which the first two were found at high concentrations in a WWTP influent in Reykjavik, Iceland,[52] and the second two were found in Greenlandic non-treated WW.[52] In addition, the PPCPs naproxen and venlafaxine were found at very high levels in untreated hospital WW in Reykjavik, Iceland.[45]

Contaminant concentrations in Arctic WWTP effluents also mostly fell in lower ranges compared to non-Arctic effluents (Tables 1 and S1). They, however, approached the maximum concentrations observed in non-Arctic systems for a few of the

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Table 1 Concentration ranges of POPs and CEACs observed in Arctic and non-Arctic WW. The complete dataset is available in SI S1[a]

Concentration ranges	Unit	Arctic WWTP influent and untreated WW	Non-Arctic WWTP influent and untreated WW	Arctic WWTP effluent	Non-Arctic WWTP effluent	Number of Arctic observations	Arctic references
Legacy POPs							
Polychlorinated biphenyls (PCBs)	$\mu g\ l^{-1}$	—	—	ND	—	1	65
Hexachlorobenzene (HCB)	$\mu g\ l^{-1}$	—	—	<0.001–<0.01	1.70	3	65–67
Polychlorinated dibenzo-*p*-dioxins	$pg\ l^{-1}$	—	—	<30	—	2	65 and 67
Polychlorinated dibenzofurans	$pg\ l^{-1}$	—	—	<20	—	2	65 and 67
2,4′-Dichlorodiphenyldichloroethane (2,4′-DDD)	$\mu g\ l^{-1}$	—	—	<0.001	—	1	67
2,4′-Dichlorodiphenyltrichloroethane (2,4′-DDT)	$\mu g\ l^{-1}$	—	—	<0.001–<0.01	ND	2	65 and 67
2,4′-Dichlorodiphenyldichloroethylene (2,4′-DDE)	$\mu g\ l^{-1}$	—	—	<0.001	—	1	67
4,4′-Dichlorodiphenyldichloroethane (4,4′-DDD)	$\mu g\ l^{-1}$	—	—	<0.001–<0.01	—	2	65 and 67
Dichlorodiphenyltrichloroethane (4,4′-DDE)	$\mu g\ l^{-1}$	—	—	<0.001–<0.01	—	2	65 and 67
4,4′-Dichlorodiphenyltrichloroethane (4,4′-DDT)	$\mu g\ l^{-1}$	—	—	<0.001–<0.01	—	2	65 and 67
Chlordanes (gamma-chlordane)	$\mu g\ l^{-1}$	—	—	<0.005	—	1	67
Mirex	$\mu g\ l^{-1}$	—	—	<0.005	—	1	67
Aldrin	$\mu g\ l^{-1}$	—	—	<0.001–<0.015	ND	3	65–67
Dieldrin	$\mu g\ l^{-1}$	—	—	<0.001–<0.015	8.9	3	65–67
Endrin	$\mu g\ l^{-1}$	—	—	<0.001–<0.015	2.8	3	65–67
New POPs							
PBDEs							
Polybrominated diphenyl ethers ($\sum$PBDEs)	$ng\ L^{-1}$	324–11 331	0.001–3000	2.2–844	0.0003–1000	9	43 and 67
2,2′,4,4′-Tetrabromodiphenyl ether (BDE-47)	$ng\ L^{-1}$	19–139	<DL-324	<0.1–80	<1.4–57	17	43, 57, 58, 65 and 67
2,2′,4,4′,5-Pentabromodiphenyl ether (BDE-99)	$ng\ L^{-1}$	18–127	<DL-219	<0.1–70	<3.7–58	17	43, 57, 58, 65 and 67
PFASs							
Perfluorooctane sulfonic acid (PFOS)	$ng\ L^{-1}$	<DL-70.6	<DL-1384	0.74–91	<DL-5663	37	39, 40, 42–44, 48, 52, 56, 58, 65 and 67
Perfluorooctanoic acid (PFOA)	$ng\ L^{-1}$	<DL-85.2	<DL-2814	<5–31.5	<DL-2746	37	39, 40, 42, 43, 48, 56, 58, 65, 67 and 78
Perfluorononanoic acid (PFNA)	$ng\ L^{-1}$	0.25–11.7	<DL-233	0.17–28	<DL-178	33	39, 40, 43, 48, 52, 56 and 67
Perfluorodecanoic acid (PFDA)	$ng\ L^{-1}$	0.18–4.7	<DL-128	<0.21–6.5	<DL-136	27	39, 40, 43, 48, 52, 56 and 67

Table 1 (*Contd.*)

Concentration ranges	Unit	Arctic WWTP influent and untreated WW	Non-Arctic WWTP influent and untreated WW	Arctic WWTP effluent	Non-Arctic WWTP effluent	Number of Arctic observations	Arctic references
Perfluorobutane sulfonate (PFBS)	ng L^{-1}	<2.0–76	<DL-2523	0.81–33	<DL-960	19	39, 40, 43, 48, 56 and 67
Perfluorohexane sulfonic acid (PFHxS)	ng L^{-1}	0.24–7.4	<DL-1313	0.15–7.8	<DL-2227	31	39, 40, 42, 43, 52, 56 and 67
HCHs							
α-hexachlorocyclohexane (α-HCHs)	μg l^{-1}	—	—	<0.001–<0.0025	—	3	65–67
β-hexachlorocyclohexanes (β-HCHs)	μg l^{-1}	—	—	<0.001–<0.0025	—	3	65–67
γ-hexachlorocyclohexanes (γ-HCHs)	μg l^{-1}	—	—	<0.001–<0.0025	—	3	65–67
Other new POPs							
Hexachlorobutadiene	μg l^{-1}	—	—	<0.0010	—	1	66
Hexabromocyclododecane (HBCDD)	ng L^{-1}	—	—	<0.100–8.07	—	2	65 and 67
Alpha-endosulfan	μg l^{-1}	—	—	<0.00008–<0.0025	—	3	65–67
Beta-endosulfan	μg l^{-1}	—	—	<0.0025	—	1	66
Short-chain chlorinated paraffins (SCCPs)	μg l^{-1}	—	—	<0, 1–<2	—	3	58 and 66
CEACs							
Organophosphate esters							
Tributyl phosphate (TBP)	ng L^{-1}	—	—	ND	—	1	42
Microplastics (5–500 μm)	L^{-1}	—	—	0–203	—	30	51
Microplastics (20–1000 μm)	L^{-1}	159–5000	—	55–1517	0.0023–132	9	61 and 79
Microplastics (300–1000 μm)	L^{-1}	0.6–2.07	—	1.4	—	4	60
Microplastics (263–5000 μm)	L^{-1}	0.7–2.64	—	0.61–2.38	—	23	59
Phenols							
4-*tert*-Butylphenol	ng L^{-1}	<10	—	NA	—	1	53
2,6-Di-*tert*-butylphenol	ng L^{-1}	<5–9	—	<30	—	6	53
4-*tert*-octylphenol	ng L^{-1}	8.5–78	<DL-1495	<10–66	<0, 67–392	19	52, 53 and 67
n-octylphenol	ng L^{-1}	<1–60.6	—	<5–17	—	6	53
Nonylphenol-mix (NP-mix)	ng L^{-1}	129–1520	<DL-10 186	<100–2173	<10–14 444	20	52 and 53
n-Nonylphenol (*n*-NP)	ng L^{-1}	<1–54.3	—	17–72	—	7	53 and 67
4-Dodecylphenol	ng L^{-1}	<125–4096	—	—	—	4	53
4-Cumylphenol	ng L^{-1}	<1–2.2	—	<1–5	—	6	53
Bisphenol-A (BPA)	ng L^{-1}	232–1016	466–12 205	<1–561	<20–7625	5	53
Tetrabromobisphenol A (TBBPA)	ng L^{-1}	<15	—	<10	—	4	53
Methylated-TBBPA	ng L^{-1}	<2	—	<3	—	5	53
Octylphenolethoxylate	ng L^{-1}	56.8–157	—	<1	—	6	53
NP-ethoxylate	ng L^{-1}	13.5–4896	—	1585	—	6	53
4-*tert*-Octylphenol (4-*t*OP) monoethoxylate	ng L^{-1}	<10–310	—	<10–453	—	15	52 and 67
4-*t*OP-diethoxylate	ng L^{-1}	<10	—	<10–838	—	15	52 and 67
4-*t*O triethoxylate	ng L^{-1}	<10	—	<10–170	—	15	52 and 67
4-NP-mono ethoxylate	ng L^{-1}	<100–3620	—	<50–1960	—	15	52 and 67
4-NP-diethoxylate	ng L^{-1}	<100–501	—	20–313	—	15	52 and 67

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Table 1 (*Contd.*)

Concentration ranges	Unit	Arctic WWTP influent and untreated WW	Non-Arctic WWTP influent and untreated WW	Arctic WWTP effluent	Non-Arctic WWTP effluent	Number of Arctic observations	Arctic references
4-NP-triethoxylate	ng L^{-1}	<20	—	<10	—	14	52 and 67
Siloxanes							
Octamethylcyclotetrasiloxane (D4)	μg l^{-1}	—	—	<0.08	—	1	54
Decamethylcyclopentasiloxane (D5)	μg l^{-1}	—	—	5.2	—	1	54
Dodecamethylcyclohexasiloxane (D6)	μg l^{-1}	—	—	0.33	—	1	54
Hexamethyldisilane (MM)	μg l^{-1}	—	—	<0.0005	—	1	54
Octamethyltrisiloxane (MDM)	μg l^{-1}	—	—	<0.001	—	1	54
Decamethyltetrasiloxane (MD2M)	μg l^{-1}	—	—	<0.0005	—	1	54
Dodecamethylpentasiloxane (MD3M)	μg l^{-1}	—	—	<0.004	—	1	54
PAHs							
Naphthalene	μg l^{-1}	<0.010–0.63	ND-2.00	<0.010–0.56	ND-0.92	16	52, 65 and 67
Acenaphthylene	μg l^{-1}	<0.010–1	ND-0.10	<0.005	ND-0.05	14	52 and 67
Acenaphthene	μg l^{-1}	<0.010–12	ND-0.35	<0.005–0.02	ND-0.09	14	52 and 67
Fluorene	μg l^{-1}	<0.010–93	ND-0.70	<0.005–0.082	ND-0.50	14	52 and 67
Phenanthrene	μg l^{-1}	0.028–57	ND-1.70	<0.005–0.10	ND-0.22	14	52 and 67
Anthracene	μg l^{-1}	<0.010–0.016	ND-0.10	<0.005	ND-0.15	16	52, 65 and 67
Fluoranthene	μg l^{-1}	<0.010–0.081	ND-0.70	<0.005–0.052	ND-0.50	16	52, 65 and 67
Pyrene	μg l^{-1}	<0.010–0.067	ND-0.50	<0.005–0.047	ND-0.70	14	52 and 67
Benz(*a*)anthracene	μg l^{-1}	<0.010–0.049	ND-0.08	<0.001–0.022	ND-0.05	14	52 and 67
Chrysene	μg l^{-1}	<0.010–0.035	ND-0.15	<0.001–0.015	ND-0.05	14	52 and 67
Benz(*b*) fluoranthene	μg l^{-1}	<0.010–0.031	ND-0.23	<0.010	ND-0.05	15	52 and 67
Benz(*k*) fluoranthene	μg l^{-1}	<0.010–0.022	ND-0.35	<0.001	ND-0.06	16	52, 65 and 67
Benz(*a*)pyrene	μg l^{-1}	0.01–0.042	ND-1.40	<0.00017–0.011	ND-0.38	16	52, 65 and 67
Dibenzo(ah) anthracene	μg l^{-1}	<0.010	ND-0.10	<0.0005	ND-0.06	14	52 and 67
Benzo(ghi)perylene	μg l^{-1}	<0.010	ND-0.23	<0.0005	ND-0.05	16	52, 65 and 67
Indeno(1,2,3-cd)pyrene	μg l^{-1}	<0.010	ND-1.05	<0.0005	ND-0.15	16	52, 65 and 67
PPCPs							
Salicylic acid	ng L^{-1}	<41.7–38 400	—	381–8740	78–2180	19	45
Sulfamethoxazole	ng L^{-1}	ND-1303	<DL-54 830	251	<DL-10.800	12	41, 46–48 and 55
Sulfapyridine	ng L^{-1}	18–358	—	<0.6–71	—	8	48
Carbamazepine	ng L^{-1}	0.53–2580	<DL-18 500	<1.2–549	<DL-36 060	12	41, 48 and 63
Trimethoprim	ng L^{-1}	0.11–609	<DL-6796	<0.8–103	<DL-37 000	13	41, 46, 48 and 55
Diclofenac	ng L^{-1}	14.3–697	<DL-22 800	55.5–890	<DL-23 500	26	42, 45, 46, 55, 58 and 63

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Table 1 (*Contd.*)

Concentration ranges	Unit	Arctic WWTP influent and untreated WW	Non-Arctic WWTP influent and untreated WW	Arctic WWTP effluent	Non-Arctic WWTP effluent	Number of Arctic observations	Arctic references
Ibuprofen	ng L^{-1}	1.62–25 305	<DL-96 519	<100–16 000	<DL-14 600	29	45, 46, 50, 55, 58, 62 and 63
Naproxen	ng L^{-1}	<1.05–89 050	<DL-13 833	7.88–1820	<DL-29 147	28	42, 45, 47 and 48
Lidocaine	ng L^{-1}	<0.42–183	—	<0.42–14	1000	19	45
Paracetamol	ng L^{-1}	<124–149 750	—	5355–40 300	8–178	19	45
Metformin	ng L^{-1}	269.5–49 150	1700–325 000	4415–7560	ND-82 700	19	45
Metoprolol	ng L^{-1}	0.8–810	<DL-7443	<0.6–653	ND-5762	33	41, 42, 45, 47, 48, 50 and 63
Atenolol	ng L^{-1}	<20.8–10 645	<DL-294 700	<0.3–1490	ND-14 200	30	41, 45, 47 and 48
Furosemide	ng L^{-1}	47.3—13 750	—	300–1140	280–9960	19	45
Amiloride	ng L^{-1}	<3.03–1250	—	8.27–217	—	19	45
Dipyridamole	ng L^{-1}	83.9–166 000	—	2997–24 600	—	19	45
Citalopram	ng L^{-1}	<0.057–1835	—	20–117	—	34	45, 46, 49, 55 and 63
Venlafaxine	ng L^{-1}	21–26 850	ND-7684	<120–746	ND-5500	23	45, 58 and 62
2-Acetaminophenol	ng L^{-1}	—	—	2050	—	1	42
5,6-Dimethylbenzimidazole	ng L^{-1}	—	—	380	—	1	42
8-Methoxypsoralen	ng L^{-1}	—	—	ND	—	1	42
Acetaminophen	ng L^{-1}	2.40	<DL-500 000	58 500	<DL-62 000	4	42, 62 and 63
Antipyrine	ng L^{-1}	—	—	ND	—	1	42
Caffeine	ng L^{-1}	61–54 700	102–273 900	9180–235 000	<DL-115 141	8	42, 46, 50, 55, 62 and 63
Carbendazim	ng L^{-1}	—	—	ND	100	1	42
Cetirizine	ng L^{-1}	—	—	3350	—	1	42
N,*N*-Diethyl-*meta*-toluamide (DEET)	ng L^{-1}	—	42 334	35–910	13–1663	3	42, 50 and 67
Icaridin	ng L^{-1}	—	—	655	—	1	42
N,*N*-dimethyl-*N*′-phenylsulfamide	ng L^{-1}	—	—	72	—	1	42
Paraxanthine	ng L^{-1}	—	—	280 000	—	1	42
Pyrimethanil	ng L^{-1}	—	—	7	—	1	42
Triphenylphosine oxide	ng L^{-1}	—	—	6100	—	1	42
Phthalates							
Dimethyl phthalate	μg l^{-1}	<0.30	—	<0.02–<0.3	—	13	52 and 67
Diethyl phthalate (DEP)	μg l^{-1}	<0.3–1.3	<DL-9.2	<0.05–3.7	<0.004–1.1	1	3, 52 and 67
Di-*n*-propyl phthalate	μg l^{-1}	<0.30	—	<0.30	—	12	52
Di-*n*-butyl phthalate	μg l^{-1}	<0.30–0.34	—	<0.05–<0.30	—	13	52 and 67
Diisobutyl phthalate (DIBP)	μg l^{-1}	<0.40–0.94	—	<0.05–<0.50	—	13	52 and 67

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Table 1 (*Contd.*)

Concentration ranges	Unit	Arctic WWTP influent and untreated WW	Non-Arctic WWTP influent and untreated WW	Arctic WWTP effluent	Non-Arctic WWTP effluent	Number of Arctic observations	Arctic references
Dipentyl phthalate (DPeP)	μg l^{-1}	<0.30	—	<0.01–<0.30	—	12	52 and 67
Di-*N*-octylphthalate	μg l^{-1}	<0.30–<0.50	—	<0.01–<0.30	—	13	52 and 67
Di(2-ethylhexyl) phthalate (DEHP)	μg l^{-1}	1.2–49	<DL-143.3	<0.30–2.4	<0.002–27.1	13	52 and 67
Butyl benzyl phthalate	μg l^{-1}	<0.30	—	<0.02–<0.30	—	13	52 and 67
Dicyclohexyl phthalate	μg l^{-1}	<0.30–0.33	—	<0.30	—	12	52
Diisodecyl phthalate	μg l^{-1}	<1.0–4.4	—	<1.0	—	9	52 and 67
Diisononyl phthalate (DINP)	μg l^{-1}	4–29	<DL-142.8	<1–5.2	<0.115–252	9	52 and 67

[a] —: No available data found. ND: not detected, and the detection limit not stated. < Value: below the stated DL (when a true value was lower than the lowest detection limit, the true value was stated as the lowest observed concentration).

target contaminants (*e.g.* total PBDEs) or exceeded them (BDE-47 and BDE-99, the PPCPs: salicylic acid, ibuprofen, paracetamol, and caffeine as well as DEP) (Tables 1 and S1).

The following paragraphs discusses the content of the different contaminant groups in Arctic domestic WW in further detail.

4.1 Legacy POPs in Arctic domestic wastewater

Only a few measurements have been made of legacy POPs in Arctic WW (Table 1), two in WWTP effluents in Finland,[66,67] and one in an Icelandic WWTP effluent (S1).[65] No reports on the concentrations of the legacy POPs heptachlor and toxaphene were found, and neither were any reports on legacy POPs in untreated Arctic WW. However, only one global review on MPs in WW included legacy POPs (PCBs with two references and organochlorine pesticides with one reference),[18] rendering the global situation equally unstudied.

For all three Arctic observations, the concentrations of the analyzed legacy POPs were found to be below the detection limits in the effluents. This is not surprising for the Finnish effluent, which had undergone tertiary treatment, given that legacy POPs are hydrophobic and tend to partition to solids during WWT rather than remain in the aqueous phase.[86] However, no significant removal was expected in the Icelandic system that had only preliminary screening. This non-detection could be partially due to the very dilute WW in Iceland.[85] In the non-Arctic studies, the concentrations of HCB, 2,4′-DDD, heptachlor, aldrin, dieldrin and endrin after secondary treatment were approximately two orders of magnitude higher than the detection limits of the Arctic studies,[18] indicating a higher presence of these compounds in WW in southern regions. This is in contrast with the particularly high concentrations of legacy POPs found in biota at the top of the food chain in the Arctic,[87–89] suggesting that the POPs observed in Arctic biota do not originate from Arctic WW to any significant extent but rather from LRET as commonly acknowledged.[90,91] Any final conclusion about the Arctic environmental load of legacy POPs from WW, however, requires more observations from a larger variety of treatment systems, including untreated WW, given that a significant fraction of Arctic and global WW is discharged untreated.[24,92]

4.2 New POPs in Arctic domestic wastewater

Among the new POPs, PBDEs[43,57,58,65,67] and PFASs[39,40,42–44,48,52,56,57,65,67] were measured on several (9–37) occasions in Arctic WW, while others (HBCDD, SCCPs, HCHs, endsulfane, and hexachlorobutadiene) were analyzed in a few (1–3) WWTP effluents only. Apart from HBCDD, these were all found to be below detection limits (Table 1), but no information about their eventual presence in untreated Arctic WW was available. Finally, many substances (hexabromobiphenyl, pentachlorophenol, chlordecone, dicofol, pentachlorobenzene, polychlorinated naphthalenes (PCNs), dechlorane plus, methoxychlor, or UV-328) were never analyzed in any Arctic WW.

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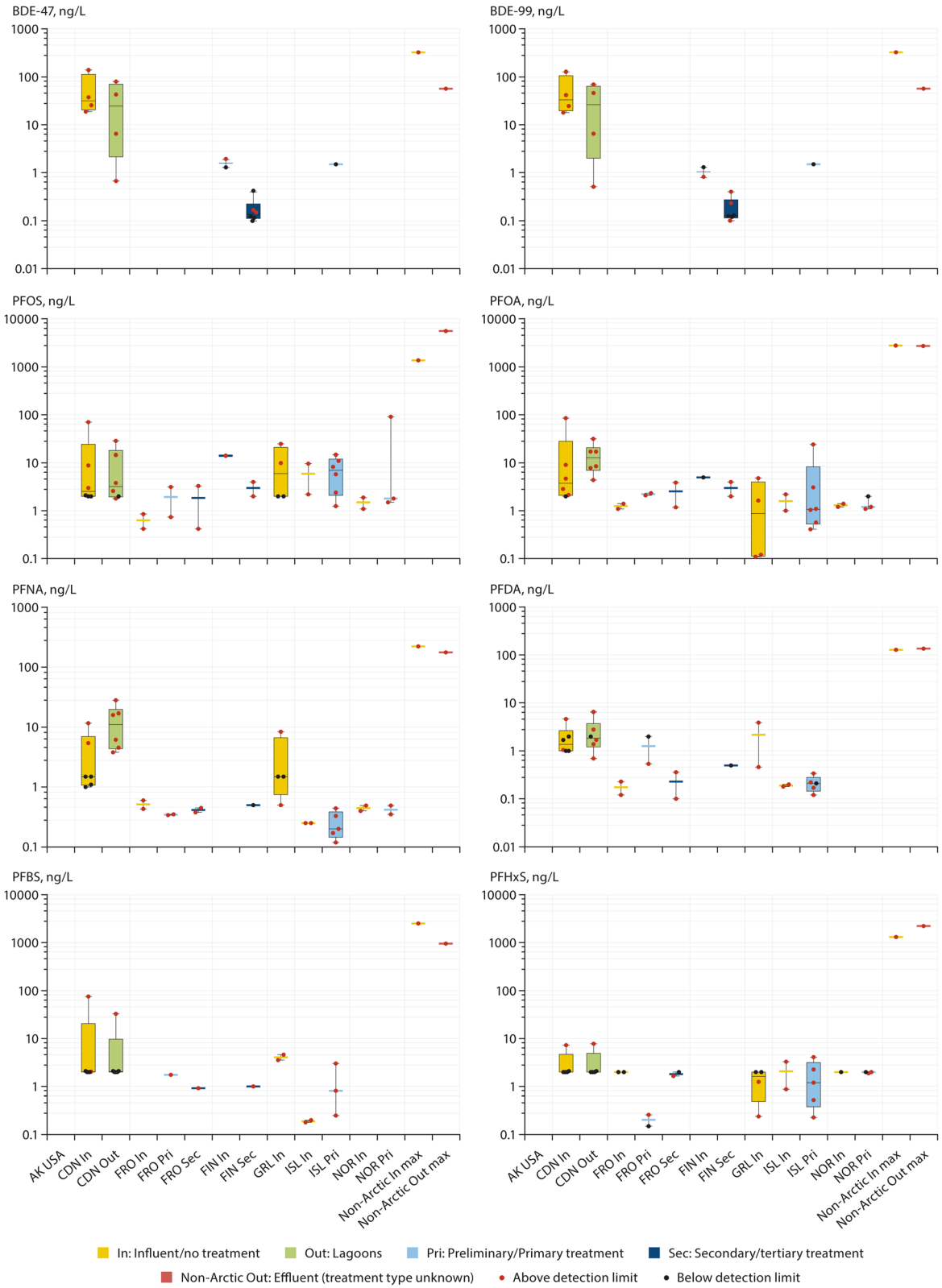

Fig. 1 BDEs and PFASs – box plots and median (line) of reported concentrations of selected contaminants in wastewater by treatment type in several parts of the Arctic region in comparison to the non-Arctic region. Boxes are only shown when number of observations ≥4. Countries are indicated by their 3-letter ISO country codes. Complete data can be found in S1 and S2.

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4.2.1 PBDEs in Arctic domestic wastewater. Fig. 1 shows the country-specific concentrations of BDE-47 and -99, which are prevalent in penta-PBDE formulations,[93] as representatives of the PBDE class of chemicals, based on them having been analyzed in WW in several parts of the Arctic region (Canada,[43] Finland,[57,58,67] and Iceland[65]) (data in S1 and S2).

The maximum concentrations of BDE-47 and -99 in Arctic untreated WW were at least 72% lower compared to non-Arctic WWTP influents (Fig. 1 and S2), which may be due to factors such as lifestyle differences or less industrial/commercial sources in the Arctic. With only two countries with observations of PBDE concentrations in untreated Arctic WW, which differ in concentrations by almost two orders of magnitude, no general conclusions could, however, be drawn.

The maximum concentrations of BDE-47 and -99 were only slightly lower in treated (80 and 70 ng L^{-1}, respectively) WW compared to untreated (139 and 127 ng L^{-1}, respectively) WW in Canada, where an NBS is used, comparable to the maximum concentrations observed in treated non-Arctic systems (Fig. 1 and S2), indicating that lagoons in Arctic climates may not be efficient for the removal of PBDE compounds. The difference between influent and effluent concentrations was more pronounced in Finland, where the maximum concentrations in WWTP effluent for BDE-47 and -99 of 0.17 and 0.13 ng L^{-1} were 10 times lower than those in the untreated WW (1.9 and 1.3 ng L^{-1}, respectively). The studied WWTPs in Finland used mechanical biological activated sludge secondary or tertiary treatment. Like legacy POPs, PBDEs tend to partition to solids during WWT,[71,94] explaining the reduction of PBDEs observed during conventional secondary or higher level WWT.

4.2.2 PFASs in Arctic domestic wastewater. Of the eight PFASs listed as new POPs, two were measured only once each (S1), while six (PFOS, PFOA, PFNA, PFDA, PFBS, and PFHxS) were analyzed in WW across the Arctic region (Canada,[40,43,48] the Faroe Islands,[39,52,56] Finland,[58,67] Greenland,[39,52,56] Iceland,[39,44,52,56,65] and Norway[42,52]) (Table 1). Fig. 1 shows their country-specific concentrations (data in S1 and S2).

The maximum concentrations of PFASs observed in Arctic WW (treated and untreated) were between one and three orders of magnitude lower than the maximum concentrations in non-Arctic WW, which could be due to less industrial sources. With the minimum PFAS concentrations in non-Arctic WWTPs being consistently below detection limits, a great range in concentrations globally was, however, indicated.

In general, within each Arctic country, the concentrations of PFASs were higher in treated compared to untreated WW. This has been observed elsewhere previously and is likely due to the transformation of unmeasured precursors into the target analytes during WWT.[6,95] Studies have also found that the formation of target PFASs during WW treatment is typically higher after conventional secondary or natural WWT compared to primary WWT[96] and that increasing concentrations of PFASs occur following biological treatment.[97] This is partly in alignment with the observations in the Faroe Islands, the only country where PFASs were analyzed at two different treatment levels and where the maximum concentrations of PFOS, PFOA, PFNA, and PFHxS were higher after secondary treatment compared to primary treatment (Fig. 1). However, the same trend was not valid for PFDA or PFBS. Apart from the complexity of processes influencing PFAS partitioning to solids and the transformation of precursors during WWT,[95,96] these results are likely also influenced by the relatively low number of datapoints, despite these chemicals being among the best studied in Arctic WW.

4.3 CEACs in Arctic domestic wastewater

Among the CEACs, many PPCPs[41,42,45–50,55,58,62,63] and most phenols,[52,53,67] PAHs,[52,65–67] and phthalates[52,67] have been

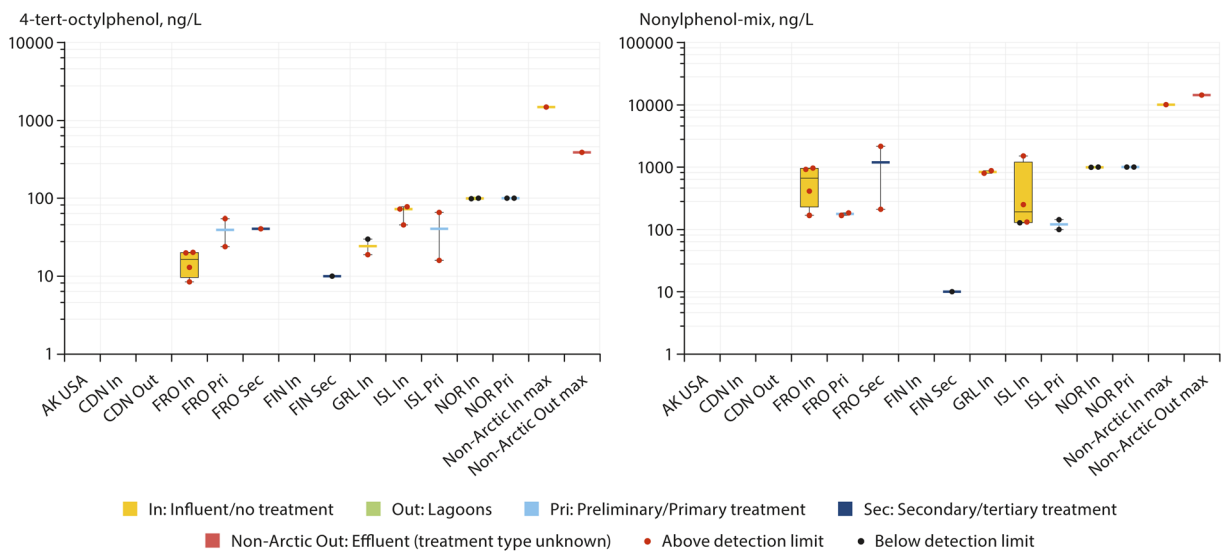

Fig. 2 Phenols – box plots and median (line) of reported concentrations of selected contaminants in wastewater by treatment type in several parts of the Arctic region in comparison to the non-Arctic region. Boxes are only shown when number of observations ≥4. Countries are indicated by their 3-letter ISO country codes. Complete data are presented in S1 and S2.

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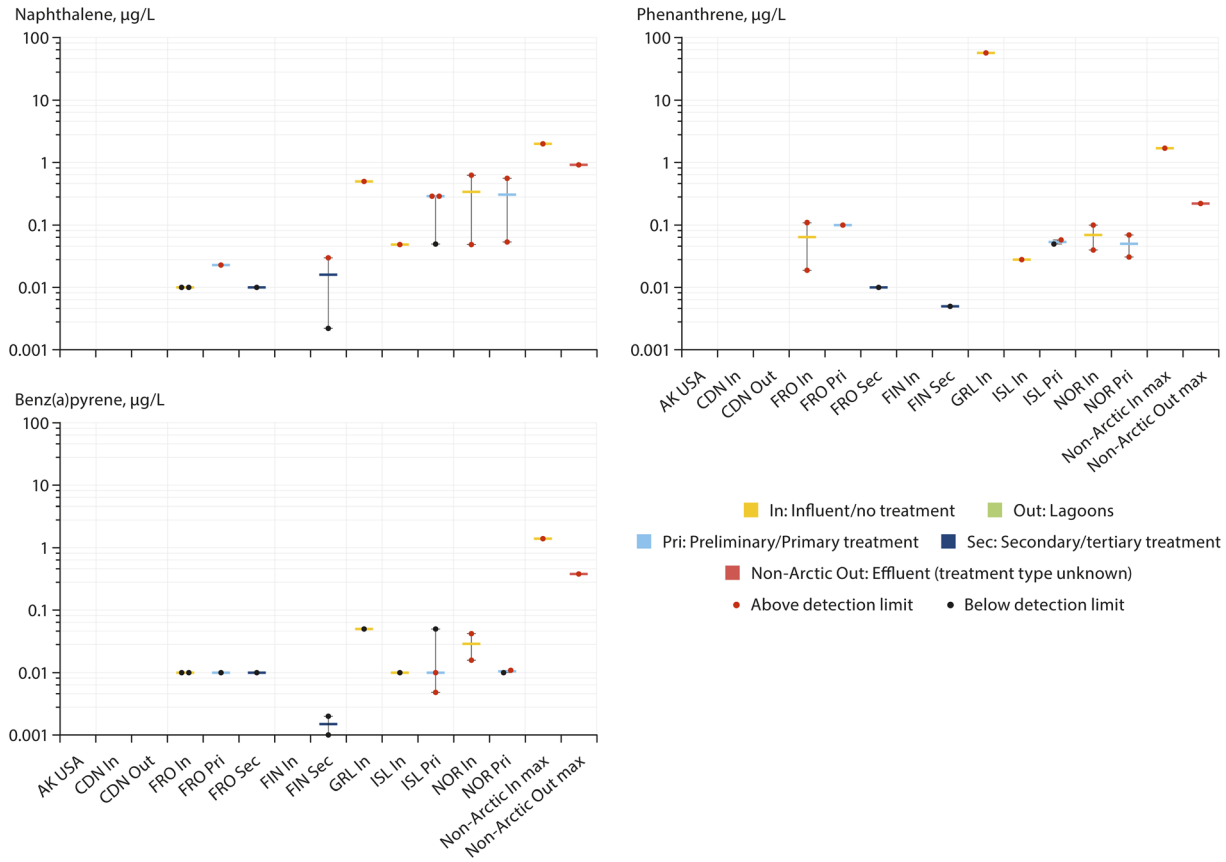

Fig. 3 PAHs – box plots and median (line) of reported concentrations of selected contaminants in wastewater by treatment type in several parts of the Arctic region in comparison to the non-Arctic region. Boxes are only shown when number of observations ≥4. Countries are indicated by their 3-letter ISO country codes. Complete data are presented in S1 and S2.

analyzed in Arctic WW on several occasions and locations (Table 1). The siloxanes, in contrast, have only been analyzed on one occasion,[54] and no observations were found for many CEACs, including organophosphate esters other than TBP (which was analyzed on one occasion),[42] medium-chain chlorinated paraffins (MCCPs), dechlorane, brominated flame retardants (BFRs), pentachloronitrobenzene (PCNB) and trifluralin and other current use pesticides, pentachloroanisole, benzotriazole ultraviolet stabilizers (BUVs), any fragrances, substituted diphenylamines, and chlorpyrifos (S1). Although PPCPs were among the most extensively monitored compounds, only five of the thirteen indicator pharmaceuticals listed for future monitoring and regulation in the EU have been analyzed in Arctic WW (carbamazepine, diclofenac, metoprolol, citalopram and venlafaxine) (marked in Table 1). However, analyses of a wide range of non-listed pharmaceuticals indicate the general presence of pharmaceutically derived CEACs in Arctic WW (Table 1).

4.3.1 Phenols in Arctic domestic wastewater. Two phenols are illustrated as representatives of this class of chemicals in Fig. 2 (exact numbers found in S1 and S2): 4-*t*OP and NP-mix. These two chemicals/mixtures are major contributors to the alkylphenol class.[53] They are also released *via* the degradation of NP ethoxylates, which are used as non-ionic surfactants, detergents and stabilizers, and have a wide range of applications as dispersants, emulsifiers, solubilizers and foaming agents.[53] 4-*t*OP and NP-mix concentrations were studied at Arctic WWTPs in the Faroe Islands,[52,53] Greenland,[52] Iceland,[52,53] and Norway (Fig. 2).[52] 4-*t*OP was also evaluated in treated WW in Finland.[67]

In general, the concentrations of both 4-*t*OP and NP-mix differ by less than an order of magnitude across WWT levels. A Finnish tertiary treated WW was the only observation showing a concentration below the lowest applied detection limit (<10 ng L^{-1} of 4-*tert*-octylphenol), indicating efficient removal at higher treatment levels, though it is not possible to truly evaluate this due to the lack of analysis of the influent concentration. Previous studies have found that 4-*t*OP and NPs are removed during both primary and secondary WWT through sorption to solids.[75,98] However, these two chemicals are also formed during treatment *via* the degradation of NP ethoxylates in treated WW.[75,98]

The maximum concentrations of 4-*t*OP and NP-mix observed in Arctic WW (treated and untreated) were six and 20-fold lower than the maximum concentrations observed in non-Arctic WWTPs, respectively (Fig. 2). The higher concentrations of 4-*t*OP and NPs in non-Arctic compared to Arctic WWTPs could be due to their industrial applications,[53] which are not prevalent in Arctic regions.

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4.3.2 PAHs in Arctic domestic wastewater. Analytical values of the three PAHs (naphthalene, phenanthrene, and benz(*a*)pyrene) in Arctic WW are presented in Fig. 3 (data in S1 and S2) as representatives of this class of chemicals. PAHs were studied at Arctic WWTPs in the Faroe Islands,[52] Finland,[66,67] Greenland,[52] Iceland,[52,65] and Norway.[52] In general, the concentrations of PAHs were comparable across WWT levels in the Arctic region. However, lower concentrations in the Finnish effluent treated by tertiary treatment and the Faroese effluent treated by secondary treatment compared to the WWs receiving only preliminary treatment (Iceland) or primary treatment (Norway and the Faroe Islands) for naphthalene and phenanthrene indicate some removal of these compounds. Previous studies in non-Arctic regions have found that PAH removals average between 60 and 90% as a result of sorption to sludge (biosolids) and microbial degradation.[69] There is no indication of treatment reaching this level in the studied Arctic systems (Fig. 3), which could be due to reduced microbial degradation at lower temperatures, though no final conclusions on this can be made based on the limited available evidence.

The maximum concentrations of naphthalene (influent and effluent) and phenanthrene (effluent only) in Arctic WWTPs were only slightly lower (between 1.6 and 3.2-fold) compared to the maximum concentrations in non-Arctic WW. In comparison, the maximum concentrations of benzo(*a*)pyrene in treated and untreated WW were over 30 times lower in Arctic WW (Fig. 3). Sources of PAHs (incomplete combustion of organic matter) exist in both Arctic and non-Arctic regions, but there are likely additional sources of PAHs in dense urban and industrialized areas that are not present in the Arctic.[99] Interestingly, the maximum concentration of phenanthrene in the Arctic of 57 μg L^{-1} (observed in untreated WW from Greenland) was 34-fold higher than the maximum concentration of this chemical observed in any non-Arctic system (1.7 μg L^{-1}). In the same study[52] fluorene in Sisimiut, Greenland, and acenaphthylene and acenaphthene in Reykjavik, Iceland, were found at surprisingly high concentrations, which warrants further evaluation. Overall, it may be concluded that the levels of some PAHs in Arctic WW are similar to those in other regions, meaning that WW may constitute a significant local source.

4.3.3 PPCPs in Arctic domestic wastewater. The concentrations of four of the most studied pharmaceutical substances (ibuprofen, naproxen, metoprolol, and atenolol) are illustrated

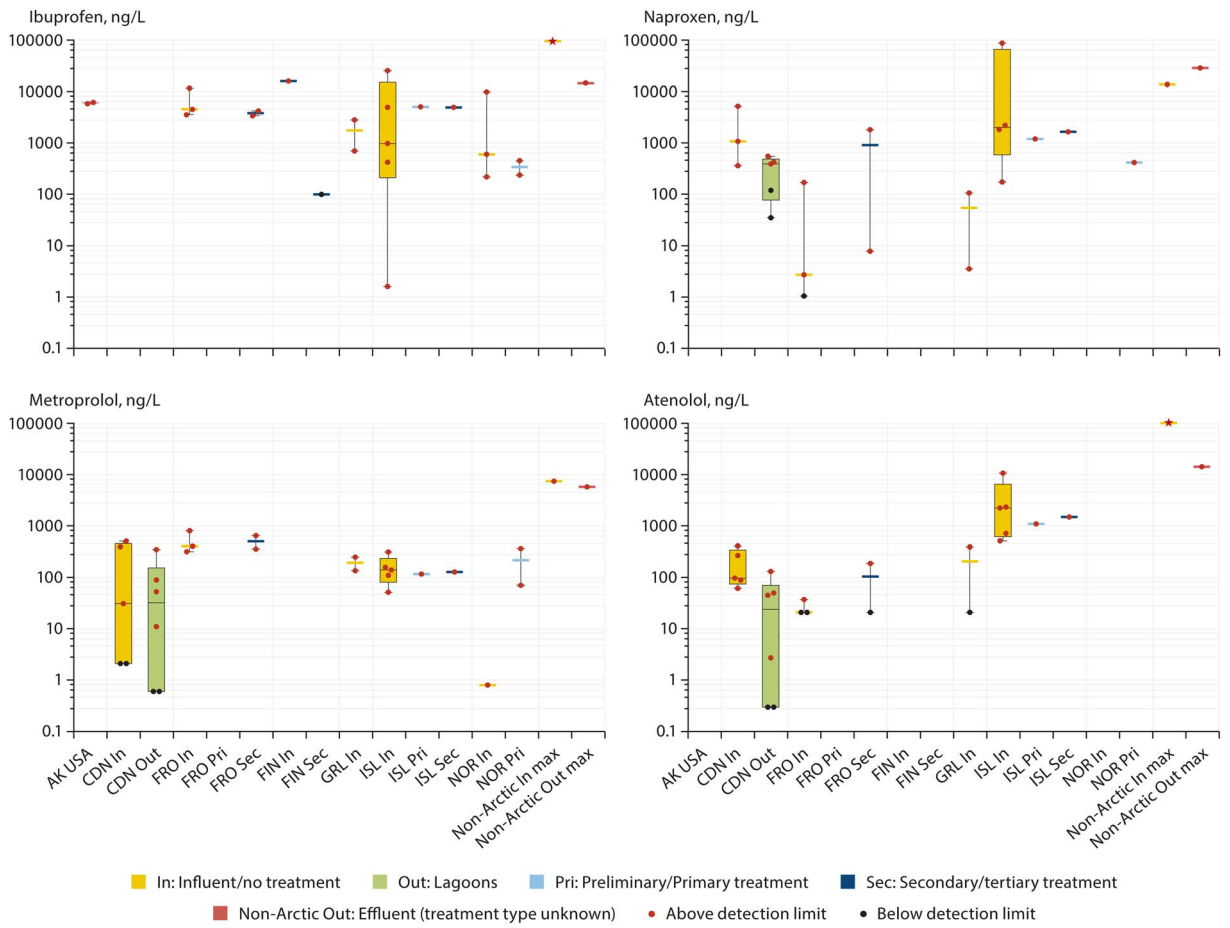

Fig. 4 PPCPs – box plots and median (line) of reported concentrations of selected contaminants in wastewater by treatment type in several parts of the Arctic region in comparison to the non-Arctic region. Boxes are only shown when number of observations ≥4. Star symbol indicates concentration above range shown. Countries are indicated by their 3-letter ISO country codes. Complete data are presented in S1 and S2.

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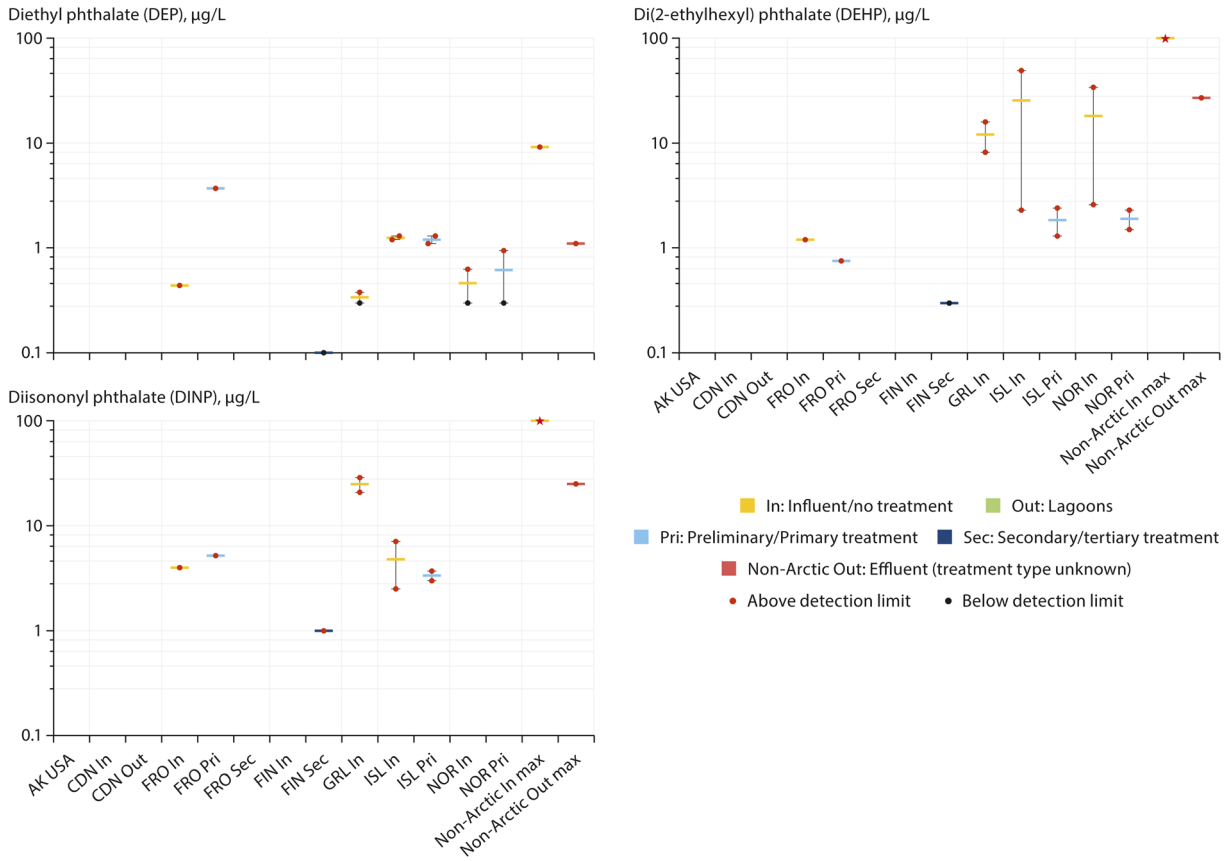

Fig. 5 Phthalates – box plots and median (line) of reported concentrations of selected contaminants in wastewater by treatment type in several parts of the Arctic region in comparison to the non-Arctic regions. Boxes are only shown when number of observations ≥4. Star symbol indicates concentration above range shown. Countries are indicated by their 3-letter ISO country codes. Complete data are presented in S1 and S2.

in Fig. 4 as representative PPCPs. These PPCPs were studied at Arctic WWTPs in Alaska (USA),[62] Canada,[41,47,48] the Faroe Islands,[45] Finland,[58] Greenland,[45] Iceland,[45] and Norway (Fig. 4, S1 and S2).[42,46,49,50,55,63]

The concentrations of PPCPs in the untreated WW are a function of the per-capita use of these substances, and the maximum concentrations in Arctic WW of ibuprofen, metoprolol, and atenolol were lower by half to one order of magnitude than the maximum concentrations in non-Arctic WWTPs indicating relatively lower consumption of these compounds in the Arctic. For example, the maximum concentration of atenolol in untreated WW in non-Arctic studies was as high as 294 700 ng L^{-1}, which was over two orders of magnitude greater than the maximum concentration in Arctic WW (10 645 ng L^{-1}) (S2). The maximum concentration of naproxen in untreated Arctic WW, however, was 89 050 ng L^{-1} which was higher than the maximum concentration in non-Arctic wastewater (13 833 ng L^{-1}). However, this maximum Arctic concentration was observed in the influent wastewater from the main hospital in Reykjavik, Iceland, which makes it a special case, and the second highest concentration of naproxen in Arctic WW influent was much lower (2225 ng L^{-1}).

In general, the concentrations of PPCPs in Arctic systems were comparable across WWT levels. However, there was a lot of variability in the data. The only significant removals observed by conventional Arctic treatment were those of ibuprofen (>99% in a Finnish tertiary treatment plant and 80% in a primary treatment plant in Norway). In comparison, naproxen, metoprolol and atenolol were reduced by 80–87% in the pond-treatment systems investigated in Canada.

It was hypothesized that the removal of PPCPs is slower in Arctic compared to non-Arctic WWTPs due to the cold temperature, which reduces microbial degradation.[46,48] However, in non-Arctic regions, the variability in removal of PPCPs was also large, ranging from less than zero to greater than 99%.[14] The extent of removal was greater in non-Arctic WWTPs using biological treatment compared to primary treatment.[100] Despite low temperatures and reduced biological activity, the implementation of higher treatment levels or use of NBS in the Arctic region can reduce the load of PPCPs to the environment.

4.3.4 Phthalates in Arctic domestic wastewater. The concentrations of three phthalate substances in the Arctic WWTS are illustrated in Fig. 5. They act as representatives of this group of chemicals due to data availability: DEP, DEHP, and DINP and were studied at Arctic WWTPs in the Faroe Islands,[52] Finland,[67] Greenland,[52] Iceland,[52] and Norway.[52]

The maximum concentrations of phthalates were between 3- and 7-fold lower in the influent of Arctic WWTPs compared to non-Arctic WWTPs (Fig. 5, S1 and S2). This is not surprising considering that phthalates are industrial chemicals that are

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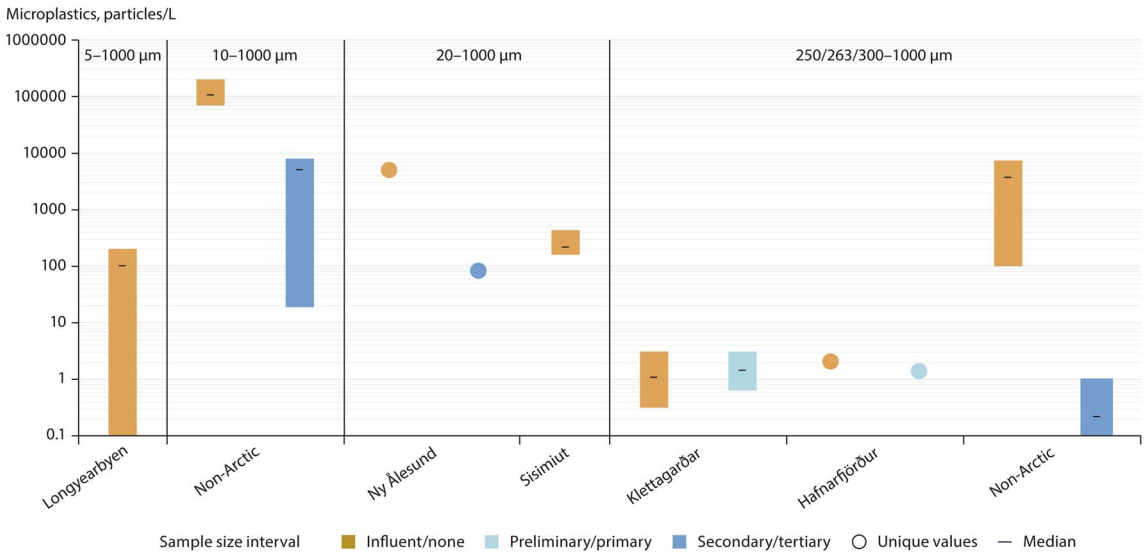

Fig. 6 Microplastic particle concentrations observed in untreated Arctic WW, WWTP influent and WWTP effluent in Longyearbyen and Ny-Ålesund in Svalbard (Norway), Klettagarðar and Hafnarfjörður in Iceland and Sisimiut and Nuuk in Greenland. The complete data set can be found in S1.

used primarily as plasticizers.[73,76] Finland was the only location where phthalates were measured in effluent from a secondary WWTP, and here the concentrations of all three substances were below the limit of detection (Fig. 5 and S2). In comparison, phthalates were detected in influent and in preliminarily and primarily treated WW in the Arctic region. Although based on limited data, this provides an indication of the greater removal of phthalates in WWTPs that use secondary treatment compared to primary or no treatment in Arctic regions, which is in accordance with findings from non-Arctic regions.[101]

4.3.5 Siloxanes in Arctic domestic wastewater. Siloxanes are not well studied in Arctic WW despite their wide use in generally consumed products such as deodorants, moisturizers, and hair products. To our knowledge, data only exist for one effluent of a primary WWTP in the Faroe Islands,[54] where only two of the seven measured siloxanes (D5 and D6) were observed above the analytical detection limit.[54] (Table 1). Siloxanes have, however, been observed in WW from non-Arctic regions.[54,102] Thus, siloxanes in Arctic WWTPs merit further study.

4.3.6 Microplastics and related chemicals in Arctic domestic wastewater. Microplastic particles are defined as plastic particles between 20 and 1000 µm according to recommendations by GESAMP.[103] They are relevant as CEACs due to the long list of chemicals they carry, either as their intended functional additives or due to non-intended adsorption during use and environmental exposure.[3,104] They have been analyzed in Arctic WW in Longyearbyen and Ny-Ålesund in Svalbard (Norway), Klettagarðar and Hafnarfjörður in Iceland, and Sisimiut in Greenland, and the observed concentration ranges are illustrated in Fig. 6 (data shown in Tables 1 and S1).

The size intervals sampled vary among different studies, and as the number of microplastic items in environmental samples increases with decreasing particle size,[51] it is inherently difficult to compare results of investigations with different cut-off sizes at the lower end. Indeed, the concentrations observed in Icelandic influent of 0.63–2.07 L^{-1}, where only items larger than 263 or 300 µm were included,[59,60] were lower than those found in the untreated WW in Greenland and Longyearbyen at Svalbard, where particles down to 20 and 5 µm were included (159–276 L^{-1} and 2–203 L^{-1}, respectively);[51,61] and much lower than the high influent concentration observed in Ny-Ålesund, Svalbard, of ~5000 items L^{-1}.[61]

When compared to results from non-Arctic studies, the observed concentrations in untreated Arctic WW were consistently low apart from those in Ny-Ålesund. The microplastic concentrations observed in untreated WW in southern Finland and Sweden were one to two orders of magnitude higher than those observed in Iceland when sampling the same size-intervals,[60] and influent concentrations at 10 different WWTPs in Denmark[105] were two orders of magnitude higher than the concentrations observed in influents and untreated WW in Greenland and Svalbard despite sampling the same size-fractions. Thus, other factors must influence the results. Specifically for Icelandic WW, the low concentrations may be explained by the generally high level of dilution of WW,[85] meaning that the load per capita is not necessarily lower than elsewhere; however, this is not a likely cause in Svalbard and Greenland, where domestic water consumption was as low as 74 L per cap per day in 2016.[106] Based on the limited evidence, it seems that WWTP influents and untreated WW in the Arctic region may contain fewer microplastic particles (by 1–2 orders of magnitude) compared to untreated WW in more densely populated areas, but also that exceptions to this exist, such as the research station in Ny-Ålesund, where inhabitants are mostly seasonally stationed researchers from the South. Here, the concentrations resemble those in other regions, suggesting that the differences may be due to differences in lifestyle.

A review of non-Arctic systems reported removal rates from a large number of different WWTPs[21] and showed microplastic removal rates from 72–99.9% and outlet concentrations ranging

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from 0.5 particles L^{-1} to more than 50 particles per L^{-1} among plants employing secondary and tertiary treatment. They also found removal rates ranging from 25–99% within the primary treatment step of different plants.[21] Carr *et al.*[107,108] concluded that skimming and settling processes in primary tanks had removed the majority of microplastic particles and that effluent from secondary and tertiary WWT facilities contributed only minimally to the microplastic loads to the environment. In accordance, the secondary treatment in Ny-Ålesund was efficient in reducing the high influent microplastic concentration by more than 99% to 83 items L^{-1}, while there was no significant difference between the influent concentrations and the preliminarily (mechanical filter) treated effluent in Iceland.[59,60] The low removal in the preliminary filter may be partly due to the Icelandic WW being so dilute, allowing for particles to pass directly through as opposed to being trapped in a filter cake. Despite the lower concentrations of microplastics observed in Arctic influent, the concentrations in untreated and preliminarily treated Arctic effluent concentrations exceeded those of primary to tertiary treated non-Arctic effluent. Considering the overall low treatment level achieved in the region,[24] Arctic WW therefore cannot be disregarded as a significant source of microplastics to the Arctic environment.

Furthermore, the disposal of plastic litter along untreated WW has the potential to seed the receiving environment with long-lasting secondary sources of microplastic particles. This was underlined by the observation of litter in untreated WW in Nuuk and Sisimiut in Greenland by Bach *et al.*,[79] who estimated that 2 tonnes of plastic were discharged *via* WW in the country on a yearly basis. Of this, approximately 1.4 tonnes were items >5 mm (including approximately 1.2 tonnes of plastic or semi-synthetic wet wipes). Though the preliminary treatment in Iceland showed no evidence of removal of microplastics, this type of treatment serves to prevent secondary microplastic particle production *via* the elimination of macro litter.

No Arctic data exist on the content or fate of microplastics in NBSs, which are often used in the North American Arctic,[24] and only very few international studies have been conducted on this topic. One study found that microplastic concentrations increased by 92 and 43% during intense rain and low precipitation periods, respectively, due to atmospheric deposition in a horizontal flow treatment wetland,[109] while another observed 95% removal in a similar treatment system.[110] The contradictory results and the lack of studies from the North American Arctic point to further studies being necessary for the evaluation of the contribution of such systems to the Arctic environment.

Some of the previously discussed chemical groups are likely to be in part linked to microplastics, including brominated and chlorinated flame retardants, certain alkylphenols and alkylphenol ethoxylates, PFASs, and PAHs.[111] Among the obviously plastic related chemicals, phthalates were also among the most well studied CEACs in Arctic WW, but only one study analyzed BPA in Arctic WW (in Iceland). This study found the content to be below the detection limits of the study.[53] We have not been able to identify any studies reporting BUVs including the specific plastic-related POP UV-238. Lastly, on a global scale, increased attention is being paid to microplastics in WW as carriers of antimicrobial resistant bacteria, potentially enhancing their spread into the recipient environment.[112]

4.3.7 Halogenated natural products in Arctic domestic wastewater. To our knowledge, halogenated natural products have not been studied in any Arctic WW. Some of these chemicals have anthropogenic sources such as water and WW chlorination, industrial use, hazardous waste incineration, and the transformation of brominated flame retardants,[113] making their presence in Arctic WW possible. A particular potential Arctic source of such compounds could be disinfecting chlorine (*e.g.*, sodium hypochlorite) used as an additive in honey bucket toilets in Greenland and Alaska to avoid odor issues and secure hygiene during handling.

5 Load of POPs and CEACs from domestic wastewater to the Arctic

The estimated discharge load of the total 20 evaluated POPs and CEAC compounds was 6 T per year (Table 2). Of this total, 53% originated from untreated domestic WW, while 47% came from WWTP effluents (39% from preliminary or primary treatment and only 8% from secondary or higher-level treatment). Despite the volumes of untreated wastewater and wastewater treated by secondary treatment or higher (55 *versus* 52 million m^3 per year) being of similar magnitude, the contribution of secondary or higher-level effluents to the total contaminant load was substantially lower (8%) compared to the untreated wastewater contribution (53%), clearly demonstrating the effectiveness of advanced treatment systems in reducing POP and CEAC discharge loads.

For individual contaminants, the estimated loads ranged between 0.3 kg per year (for PFDA) and 1461 kg per year (for DINP). The order of mass loads for the compounds constituting more than 1% of the mass load of chemicals from WW to the Arctic was found to be

$$\text{DINP} > \text{DEHP} > \text{ibuprofen} > \text{phenanthrene} > \text{DEP} > \text{naproxen} > \text{NP-mix} > \text{atenolol}$$

Thus, CEAC compounds (DINP, DEHP, and ibuprofen) appeared to constitute the largest proportion of chemicals in the discharged WW, representing a total of 68% of the included load. This order represents the general trend observed across the evaluated Arctic regions; however, the magnitude of loads varies substantially among regions. For instance, Greenland reported considerably higher influent concentrations of phenanthrene compared to the other studied regions (S2), illustrating how regional variability can influence the absolute and relative contaminant loads.

Broader regional-scale assessments of combined POP and CEAC loads are lacking, but in Australia and North Korea the loads of PFASs were estimated: in Australia an annual discharge of around 250 kg per year for 21 PFASs from WWTP effluents serving more than 12 million inhabitants corresponded to about 0.021 g per year capita,[107] and in Korea the emission of 15 PFAS compounds *via* domestic WW was estimated to range between

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Table 2 Summary/estimation of selected POP and CEAC concentrations and loads in Arctic wastewater,[1] based on data from Jensen *et al.*,[24] calculated based on total PE load in the Arctic (5.2 million) and the average water quantity standard of 145 L per person per day reported for the Arctic.[3] Average concentrations of the 75th percentile concentrations reported for all Arctic regions for each contaminant (complete data in S2) are shown. Data from wastewater treatment by lagoons was incorporated for the calculation of both preliminary/primary and secondary treatment concentration averages

	No treatment		Preliminary/primary		Secondary+		Total
Status of wastewater treatment (%)	20%		61%		19%		100%
Discharge volume (m^3 per year)	55.042.000		167.878.100		52.289.900		275.210.000
Concentration and loads	Avg. Conc. ng L^{-1}	Load kg per year	Avg. Conc ng L^{-1}	Load kg per year	Avg. Conc. ng L^{-1}	Load kg per year	Total load kg per year
BDE-47	32	1.8	27	4.5	26	1.4	7.6
BDE-99	32	1.8	27	4.5	26	1.4	7.6
PFOS	7.6	0.4	18	3.0	6.0	0.3	3.7
PFOA	3.3	0.2	5.8	1.0	7.9	0.4	1.6
PFNA	1.7	0.1	4.5	0.8	6.0	0.3	1.2
PFDA	1.3	0.1	1.1	0.2	1.1	0.1	0.3
PFBS	3.3	0.2	1.9	0.3	1.3	0.1	0.6
PFHxS	1.3	0.1	1.7	0.3	1.3	0.1	0.4
4-*t*OP	56	3.1	67	11	26	1.3	16
NP-mix	840	46	438	74	1682	88	208
Naphthalene	260	14	248	42	17	0.9	57
Phenanthrene	14 300	787	72	12	7.5	0.4	800
Benz(*a*)pyrene	27	1.5	17	3.0	6.0	0.3	4.6
Ibuprofen	7287	401	3834	644	3760	197	1241
Naproxen	1384	76	684	115	1150	60	251
Metoprolol	277	15	163	27	263	14	56
Atenolol	731	40	570	96	562	29	165
DEP	665	37	1927	323	50	2.6	363
DEHP	19 550	1076	1650	277	300	16	1369
DINP	12 333	679	4350	730	1000	52	1461
TOTAL (SUM)	—	3181	—	2368	—	465	6014
% FROM TOTAL	—	53%	—	39%	—	8%	100%

590 and 780 kg per year for a population of approximately 50 million inhabitants (0.012–0.014 g per year per capita).[114] In comparison, the estimated per capita discharge load of PFASs derived from domestic wastewater (treated and untreated) in the Arctic region was 0.0015 g per year per capita, based on an Arctic population of 5.2 million inhabitants and a total load of 7.8 kg per year for the 6 evaluated PFAS compounds. This is approximately one order of magnitude lower than the values reported for Australia and Korea. In the Arctic dataset, PFOS, PFOA, and PFNA were the dominant PFAS compounds. Similarly, PFOA was among the major contributors reported in both Australia and Korea, whereas PFHxA and PFPeA were also prominent in Australia and PFHxA was prominent in Korea, but these compounds were not evaluated in the present study.

6 POPs and CEACs in Arctic WW sludge

During WW treatment of the approximately 80% of Arctic WW which is somewhat treated,[24] POPs and CEACs that are not degraded/transformed, vaporized or discharged with the WW are captured in WW sludge. The majority of Arctic WW sludge is deposited without any further treatment or stabilization in the terrestrial environment *via* either landfilling or use as landfill coverage.[24] This may give rise to exposure to sludge-contained contaminants, for example, *via* leaching to the environment or uptake in local or migrating biota. Information about the content of POPs and CEACs in sludge and sludge handling is therefore essential to assess exposure. As a result of the often rudimentary WWT in the Arctic region compared to temperate regions,[24] sludge generation in the region is highly variable in quantity and quality across the region. We have found no studies assessing the risk posed by contaminant exposure related to WW sludge deposits in the Arctic region, but found several studies that evaluated the content of a range of POPs and CEACs in sludge, that could be useful for a preliminary evaluation.

Key findings on the presence of POPs and CEACs in Arctic WW sludge from existing studies are summarized in Table 3.[45,53,54,56,58,115,116] The substances analyzed in sludge from the Arctic region included pharmaceuticals, PFASs, phenolic substances, siloxanes, PAHs, and organophosphorus compounds. However, the total number of investigated samples was small, and the geographical coverage was limited to the North Atlantic/Arctic Islands (the Faroe Islands, Svalbard (Norway), Iceland and Greenland (Table 3)).

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Table 3 Reported selected organic pollutants and their concentrations in sewage sludge from the Arctic region. The table summarizes findings from targeted monitoring and screening studies, including compound groups, geographic coverage, and concentration ranges. dw: dry weight

Substance group	Location	Scope and reference	Key concentrations/findings
Siloxanes, OPFRs, SMCs, phthalates, BUVSs, PAHs, NBFRs, and PBDEs	Ny-Ålesund, Svalbard	Non-target and suspect screening of a sludge from tertiary treatment[115]	Non-target; concentrations not stated
PPCPs, hormones, and CEACs	Faroe Islands, Iceland, and Greenland	PPCPs were measured in sludge in the Faroe Islands and Iceland[117]	Venlafaxine 11 400; metformin 7810; estriol 210; ATAC-C16 680 000 (μg per kg dw)
PFASs[1]	Faroe Islands[2]	PFCAs, PFSAs, PFCA and PFSA precursors, PFPiA/PFPA, and novel PFASs were measured in two sludge samples from the Faroe Islands[56]	Detected PFASs were dominated by diPAPs (PFCA precursors); PFPiA/PFPA and novel PFASs were not detected
Phenolics and BFRs	Faroe Islands[3] and Iceland[13]	Two sludge samples from the Faroe Islands were included in the study, one from a WWTP, one from a hospital; four sludge samples from two WWTPs in Reykjavik, Iceland, were included in the study[53]	NP isomers mix[a] 1460–2413; 4-*t*BuP[a] 348–1447; BPA 451–637; TBBPA[b] 38.8–56.7 (μg per kg dw)
Siloxanes	Faroe Islands and Iceland[16]	One sludge sample from the Faroe Islands and two from Iceland[54]	D4 96–190; D5 1100–4300; D6 220–1000; MD2M 1–23; MD3M 3–10; MM and MDM below quantification (ng per g dw)
Organophosphorus compounds	Northern Sweden (near AMAP[17])	Sludge from a northern Swedish plant situated just south of the Arctic boundary (Arctic region) was sampled[116]	EHDPP 320; TCPP 200; TBP 65; TPP 68, total analysed OP 700 (μg per kg dw)

[a] Estimates, outside the calibration range. [b] Detected only in one of the two samples of each country.

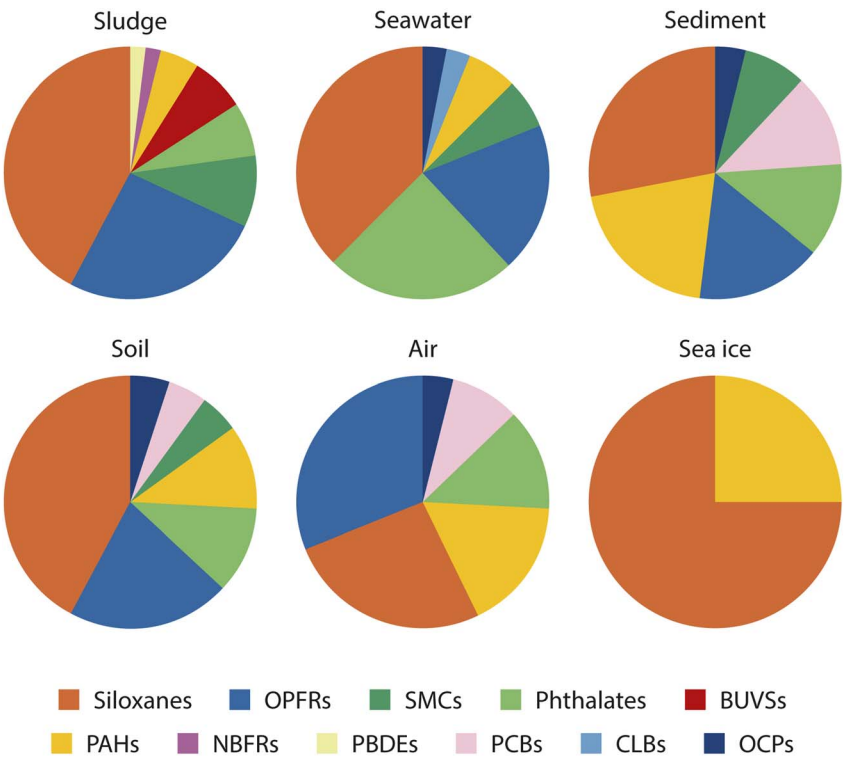

Fig. 7 Percentage of detected contaminant substances observed through suspect screening analysis of environmental samples collected from Ny-Ålesund, Svalbard. Contaminant groups over 10% of the total contaminant numbers are labelled on the pie chart. The figure is reproduced with permission from Lee *et al.* 2019.[115]

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Overall, sewage sludge in this part of the Arctic region can be confirmed to be a sink for organic MPs, but more detailed information on the content and fate of MPs in Arctic WW-sludge and sludge from across the region is needed to fully understand the risk of environmental exposure. A detailed discussion of the different compound groups can be found below.

6.1 Legacy POPs in Arctic WW sludge

Hydrophobic, persistent compounds such as most legacy POPs tend to partition to solids during WW treatment; therefore, POPs originating from Arctic WW could be expected to be found in WW sludge. The only study that included an analysis of legacy POPs in Arctic WW sludge analyzed sludge from the tertiary WWTP at the research village Ny-Ålesund in Svalbard, Norway.[115] Due to the particular demography and high treatment level in Ny-Ålesund compared to the rest of the region,[24] this sludge is not necessarily representative of sludge from the Arctic region in general. Nevertheless, the results can provide (a) valuable insights into the dominant chemical groups in WW sludge from such treatment to take into account in sludge handling, (b) information on the correlation between compounds identified in WW effluents, recipients and sludge based on their analysis of multiple compartments, and (c) information on the importance of WW as a source of hydrophobic contaminants to the Arctic environment.[115] Interestingly, *via* suspect screening analysis of 215 contaminants, the study showed that only 2% of the chemical species detected in the sludge were POPs and among those, no legacy POPs were identified (Fig. 7).[115]

This finding supports the conclusion of Section 4.1 of this paper that the POPs observed in the arctic environment, including local biota, do not originate from arctic WW to any significant degree, but rather from LRET. Studies including sludge from a wider variation of geographical locations with a more representative demography, including Indigenous communities relying on a traditional diet,[118] which may show higher POP concentrations in excreta as suggested by Hermanson *et al.*[119] would, however, be needed to draw a final conclusion.

6.2 New POPs in Arctic WW sludge

Only a few studies of Arctic WW sludge have included an analysis of any new POPs. PBDEs, PFASs, and BUVs have, however, been studied and found in one case each.[56,115]

6.2.1 PBDEs in Arctic WW sludge. The study engaging non-target and suspect screening analysis of WW sludge from the tertiary treatment plant in Ny-Ålesund in Svalbard, Norway,[115] found that 2% of the detected chemicals in the sludge were PBDEs. In combination with the finding that PBDEs were not among the detected substances in the recipient water or sediment (Fig. 7),[115] this supports the finding from Section 4.2.1 of this paper that tertiary WWT removes PBDEs from WW well, but also that untreated or insufficiently treated WW elsewhere in the region may be a source of PBDEs to the local environment.

6.2.2 PFASs in Arctic WW sludge. In contrast, the sludge partitioning of PFASs in a study in Finland appeared to be relatively low, with a total of 40% and 10% of influent PFOS and PFOA partitioned sludge, respectively.[58] In the Faroe Islands, while PFASs, dominated by polyfluoroalkyl phosphate diester (diPAPs – PFCA precursors), were reported to be found in sludge from primary WWT,[56] only PFHxA and linear isomers of (L-PFOA) were detected among the PFCAs and perfluoroalkyl sulfonates (PFSAs) analyzed. This was in contrast with sludge from other Nordic treatment plants, which generally contained PFDA and linear isomers of PFOS (L-PFOS).[56] PFSA precursors were, however, detected in the Faroe Islands, many of which were at similar concentrations as in other countries.[56] These results indicate that the transformation of PFAS precursors may be reduced in Arctic preliminary treatments compared to higher treatment levels, possibly influenced by the cold environment. In accordance, no removal *via* biodegradation was observed in Finland.[58]

6.2.3 Other new POPs in Arctic WW sludge. BUVs including UV-328, which is listed as a new POP according to the Stockholm convention,[1,2] were found to constitute 7% of the detected chemical compounds in sludge in the Ny-Ålesund WWTP (Fig. 7).[115] None of these compounds were found in the recipient water or sediment,[115] suggesting that these types of compounds are efficiently removed by tertiary WWT, which would also be the case in the Arctic region and that untreated or insufficiently treated WW elsewhere in the region may be a source of BUVs to the local environment, despite not having been analyzed in WW in the region.

6.3 CEACs in Arctic WW sludge

CEACs constituted the vast majority of contaminant species detected in the WW sludge from the Ny-Ålesund WWTP analyzed by non-target and suspect screening analysis, which confirms the importance of addressing this substance group. Altogether, 91% of the contaminant compounds detected in the sludge were defined as CEACs, including phthalates, UV-stabilizers, organophosphate esters, siloxanes and synthetic musks:

Siloxanes (42%) > OPFRs (26%) > SMCs (synthetic musk compounds – 9%) > phthalates (7%) > BUVSs (7%) > PAHs (5%)> BFRs (2%) > PBDEs (2%).[115]

In addition, CEAC compounds that were not detected in the Ny-Ålesund sludge by non-target and suspect screening analysis were detected *via* targeted analysis in sludge elsewhere. The detailed results according to substance group are discussed below.

6.3.1 Phenols in Arctic WW sludge. Phenolic substances, including NPs, 4-*tert*-butylphenol (4-*t*BuP) and BPA, which were analyzed but not detected in Faroese and Icelandic WW (see S1), were detected in sludge from primary treatment in three of four WWTP sludges from the Faroe Islands and Iceland at similar levels to sludge from WWTPs from the Nordic countries. For the phenolic compounds that were detected in both the WW and the sludge, sludge concentrations ($\mu g\ kg^{-1}$) were 2–4000 times higher than those in WW ($\mu g\ L^{-1}$) from the same countries (Fig. 2), confirming the presence of these compounds in Arctic WW and their dominant partitioning to the sludge.[53]

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6.3.2 PAHs in Arctic WW sludge. The observation of PAHs constituting 5% of the identified chemicals in sludge in the Ny-Ålesund sediment analyzed by non-target and suspect screening analysis[115] (Fig. 7) confirms the findings of Section 4.3.2 that Arctic WW is a source of PAHs and that PAHs can be, at least partly, removed by WWT.

6.3.3 PPCPs in Arctic WW sludge. The pharmaceuticals, hormones and additives to personal care products analyzed in primary and secondary WWTP sludge from the Faroe Islands, Iceland and Greenland showed levels of venlafaxine up to 11 400 μg per kg dw (approximately 10 000 times higher than those in the corresponding WW in μg L^{-1}), metformin up to 7810 μg per kg dw and estriol up to 210 μg kg^{-1}, while the surfactant ATAC-C16 was as high as 680 000 μg per kg dw.[45] In total, 33 of 37 investigated pharmaceutical substances and all seven studied personal care product additives were detected in WW sludge.[45] The major PPCP contributors to sludge revealed by the non-target and suspect screening of sludge from Ny-Ålesund tertiary WWTP in Svalbard, however, were synthetic musks, constituting 9% of the chemicals in the sludge.[115] The findings on PPCPs in WWT sludge provide evidence that removal of PPCPs is obtained *via* WWT; although this is at levels below quaternary and with indications of improved removal at higher treatment levels.

6.3.4 Phthalates in Arctic WW sludge. The non-target and suspect screening of sludge from a Ny-Ålesund tertiary WWTP in Ny-Ålesund at Svalbard (Fig. 7) showed that phthalates constitute 7% of the chemical compounds detected in the sludge.[115] This confirms the findings from Section 4.3.4 that phthalates are efficiently removed by WWT at higher levels in the Arctic region.

6.3.5 Siloxanes in Arctic WW sludge. Through targeted analysis, siloxanes were found in sludge from the Faroe Islands and Iceland at levels up to 4300 μg kg^{-1} (ref. 54) (*i.e.* at concentrations up to 1000 times higher than those in treated WW (μg L^{-1}) effluent in the region). Compared to sludge samples from WWTPs in cities in the southern areas of Norway, Sweden, and Finland, the siloxane concentrations in the sludge samples from the Arctic region were generally low, but with few analyses of both sludge and WW (Section 4.3.5) available, no firm conclusions can be made on the general level in the overall Arctic region.[54] Non-target and suspect screening, however, showed the siloxanes D5–D6 and L5–L20 to constitute as much as 42% of the chemicals detected in sludge from a Ny-Ålesund tertiary WWTP in Ny-Ålesund at Svalbard (Fig. 7),[115] suggesting that untreated WW could be a major contributor of siloxanes to the Arctic environment.

6.3.6 Organophosphate esters in Arctic WW sludge. The finding that OPFRs were the second most abundant substance group (26%) in sludge from the Ny-Ålesund tertiary WWTP[115] is supported by a study in which organophosphorus compounds were detected in sludge from a small northern Swedish WWTP located close to the Arctic region (Table 3). However, less than 1% of organophosphorus compounds were estimated to end up in the sludge in Swedish WWTPs, while 49% was estimated to be degraded and 50% was estimated to be discharged to the recipients.[116] The study also provided evidence that after 4–6 months of outdoor storage, the concentrations of OPEs in the sludge remained stable,[116] suggesting that OPE compounds persist under Arctic sludge storage conditions.

6.3.7 Halogenated flame retardants in Arctic WW sludge. Hexachlorocyclopentenyl-dibromocyclooctane, a "novel" brominated flame retardant (NBFR), was observed in the sludge from a Ny-Ålesund tertiary WWTP, showing that relatively new chemicals have also made their way to Arctic communities and potentially to the Arctic environment.[115]

7 POPs and CEACs in Arctic WW recipient waters and sediments

POPs and CEACs have been investigated in the sediment and surface water of several Arctic recipient waters. However, while many chemical compounds have been analyzed in marine recipients, freshwater recipients have been largely ignored, with only one study investigating the presence of one contaminant group (PCBs) in a recipient lake[119] and two studies investigating microplastics at river discharge points.[120,121] Furthermore, the geographical coverage was highly uneven, with most studies being from Norway and Canada. Microplastics were the only target compounds also studied in recipients in Greenland, Iceland and Russia, and no studies of POPs or CEACs could be identified from Sweden, Finland, the Faroe Islands or Alaska.

The Norwegian studies focused almost exclusively on four specific recipients *i.e.*, the marine recipient used by the town of Tromsø (~80 000 inhabitants) and its secondary WWTP and three fjords in Svalbard: Adventfjorden with the discharge from the larger village of Longyearbyen (~2500 PE) following preliminary WWT, Kongsfjorden with discharge from the small research village of Ny-Ålesund (<200 PE) following tertiary WWT, and Grønfjorden (no regular discharge, reference site) near the former Russian mining village of Barentsburg.

According to non-target and suspect screening analysis (Fig. 7),[115] the contaminant profiles of sediment and seawater in Kongsfjorden were relatively similar to those observed in the sludge from the Ny-Ålesund WWTP, suggesting that the contaminants detected in the fjord primarily originated from the discharge of WW. While siloxanes dominated and OPFRs were abundant in all the investigated matrices, except sea ice, some differences were, however, noticeable:[115]

- PCBs were observed in the recipient sediment, soil and air but not in the WWTP sludge.
- BUVSs were not detected in the recipient but were detected in the WWTP sludge.
- More phthalate compounds were observed in the recipient seawater (23%) and sediment (12%) than in WWTP sludge (7%).
- More PAH compounds were found in the recipient sediment (20%) compared to WWTP sludge (5%) or seawater (6%).

These observations suggest that while Arctic WW appears to be a significant local source of siloxanes and OPFRs, this is not the case for PCBs or PAHs. Rather, these chemicals also appeared in the air and, for PAHs, in soil and sea ice (Fig. 7),[115] supporting the dominance of LRET sources.

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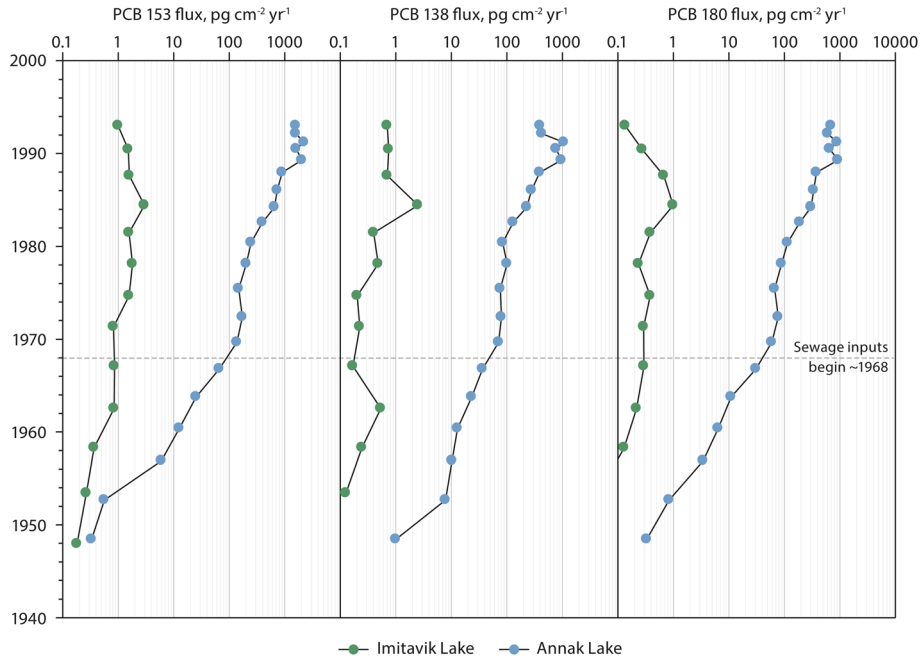

Fig. 8 Depth profiles of PCB 153, PCB 138 and PCB 180 flux over time to Imitavik (reference) and Annak (WW impacted) Lakes, Sanikiluaq, NU, Canada. The figure is reproduced with permission from Hermanson *et al.* 2010.[119]

Targeted studies of Arctic recipient waters and sediments have been conducted with a focus on PCBs, organochlorine pesticides (HCH), siloxanes, PBDEs, and phthalates. These studies are discussed below for each substance group.

7.1 Legacy POPs in Arctic WW recipients

Due to the high POP exposure *via* traditional Indigenous diets,[118] Hermanson *et al.*[119] suggested that POPs are likely to be excreted at elevated concentrations in Arctic Indigenous communities. Indeed, when comparing sediment cores from the WW impacted Lake Annak, located close to an Indigenous community in the Canadian Arctic, with sediment cores from a reference lake (Lake Imitavik), clear evidence of PCB accumulation in the sewage-impacted lake sediments was found (Fig. 8).[119] However, the presence of PCBs in lake sediments dated before the initiation of the WW discharge to the lake warrants further research needed to finally establish the source.

Marine surface sediments from the harbors in Sisimiut, Greenland, and Hammerfest, Norway, were also investigated for PCBs. The PCBs detected in Hammerfest were found to mainly originate from Clophen A60 and Sovol produced in Germany and Russia, respectively, while the PCB pollution in Sisimiut appeared to be related to a mixture of products, but the most dominant were Kanechlor 500, Kanechlor 1000 (both manufactured in Japan), Sovol and Aroclor 1254.[122] Multivariate analysis based on PCB congeners revealed that, although the PCB concentration was markedly higher at a site where WW discharge had previously occurred (Fig. 9, H4 in Hammerfest),

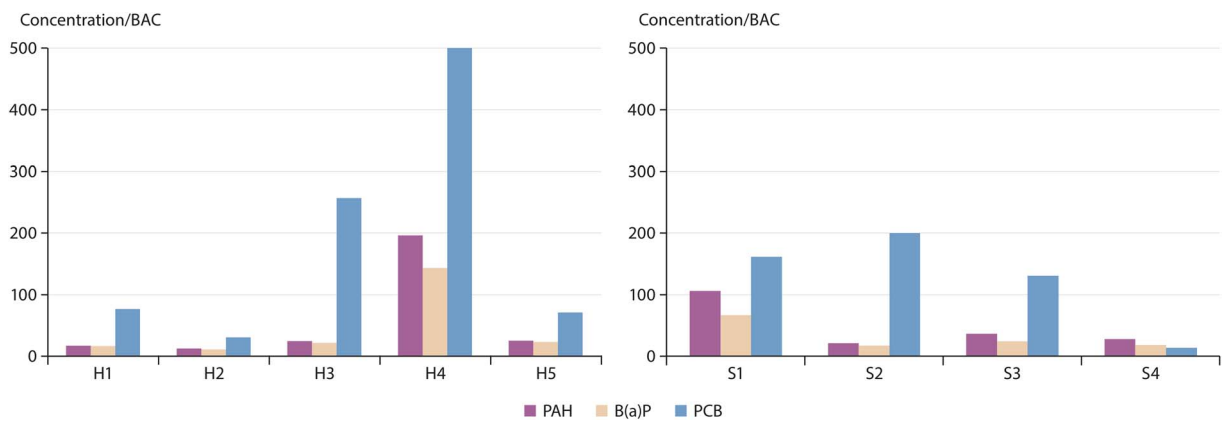

Fig. 9 Concentrations of PCBs, B(*a*)P and PAHs measured in the sediment of the harbors in Hammerfest, Norway, and Sisimiut, Greenland. H4 is near a sewage outlet. The figure is reproduced with permission from Pedersen *et al.* 2015.[122]

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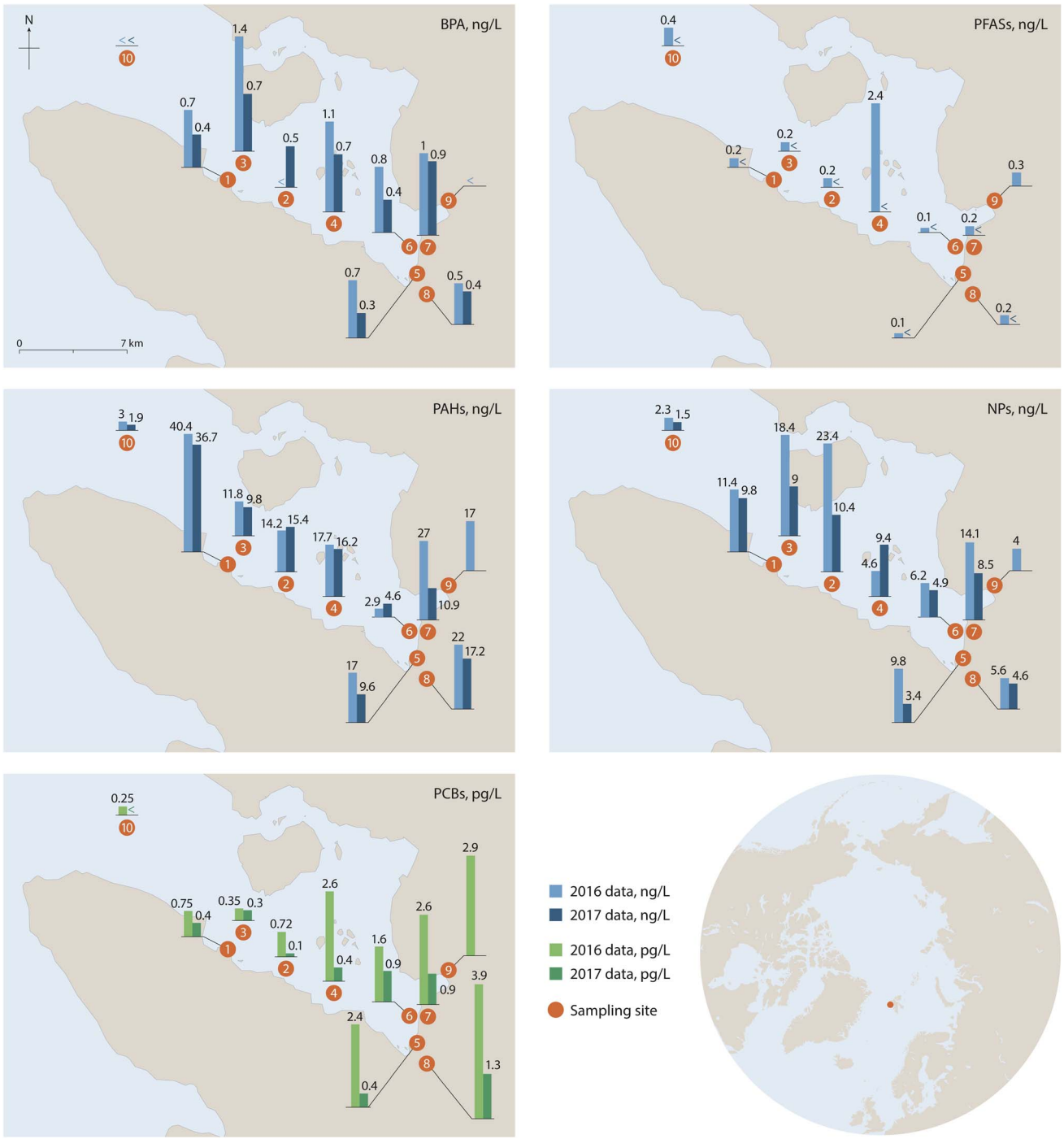

Fig. 10 Total amounts of PAHs, BPA, NPs, PFASs and PCBs measured in seawater during the summer and winter campaigns (2016–2017) in surface seawater from the research village Ny-Ålesund in Svalbard during summer and winter campaigns (2016–2017). Pt. 1 is by the harbor and sewage outlet. The figure is reproduced with permission from Ademollo *et al.* 2021.[123]

the most likely source was LRET/regional sources *via* a nearby lake discharge.[122]

In accordance, Ademollo *et al.* (2021)[123] showed that the ΣPCB concentrations in the surface seawater of Kongsfjorden in Svalbard were influenced mainly by season and the distance to the glacier and not by harbor activities or WWTP effluent (Fig. 10). In the corresponding marine sediment of Kongsfjorden, the predominant impact of the glacier and minimal impact of WWTP effluent were later confirmed for PCBs as well as for the legacy pesticides DDT and DDE.[124]

Among other POPs, polychlorinated dibenzodioxins and -furans were analyzed in sediment samples from the impacted Adventfjorden and unimpacted Grønfjorden.[125] In both places, results were below the DL of the analysis. Furthermore, HCB

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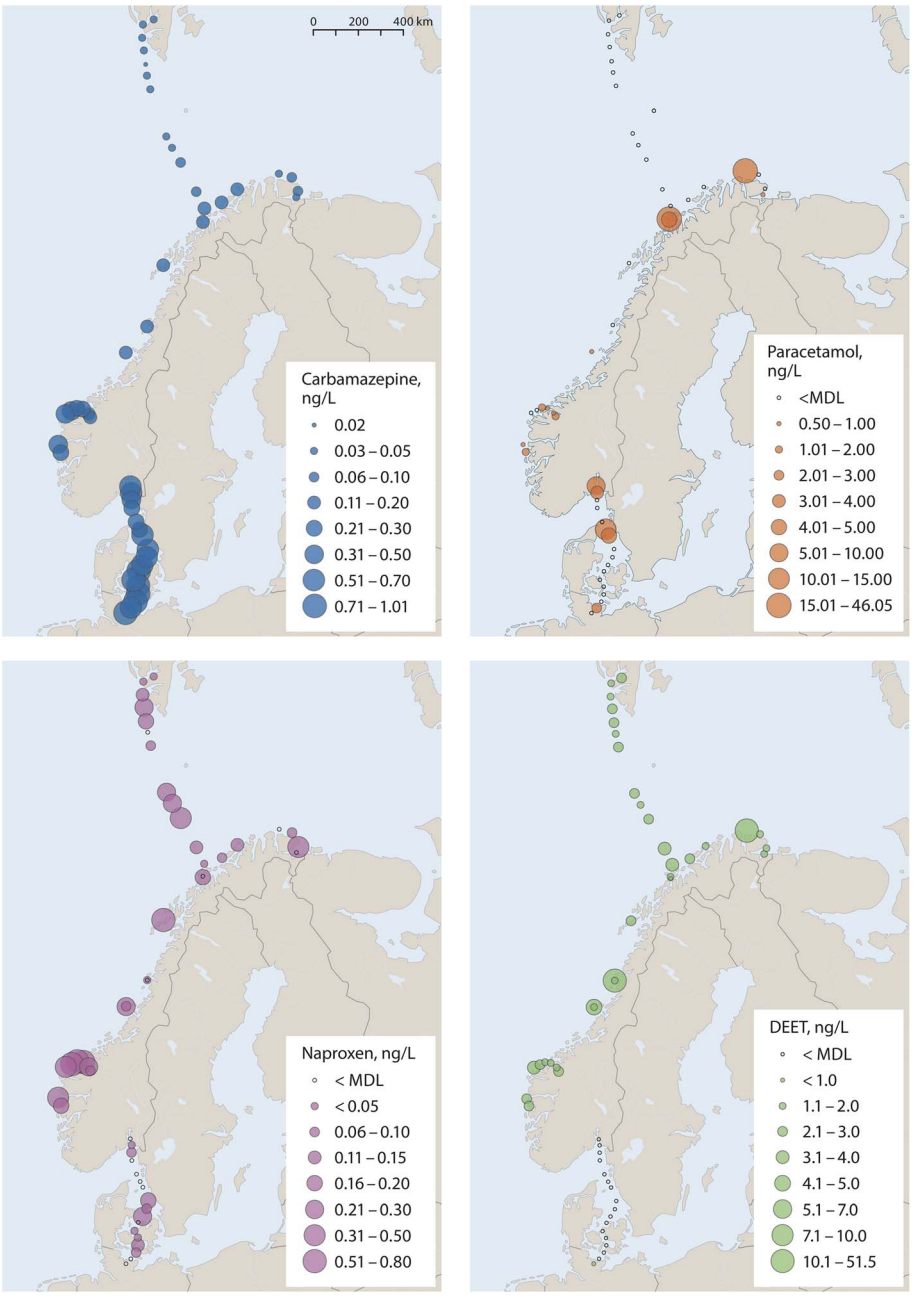

Fig. 11 Levels of PPCPs carbamazepine, paracetamol, naproxen, and DEET in seawater. Measured concentrations are depicted as circles at individual sampling sites. The figure is reproduced with permission from Brumovský *et al.* 2022.[131]

was analyzed in sediment cores of three Svalbard fjords (Adventfjorden, Kongsfjorden and Hornsund as references (<10 PE)), where concentrations ranged from below the DL to 144 pg per g dw. The highest concentrations were found in the surface sediment layers of a core collected in Hornsund near the melting glacier, while the lowest was measured in Adventfjorden, suggesting that local sources of HCB, including from WW, were insignificant.[126]

Overall, based on the sparse available results, WW does, thus, not seem to be a dominant source of legacy POPs to Arctic recipients, though studies of additional substances, sites with no WWT, sites impacted by larger communities and additional sites impacted by Indigenous communities relying on traditional diets are needed.

7.2 New POPs in Arctic WW recipients

Among the new POPs, PBDEs, PFASs, HCHs, and Current-Use Pesticides (CUPs) have been analyzed and observed in Arctic WW recipients.[48,115,122–124,127–130]

7.2.1 PBDEs in Arctic WW recipients. A total of 23 PBDE congeners were analyzed in ten sediment samples obtained in Svalbard from (i) Adventfjorden, near local sources such as the WW outlet and the airport in Longyearbyen; (ii) Grønfjorden

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near the Barentsburg waste disposal sites; and (iii) Kongsfjorden (reference site) in 2015–16. Only BDE-99 could be detected with the highest concentrations near the WW outlet in Adventfjorden (26.7–30.8 pg per g dw) and close to the landfill in Grønfjorden (DL – 22.8 pg per g dw). No PBDEs were detected at the reference site, and there was no significant correlation between grain size or total organic carbon (TOC) and the concentration of BDE99.[125] This confirms that the presence of PBDEs is likely due to local sources, *i.e.*, WW. samples collected in 2005 and 2009 showed similar results.[125] At that time, however, other BDEs were also detected in Adventfjorden. The lack of detection of these compounds in the 2015 and 2016 studies was likely due to the higher DL.[115,125] The results point to low sediment concentrations, supported by the non-detects of PBDEs by non-target and suspect screening.[115]

No direct links between the concentrations observed in the sediment and the concentrations observed in Arctic WW can be drawn because analyses were not done at the same sites. However, the results from Svalbard confirm the indications from the analysis of WW and WWTP sludge (Sections 4.2.1 and 6.2.1) that WW may be an important source of PBDEs to the Arctic environment compared to the other sources, including LRET.

7.2.2 PFASs in Arctic WW recipients. In Meretta Lake in the Canadian Arctic, which served as a WW recipient between 1949 and 1998, and its downstream Resolute Lake, elevated concentrations of PFASs were observed in sediment and surface water compared to reference lakes in the region (>50 times for ΣPFAS and PFOS in water and >30 times in sediment). This was partly attributed to activities at the Resolute Airforce Base and also to the WW discharges.[127] In contrast, marine sediment cores from the Koojesse Inlet, Nunavut, showed similar or lower ΣPFAS concentrations in the core closest to the town compared to further out, suggesting that local sources from Iqaluit, including the WW pond, were not significant.[128] A third Canadian study found water concentrations in the recipient Frobisher Bay to be below the detection limit, although significant PFAS levels were documented in the WW pond system. This was attributed to dilution as opposed to elimination of the PFAS compounds during treatment.[48]

The Canadian findings agree with findings from Svalbard, where, in the Kongsfjorden marine environment, the PFAS profile in surface seawater indicated that long-range hydrospheric transport was the most likely source, while showing no impact of local point sources including harbor activity or WWTP discharge (Fig. 10).[123] In concordance, marine sediments sampled near settlements and at a reference site in Svalbard showed no significant differences in $\sum$PFAS between sampling sites.[129]

The studies, however, showed significant differences in PFAS congeners at the different sampling sites, indicating that sources differ.[123,128,129]

7.2.3 HCHs in Arctic WW recipients. Hexachlorocyclohexanes (HCHs), originating mostly from the historical use of the insecticide lindane, were analyzed in sediment samples from Kongsfjorden in Svalbard. Samples collected in 2009 indicated that concentrations of HCH isomers decreased when moving from the outer, seaward end of the fjord to the inner, glacier end of the fjord,[130] while more recent sampling conducted between 2018 and 2022 showed the opposite trend,[124] possibly due to the increased importance of the glacier melt-off compared to the contribution from ocean currents, showing the insignificant impact of local sources. This was also confirmed by the α/γ HCH ratios, which were found to be close to one.[124]

7.2.4 Current use pesticides in Arctic WW recipients. The CUPs, chlorpyrifos, dacthal, and endosulfan, were analyzed in the surface marine sediment of Kongsfjorden, Svalbard, over five years, from 2018 to 2022.[124] In general, the concentrations in the sediment were lower for these compounds compared to the legacy pesticides HCHs, DDT and DDE (<0.5 ng per g dw in total, compared to 1–2 ng per g dw for the sum of legacy pesticides), but illustrate their widespread presence in the Arctic environment, despite the obvious lack of local agriculture. Their concentration profile indicated ocean currents and glacier melt-off to be main sources, with no significant local sources indicated.

In the Canadian Arctic, the current use pesticides 2,4-dichlorophenoxyacetic acid, atrazine, chlorpyrifos, clothianidin, diazinon, imidacloprid and thiamethoxam were analyzed in the water of WW systems in four communities with natural treatment systems (lagoons, engineered wetlands, and natural lakes) and their receiving waters.[48] No pesticides were detected in any sample.[48]

These limited results suggest that WW is not a significant source of CUPs to the Arctic environment.

7.3 CEACs in Arctic WW recipient waters and sediments

Among the CEACs, phenols, PAHs, a range of PPCPs, phthalates, microplastics, siloxanes and OPEs have been investigated in Arctic WW recipients.[8,41,48–51,55,60,61,120–123,125,129,131–144]

7.3.1 Phenols in Arctic WW recipients. Analysis of BPA and NP in surface seawater sampled in Kongsfjorden, Svalbard, in 2016–17 [123] revealed the harbor area close to the WWTP effluent discharge point as a point source of phenols (Fig. 10, Pt 1).[123] Concordant with the findings of phenols in Arctic WW and WW sludge (Sections 4.3.1 and 6.3.1), WW thus appears to be a significant source of phenols to the Arctic environment.

7.3.2 PAHs in Arctic WW recipients. An investigation of harbor sediment sampled in Hammerfest, Norway, and Sisimiut, Greenland, in 2010 and 2012, respectively, revealed that the predominant sources of PAHs, including B(*a*)P, in both harbors were pyrogenic, thus related to coal/biomass combustion. Like PCBs, the PAH concentrations were markedly higher at a site impacted by past WW discharge (Fig. 9, H4 in Hammerfest) compared to any other site investigated.[122] Unlike PCBs, WW was seen as the most likely main source. In 2016–17 in Kongsfjorden, Svalbard, the concentrations of PAHs were analyzed in surface seawater.[123] In contrast to PCBs, but similar to the phenols, the harbor/WWTP effluent discharge point was identified as a likely source of PAHs (Fig. 10, Pt 1).[123] Both available studies thereby indicate that WW may be a significant source of PAHs to the local marine environment, and the study in Kongsfjorden indicates that the impact may extend up to 10 km of distance from the WW discharge point.[123]

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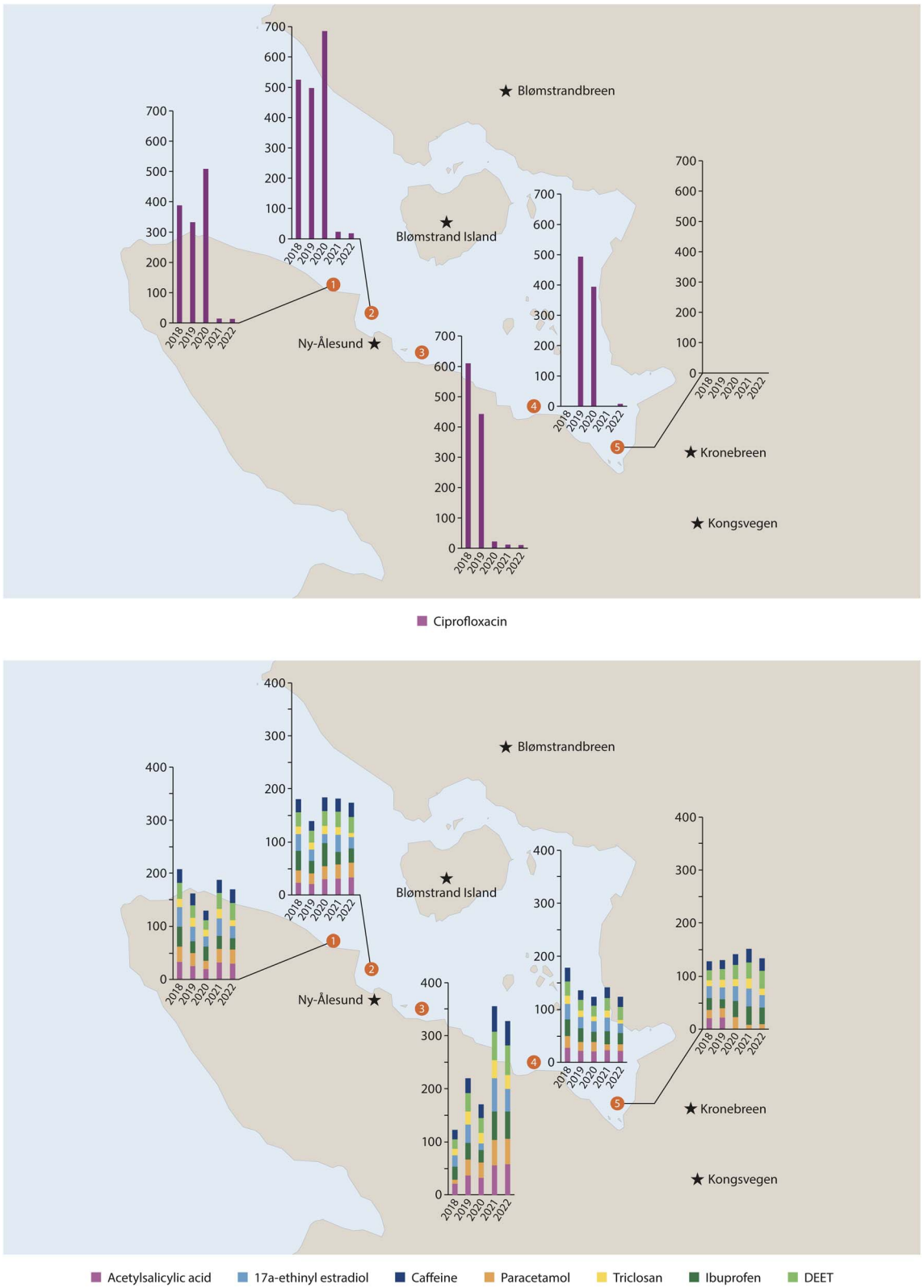

Fig. 12 Temporal and spatial distributions of PPCPs detected in Kongsfjorden sediment samples collected from 2018 to 2022. The figure is reproduced with permission from Rauseo *et al.* 2024.[132]

7.3.3 PPCPs in Arctic WW recipients. Several studies have evaluated the presence of PPCPs in marine WW recipients of the communities in Svalbard and Tromsø.[49,50,55,143]

Caffeine, ibuprofen and DEET were observed in the water of the marine recipient in Tromsø in 2002, though at low concentrations approaching, and sometimes below, the DL.[50]

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These compounds were also found in several different sewage samples (sewage treatment plants and hospital effluents).[50] In contrast, anti-epileptic and anti-depressants (carbamazepine, paroxetine and sertraline), which were found in the effluent from Tromsø hospital only, were not detected in the recipient.[50] The occurrence of ibuprofen and its metabolites in the recipient was noted as these compounds are normally easily eliminated during WWT and environmental exposure, but low temperatures and low biological activity could delay their transformation.[50] In contrast, the study surprisingly observed no signs of clofibric acid (anticholesteremic and antilipemic), despite the omnipresence of this medication in other recipients. A transect through the WW discharge point showed no significant differences in caffeine concentrations upstream and within the sewage plume; even at two reference sites at the coastline of the open North Atlantic/Arctic Ocean, caffeine was present at concentrations of 3–30% of the concentrations observed in the WW effluents, pointing to its ubiquitous distribution even in remote areas.[50]

The observed tendencies were confirmed in a later study involving eight sampling campaigns in Tromsø and one in Longyearbyen in 2007.[55] This study analyzed five antidepressants (citalopram, sertraline, fluoxetine, fluvoxamine and paroxetine), four of their metabolites (desmethylcitalopram, didesmethylcitalopram, norfluoxetine and desmethylsertraline) and two antibiotics (tetracycline and trimethoprim) in the marine recipient water as well as in WW.[49,55] While none of the compounds were detected in the Tromsø recipient, ibuprofen, its metabolites and caffeine were detected in the recipient by Longyearbyen, despite its much smaller population size. This was also the case for diclofenac and triclosan, although at low concentrations (<4 ng L^{-1}).[49,55] Ocean current patterns were speculated to be the reason for this observation. In addition, paroxetine, sertraline and fluvoxamine were detected as far as 600 meters from the WW discharge point in Longyearbyen, despite no content observed in the WW.[49,55] This demonstrates how some less abundantly used and discontinuously excreted pharmaceuticals may persist in the environment.

Finally, a five-year monitoring of 17 PPCPs in surface seawater was conducted in Ny-Ålesund, Svalbard, during the period of 2018–2022, including the five antibiotics ciprofloxacin, enrofloxacin, amoxicillin, erythromycin and sulfamethoxazole; the antibiotic metabolite N4-acetylsulfamethoxazole; the antidepressant carbamazepine; the pain relievers diclofenac, ibuprofen, and paracetamol; the hormones estrone-E1, 17β-estradiol and 17α-ethinyl estradiol in addition to caffeine; triclosan; and DEET.[143] In this study, while enrofloxacin, amoxicillin, erythromycin, sulfamethoxazole and N4-acetylsulfamethoxazole consistently showed concentrations below the DL in the WW as well as the recipient, the PPCPs detected in WW were also observed in the recipient at minimum once, with the main contributors being acetylsalicylic acid (39.2 ± 12.9 ng L^{-1}) and 17α-ethinyl estradiol (32.5 ± 11.9 ng L^{-1}).[143] The results thereby suggest the local WW emissions to be the main source, although fjord circulation (in particular for caffeine) and possibly broader oceanic contributions (in particular for ibuprofen) and atmospheric transport (of DEET) were indicated.[143] Based on the results, an environmental risk assessment identified the individual PPCPs ciprofloxacin and diclofenac, ibuprofen, the three analyzed hormones, caffeine and triclosan as potentially harmful to the Arctic marine ecosystem. When evaluated as a mixture, all compounds contributed additively to the overall risk.[143] The environmental risk from the antibiotic ciprofloxacin was found to be low.[143]

Apart from the Norwegian studies, several studies have evaluated PPCPs in Canadian Arctic recipients. An ecotoxicological assessment of the impact of an Arctic WW lagoon in Cambridge Bay was carried out by analyzing six pharmaceuticals (atenolol and metoprolol (beta blockers), clarithromycin, sulfamethoxazole and trimethoprim (antibiotics) and carbamazepine) in the water downstream of the lagoon upon discharge in 2014.[41] Limited to no detection of the pharmaceuticals was observed at the effluent discharge point and up to 300 m away, pointing to no significant hazard to aquatic organisms at the time.[41] Cambridge Bay was revisited in 2018 alongside three other communities in Nunavut, Canada (Iqaluit, Baker Lake and Kugluktuk) representing different WW treatment systems ranging from primary lagoons and engineered wetlands to natural lakes.[48] Seven (atenolol, carbamazepine, metoprolol, naproxen, sulfapyridine, sulfamethoxazole, and trimethoprim) of 27 target pharmaceuticals were found at least once in the WW systems. However, with the exception of 5.2 μg naproxen per L in Iqaluit, most recipients showed negligible amounts of contamination, and the measured pharmaceutical concentrations were concluded not to pose any significant acute toxicological hazard at the time.[48]

Altogether, these studies provide substantial evidence for the presence of a wide range of PPCPs in Arctic recipient waters, which is not surprising considering the evidence of such compounds being widely present in untreated and treated Arctic WW effluents (Section 4.3.3 of this paper). While the concentration of PPCPs in treated and untreated Arctic WW ranged from < DL over few hundred ng L^{-1} to 500 μg L^{-1}, PPCPs in recipient seawater were low and often approaching or below the DL, and non-detects were frequent.

The generally lower concentrations in the Arctic environment of many PPCPs were confirmed by a study utilizing unmanned sampling from a fleet of ships to monitor the distribution of 11 pharmaceuticals (atenolol, caffeine, carbamazepine, clofibric acid, diclofenac, hydrochlorothiazide, ibuprofen, ketoprofen, naproxen, paracetamol, and sulfamethoxazole), three personal care products (DEET, triclocarban, and triclosan) and three artificial sweeteners (acesulfame, saccharin, and sucralose)[131] in seawater along a Europe-Arctic marine transect during 2016–17.[131] Examples of the results are shown in Fig. 11. While the results demonstrate that some PPCPs were found in marine water in the Arctic beyond local recipients, others were not (*e.g.*, paracetamol). For those detected, the detection frequency and concentration ranges were lower in the Arctic Ocean compared to more southern locations.[131]

Only one study examined the presence of PPCPs in marine WW recipient sediment.[132] This was done in a transect along the fjord by Ny-Ålesund, Svalbard,[132] and supplements the five-year

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study of the recipient water by analyzing the same 14 compounds.[139] The concentrations observed here were similar in most cases to those reported from urbanized areas in more southern regions, ranging from a minimum of 6.85 ng g^{-1} for triclosan to a maximum of 684.5 ng g^{-1} for ciprofloxacin (Fig. 12).[132] The latter was the only antibiotic detected but was the most abundant compound (positive in 32% of samples) followed by paracetamol and acetylsalicylic acid (16%), the two hormones (14%), ibuprofen (13%), DEET (11%), caffeine (9%), and triclosan (5%). Concentrations of carbamazepine and most of the antibiotics (enrofloxacin, amoxicillin, erythromycin and sulfamethoxazole) were always below the DL. The highest concentrations in the sediment were found close to Ny-Ålesund (Pt. 3, Fig. 12), where human activities and the lack of appropriate wastewater treatment technologies were recognized as primary causes of local contamination.[132] An environmental risk assessment based on the sediment-analysis warned of a medium to high risk for organisms living in this Arctic marine ecosystem, including a high risk of the spread of antimicrobial resistance genes.[132]

Though much valuable information was provided by the cited studies, significant contrasts and gaps in knowledge prevail: (a) the low/insignificant concentrations in recipient waters of most PPCPs are contrasted by more significant concentrations in recipient sediments, (b) several of the PPCPs detected at high concentrations in Arctic WW effluents (dipyridamole, naproxen, metformin, and venlafaxine) have seemingly never been analyzed in Arctic WW recipients, (c) the available studies cover only a narrow geographical fraction of the Arctic region with none from larger cities, and (d) the few studies representing small Indigenous communities suggest that WW release of PPCPs poses less of a risk to the environment there.

7.3.4 Phthalates in Arctic WW recipients. Only one study analyzed phthalates in an Arctic WW recipient, namely in sediment sampled in Adventfjorden and Grønfjorden, Svalbard, in 2016. None of the samples showed concentrations of any of the 10 analyzed phthalates above the DL of 0.80 mg kg^{-1} dw. However, this does not preclude that it was present as the DL was above the common level observed in untreated WW.[129]

7.3.5 Siloxanes in Arctic WW recipients. The presence of D5 siloxanes was investigated in only one Arctic WW recipient study which reported a decrease in sediment concentrations with increasing distance from the wastewater outlet in Adventfjorden.[133] This indicates that the local settlement of Longyearbyen is a point source to the local aquatic environment (Fig. 13).[133] D4 and D6 were not detected above the DL of the study.

7.3.6 Microplastics in Arctic WW recipient waters and sediments. Numerous studies have documented the presence of microplastics in Arctic marine water including WW recipients (Table 4). As with WW, the comparison of studies is limited by the sampling of different particle size intervals. While some studies[134–136] agree that Arctic coastal recipients contain concentrations of microplastics orders of magnitude higher than those of recipients in the Nordic region[8,60,137] (Table 4), other studies show concentrations to be similar to those of

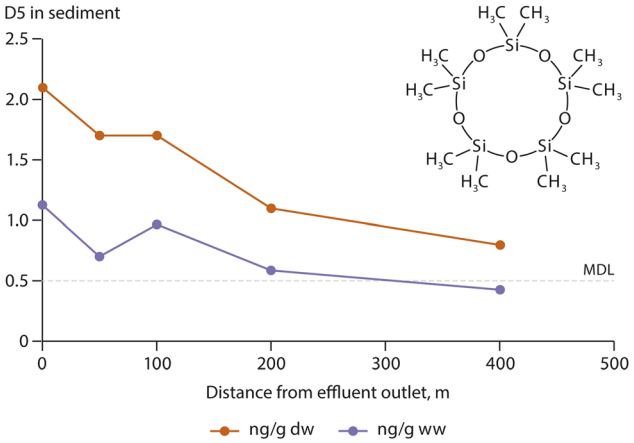

Fig. 13 Sediment concentration profile for siloxane D5 in Adventfjorden reported in ng g^{-1} wet weight (ww) and dry weight as a function of distance to the WW outlet. The figure is reproduced with permission from Warner *et al.* 2010.[133]

Nordic recipients.[61,138] When comparing findings observed across studies and sites, the following trends appear to be consistent:

(a) Microplastics in the Arctic marine environment are connected to human activities occurring both outside and within the Arctic region.[144]

(b) The Arctic Ocean appears to function as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation Arctic accumulation zone. Thus, the high concentration of fibers here most likely originates primarily from LRET.[125,134,139,140]

(c) A significantly higher microplastic concentration is observed close to local settlements/sources[134,136,138] compared to local reference sites, indicating that local sources are critical near the coastline.[61,136,138]

Nuuk, the capital of Greenland with 19 000 inhabitants, was identified as the primary important point source of microplastics in the adjacent fjord Nuup Kangerlua,[138] by the increased concentrations in waters downstream from the town compared to upstream (Fig. 14).

While it is generally acknowledged that rivers serve as vectors for the LRET transport of microplastics to the Arctic region,[141] only one study reported a partial local riverine source,[120] the Northern Dvina River in Russia at the border of the Arctic region. The study concluded that in comparison to other rivers in the world, the river was about 1–2 orders of magnitude less polluted with microplastics and that, apart from a significant pulse discharge in May in relation to the spring flood, no seasonal variation in microplastic concentrations was observed.[120] Although it is likely that a significant fraction of the microplastics in the river originate from the local major city of Arkhangelsk, the river is also likely to carry contributions from the non-Arctic town of Vologda, as well as many smaller towns in the catchment area. Thus, the respective local and LRET contributions are unknown, as is the fraction contributed by wastewater. The same limitations apply to a study that evaluated microplastics in the southern Beaufort Sea serving as an

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Table 4 Concentrations of microplastics detected in Arctic marine waters, including WW recipients, compared to non-Arctic waters, with only synthetic microplastics included and dominant polymer types (PA (polyamide), PCP (polychloroprene), PE (polyethylene), PP (polypropylene), PES (polyester), PET (polyethylene terephthalate), PS (polystyrene), PVA (polyvinyl alcohol), and PVC (polyvinyl chloride)). All results are rounded to two significant figures

Area	Size [mm]	Microplastic concentration (average) [m^{-3}]	Dominant polymer	Dominant morphology	Reference
Sites potentially impacted by concentrating sea currents					
Northeast Greenland	0.08–0.5	2.4 ± 0.8[a]	PE, PP, and PVC	Fragments	145
East Greenland Current (EGC), GL	0.1–0.5	$1.2 \times 10^3 \pm 0.3 \times 10^3$	PES and PE	76% Fibers	140
Greenland Sea Gyre (GSG), GL	0.1–0.5	$2.4 \times 10^3 \pm 0.8 \times 10^3$	PES and PE	87% Fibers	140
Arctic open ocean	>0.1	1.5×10^4[d]	PES and PET	91% Fibers	134
Fram Strait, SV	> 0.32	0–1.3×10^3 (9.5×10^1)	PA	Excluding fibers	125
Arctic sites potentially impacted by local sources					
Nuuk Kangerlua, GL	0.01–0.5	67–278 median 142	PES	Non-fibrous particles	138
Kongsfjorden, Ny-Ålesund, SV	>0.05	3.0 10^3–2.1×10^4[b]	Paint	Fibers	136
Ny-Ålesund, SV	0.05–5	≈19[c]	Paint, PET, and PP	≈50/50 Fragments and fibers	61
Arctic coastline	>0.1	3.7×10^4[d]	PES and PET	91% Fibers	134
Klettagarðar recipient, IS	>0.1	2.4–5.2	—	—	60
Nuuk Kangerlua, GL	0.3–0.5	0.08–0.4 median 0.12	PES	Fibers	138
Non-Arctic sites potentially impacted by local sources					
Kattegat, DK/SE	>0.01	17–286 (103 ± 86)	PA, PE, and PP	Fragments	8
West-coastal Vancouver Island, CA	0.0625–5	$1.7 \times 10^3 \pm 1.1 \times 10^3$	—	Fibers	135
Queen Charlotte Sound, CA	0.0625–5	$7.6 \times 10^3 \pm 1.4 \times 10^3$	—	Fibers	135
Strait of Georgia, CA	0.0625–5	$3.2 \times 10^3 \pm 0.6 \times 10^3$	—	Fibers	135
Göta älv, Ryaverket recipient. SE	>0.333	0.9–10.5	—	—	60
Kalteva recipient, SE	>0.3	0.7–12.7	PES, PE, and PVA	—	60
Baltic Sea, South Funen, DK	>0.3	0.07		71% Fibers	137
Arctic reference sites/open sea					
Barentsburg, SV	0.05–5	≈25[c]	PCP and PP	Fragments	61
Rijpfjorden, SV	>0.05	Up to 3.2×10^3[b]	Paint	Fibers	136
Water below sea ice	>0.25	0–18	PES	Polyester	146
Barents Sea south and southwest of Svalbard – surface	0.25–7.71	0.34 ± 0.31	PES, PA, PE, acrylic, PVC, and cellulose/rayon	95% Fibers	147
Barents Sea south and southwest of Svalbard – subsurface	0.25–7.71	2.68 ± 2.9	PES, PA, PE, acrylic, PVC, and cellulose/rayon	95% Fibers	147
Adventfjorden, Kongsfjorden and Isfjorden, SV	0.25–5	1–2	—	—	148
Arctic Central Basin	0.25–2.5	0–375 (0.7)	PES, blends, PAN, PA, and PVC	96% Fibers	149
Ckchi sea	>0.33	0.086–0.31	PET and PA	96% Fibers	150
Bering Sea	>0.33	0.035–0.26	PET and PA	96% Fibers	150
East Greenland – ice present	>0.5	1.0 ± 0.6	PES	97% Fibres	151
East Greenland – ice absent	>0.5	2.4 ± 1.1	PES	97% Fibers	151
Non-Arctic reference sites/open sea					
Signehamna, SV	0.05–5	≈0[c]	Only wool and cotton detected	—	61
Northeastern Pacific Ocean, CA	0.0625–5	279 ± 178	—	Fibers and angular fragments	135
West Pacific	>0.33	0.018–0.035	PET and PA	96% Fibers	150

[a] High numbers of fibers in the thousands to tens of thousands of items per m^3 were observed but fibers were excluded due to a suspected risk of contamination. [b] Calculated as 43% synthetic (plastic) particles. [c] Number estimated from the bar chart. [d] Calculated as 68% synthetic (plastic) particles.

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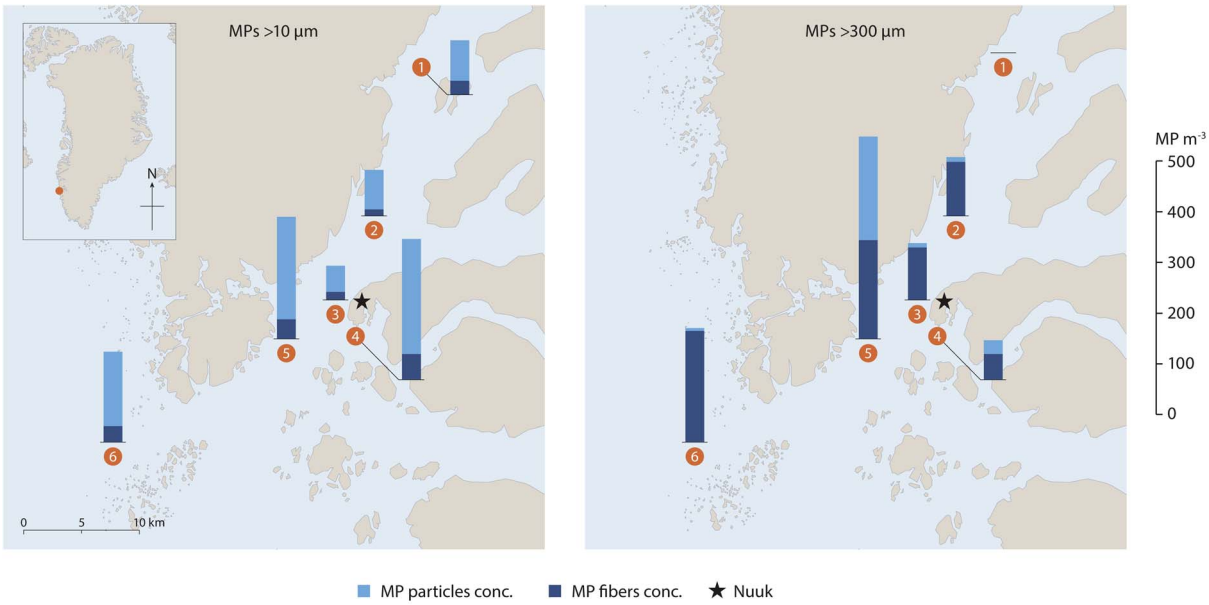

Fig. 14 Microplastic concentrations (microplastic particles m^{-3}) observed in the Nuuk Fjord water in May 2019. The figure is reproduced with permission from Rist *et al.* 2020.[138]

estuary of several major Arctic rivers,[121] which concludes that some plastic particles originate from local industrial activities and fisheries in the Arctic. Thus, further studies are needed to reveal details on the origin of microplastics observed in Arctic river discharges. No studies could be found reporting microplastics in Arctic lakes serving as recipients of WW.

7.3.7 OPEs in Arctic WW recipient waters and sediments. Ten of the 14 analyzed OPFRs were detected in sediment sampled from Adventfjorden and Grønfjorden in Svalbard in 2015, while no OPFRs were detected in sediment from the reference station in Kongsfjorden.[129] This indicates that the settlements of Longyearbyen and Barentsburg are local sources.[129] However, as the OPFR content correlated with the content of organic carbon in the sediment, low levels of organic carbon in Kongsfjorden may also in part explain the absence of OPFRs here; thus LRET cannot be completely disregarded. Nevertheless, both in Adventfjorden and Grønfjorden, the ΣOPFRs were highest close to the sewage outlet, and substances having been used in hydraulic fluids in aircraft were detected only at the airport (Fig. 15). These local variations in the relative abundance indicate that local sources including WW impact the recipient with a radius of up to 2 km.[129]

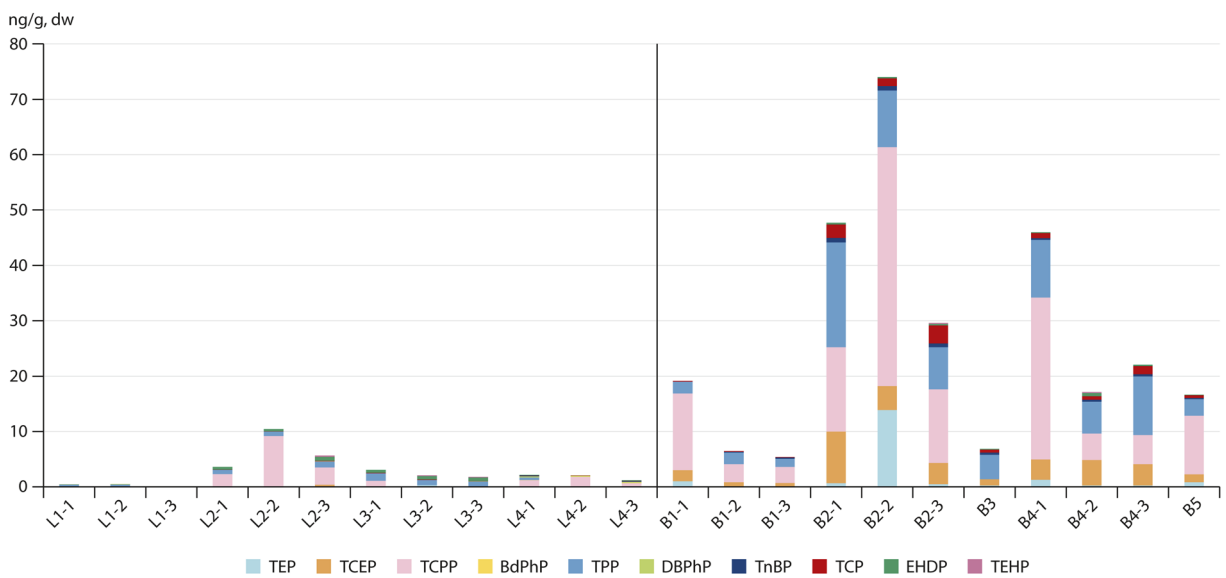

Fig. 15 OPFRs in sediment-samples from Adventfjorden (L) and Grønfjorden (B), September 2015. No OFPRs were detected in the reference samples collected in Kongsfjorden. Sampling sites L2 and B2 are near the sewage outlets. In addition to the sewage, the landfill may impact B2–L4 near the airport. The figure is reproduced with permission from Evenset *et al.* 2018.[129]

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8 Industrial wastewater in the Arctic region

While almost 50% of UN member states reported their domestic WW generation and treatment in 2024, less than 10% of the states reported their industrial WW generation and treatment.[25] Based on this limited UN reporting, it was estimated that only 27–38% of global industrial effluents are safely treated.[25] The only Arctic nation providing information on industrial effluents to the UN was Canada, reporting 50% of their industrial WW to be safely treated and 20% to be somewhat treated, leaving 30% of Canadian industrial effluents untreated.[25] However, no specific data for the Canadian Arctic was provided; thus the volumes, treatment and contents of Arctic industrial effluents remain largely unreported publicly.

Fig. 16 exemplifies water consumption by sector in two Arctic countries.[106] The figure illustrates how industrial water consumption is higher than domestic water consumption in both countries, constituting 63 and 73% of the total water consumption in Greenland and Iceland, respectively. Thus, industrial effluents cannot be ignored volume-wise in a discussion of WW as a source of contaminants.

Tourism, the public sector, and service, health, educational and trades sectors, which all produce WWs similar in content to domestic WW, are included in the inventory by Jensen *et al.*[24] and are encompassed by the observations reviewed in the previous sections. Aside from these sectors, the Arctic region and its subregions rely economically on relatively few major industrial sectors, including mining, refining, fishery, forestry, agriculture, defense, and offshore industries.[152] The listed industries are variably represented across the region, with fisheries dominating the economies of the Faroe Islands, Iceland, Greenland and Arctic Norway (in Norway and the Faroe Islands this includes aquaculture) and being the second most important industry in Alaska. Natural gas and oil production dominates the economies of the Russian Arctic and Alaska and mining dominates in the Canadian and Swedish Arctic, while in Finland mining is the second most important industry after forestry.[153] An indication of the type of chemicals in Arctic industrial WW can thus be obtained through observation of the typical contaminants from these predominant industries.

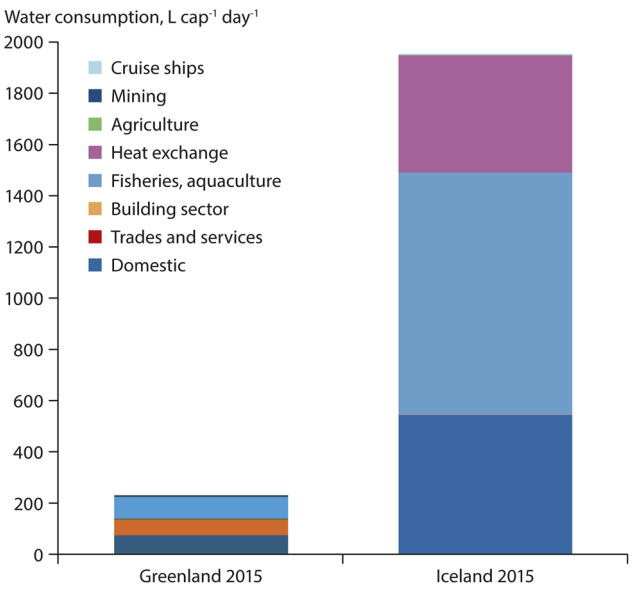

Fig. 16 Examples of water consumption by sector in two Arctic countries in 2015.[106] The consumption by fisheries and aquaculture includes processing.

WW from fish and seafood processing, which is the main water consuming process in the fisheries sector, typically has very high levels of dissolved and suspended organic materials. This results in high biological oxygen demand (BOD) and chemical oxygen demand (COD). Natural fats, oil and grease are also present in large amounts, and nutrients such as nitrogen and phosphate can often be found in high levels too.[154] Anthropogenic organic contaminants are not typically associated with WW from food production, apart from the cleaning agents used for hygiene purposes. On the other hand, a wide range of pharmaceuticals have been closely related to aquaculture, including antibiotics, disinfectants and anthelmintic drugs, which are used for disease control.[155,156] However, most of the available information is from Asia where 90% of the global aquaculture takes place and the situation is not necessarily comparable to Norway or the Faroe Islands. For example, in Norway, through strict regulation of the use of pharmaceutical drugs, aquaculture reduced its total consumption of antibiotics by more than 99% between 1995 and 2019,[157] and in the Faroe Islands, antibiotics have not been used in salmon farming since 2004.[158]

The oil and gas industry produces WW composed of drilling additives and containing high concentrations of COD and total suspended and dissolved solids.[159] The environmental toxicity and persistence of drilling chemicals can vary significantly and the choice of chemicals used is typically a compromise between process stability and environmental safety. Among the listed target POP and CEAC compounds, PFASs are extensively utilized as oilfield production chemicals and aqueous film-forming foams in oilfields.[160] Phenols and PAHs are also found in offshore gas and oil exploitation WW,[161] and it was noted that technologies that can tackle these issues are significantly limited by the challenges of offshore operations in harsh/Arctic environments.[161]

Mine waters are primarily connected to acid mine drainage, heavy metal and radioactive element contamination.[162] But a range of organic chemicals are also frequently used in mineral processing, including PFASs, which are used in surfactants, in ore-flotating chemicals, in other performance enhancing chemicals such as hydraulic fluids and fuel additives, and in firefighting chemicals. PFASs may thus be present in mine waters alongside other chemicals used for processing and dust control. One study investigated the concentration of a range of contaminants in water collected from 10 lakes within the Coppermine and Lockhart Watersheds in the continuous permafrost region in the Northwest Territories, Canada (Fig. 17). Among our target compounds, slightly elevated concentrations of caffeine, acesulfame-K, PFOA and PFOS were observed across the two watersheds investigated, especially downstream of the mining sites. This indicates the influence of mining activity on

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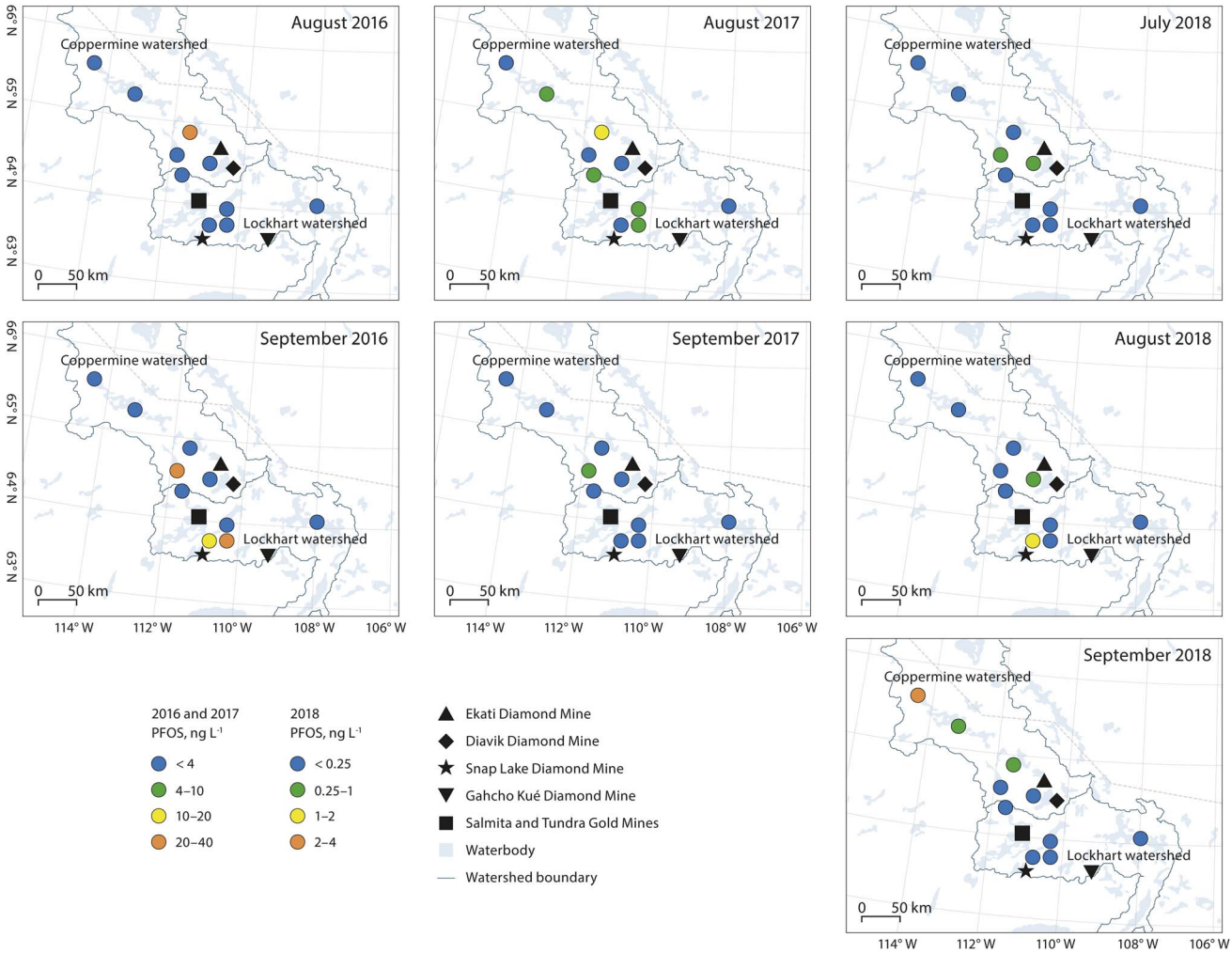

Fig. 17 PFOS distribution in lake water in the Coppermine and Lockhart Watersheds in the Northwest Territories, Canada. The distribution of PFOA was similar. The figure is reproduced with permission from Liu *et al.* (2022).[163]

receiving waterbodies, whether from process WW, domestic WW or surface run-off.[163]

Administration and practice regarding industrial effluents differ across the Arctic region; however, in all countries, discharge permits for industrial waters containing chemicals or high loads of organics are subject to approval by authorities, who assign treatment. Across the Arctic, it is the responsibility of local authorities to issue specific treatment requirements depending on the type of industry and the compounds present, often as part of the issuing of environmental permits. In places with central treatment plants, industries must often install separate pre-treatment if their effluents do not comply with standards.[164] These procedures moset often leave the environmental burden of industrial effluent publicly inaccessible.

9 POPs and CEACs in urban runoff in Arctic communities

Urban stormwater (*i.e.*, surface runoff originating from roads and residential, commercial and industrial areas) can also contain a variety of chemical compounds. Many of the chemicals examined in this review are used to manufacture/protect vehicle components, or in deicing fluids and various household products; therefore, their presence in urban runoff can be expected. Zhang *et al.*[142] recently completed a systematic review and analysis of trace organic pollutants in urban stormwater, reporting that a wide range of these chemicals are routinely present, some at levels that pose ecological risks. They were also able to identify statistically significant relationships between land use and the levels of several chemicals. Studies focused on trace organic contaminants in stormwater in Arctic communities are scarce but have demonstrated the relevance of urban runoff as a source of POPs. Hagedorn *et al.*[165] and Alvey *et al.*[166] detected several triazole compounds in snowmelt runoff from urban landscapes and snow storage facilities in Anchorage, Alaska, at concentrations comparable to those reported in non-Arctic regions. Grzegorzek *et al.*[167] examined concentrations of BUVs and bisphenols in urban drainage in several cities and towns in Iceland and reported that they are routinely present at concentrations comparable to those in non-Arctic studies.[142,165–167]

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10 Conclusions, knowledge gaps and recommendations

• While some target compounds are relatively well studied in Arctic WW (PBDEs, PFASs, phenols, PAHs, microplastics, PPCPs and phthalates), the region is unevenly represented in time and space and most other POPs and CEACs have only sporadically or never been analyzed.

• Based on limited but consistent data, Arctic WW does not appear to be a significant source of legacy POPs, HCHs, or CUPs, but further studies targeting additional substances, recipient sites with no WWT, recipients impacted by larger communities, and recipients impacted by Indigenous communities relying on traditional diets are needed.

• Results show that Arctic WW is a source of PFASs to the Arctic environment, but other local and more distant sources are of equal importance.

• Insufficiently treated Arctic WW is a significant source of PBDEs, BUVs, phenols, PAHs, PPCPs, phthalates, siloxanes, microplastics, halogenated flame retardants and OPFRs to the Arctic environment.

• Despite low temperatures and reduced biological activity, the implementation NBSs and of conventional treatment at higher WW treatment levels appears to reduce the load of these compounds to the Arctic environment.

• The majority of the target compounds studied were found at concentrations in the lower range in the Arctic (WW, sludge and recipients) compared to other regions of the world. The maximum concentrations observed in non-Arctic regions were, however, approached for some of the target contaminants (BDE-47, BDE-99, naphthalene, naproxen, venlafaxine and microplastics), or even slightly exceeded (total PBDEs, DEP, caffeine in untreated WW, the PPCP salicylic acid, ibuprofen, and paracetamol in treated effluents, and some PAHs) in single Arctic sampling occasions, which warrants further study.

• Studies regarding the fate of the listed chemicals in WW recipients in the Arctic region are needed to understand whether non-detects and low concentrations are due to degradation, dilution or uptake in biota.

• More than 6 tonnes of POP and CEAC listed chemicals are discharged with WW in the Arctic region annually, and phthalates and ibuprofen constitute the largest mass of POP and CEAC chemicals discharged by WW in the Arctic among the 20 most well studied chemicals.

• Overall, sewage sludge in the Arctic region is a sink for organic MPs, but more detailed information on the content and fate of MPs in Arctic WW sludge and from across the region is needed to fully understand the risk of environmental exposure.

• Very little is known about the treatment and discharge of industrial WW in the region. WW from the oil, gas and mining industries is likely to contain organic chemicals such as PFASs.

• Urban run-off is likely to contain chemicals related to road, building and vehicle materials and use.

Author contributions

Conceptualization and methodology: Pernille Erland Jensen, Sarah Gewurtz, Debora Boratto, Rob Jamieson. Retrieving data and scientific literature: Sarah Gewurtz, Inga Herrmann, Rob Jamieson, Pernille Erland Jensen, Elisangela Heiderscheidt, Pekka M. Rossi, Hrund Ólöf Andradóttir. Retrieval of country-specific information and grey literature/information or the lack thereof on CEACs and PPCPs in WW: Alaska: Aaron Dotson; Canada: Rob Jamieson, Sarah Gewurtz, Debora Boratto; Faroe Islands: Rakul Mortensen, Katrin Hoydal and Lisbeth Truelstrup Hansen; Greenland: Pernille Erland Jensen; Iceland: Hrund Olöf Andradottir; Norway: Ida Beathe Øverjordet; Finland: Pekka M. Rossi and Elisangela Heiderscheidt; Russia: Maria Velmitskaya; Sweden: Inga Herrmann. Data curation: Sarah Gewurtz, Debora Boratto, Lisbeth Truelstrup Hansen, Pernille Erland Jensen. Draft Sections 1, 3, 4.3.6, 7, and 8, Abstract and Conclusions: Pernille Erland Jensen. Draft Section 4 apart from 4.3.6: Sarah Gewurtz. Draft Section 5: Debora Boratto. Draft Section 6: Inga Herrmann. Draft Section 9: Rob Jamieson. Graphical visualization: Lisbeth Truelstrup Hansen, Débora Boratto. Review & editing: all.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

AMAP	Arctic monitoring and assessment program
B(*a*)P	Benzo(*a*)pyrene
BDE	Brominated diphenyl ether
BDE-47	2,2′,4,4′-Tetrabromodiphenyl ether
BDE-99	2,2′,4,4′,5-Pentabromodiphenyl ether
BFRs	Brominated flame retardants
BOD	Biological oxygen demand
BPA	Bisphenol A
BUVs	Benzotriazole ultraviolet stabilizers
CEACs	Chemicals of emerging Arctic concern
CLBs	Chlorobenzenes
COD	Chemical oxygen demand
CUPs	Current-use pesticides
D4	Octamethylcyclotetrasiloxane
D5	Decamethylcyclopentasiloxane
D6	Dodecamethylcyclohexasiloxane
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DEET	*N*,*N*-Diethyl-*meta*-toluamide
DEHP	Di(2-ethylhexyl) phthalate
DEP	Diethyl phthalate
DIBP	Diisobutyl phthalate
DINP	Diisononyl phthalate
diPAP	Polyfluoroalkyl phosphate diester
DL	Detection limit
DPeP	Dipentyl phthalate
dw	Dry weight

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EHDPP	2-Ethylhexyl diphenyl phosphate
HBCDD	Hexabromocyclododecane
HCB	Hexachlorobenzene
HCH	Hexachlorocyclohexane
LRET	Long-range environmental transport
MCCPs	Medium-chain chlorinated paraffins (or medium-chain chlorinated alkanes)
MM	Hexamethyldisilane
MDM	Octamethyltrisiloxane
MD2M	Decamethyltetrasiloxane
MD3M	Dodecamethylpentasiloxane
MP	Micropollutant
NBSs	Nature-based solutions
NBFR	Novel brominated flame retardant
ND	Not detected (below the unstated DL)
NP	Nonylphenol
OCPs	Organochlorine pesticides
OPEs	Organophosphate esters
OPFRs	Organophosphate flame retardants
PBDEs	Polybrominated diphenyl ethers
PA	Polyamide
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCP	Polychloroprene
PE	Polyethylene
PES	Polyester
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl alcohol
PVC	Polyvinylchloride
PE	Population equivalent
PFASs	Per- and polyfluoroalkyl substances
PFBS	Perfluorobutanesulfonate (a PFSA)
PFCAs	Perfluoroalkyl carboxylates
PFDA	Perfluorodecanoate (a PFCA)
PFHxS	Perfluorohexanesulfonate (a PFSA)
PFNA	Perfluorononanoate (a PFCA)
PFOA	Perfluorooctanoate (a PFCA)
PFOS	Perfluorooctanesulfonate (a PFSA)
PFSAs	Perfluoroalkyl sulfonates
POP	Persistent organic pollutant
PPCP	Pharmaceutical and personal care product
SCCPs	Short-chain chlorinated paraffins (or short-chain chlorinated alkanes)
SMCs	Synthetic musk compounds
4-*t*BuP	4-*tert*-butylphenol
TBP	Tributyl phosphate
TBBPA	Tetrabromobisphenol A
4-*t*OP	4-*tert*-octylphenol
TOC	Total organic carbon
UV-328	A phenolic benzotriazole used as a UV absorber to protect surfaces against discoloration and degradation under UV/sunlight
WW	Wastewater
WWT	Wastewater treatment
WWTP	Wastewater treatment plant
WWTS	Wastewater treatment system

Data availability

The data that supports this study are included as part of the supplementary information (SI). Supplementary information: S1: literature data (until and including 2025) on concentrations of POPs and CEACs in wastewater in the Arctic region. S2: maximum detected concentrations and calculated 75th percentila concentrations based on the data from S1. See DOI: https://doi.org/10.1039/d6va00108d.

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