Nordic Council of Ministers

Plastic in raw wastewater in Greenland

Load to the marine environment and mitigation

Plastic in raw wastewater in Greenland

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Funding: This project was financed by the Swedish Environmental Protection Agency as a contribution to the Nordic Council Project "*Norden som en motor i arbetet mot marin nedskräpning regionalt och globalt*".

Contents

This publication is also available online in a web-accessible version at: https://pub.norden.org/temanord2024-516

Summary/Abstract

Plastic litter is ubiquitous in the Arctic marine environment and discussions about appropriate mitigations prevail, but knowledge about the importance of specific sources is limited. This project aimed to investigate the loads of plastic from untreated sewage discharged to the sea in Greenland. For this purpose, a method was developed to sample and quantify loads of plastic in different size fractions from wastewater effluents from two locations in the towns of Nuuk and Sisimiut in Greenland. Plastic findings were visually characterized in terms of abundance, morphology, size, and chemically by characterizing the polymer composition using FTIR spectroscopy. The results showed that wastewater is a source of both macro- and micro-sized plastic litter in the Arctic marine environment in Greenland. The most abundant polymer type was PET (PES) in all size fractions. The macro-plastic fraction > 25 mm consisted primarily of wet wipes, but also other sanitary items were found, e.g., condoms and pads. The larger microplastic fractions sizing 300 µm 25 mm showed mainly to be PET fibers and fragments, while the smaller microplastic fraction primarily consisted of PES (including PET). The main mass load (70%) was from plastic items larger than 25 mm, and only 1% was smaller than 1 mm. Among the large items, wet wipes were dominating and constituted 59% of the total emitted plastic by mass. On top of that, our findings suggest that a fraction of the micro-plastic is directly related to the presence of wet wipes. Thus, eliminating wet wipes from the sewage could drastically reduce the emission of plastic in all sizes from sewage in Greenland. A literature review of the retention capacity of wastewater treatment systems showed that even simple preliminary (i.e., grit or filter) or primary treatment (e.g., filter or settling) can reduce plastic from sewage from entering the sea significantly by retaining all particles larger than the grit/filter size, and, additionally, 50-80% of the micro plastic particles, which are retained due to floc formation occurring in concentrated wastewaters. It is recommended to investigate the efficiency of specific filters towards specific wastewater before eventual extensive implementation.

Resumé

Plastikaffald er udbredt i det arktiske marine miljø og der pågår diskussioner omkring implementering af foranstaltninger for at mindske lokale bidrag, men viden om specifikke kilders betydning er begrænset. Formålet med dette projekt var at undersøge mængden af plastik udledt til havet med ubehandlet spildevand i Grønland, og undersøge potentielle foranstaltninger for at reducere kilden. Der blev udviklet en metode til at prøvetage og kvantificere mængden af plastik i forskellige størrelsesfraktioner fra to spildevandsudledninger i henholdsvis Nuuk og Sisimiut i Grønland. Plastik indsamlet fra spildevandet blev visuelt karakteriseret med hensyn til mængde, morfologi, størrelse og kemisk sammensætning ved hjælp af FTIR-spektroskopi. Resultaterne viste, at spildevand er en kilde til både makro- og mikroplastik i det arktiske marine miljø i Grønland. Den mest almindelige polymertype var PET (PES) i alle størrelsesfraktioner. Makroplastikfraktionen > 25 mm bestod primært af vådservietter, men der blev også fundet andre sanitetsartikler såsom kondomer og hygiejnebind. De større mikroplastikfraktioner i størrelsen 300 µm - 25 mm bestod hovedsageligt af PET-fibre og fragmenter, mens den mindre mikroplastikfraktion primært bestod af PES (inklusive PET). Den primære massebelastning kom fra plastikgenstande større end 25 mm, og kun 1% var mindre end 1 mm. Blandt de store genstande dominerede vådservietter, som udgjorde 59% af det samlede massebidrag af plastik. Derudover antyder vores resultater, at en del af mikroplastikken direkte er relateret til tilstedeværelsen af vådservietter. Dermed kan fjernelse af vådservietter fra spildevandet potentielt markant reducere udledningen af plastik i alle størrelser fra spildevand i Grønland. En litteraturgennemgang af eksisterende spildevandsbehandlingssystemers kapacitet til at tilbageholde plastik i andre dele af verden viste, at selv en simpel præliminær (gitter og/eller filter) eller primær (filter eller sedimentering) behandling kan reducere plastiktilførslen til havet betydeligt ved at tilbageholde alle partikler større end gitter/filterstørrelsen, og derudover fjerne 50-80% af mikroplastikpartiklerne, som tilbageholdes ved den flokkulering, der sker i koncentreret spildevand. Det anbefales at foretage yderligere undersøgelser og dokumentation for anvendeligheden og effektiviteten af specifikke filtre og spildevand inden en eventuel omfattende implementering.

Abbreviations

µFTIR spectroscopy	µFourier Transform InfraRed spectroscopy
ABS	Akrylonitril-butadien-styrene
ATR	Attenuated Total Reflectance
ATR-FTIR	Fourier Transform InfraRed Spectroscopy-Attenuated Total Reflectance
Danish EPA	Danish Environmental Protection Agency
DL	Detection Limit
EU's REACH	EU Registration, Evaluation, Authorisation and Restriction of Chemicals
EVA	Ethylen-Vinylacetat
FEDSM	Fluids Engineering Division Summer Meetings
FPA	Focal Plane Array
FTIR	Fourier Transform InfraRed spectroscopy
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
HDPE	High Density Polyethylene
IR	Infrared
MBR	Membrane Bioreactor
MP	Microplastic
PA	Polyamide
PAME	Protection of the Arctic marine Environment
PAN	Polyacrylnitrile

PBT	Polybutylene terephthalate
PC	Polycarbonate
PCP	Polychloroprene
PE	Person Equivalents
PE	Polyethylene
PES	Polyester
PET	Polyethylene terephthalate
PMMA	Polymethylmethacrylate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethan
PVA	Polyvinyl alcohol
PVC	Polyvinylchloride
SD	Standard Deviation
SDS	Sodium Dodecyl Sulphate
SUP	Single-Use Plastics
UN	United Nations
WWTP	Wastewater Treatment Plant

1. Introduction

Concern has been raised upon observations of high concentration of litter and microplastics (MPs) along the Greenlandic coastline (Rist et al. 2020; Mallory et al. 2021; Strietman et al. 2021). The undesirable omnipresent MPs and the scatter of plastic litter in the environment, gives rise to emerging worldwide environmental concerns, including in the Arctic (PAME, 2019). Plastic litter can physically affect marine organisms by, e.g., ingestion or entanglement, chemically by acting as an introducer, or a vector of adsorbed chemicals in the environment (AMAP, 2016; Collard and Ask, 2021), and by causing biodiversity and ecosystem disturbances (Villarrubia-Gómez et al. 2017). To combat the effects and presence of plastics in the Arctic environment, PAME (Protection of the Arctic marine Environment), a working group of the Arctic Council, has produced a regional action plan on marine litter (PAME, 2021), which includes improving onshore waste and wastewater management.

The presence of plastic in the Arctic marine waters is connected to human activities occurring both outside and within the Arctic region (Bergmann, 2022). Marine plastic litter pollution was recently documented to be significant in Greenland (Mallory et al. 2021). They investigated the marine waters and coastlines of the Arctic Canada and West Greenland and found that litter densities do not decrease with increasing latitude, that litter densities were largest within 5 km of communities, and that much of the litter near remote communities was clearly from local sources (Mallory et al. 2021). This is in accordance with an in-depth beach litter analysis in West Greenland (Sisimiut, Maniitsoq, and Qaqortoq), where marine litter was found to be mostly of local origin and consisted primarily of everyday use products and products related to fishing and hunting (Strietman et al. 2021).

It is recognized that the number of items in sea water increases with decreasing size (e.g., Herzke et al. 2021). It is, therefore, inherently difficult to compare results on numbers of particles of investigations with different cut-off sizes in the lower end (Table 1). Some general trends, however, appear to be consistent: One is the concentration of MPs from long distance sources in the Arctic Ocean (sites mentioned as potentially impacted by concentrating sea-currents in Table 1), where studies showed very high MP concentrations (Cózar et al. 2017; Barrows et al. 2018; Jiang et al. 2020; Tekman et al. 2020). The other is the increased concentration of MPs in seawater close to local sources compared to local reference sites away from sources (Table 1), as documented by Rist et al. (2020), who identified Nuuk, the capital of Greenland with 19,000 inhabitants as the primary important point source of MPs in the adjacent fjord Nuup Kangerlua, and by Herzke et al. (2021), who showed that untreated sewage from Longyearbyen, Svalbard, with only 2,000 inhabitants, emits microplastic fibers at a scale similar to a modern wastewater treatment plant serving 1.3 million persons. Several studies (Desforges et al., 2014; Barrows, 2018; Von Friesen et al., 2020) show that Arctic coastal recipients contain several size-orders higher concentrations of MPs in comparison to recipients in the Nordic region (Magnusson, 2016; Tamminga et al., 2018; Liu et al. 2023) (Table 1), while other studies show lower concentrations similar to the Nordic recipients (Rist et al. 2020; Granberg et al. 2019).

Table 1 Results reported in the literature on plastic microfibers in Arctic seawater, only synthetic MPs included.

Area	Size [mm]	MP concentration (average) [MPs m^{-3}]	Dominant polymer	Dominant morphology	Reference
Northwestern Pacific					
Northwest Pacific, the Bering Sea, and the Chukchi Sea	>0.33	0.018-0,31 (0.13)	PET	Fibers	Mu et al. 2019
Sites potentially impacted by concentrating sea-currents					
East Greenlandic Current (EGC), GL	0.1-0.5	$1.2 \cdot 10^3 \pm 0.3 \cdot 10^3$	PES and PE	76% fibers	Jiang et al. 2020
Greenlandic Sea Gyre (GSG), GL	0.1-0.5	$2.4 \cdot 10^3 \pm 0.8 \cdot 10^3$	PES and PE	87% fibers	Jiang et al. 2020
Northeast Greenland	0.08-0.5	2.4±0.8*	PE, PP, PVC	Fragments*	Morgana et al. 2018*
Arctic open ocean	>0,1	$1.5 \cdot 10^4$*****	PES, PET	91% fibers	Barrows et al. 2018
Fram Strait, SV	0.32-	$0\text{-}1.3 \cdot 10^3$ ($9.5 \cdot 10^1$)	PA	Excluding fibers	Tekman et al. 2020

Sites potentially impacted by local sources					
Nuuk Kangerlua, GL	0.01-0.5	ca. 200-278	PES	Non-fibrous particles	Rist et al. 2020
Kongsfjorden, Ny Ålesund, SV	>0.05	$3.0 \cdot 10^3$-$2.1 \cdot 10^4$**	Paint	Fibers	Von Friesen et al. 2020
Ny-Ålesund, SV	0.05-5	≈ 19***	Paint, PET, PP	≈50/50 fragments, fibers	Granberg et al. 2019
Göta älv, Ryaverket recipient. SE	>0.333	0.9-10.5	-	-	Magnusson et al. 2016
Kalteva recipient, SE	>0.3	0.7-12.7	PES, PE, PVA	-	Magnusson et al. 2016
Klettagarðar recipient, IS	>0.1	2.4-5.2	-	-	Magnusson et al. 2016
Baltic Sea, South Funen, DK	>0.3	0.07		71% fibers	Tamminga et al. 2018
Kattegat, DK/SE	>0.01	17–286 (103 ± 86)	PA, PE, and PP	Fragments	Liu et al. 2023
West-coastal Vancouver Island, CA	0.0625-5	$1.7 \cdot 10^3 \pm 1.1 \cdot 10^3$	-	Fibers	Desforges et al. 2014
Queen Charlotte Sound, CA	0.0625-5	$7.6 \cdot 10^3 \pm 1.4 \cdot 10^3$	-	Fibers	Desforges et al. 2014
Strait of Georgia, CA	0.0625-5	$3.2 \cdot 10^3 \pm 0.6 \cdot 10^3$	-	Fibers	Desforges et al. 2014
Arctic coastline	>0,1	$3.7 \cdot 10^4$*****	PES, PET	91% Fibers	Barrows et al. 2018
Reference sites/Open sea					
Nuuk Kangerlua, GL	0.01-0.5	67-ca. 100	PES	Non-fibrous particles	Rist et al 2020
Barentsburg, SV	0.05-5	≈25***	PCP, PP	Fragments	Granberg et al 2019

Signehamna, SV	0.05-5	≈0***	Only wool and cotton detected	-	Granberg et al 2019
Northeastern Pacific Ocean, CA	0.0625-5	279 ± 178	-	Fibers and angular fragments	Desforges et al. 2014
Water below sea-ice	>0.25	0-18	PES	Polyester	Kanhai et al. 2020
Barents Sea south and southwest of Svalbard - surface	0.25- 7.71	0.34±0.31	PES, PA, PE, acrylic, PVC, cellulose/rayon	95% fibers	Lusher et al. 2015
Barents Sea south and southwest of Svalbard - subsurface	0.25- 7.71	2.68 ±2.9	PES, PA, PE, acrylic, PVC, cellulose/rayon	95% fibers	Lusher et al. 2015
Adventfjorden, Kongsfjorden and Isfjorden. SV	0.25-5	1-2	-	-	Sundet et al. 2020
Artic Central Basin, NP	0.25-2.5	0-375 (0.7)	PES, blends, PAN, PA, PVC	96% fibers	Kanhai et al. 2018
Chukchi Sea	>0.33	0.086-0.31	PET, PA	96% fibers	Mu et al. 2019
Bering Sea	>0.33	0.035-0.26	PET, PA	96% fibers	Mu et al. 2019
West Pacific,	>0.33	0.018- 0.035	PET, PA	96% fibers	Mu et al. 2019
East Greenland – ice present	>0.5	1.0 ± 0.6	PES	97% fibres	Amélineau et al. 2016
East Greenland- ice abcent	>0.5	2.4±1.1	PES	97% fibers	Amélineau et al. 2016
Rijpfjorden, SV	>0.05	Up to $3.2 \cdot 10^3$**	Paint	Fibers	Von Friesen et al. 2020

*High numbers of fibers in the thousand to tens of thousands items/m^3 were observed but fibers were excluded due to suspected risk of contamination. **Calculated as 43% synthetic (plastic) particles, ***number estimated from bar chart, ****Calculated as 68% synthetic (plastic) particles. All results rounded to two significant figures. GL: Greenland; SV: Svalbard; SE; Sweden; DK: Denmark; IS: Iceland; CA: Canada

A national action plan to reduce plastic consumption was enacted by the Greenlandic government (Naalakkersuisut, 2021). Because wastewater in Greenland is discharged to the sea untreated, it is hypothesized that raw wastewater contributes as a local source to the marine litter (macro- and microplastics) in Greenland, as was shown for Svalbard (Granberg et al. 2019). An implementation of wastewater treatment is considered as a future point of action (Naalakkersuisut, 2021).

The aim of this project was twofold: First, to estimate the burden of plastic litter and MPs to the marine environment originating from untreated piped sewage in Greenland by sampling and investigating sewage from the two biggest towns of Greenland, Nuuk and Sisimiut. Second, based on the results, to recommend interventions to reduce plastic contamination to the sea from wastewater in Greenland.

2. Methodology

2.1 Study areas

Sampling for plastics was conducted at two wastewater outlets in Greenland, one in the capital of Greenland, Nuuk, with ~ 19,870 inhabitants and one in the second largest town, Sisimiut, with ~ 5,460 inhabitants. The sampling sites were chosen based on the preference for outlets receiving wastewater primarily from households while avoiding wastewater from fish and seafood processing industry. Two outlets meeting this criterion, and with similar PE (Person Equivalents) loads of approximately 2,000 PE (i.e., 3.6% of the Greenlandic population) and easy accessibility were selected. The outlet sampled in Sisimiut was U1, where samples were taken from well number 08A0001A, while the outlet sampled in Nuuk was U15, which was sampled from well number 0620004 (Figures 1, 2 and 3).

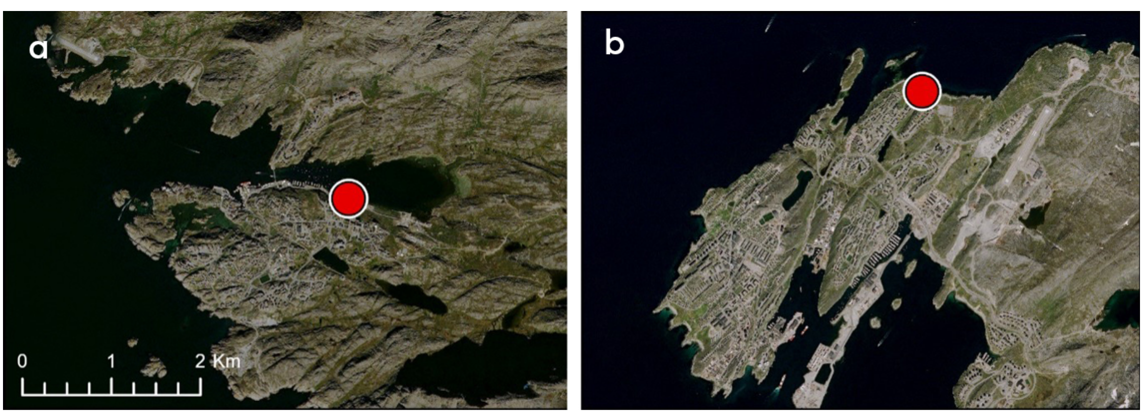

Figure 1 Site of sampling in a) Sisimiut and b) Nuuk. At both sites, the sewer discharges raw wastewater from approximately 2000 PE.

Figure 2 a) Wastewater outlet U1 in Sisimiut, March 2022, b) Sampling of macroplastics, c) Sampling of meso-plastic, d) Cleaning of meso-plastic and macro-plastic samples in Sisimiut. Photos: Pernille E. Jensen

Figure 3 a) Sewer U15 sampled in Nuuk, b) Sampling of macro-plastic in Nuuk, c) sampling meso-sized plastic in Nuuk. Photos: Pernille E. Jensen

2.2 Sampling and processing

Sampling was conducted to distinguish four plastic size fractions: macro-plastics (> 25 mm), meso-plastics (5–25 mm), large-sized microplastics (1–5 mm) and microplastics (20 µm–1 mm) according to the recommendations of the GESAMP for the monitoring and assessment of plastic litter in the ocean (GESAMP, 2019). These recommendations were also followed when classifying the plastics into color, shapes, and sources.

As differences in amounts and types of litter in the wastewater during daily routines and throughout the week are expected, the sampling was conducted at times representing different times throughout the day and different weekdays. Despite the sewers in Greenland being separate (i.e., rainwater and snow melt water runs in separate ditches), increased flow of sewage in pipes has been visually observed on previous occasions. Samples diluted by rainwater were avoided by not sampling for at least 48 hours after any rainfall. A detailed overview of the sampling scheme can be found in Table S1.

2.2.1 Sampling of macro-plastics (> 25 mm) in Nuuk and Sisimiut

To collect macro-plastics, a steel sieve with a pore size of 25 mm was designed and positioned in the sewer ensuring that all wastewaters would flow through while collecting litter of > 25 mm. Sampling was continued until the matter collected in the sieve clogged the sewer (between 30 minutes and 3 hours). Detailed information about the duration of sampling can be found in supplementary material S1. After sampling, the steel sieve was thoroughly rinsed with tap-water via a hose to remove any matter smaller than 25 mm trapped within the sieve. To dissolve any remaining easily degradable organic matter such as toilet paper, food items and feces, as well as to disinfect the sieve and remaining material, the sieve was submerged in a 60 L blue HDPE (High density polyethylene) plastic barrel filled with an alkali solution pre-prepared by mixing cleaning agent Vip 1 (a mixture of sodiumhydroxide, disodiummetasilicate, penta-hydrate and sodiumhypochlorite, commonly used for cleaning and disinfection of milking equipment supplied by linds.dk) with tap-water in a 1:1 solution, and left for 24 hours. Finally, the sieve with remaining content was removed, rinsed with tap-water and left to air-dry before the collected items were retrieved, packaged and transported by plane to the laboratory at Ecoscience, Aarhus University in Roskilde, Denmark, for further analysis.

2.2.2 Sampling of meso-plastics (5-25 mm) in Sisimiut

Over the course of three individual days, a total of 90 L of raw wastewater was collected from each sampling site using a 1 L steel beaker measuring cup. Each day, 30 L of raw wastewater was collected in a blue HDPE plastic barrel by collecting 1 L at a time over a duration of a 2.5-hour period. Wastewater from the entire flow was collected. The collected wastewater was filtered through a 5 mm metal sieve. No items larger than 25 mm were collected, and the resulting sample represents particles ranging from 5–25 mm in size, only. The samples were rinsed, disinfected, packed and shipped according to the procedure described in 2.2.1.

2.2.3 Sampling of large-sized microplastics (1-5 mm) in Nuuk and Sisimiut

After the 5 mm filtration for collection of meso-plastics (as described in section 2.2.2), a subsample (30 L) of the filtrate was further filtered through a 1 mm plankton-net to achieve a sample of large-sized microplastics (1–5 mm). The 1 mm net including retained particles was rinsed, disinfected, packed and shipped according to the procedure described in 2.2.1.

2.2.4 Sampling of microplastics (20-1000 µm) in Sisimiut

Sampling for microplastics was done in Sisimiut, in digested (muffled) 1 L blue-cap glass flasks by hand by a person wearing no synthetic textiles, to avoid plastic contamination. Two flasks were filled with approximately 1700 mL of wastewater from three sampling occasions (due to shallow water they could not be filled completely). A blind sampling subjected to an identical procedure, though not letting any water in, was also included at each sampling round. These samples served as field blanks. All flasks were transported by plane to the laboratory at Ecoscience, Aarhus University, in Roskilde, Denmark, for further analysis.

Two of the collected wastewater samples (~ 600–700 ml each) were analyzed for the smallest types of MPs in the size fraction of 20–1000 µm, applying a modification of the procedure described for sample preparation in Rasmussen et al. (2021). The samples were weighed and thereafter purified to remove as much natural material as possible. Initially, the samples were filtered through a 20 µm stainless-steel filter, whereafter the filter with the collected material was subjected to ultrasonication in acetate buffer (pH 4.8) with the addition of SDS (sodium dodecyl sulphate) as a detergent. The samples were transferred to a bottle with cellulose-degrading enzymes (cellulase and viscozyme), followed by 40 hours reaction time in a water bath at 50 °C. Subsequently, the samples were filtered (20 µm), and the filter was ultrasonicated in the acetate buffer for 5 minutes once more. The samples were then treated with a mixture of a strong alkaline solution (10% KOH) and hypochlorite (7% NaOCl) as an oxidizing agent for 24 hours, after which the samples were filtered again (20 μm). Finally, a solution of zinc chloride with a density of 1.5 g/ml was used to separate heavier particles from those suspended in the liquid in a separating funnel. The upper part of the liquid fraction was then filtered through a series of stainless-steel filters with mesh sizes of 1000, 100, and 20 μm. The lower part of the liquid fraction was discarded.

The size fractions 20–100 μm and 100–1000 μm of the purified sample were transferred to separate silicon membranes (MakroPor, SmartMembranes) with a diameter of 13 mm and a pore size of 5–6 μm. The size fraction 100–1000 μm was examined under a microscope for particles resembling microplastics.

2.3 Sample analyses

2.3.1 Analyses of macro-plastics (>25 mm)

Initially, the plastic items >25 mm were visually characterized according to EUs JRC 2021 technical report 'A Joint List of Litter Categories for Marine Macro-litter Monitoring' (European Commission Joint Research Centre, 2021).

To validate the visual classification along with polymer specific identification, representative items and particles >25 mm were identified using the ATR-FTIR (Fourier transform infrared spectroscopy-attenuated total reflectance) spectroscopy and relevant spectral libraries. Measurements were carried out using Agilent Technologies 4500a Series Portable FTIR. The spectrometer was equipped with a triple-reflection diamond ATR sample interface and an in-depth ATR polymer library. The absorbance spectra were collected using 32 background scans at a 4 cm^{-1} resolution, measuring a spectral range between 650 and 4000 cm^{-1}. A background atmospheric spectrum was subtracted from all sample spectra, and 8 sample scans were performed for each sample. The library used for the polymer identification was an in-house spectral reference library of FTIR-ATR spectra of multiple synthetic and natural materials developed by the Department of Ecoscience at Aarhus University. All the items/particles were dried prior to chemical analysis to reduce interference of H_2O in the IR (infrared) spectrum.

For the ATR-FTIR analyses, the 'Microlab' software was used as an initial assessment as it automatically compares the collected spectrum with a spectral library and associates the best spectral match. Subsequently, the 'Essential FTIR' software was applied for the data processing and interpretation of the final polymer ID. All generated spectra in this study were smoothed and baseline adjusted as such corrections are critical preprocessing techniques for improving the quality of raw FTIR spectra and obtaining a more precise analysis.

2.3.2 Analyses of meso-plastics (5-25 mm) and large-sized microplastics (1-5 mm)

Particles within the two size groups, i.e., meso-plastics of 5–25 mm and large-sized microplastics (1–5 mm), were visually characterized according to their morphology (e.g., fibers, films, fragments, pellets, etc.), color, length, and width using a "Nikon SMZ18" stereomicroscope. Subsequently, the particles were polymer characterized by the same method that was applied for analysis of macro-plastics (ATR-FTIR) and described above in section 2.3.1.

2.3.3 Analyses of microplastics (20-1000 μm)

The particles collected by the silicon membranes were analyzed using μFTIR spectroscopy in transmission mode, utilizing an Agilent Cary 620/670 FTIR microscope with a 128 x 128-pixel resolution FPA (Focal Plane Array), where each pixel size was 5.5 μm. The analyses were performed with a resolution of 4 cm^{-1} and 8 scans per pixel measuring a spectral range between 870 and 4000 cm^{-1}. To cover the entire area of the silicon membrane, a mosaic of 15 x 15 = 225 image parts were assembled, resulting in a total dataset of 3,686,400 FTIR spectra. These extensive spectral image mosaics were analyzed using siMPle software developed for automated image analysis (https://simple-plastics.eu/) (Figure 4). For polymer identification, a μFTIR spectral reference library (MP-AU4a) developed at Aarhus University was used, containing 106 spectra of the 10 primary plastic polymer groups (PE (polyethylene), PP (polypropylene), PES (polyester), PS (polystyrene), PVC (polyvinylchloride), PC (polycarbonate), PMMA (polymethylmethacrylate), PA (polyamide), PUR (polyurethan), and ABS (akrylonitril-butadien-styrene) as well as broader groups for other plastic-polymers and rubbers. In addition, the reference library also contained μFTIR spectra of various types of naturally occurring organic materials made of cellulose, proteins, and minerals. Additionally, siMPle software was used to estimate the mass of the microplastics based on their volume, taking into account particle area and assuming a proportional relative thickness.

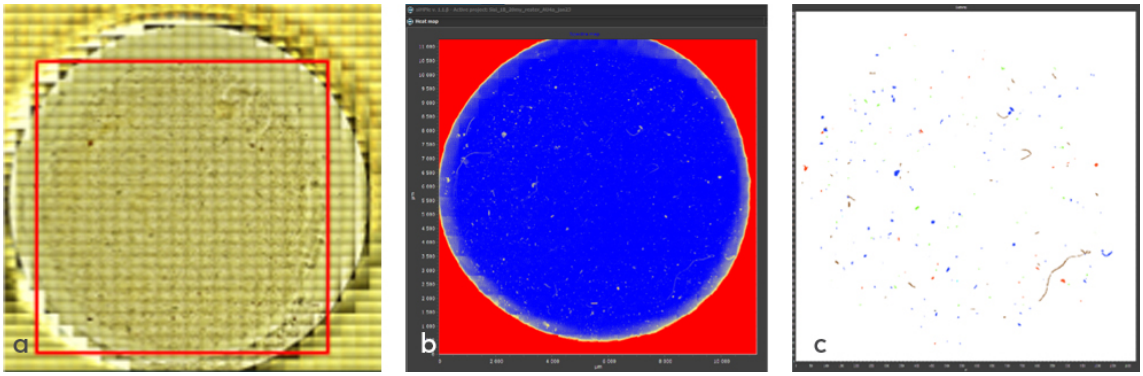

Figure 4 Different types of images of the full sample 1B collected at the 20 µm filter fraction and transferred to a silicon membrane and analyzed with µFTIR spectroscopy. a) the visual image where the analyzed part is marked with red square, b) the spectral heatmap of all particles on the silicon membrane disk and c) the map of all identified microplastic particles at a mosaic consisting of 225 tiles, each tile composed by 128x128 times of 5.5 µm pixels.

To minimize the risk of contamination, all reagents were filtered through a 0.2 µm GF filter, and all glassware and steel filters were wrapped in aluminum foil and heated at 450 °C. Rubber seals and stainless-steel filter chambers were cleaned through regular machine dishwashing, followed by ultrasonic treatment in SDS solution and then ethanol.

Field blank samples and laboratory blind samples were analyzed to assess the potential risk of external contamination during sample handling. In total, 2 field blank samples and 2 laboratory blind samples were analyzed, each divided into size fractions of 20–99 µm and 100–999 µm. Based on the blind samples, analytical detection limits (DL) were determined being equivalent to the mean value plus 3 standard deviations for individual polymer types and for the total number of identified microplastics, as shown in Table S2. For polymer types not identified in the blind samples, the detection limit is set at 1 per sample, corresponding to 2 L^{-1} when analyzing sample volumes of approximately 650 mL.

The quantification of fibers on the silicon membranes using visual microscopy revealed a possible internal contamination of the blind samples. With quantification of an average 35 transparent or white fibers per sample, and an average of 9 colored fibers per sample in predominantly black, blue, and red colors, this likely points to an internal fiber contamination, which would result in a detection limit of 77 white/transparent fibers and 39 colored fibers per sample (calculated as average + 3 x standard deviation (SD)). As a result of the relatively high level of fibers in the blind samples, which for the colored fibers was at the same level as the number of colored fibers found in wastewater samples, the data on colored fibers are reported as < SD for these samples.

2.4 Survey of wet wipes in trade in Greenland

Due to the identification of wet wipes in the sewage as a significant source of plastic litter pollution, a survey of the wet wipes in trade in Greenland was made. In Sisimiut, we purchased any commonly available wet wipes both for sanitary and cleaning purposes. During the 1st – 3rd of July 2023, we visited all grocery stores in Sisimiut as well as other stores that sell beauty products. All different types of wet wipes available were collected. The wet wipes were analyzed for primary and possible secondary polymer by the same method (ATR-FTIR) as described for macro-plastics and described above in section 2.3.1.

2.5 Beach surveys

Due to the findings of significant amounts of wet wipes in the sewage, two rounds of survey of the beach in the inner part of the Kangerluarsunnguaq Bay in Sisimiut, the recipient of the sewage samples was done in June and July 2023.

3. Results

3.1 Macro-plastics (>25 mm)

All items with size >25 mm were easily defined and characterized due to their relatively well conserved structure. The results revealed significant amounts of items as wet wipes, sanitary pads and condoms in the wastewater in both Sisimiut and Nuuk, with total loads of 32 items in a sampling time of 445 minutes for Sisimiut, and 13 items in a sampling time of 190 minutes for Nuuk, corresponding to an equal daily input of 104 and 99 items, respectively (Table 2). The polymeric characterization of the macro-items by ATR-FTIR analyses (Figure 5) revealed that for Sisimiut the 23 wet wipes were of PET (polyethylene terephthalate), the single condom of rubber, the 3 sanitary pads of PP (polypropylene), one piece of foil and 3 cotton buds of cellulose. In Nuuk, the wet wipes were characterized as 6 pieces of PET, 3 of viscose and 3 of cellulose. Also, one sanitary pad was characterized as PE (polyethylene). Thus, 87% and 77% of the items were of synthetic (PET, PE, PP, rubber) or semi-synthetic (viscose) origin in Sisimiut and Nuuk, respectively (Figure 5).

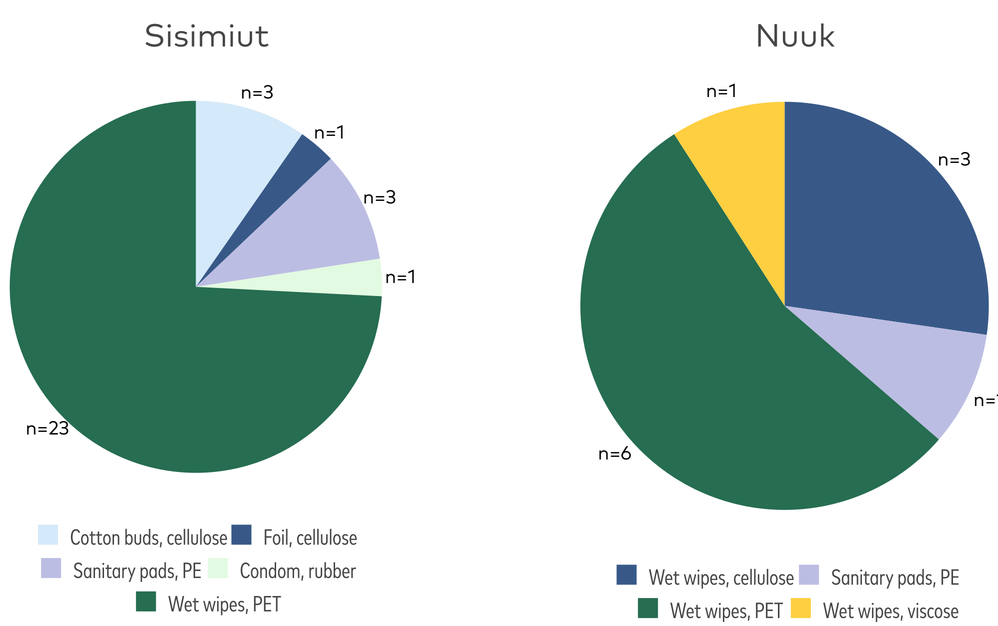

Figure 5 Items with size >25 mm in wastewater in a) Sisimiut, where a total number of 31 items were found in a raw wastewater sample collected during 445 min, and b) Nuuk, with a total of 13 items in a raw wastewater sample collected during 190 min. n indicates number of items.

Table 2 Quantification and dominant polymer of different plastic or plasticized fractions found in wastewater in Sisimiut and Nuuk. The sampling of macro-plastics was conducted over a total of 445 minutes in Sisimiut and 190 minutes in Nuuk. Meso- and large sized microplastics were sampled in 90 L in both Sisimiut and Nuuk and microplastics in 650 mL in 2 replicates in Sisimiut. The yearly input of mass of plastic items through wastewater is estimated assuming a normal capitata consumption of 104 L of water pr day (Marechal et al. 2022).

Site	Size Fraction	Type of items	Abundant Polymer	Number of items	Mass (g)	Total mass (g)	Yearly marine input of plastic (g/year/capita)
Sisimiut	> 25 mm	Wet wipes	PET	25	37.4 g	46.5 g	27.5
		Sanitary pads	PP	3	7.5 g		
		Condoms	Rubber	1	1.6 g		
		Cotton buds	Cellulose	3	0.87 g**		
	5-25 mm	Film/foil	PE	1	<0.005 g***	0.005 g	2.3
	1-5 mm	Fiber/thread bundle	PET	1	0.01 g	0.015 g	6.9
		Film/foil	PE	1	<0.005 g***		
	20-1000 μm	Microplastic fragments	PE	$32\ L^{-1}$		$12.8\ \mu g\ L^{-1}$	0.5
			PP	$131\ L^{-1}$			
			PES	$20\ L^{-1}$			
			PS	$7\ L^{-1}$			
			PVC	$<3\ L^{-1}$***			
			PC	$<2\ L^{-1}$***			

			PMMA	<2 L^{-1}***			
			PA	<2 L^{-1}***			
			PUR	<2 L^{-1}***			
			ABS	<2 L^{-1}***			
			Other polymers	28 L^{-1}			
			Other rubbers	<5 L^{-1}***			
Nuuk	> 25 mm	Wet wipes	PET	6	10.2 g	16.9 g	23.4
			Viscose	3	4.8 g*		
			Cellulose	3	4.8 g*/**		
		Sanitary pads	PE	1	1.9 g		
	5-25 mm	N/A	-	-	0 g	0 g	0
	1-5 mm	Film/foil/ fragment	PE	4	0.02 g*	0.03 g	12.7
		Film/foil/ fragment	PUR	2	0.01 g*		

Polymer type: PE (polyethylene), PP (polypropylene), PS (polystyrene), PES (polyester), PVC (polyvinylchloride), PC (polycarbonate), PMMA (polymethylmethacrylate), PA (polyamide), PUR (polyurethan), ABS (akrylonitril-butadien-styrene)

N/A: Not detected, *Estimated weight. **The masses of cellulose wet wipes and cotton buds are not included in the estimation of yearly marine input of plastic. *** Under detection limit (the total mass and yearly marine input for these items are therefore an absolute maximum). See Table S2 for detection limits of quantification of polymer types.

3.2 Meso-plastics (5-25 mm)

Only one meso-plastic sized particle polymeric characterization as PE was sampled in Sisimiut, whereas no particles in this size range were found in Nuuk (Table 2).

3.3 Large-sized Microplastics (1-5 mm)

Of the large sized microplastics, 2 and 6 items were sampled in Sisimiut and Nuuk, respectively. The items from Sisimiut consisted of one PET fiber/thread and one PE film/foil (Table 2). The 6 items from Nuuk consisted of 2 items of film/foil, besides 2 pieces of PE and 2 pieces of PUR (polyurethane). The latter four items were not visually characterized as they were lost between the ATR-FTIR analysis and the visual characterization and size measurement. The items are denoted film/foil/fragments in Table 2 and for inclusion in data, the mass of the items was estimated based on the mass of similar items.

3.4 Microplastics (20-1000 µm)

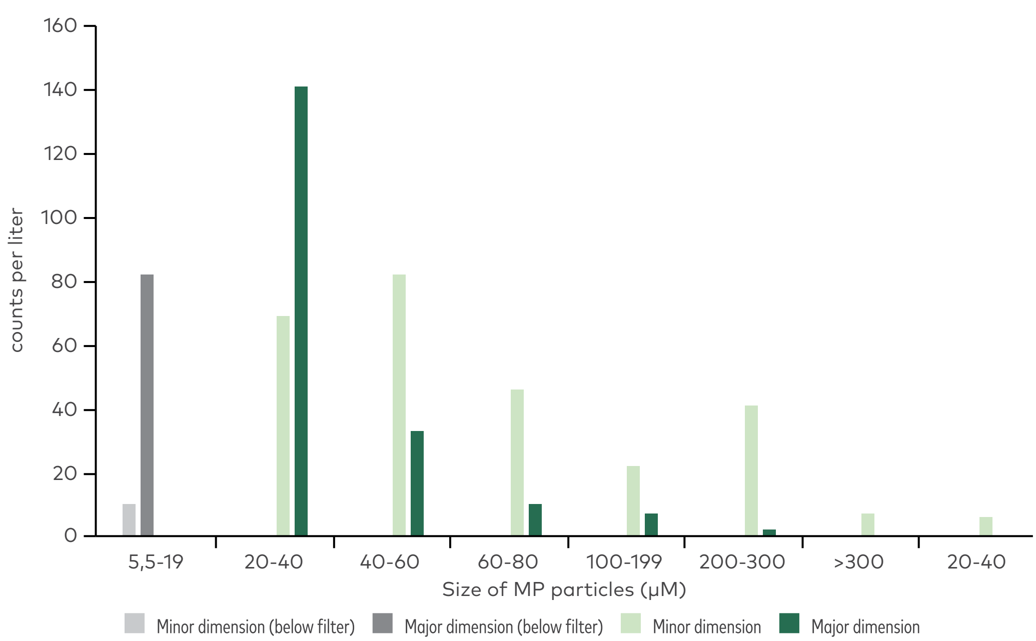

Figure 6 Size distribution of MPs identified in sewage water samples from Sisimiut. The figure indicates counts of particles within each size group per liter sample. Minor and major dimensions describe the shortest and the longest length of the particle, respectively. *Note*: the size group of 5.5-19 µm (grey colors) is below the filter used in the extraction procedures, wherefore the number must be seen as an absolute minimum. The size distribution is shown for the dimensions of the particles measured on the longest and the shortest edge by µFTIR image analysis and use of siMPle software (https://simple-plastics.eu/) data output.

The content of microplastics in the two wastewater samples (each of 650 mL) from Sisimiut determined by μFTIR analyses showed a presence of microplastics at levels significantly higher than the detection limits (Table 2 and S2). By employing μFTIR analyses on the sample, the average number of MPs was determined to 217 L^{-1} (range: 159-276 L^{-1}). By μFTIR analyses the primary polymer types were identified as PP (65%), PE (15 %), and PES (polyester, 6% (PES includes PET, PBT and other polymers)), but a few microplastic particles consisting of PS (polystyrene) were also identified in the samples (1%). The group of other synthetic polymers like EVA (ethylen-vinylacetat) contributed ~13% (Figure 7).

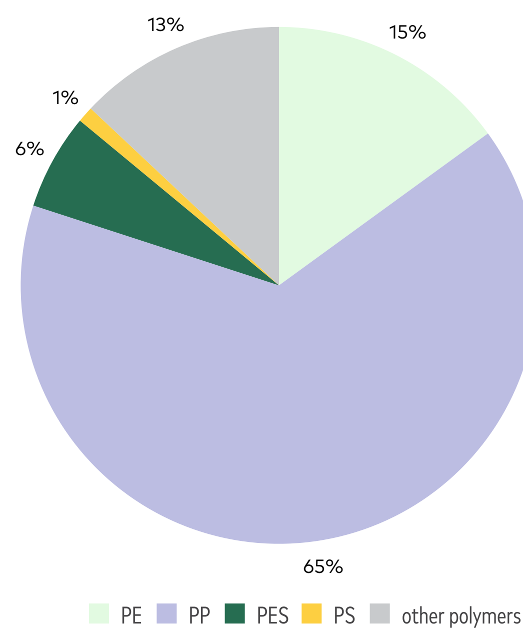

Figure 7 Polymer distribution of the MPs in sewage water samples from Sisimiut identified by μFTIR analysis. The largest part of the MPs was polypropylene (PP, 65 %), but also MPs of polyethylene (PE, 15%), polyester (PES, 6%, PES includes PET, PBT and other polymers), polystyrene (PS) and also other polymers were detected (13 %).

Looking into the microfiber content of the wastewater, visual inspection revealed a rather large contribution of white/transparent fibers (range 102–352 fibers L^{-1}) well above the detection limit (DL: 77 fibers L^{-1}; range 17-64), while the colored fibers in the wastewater (range 7–8 fibers L^{-1}; range 0-31) were below the detection limit (DL: 39 fibers L^{-1}). This visual quantification was confirmed by the μFTIR analyses.

The μFTIR analyses revealed that the most part of the fibers was of organic material (cellulose or protein) and only 18% were of plastic polymers (10% PES and 8% PP) (Figure 8). Figure 9 shows a PET fiber likely to be a result of laundry. Due to methodological limitations the cellulose fraction, or at least a portion of it, may be considered as viscose. This uncertainty arises from the limitations of FTIR analysis in separating cellulose and viscose, and the inclusion of cellulose-degrading enzymes in the extraction methods, potentially leading to the degradation of true cellulose during the extraction process.

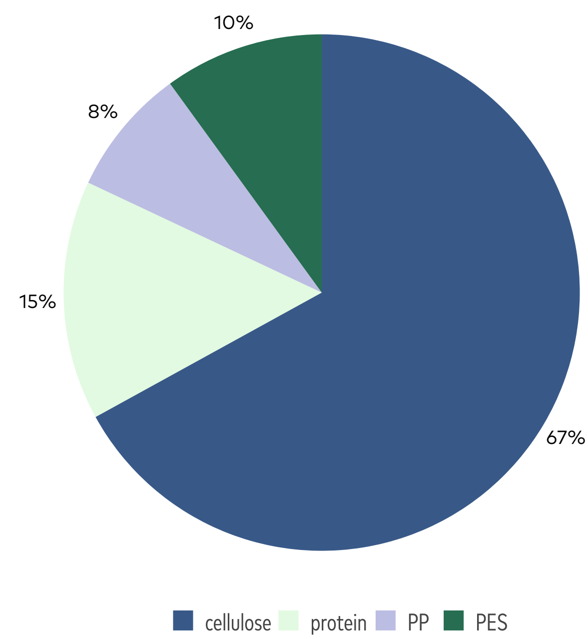

Figure 8 Polymer distribution of the fibers only (20-1000 μm) identified in sewage water samples from Sisimiut by μFTIR imaging analysis. A total number of 124 fibers were detected in total in the two samples, equaling 94 fibers per liter. The figure shows that of all fibers in the sample, only 18 % was identified as MP plastic fibers as polyester (PES that in the analyses includes PET, PBT and other polymers) and polypropylene (PP). 67 % of the fibers were identified as cellulose, but due to μFTIR analytic limitations and extraction methodologies using cellulose-degrading enzymes, it cannot be excluded that this fraction is fully or partly viscose fibers.

Figure 9 A PET fiber bundle was found in the larger microplastic fraction (1-5 mm) in the wastewater sample collected in Sisimiut. The PET fiber bundle is probably a result of machine washing of textiles. Photo by Hadi Salame.

The size distribution of the identified microplastic particles revealed that 81% of the particles were in size fractions less than 100 μm, measured along the longest dimension, while only 2% were longer than 300 μm (Figure 6). Only 4% were smaller than 20 μm, which is due to methodology limitations of the usage of a 20-μm mesh steel filter during the extraction process. Additionally, during the image analysis using siMPle software, the identification of microplastic particles was set to include only particles where at least 2 neighboring pixels, each measuring 5.5 μm, support the same identified polymer for a given particle. In addition, the μFTIR analyses are also limited by the so-called diffraction index, generally affecting the spectroscopic quality needed for identifying particles smaller than 15–20 in thickness, which also affect the inclusion of microplastic particles smaller than 20 μm. Without these methodology limitations, the size fraction of < 20 μm would most likely have held significantly higher amounts.

3.5 Estimated loads of plastic litter entering the marine environment.

The annual input of marine plastic litter from the household wastewater to the marine environment was estimated using the PE loads of 2000 for each of the two outlets in Sisimiut and Nuuk, the sampling time period (Table S1) and average daily water consumption capita^{-1} of 104 L day^{-1} person^{-1} in Greenlandic towns (Marechal et al. 2022).

In Sisimiut, the macro-plastic items contributed the most to the mass of litter items, which consisted primarily of wet wipes (74% of the total input) but also sanitary pads and condoms, would by estimate give a yearly input to the marine environment of 27.5 g capitata^{-1}. Taking all size fractions into consideration, an estimated yearly input will be 36.4 g capitata^{-1}, thus the 5,460 inhabitants in Sisimiut (Statbank Greenland, 2023) emit approximately 199 kg plastic L year^{-1} to the marine environment via the 11 sewage outlets.

In Nuuk, the macro-plastic items, which consisted of wet wipes and sanitary pads (23.4 g capitata^{-1} year^{-1}) contributed somewhat more than the larger microplastic items (12.7 g capitata^{-1} year^{-1}) to the input of litter to the marine environment. In total, the data points to a yearly input of 36.0 g capitata^{-1} in Nuuk, and with a population of 19,866 inhabitants (Statbank Greenland, 2023), this approximates to a total annual input of 716 kg plastic litter to the marine environment of Nuuk Fjord via 19 sewage outlets. It is however important to note that these Nuuk estimations do not include the MP size fraction of 20–1000 μm.

3.6 Survey of wet wipes in trade in Greenland

In total 26 different wet wipes for sanitary (n = 17) and cleaning (n = 9) purposes, were collected during the trade survey in Sisimiut. The ATR-FTIR analysis of the wet wipes (Figure 10) revealed that the primary polymer for wet wipes for both cleaning and sanitary purposes mainly were viscose (41%) and PET (37%), while the primary polymer was cellulose for a minor part (15%). By ATR-FTIR analyses, we found that the product declaration of wet wipes did not fully correspond to our analyses on polymer composition (Table S3). For example, were some products declared as being biodegradable determined by ATR-FTIR to be of viscose.

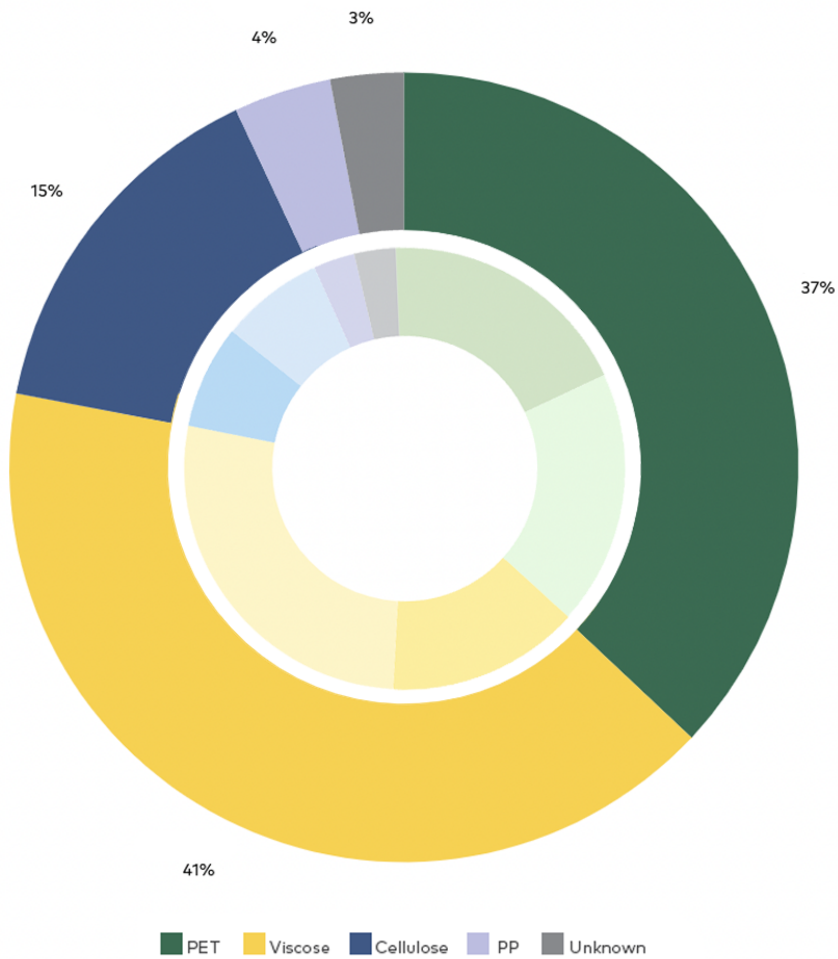

Figure 10 Polymer composition of wet wipes in grocery stores and healthcare shops in Sisimiut (shown as average in outer circle). The polymers were characterized by FTIR analyses. The wet wipes were either related to sanitary (darker in inner circle) or cleaning purposes (lighter in inner circle).

3.7 Beach surveys

During the two 'wet wipe surveys' at an adjacent beach to the wastewater outlet in Sisimiut, we could not identify any wet wipes. This was supplemented by visual inspection adjacent to the wastewater outlet in Sisimiut at low tide, and in Aasiaat, clearly showing wet wipes at the seabed (Figures 11a & c).

Figure 11 a) FaceBook post regarding clogging of sewage pumps due to wet wipes in sewer, November 2023. Text says: *I hope more people will understand this message. I want to encourage everyone to NOT discharge wet wipes in the toilet and flush them in the sewer. This evening we needed an electrician, a vacuum tanker, and municipality professionals to clean the pump and the well, which were clogged by wet wipes. Wet wipes do not dissolve, and they clog the sewer.* b) Wet wipes at the seabed next to the sampled outlet U1 in Sisimiut at low tide. Photo Haid Salamé. c) White objects likely to be wet wipes at the seabed by a wastewater outlet in Aasiaat, Greenland. Photo: Pernille Erland Jensen.

4. Discussion

In the current study we found a large input of litter and microplastics to the sea via wastewater. In accordance with the findings of Rist et al. (2020), we found that the number of items increased with decreasing size (Figure 6), while the largest size fraction contributed to the highest mass of plastic (Figure 12).

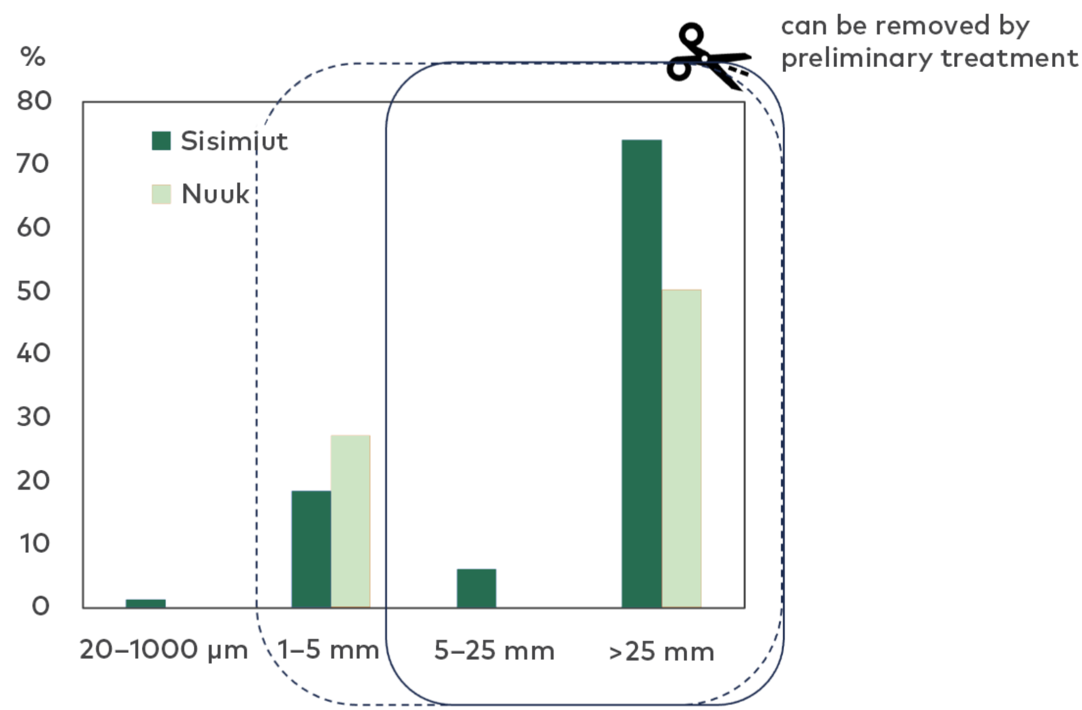

Figure 12 The figure shows the distribution of litter in the wastewater effluent in percentage based on mass data for Sisimiut and Nuuk. Note: the contribution for the 1–5 mm fraction is considered as estimates, as the weight measurements for the individual particles are based on very few items and that weights were below detection limit for some items. The full scissor line indicates the fractions that will be removed by a preliminary 3mm screen. The dotted line indicates our hypothesized additional removal of a significant fraction of the 1–5 mm items, and even below by a preliminary 3 mm screen.

4.1 Load of macro- versus microfibers from sewage in Greenland

Extrapolating the results from the 4,000 PE sampled to the 56,696 inhabitants in Greenland (Statbank Greenland, 2023), approximately 2 tonnes of plastic litter $year^{-1}$ is discharged to the marine environment from local sources. Out of this, 59%, equivalent to 1.2 tonnes $year^{-1}$ comprises plastic or semisynthetic wet wipes. Due to sampling methods and the fact that data on meso- and larger sized microplastic items are based on very few items, the following numbers must be seen as rough estimates: Approximately 70%, equivalent to 1.4 tonnes $year^{-1}$ are items larger than 5 mm, while 29% equivalent to approximately 0.6 tonnes $year^{-1}$ are items between 1 and 5 mm, while 1% equivalent to 28 kg $year^{-1}$ are smaller than 1 mm and consist of 43% fibers. These approximations indicate that the largest proportion of litter enters the marine environment as macro plastic via wastewater.

The degree of littering through wastewater may vary across different regions in Greenland e.g. due to different infrastructural conditions. Figure 11c indicates, however, that in the town of Aasiaat, wet wipes also constitute a significant source of litter to the sea from sewage. Thus, wet wipes do appear to be a general problem in Greenland, like it was shown in Britain (Marine Conservation Society, 2017). Another source of uncertainty arises due to the absence of data on the extent of littering through bucket toilets (also known as honey buckets) used in 20% of households in Greenland. We have initially assumed similar littering patterns as with sewers, but this may not be accurate.

4.2 Sources of macro-plastic in sewage in Greenland

In Nuuk as well as Sisimiut, wet wipes made of plastic and semi-synthetic plastic materials were identified as the major contributor to the macro-plastics mass in the sewage let out to the marine environment. They constituted 82% of the macro-plastic mass, and 59% of the total identified plastic mass in the sewage. Of the 37 wet wipes that were found in the wastewater in the present study, only 3 were made from cellulose, while the rest were made from PET (31) or viscose (3). In consistency, the majority of wet wipes sampled from stores in Sisimiut were of PET or viscose, and even those declared to be of natural material (declared as natural fibers, or bamboo) turned out to be of a combination of biodegradable cellulose-based fibers and less degradable synthetic fibers as viscose. In accordance with our results, Munoz et al. (2018) demonstrated the presence of PET in all non-flushable wet wipes examined, while also identifying the presence of PET and other synthetic materials in a substantial number of flushable wet wipes. Similar to the conclusions of our trade survey, they concluded that commercially available wet wipes even those labelled as flushable or natural - can be considered as a possible source of microplastic fibers in wastewater streams. Apart from contributing to plastic contamination, the content of synthetic material in wet wipes marked as natural may also increase their durability, i.e. decrease their rate of degradation, as do the diverse chemical additives designed to enhance their properties (Allison et al. 2023). Even wet wipes marked as natural, biodegradable or flushable may therefore last for long periods (Flury and Narayan, 2021; Allison, et al. 2023, Afshar et al. 2024), during which they can harm the environment e.g. by shading, leaving traces of chemicals, synthetic fibers, or being accidentally ingested by wildlife.

Despite that we could not identify any beach stranded wet wipes during the two 'wet wipe beach surveys' in Sisimiut in June and July 2023, evidence of wet wipes in the sea exists. Figure 11b clearly shows how wet wipes accumulate on the seabed at the outlet point in Sisimiut, which is in a relatively closed bay with low current. Similarly, Figure 11c indicates the same issue in the Greenlandic town of Aasiaat where the wastewater outlet points to the open sea, where stronger currents are expected. It is thus hypothesized that the wet wipes deposit on the seafloor rather than being washed ashore. This is in contrast to the Marine Conservation Society's analysis of the Great British Beach Clean 2017 (MCS 2017) that determined that the presence of wet wipes along the UK coastline increased by 94% in 2017. The accumulation on the beach in UK was found to make a substantial 400% rise over the past decade (equivalent to 27.5 pieces of wet wipes per 100 meters of beach cleaned). Thus, local current patterns may also be responsible for the lack of wet wipes at the specific site surveyed in Sisimiut.

4.3 Sources of MP in sewage in Greenland

The results of this study showed that the most abundant shape of MP particles in Greenlandic sewage is fibers. This correlates well with the findings of Rist et al. (2020) who found fibers <300 μm to be the dominant MPs at 3 marine stations in fjord of Nuuk near the site investigated in the present study. In general, fibers are the most frequently documented MP type found in the marine environment (Cesa et al. 2017), including in the Arctic region (Table 1) as well as in wastewater (Table 3).

Table 3 Results reported in the literature on plastic microfibers in raw and treated wastewater. *** Only MP included, number estimated from bar chart.

Country	Area	Treatment technology	Size fraction [mm]	Average MP concentration [item/m^3]	Remov rate [%]	Dominant polymer type	Morphology	Reference
				Raw wastewater				
Greenland	Sisimiut	-	0.020-1 1-5	217,000 22	-	Polyester	57% Fibers	This study
Svalbard	Longyearbyen	-	0.05-5	60,000 (0-203,000)	-	-	86-92 % Fibers, 8-14% particles	Herzke et al., 2021
	Ny-Ålesund wastewater treatment plant	-	0.02-5	5,000,000***	-		98% Fibers 2% Particles	Granberg et al., 2019
Sweden	Långevik	-	> 0.3	12,120±6,820	-	Thermoset plastic based on aliphatic polyester resin	Fibers ≈ 80 %, fragments and flakes	Magnusson et al., 2016
	Ryaverket	-	> 0.3	7,340±13	-	Polypropylene	Fibers ≈ 60 %, fragments & fakes	Magnusson et al., 2016
Finland	Viikinmäki	-	> 0.3	100,000±43,300	-	-	Fibers ≈ 50 %, flakes	Magnusson et al., 2016
	Kalteva		> 0.3	91,570±28,300	-	-	Fibers ≈ 80 %, flakes, fragments	Magnusson et al., 2016

Iceland	Klettagarðar	-	> 0.3	631	-	-	Fragments ≈ 50 %, fibers, flakes	Magnusson et al., 2016
	Hafnarfjörður		> 0.3	2,070±200	-	-	Fibers ≈ 75 %, fragments, flakes	Magnusson et al., 2016
Denmark	10 different plants	-	0.02-0.5	13,000,000-442,000,000 Average 127,000,000	-	Nylon, PVC	-	Vollertsen and Hansen, 2017
				Treated wastewater				
Svalbard	Ny-Ålesund wastewater outlet	**Tertiary:** Sedimentation, Chemical and Biological treatment	> 0.020	55,000***	98.9***	LDPE, PET, Polyester, PU, Polyamide	93 % Fibers 7 % Particles	Granberg et al., 2019
Sweden	Långevik	**Tertiary:** Mechanical, Chemical and Biological	> 0.3	23±1	99.8	Polyethylene Polypropylene	Fibers ≈ 50 %, fragments ≈ 50%	Magnusson et al., 2016
	Ryaverket	**Tertiary/ advanced:** Mechanical, Chemical and Biological treatment, 15µm filter	> 0.3	8±7	99.999	Polypropylene PET	Fragments ≈ 75 %, fibers, flakes	Magnusson et al., 2016

Sjölunda	**Tertiary**: Sedimentation, active sludge, nitrification and denitrification.	0.01-5	NA	> 99	NA	NA	Ljung et al., 2018	
Finland	Viikinmäki	**Tertiary:** Mechanical, Chemical and Biological	> 0.3	43±36	99.999	-	Fragments ≈70 %, fibers, flakes	Magnusson et al., 2016
	Kalteva	**Tertiary**: Mechanical, Chemical and Biological	> 0.3	29±10	99.97	-	Fragments ≈ 60 %, fibers	Magnusson et al., 2016
Iceland	Klettagarðar	**Primary:** Sedimentation, 3mm filter	> 0.3	1,378	≈0	-	Flakes ≈ 50 %, fibers, fragments	Magnusson et al., 2016
	Hafnarfjörður	**Primary:** Sedimentation, 3mm filter	> 0.3	1,400±66	≈30	-	Fibers ≈ 65 %, flakes, fragments	Magnusson et al., 2016
Denmark	10 different plants	**Tertiary**	0.02-0.5	Average 5,800,000	Average 99.7	Nylon. PE	-	Vollertsen and Hansen, 2017

Polymer type: PE (polyethylene), PP (polypropylene), PS (polystyrene), PES (polyester), PVC (polyvinylchloride), PC (polycarbonate), PMMA (polymethylmethacrylate), PA (polyamide), PUR (polyurethan), ABS (akrylonitril-butadien-styrene)

A dominance of white/transparent MP fibers was observed in the raw wastewater samples in our study, where a large fraction was proposed to be of viscose origin. This is in accordance with the findings of Yuan et al. (2021), who studied two Chinese wastewater treatment plants (WWTPs) and found transparent and white microplastic fibers to be the most abundant. As the fibers identified in our study were primarily of the same plastic polymer as the majority of the wet wipes (PET and viscose), it is reasonable to believe that a fraction of the fibers may be linked to the presence of wet wipes. Our research thereby indicates that wet wipes may play a substantial role in microplastic (fiber) pollution, contributing not only indirectly via the emission of the wet wipes themselves left for degradation in the marine environment, but also through the direct release of fibers from wet wipes during their passage in the sewer system. These findings align with the conclusions of Lee et al. (2021), who investigated the release of microfibers from wet wipes subjected to different impacts. They found that immersing wet wipes in water for one hour resulted in a greater release of MP fibers (1966 fibers per sheet) than subjecting them to physical abrasion. Thus, direct disposal of wet wipes in the sewage system will induce a significant release of fibers. In accordance, Briain et al. (2020), found that the disposal of wet wipes and sanitary towels into toilets represents an underestimated source of white microplastic fibers in the environment, based on fiber determination from intertidal sediment samplings and field observations of washed-up deposit of sewage-derived waste.

Main sources of MPs in wastewater commonly mentioned in literature are personal care products, laundry, surface runoff including tire wear and atmospheric deposition (Cesa et al. 2017; Liu et al. 2023b). Laundry is shown to be a major source with up to 7–800,000 fibers released from a single load of laundry (Kelly et al. 2019, Electrolux, 2022). The MPs identified in the Greenlandic wastewater in our study thus most likely constitute a mixture of fibers from wet-wipes and laundry, as well as other personal care products and atmospheric deposition as secondary sources. Road run-off is not a likely important contributor to piped sewage in Greenland since Greenland applies separate sewers for surface-runoff in ditches.

4.4 Retention capacity of wastewater treatment systems

Wastewater treatment systems in general can be expected to retain large items efficiently, and items larger than 5 mm may be expected to be fully retained even in plants with preliminary treatment only.

In- and output concentrations of MPs from different sewage treatment plants in the Arctic and the Nordic region are shown in Table 3. Input concentrations (number of items) vary several size orders from 631 items m^{-3} in Klettagarðar, Iceland, (Magnusson et al. 2016) to five million items m^{-3} in Ny Ålesund, Svalbard (Granberg et al. 2019). This difference may be partly explained by the differences in size-fractions included: Magnusson et al. (2016) only included items larger than 0.3 mm, while Granberg et al. (2019) included items larger than 0.02 mm. In accordance with our results (Figure 12), the items considered as macro plastics have been shown to constitute the majority of plastic mass entering WWTPs (Rasmussen et al. 2021). The loads can, however, vary significantly: Magnusson et al. (2016), used identical cut-off size, but still found size-orders of difference among MP concentrations in raw wastewaters in Finland and Sweden compared to Iceland. This may be explained by the fact that Icelandic wastewater is known to be very dilute, due to mixing with rainwater and a general high-water consumption by industry in Iceland (more than 2,000 L capita^{-1} day^{-1} in 2015 all-inclusive according to Statistics Iceland). Dilution by runoff has by others been shown to impact concentrations of MPs in raw sewage concentration in combined sewer systems (Kittipongvises et al. 2022).

The removal rates of MP in percentage for WWTPs in the Arctic and Nordic region are stated in Table 3. Most wastewater treatment plants are successful in reducing the content of MPs significantly (Table 3), though among the listed investigations, the removal ranges between none and almost 100%, and the outlet concentrations vary from 8 items m^{-3} in Ryaverket in Sweden (Magnusson et al. 2016) to 55,000 items m^{-3} in Ny Ålesund, Svalbard (Granberg et al. 2019). Here again the numbers are expected to be impacted by the differences in the lower-end cut-off sizes. In a review reporting removal rates from a large number of different wastewater treatment plants, Gkatzioura et al. (2021) likewise concluded that data are extremely heterogeneous due to discrepancies in included size fractions, and are thus difficult to assess and compare. Their data showed removal rates from 72–99.9% and outlet concentrations ranging from 0.5 particles L^{-1} to more than 50 particles L^{-1} among plants employing secondary[1] and tertiary treatment. They also found removal rates ranging from 25–99% already in the primary treatment step of different plants. The three plants showing lowest removal rates in their study (i.e. 70–80% removal) all applied secondary treatment, but the one plant showing 80–90% removal applied tertiary treatment, while several plants applying only secondary treatment removed above 90%. No clear link between treatment method and removal rate obtained could be observed, though plants employing membrane processes seem to consistently exhibit high-end removal rates, as also observed in the review by Zhang et al. (2022). Zhang et al. (2022), however, also noted that the deposition of pollutants and MPs on the surface of the membrane can greatly reduce the permeability, creating membrane contamination and reducing purification efficiency. Poerio et al. (2019) specifically reviewed literature on membrane processes for plastic removal and found that among membrane

1. In Conventional wastewater treatment PRELIMINARY TREATMENT involves removal of larger particles by screening and filtering, PRIMARY TREATMENT involves removal of solids by screening and/or sedimentation. The residual sludge contains nearly 50 % of the suspended solids within wastewater including a significant fraction of the organic matter. SECONDARY TREATMENT most often makes use of biological and/or chemical treatment, though effluents of secondary quality may also be obtained by mechanical means. Secondary treatment removes smaller biodegradable organics and suspended solids. In addition, it has a disinfection effect. TERTIARY TREATMENT is aimed for improved removal of phosphates and nitrates. Further disinfection is also obtained. In some treatment plants ADVANCED polishing steps may be engaged to reduce specific remaining components.

technologies, membrane bioreactors (MBRs) are the most efficient, supposedly due to their biodegradation ability. This is in accordance with Vuori and Ollijainen (2022), who made a cost-effectiveness analysis of removal of microplastics from wastewater, and also recommended MBR technology. Carr et al. (2016) found that conventional wastewater treatment processes remove MPs effectively, and that in particular skimming and settling processes in primary tanks remove the major fraction of MPs. They conclude that effluents from either secondary or tertiary wastewater treatment facilities contribute only minimally to the microplastic loads in oceans and surface water environments. High removal may also be obtained by more simple wastewater treatment systems. In an investigation of three Australian wastewater treatment plants with advanced secondary treatment (Ziajahromi et al. 2021), it was shown that most microplastics (69–79%) were retained during the initial screening and grit removal process (i.e. the preliminary treatment). In accordance Rasmussen et al. (2021) found that most plastic (73%) was removed in the initial bar screening (20 mm and 2 mm bars) in Ryaverket in Sweden, and furthermore that the bar screens retained plastics smaller than the screen size and in total retained 50% of all incoming MPs (Rasmussen et al. 2021). As an example from the Arctic region, a recently installed treatment plant in the small settlement of Ny Ålesund, Svalbard, engaging tertiary treatment was shown to be successful in retainment of > 99% of the incoming MPs (Granberg et al. 2019). Only very few studies exist on the fate of MPs in non-conventional wastewater treatment systems such as constructed wetlands, which are used in the Canadian Arctic (Kadlec and Johnson, 2023) and Nordic region (e.g. Postila and Heiderscheidt, 2020). Büngener et al. (2023) found that the MP concentration increased by 92% during intense rain and 43% in low precipitation periods, respectively, due to atmospheric deposition in a horizontal flow treatment wetland, while Bydalek et al. (2023) observed 95% removal in a similar treatment system. Further evidence is therefore needed before choosing constructed wetlands to mitigate plastic pollution from sewage in Greenland or beyond.

Removal of MPs from more pristine waters such as sea- or lake water was shown to be significantly more challenging and with lower removal percentages compared to wastewater (Badola et al. 2022). This is likely due to the mix of MPs with a cellulosic matrix composed of toilet paper fibers, food waste, and other sewer solids causing floc formation and thus effective removal via skimming and settling processes at the preliminary, primary and secondary treatment stages (Carr, 2017). Therefore, the very limited removal (0–30%) of MPs in Icelandic wastewater observed in both Klettagarðar and Hafnarfjörður (Magnusson et al., 2016), can be speculated to be due to the very dilute Icelandic wastewater, which does not allow the formation of flocs. The low removal in Iceland can therefore not necessarily be extrapolated to situations with more concentrated wastewater like that in Greenland where wastewater has been shown to be of medium to concentrated quality (Jensen et al. 2013).

Implementing wastewater treatment in small, remote, Arctic communities is practically and economically challenging. First, is the issue of scaling: The cost $capita^{-1}$ of some commercial wastewater treatment technologies double when the feed person equivalents (PE) is reduced by a size order (Vuori and Ollikainen, 2022). Second, building and construction projects in Arctic locations is more costly compared to similar projects in Europe due to among others remoteness from supplies and low activity during long winter seasons. Third, specialized personnel with skills to operate and manage advanced technical systems are in high demand in such locations with few people and many technical installations to care for. Fourth, particularly relevant for Greenland, to reduce the need for technical repair and maintenance and possibly save some on the construction costs, the municipalities of Greenland have implemented sewer systems, which are primarily gravity-driven. This implies that the wastewater is not collected in one single sewer outlet. Instead, the wastewater is discharged via several minor outlets spread along the coastline of the towns. An intention to treat the water further adds to the complexity and cost by either having to extend sewer lines and introduce pumping stations to collect the sewage or installing multiple treatment facilities. Fifth, the most significant cost of commercial wastewater treatment plants (WWTPs) was shown to be attributed to the abatement of natural organic matter and nutrients (Vuori and Ollikainen, 2022), which has been the focus of wastewater treatment in densely populated areas. Finally, many wastewater treatment processes, both physical, chemical, and biological ones are more efficient at higher temperatures because longer residence times and thus larger reactor sizes must be expected in cold regions.

Based on the above reviewed literature, and in due consideration of the listed challenges, selecting a simple preliminary method based on screening to remove the macro plastic and reduce the microplastic could be a balanced way of mitigating plastic to the marine environment from sewage in Greenland.

4.5 Clogging of sewage pumps due to wet wipes

A major part of the plastic litter in the sewer in our study was wet wipes. Disposal of wet wipes into sewer systems not only pose implications for the marine environment, but also raises significant practical concerns, as indicated by figure 11a in that the flushing of larger items like wet wipes can lead to clogging of the sewer system (Durukan and Karadagli, 2019). The Facebook post (Figure 11a) urged citizens to stop flushing wet wipes. From the continued occurrence of wet wipes items during that last sampling occasion, the Facebook post, however, must be concluded to have had limited impact on citizens acting. Via dialogue with Qeqertalik municipality, it was confirmed that in Aasiaat, they regularly also suffer clogging of pumps due to wet wipes in the sewage.

At the Fluids Engineering Division Summer Meetings (FEDSM), clogging of sewer pumps gained high attention in recent years, because it is a growing nuisance worldwide (Jensen, 2017; Mitchell et al. 2019; Müller et al. 2022; Beck et al. 2021). Müller et al. (2022) tested the effect of pump speed variation on clogging of sewage pumps and found that speed influences on the clogging of pumps. Some pumps improve their ability for pumping wipes in sewage water with increasing speed. Among the tested pumps, the hydraulic pumps with vortex impeller showed a significantly better capability transporting fibrous contaminated fluid with higher speed (Müller et al. 2022). Furthermore, Beck et al. (2021) showed that pumps behave very differently, and that some retain their hydraulic performance despite large amounts of wet wipes, but at high energy costs. Durukan and Karadagli (2019) hypothesized, based on their investigations of tensile properties of different types of wet wipes, that flushable wet wipes containing synthetic fibers i.e. regenerated-cellulose fibers, seem to be the key reason for operational problems in sewer systems. Mitchell et al. (2019) found that profound differences in the clogging effect of the nonwoven wet wipes could be observed. Wet wipes labelled as "flushable" had different clogging effects, depending on whether they complied with industry flushability guidelines or not.

4.6 Legislative measures

Several authors commented on the necessity of taking steps to enforce legislation to combat the growing problem of wet wipes in the environment in general (e.g., Mitchell et al., 2019; Badola et al., 2022; Vuori and Ollikainen, 2022). Mitchell et al. (2019) concludes that the main part of the clogging-problem can only be solved if users of non-flushable wipes change their disposal behavior. The authors also point out. that steps must be taken to ensure the compliance of flushable nonwoven wipes with industry guidelines, and that wastewater system operators have to educate their clients on what belongs in the toilet, and wipe manufacturers and retailers have to ensure the reliability of the term "flushable". Vuori and Ollikainen (2022) recommend that in addition to wastewater treatment, policies targeting companies using microplastics in their products are necessary to solve the problem ultimately. Lam et al. (2018) provided a comprehensive analysis of plastics and microplastic legislation worldwide. They showed how levies, taxes, bans as well as voluntary campaigns all are strategies used to reduce plastic consumption and thus emission of plastic litter. In addition, efforts were put into the increased recovery and recycling, for which in some cases the measures were successful, while in others not (Lam et al. 2018).

To reduce the environmental load of MPs, comprehensive legislation to limit the inclusion of microplastics in cosmetics is operational in an increasing number of countries (Lam et al. 2018). Reduction of microfibers from laundry of synthetic clothes is inherently difficult and the only way is to cease the use of these completely. Lam et al. (2018) suggests that a reduction could be obtained by encouraging the usage of longer length of fibric yarn, and the use of liquid detergent rather than powder form. A tax could apply for fibric materials with shorter lengths of yarns, and for detergents which generate the release of more microfibers (Lam et al. 2018). These measures could effectively reduce the origins of pollution according to the authors. They finally suggest that to achieve better cooperation at the global level, an institutional setting needs to be devised with a multilateral agency or initiative, to integrate national efforts and promote the global policy agenda e.g. under the frame of UN.

The Greenlandic action-plan to reduce consumption of plastics was published in 2021 (Naalakkersuisut, 2021). One of the actions is establishment of knowledge on simple wastewater treatment methods to reduce the emission of microplastics to the environment.

The decision of not treating wastewater in Greenland is based on the conclusion of a consultant report made in 2005 for the Danish EPA (COWI, 2005), when Greenlandic environmental policy was still under Danish legislation. The report concluded that the recipients (exclusively the sea) were in general unimpacted by wastewaters, and that treatment for removal of organic matter and nutrients was thus not needed. The relevance of treatment was mentioned as a potential future possibility for wastewater discharge to recipients with low water exchange, and where local eutrophication was observed. At that time, plastic as well as many types of chemicals were not in focus in Greenland, and thus not assessed in the report. An up-to-date evaluation of the same issue may result in another conclusion.

As a result of the Greenlandic action-plan to reduce consumption of plastics, the "Act on use of plastic bags and single-use plastics (SUP)" (Naalakkersuisut, 2022) was enforced. In the act a number of SUP items is prohibited in Greenland (§4). The list of banned items is identical to the list in the EU Directive on SUP (EU, 2019), and does thus not take its offset in the specific Greenlandic context, where most abundant plastic items identified in nature were linked to fishing, hunting and other outdoor activities (Strietman et al. 2021; Mallory et al. 2021). Our investigation, however, revealed the presence of three cotton buds in the wastewater, made from cardboard and cotton rather than plastic. That the sticks of the cotton buds were made of cellulose and not plastic may reflect a direct effect of the Greenland action plan on SUP, indicating a shift towards more eco-friendly alternatives for the products that have been banned. More evidence is, however, needed to draw a safe conclusion.

The EU directive includes requirement for labelling of wet wipes, extended producer responsibility and awareness raising measures. The labelling and extended producer responsibility are not adopted in the Greenlandic act, but, since almost all products are imported via EU, the EU directive would still entail for these imported products through EU. This is in accordance with the observations made in our survey of products in retail in this project, where all products were marked as non-flushable (except one product solely made of cellulose). Due to the apparent lack of impact of the labelling, additional measures need to be taken to prevent wet wipes and related MPs and other items from entering the sea via sewage. The requirement for awareness raising measures is not mentioned in the legislation (Naalakkersuisut, 2022), but is so in the Action Plan (Naalakersuisut, 2021).

EU's REACH legislation has recently been adopted to include the banning sale of both microplastics themselves and products to which they have been intentionally added. For cosmetics containing microbeads (small plastic beads used for exfoliation) and loose glitter made of plastic, the ban took effect in mid-October 2023. While for other cosmetics, there will be a transition period of between four and 12 years, depending on the complexity of the product and availability of suitable alternatives (EU, 2023). As this legislation is implemented in EU, it is considered that the legislation will also automatically function to reduce microplastics in sewage in Greenland for the same reason as mentioned above.

4.7 Recommendations for action in Greenland

The findings of this study highlight a significant contribution of micro- and macro-plastic discharged by untreated wastewater in Greenland to the marine environment in the Arctic. The main contribution by mass is from plastic items larger than 25 mm, and only 1% is smaller than 1 mm. Among the large items, wet wipes are highly dominating, constituting 59% of the emitted plastic by mass. On top of that our findings suggest that a fraction of the micro-plastic is directly related to the presence of wet wipes. Thus, eliminating wet wipes from the sewage could drastically reduce the emission of plastic from sewage in Greenland. Apart from constituting an environmental threat, wet wipes are also of significant nuisance to the operation of the sewage systems in Greenland. Therefore, measures to exclude wet wipes from entering the sewage system could be prioritized above measures to treat the wastewater to remove them. We suggest the following measures be taken in prioritized order:

1. Behavioral change campaigns to eliminate the discarding of wet wipes and other unwanted items in toilets and sinks.
2. Market regulation to preferably allow only fully biodegradable natural material wet wipes on the Greenlandic market, if at all.
3. Wastewater treatment to remove residual plastics from entering the sea. We hypothesize that a 3-mm mechanical filter as the one being implemented at a test-site in Nuuk currently, could potentially remove most particles larger than 1 mm, i.e. almost 99% of the current load, but this needs to be documented by sampling and analysis of influent and effluent water before extending the method to further sites.

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Supplementary

Table S1 Summary of the sampling scheme. Macro-plastics were sampled in a total of 445 minutes in Sisimiut and 190 minutes in Nuuk. Meso- and large sized microplastics were sampled in 90 L in both Sisimiut and Nuuk and microplastics in 650 mL in 2 replicates in Sisimiut.

Sample	Town	Date of sampling	Duration of sampling (start and end time)	Weekday/ weekend day	Field blank
Macro-plastics	Nuuk	06/09/2022	08:50-12:00	Weekday	N
	Sisimiut	30/08/2022	05:45-09:10	Weekday	N
		16/09/2022	16:15-18:15	Weekday	N
		23/11/2022	07:30-9:00	Weekday	N
		23/11/2022	20:30-21:00	Weekday	N
Meso-plastics	Nuuk	01/09/2022	16:00-18:25	Weekday	N
		04/09/2022	17:45-20:10	Weekend day	Y
		06/09/2022	06:20-08:45	Weekday	Y
	Sisimiut	25/08/2022	18:30-21:00	Weekday	Y
		26/08/2022	05:45-08:10	Weekday	Y
		27/08/2022	13:20-15:45	Weekend day	N
Microplastics	Sisimiut	22/11-2022	11 am	Weekday	Y
		23/11-2022	7am	Weekday	Y
		23/11-2022	8pm	Weekday	Y

Table S2 Indication of the mean number of microplastics in the analyzed blind samples (field- and lab-blinds, n=8) as well as detection limits (DL) calculated as the mean value + 3 x SD for the primary polymer types, and the total content of microplastics per sample and per liter of wastewater.

Polymer type*	PE	PP	PES	PS	PVC	PC	PMMA	PA	PUR	ABS	Total	Mass (µg)
Average number of MP per blind sample	2.0	3.5	0.3	0	0.2	0	0	0	0	0	6.0	0.12
DL (number of MP per sample)	10	12	2	1	2	1	1	1	1	1	17	0.26
DL (number of MP per liter)	15	18	3	2	3	2	2	2	2	2	26	0.39

* Polymer type: PE (polyethylene), PP (polypropylene), PS (polystyrene), PES (polyester), PVC (polyvinylchloride), PC (polycarbonate), PMMA (polymethylmethacrylate), PA (polyamide), PUR (polyurethan), ABS (akrylonitril-butadien-styrene)

Table S3 Summary of a wet wipe survey in shops in Sisimiut. An item of all types of wet wipes in the shops in Sisimiut was acquired and undergone FTIR-analyses to determine the primary polymer and eventual secondary polymer of the tissue.

Brand	Trade name	Application purpose (baby, sanitary, cleaning)	Declaration (%PET, %viscose, bamboo etc)	FTIR-analysis	
				Primary polymer	Secondary polymer
Sanitary purposes					
Änglamark	Bamboo wipes	Baby	Bamboo	Viscose	
Änglamark	Dermacare makeup wipe	Sanitary, facial	Bamboo	Viscose	
Änglamark	Make up cleansing wipe	Sanitary face	?	PES (PET)	
Änglamark	Wipes	Baby	60% PES, 40% viscose	PES (PET)	
Cherish	Facial cleansing wipes 4 in 1	Sanitary, facial	?	PES (PET)	
Domestos	Absolute Hygiene	Cleaning universal	Natural fibers	Viscose	
Everyday eye depend	Make up removal wipe	Sanitary, face	100% viscose	Viscose	?
Grøn balance	Make-up 3i1 renseservietter	Sanitary, facial	70% viscose / 30% polyester	PES (PET)	
Grøn balance	Vådservietter	Baby	40% viscose / 60% polyester	PES (PET)	
Huggies	Natural	Baby	Natural fibers	Cellulose	
Hygienic Wipe	Hygienic Wipe	Sanitary, hands, facial and surfaces	?	Viscose	?
Kleenex	Water fresh wipes	Sanitary, hand & facial	?	PP	Cellulose
Libero	Hand & face wipes	Sanitary, hand & facial	?	Cellulose	
Libero	Wet wipes	Baby	100% viscose	Viscose	

Libresse	Dailies V-gentle	Sanitary, intimate areas	?	PES (PET)
Lotus	Sensitive	Sanitary (toilet paper)	Natural fibers	Cellulose
Nivea	Cleansing wipes	Sanitary, facial & eyes	Natural fibers	?
Vivag	Intimservietter	Sanitary, intimate areas	?	Viscose
Vivag	Intimservietter specielt til intimzonen	Sanitary, intimate areas	?	Viscose
Cleaning purposes				
Ajax	Multi action	Cleaning glass wipes	Natural fibers	Viscose
Ajax	Universal	Cleaning universal	Natural fibers	Viscose
Ajax	Universal antibacterial	Cleaning universal		Viscose
Coop	Cleaning wipe lemon	Cleaning universal	Viscose / Polyester	PES (PET)
Coop	Cleansing wipes-bathroom	Cleaning bathroom	Viscose / Polyester	PES (PET)
Coop	Stad-servetter	Cleaning bathroom	Viscose / Polyester	PES (PET)
Klorin	Klorin wipes	Cleaning universal	?	PES (PET)
Lysol	Multipurpose wipes	Cleaning universal	?	Viscose

About this publication

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Load to the marine environment and mitigation

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TemaNord 2024:516

ISBN 978-92-893-7827-7 (PDF)
ISBN 978-92-893-7828-4 (ONLINE)
http://dx.doi.org/10.6027/temanord2024-516

Cover photo: Wastewater outlet U1 in Sisimiut, ©Master Media
Published: 17/6/2024

Disclaimer

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