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Research Paper

Cryosphere as a temporal sink and source of microplastics in the Arctic region

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ABSTRACT

Microplastics (MPs) pollution has become a serious environmental issue of growing global concern due to the increasing plastic production and usage. Under climate warming, the cryosphere, defined as the part of Earth's layer characterized by the low temperatures and the presence of frozen water, has been experiencing significant changes. The Arctic cryosphere (e.g., sea ice, snow cover, Greenland ice sheet, permafrost) can store and release pollutants into environments, making Arctic an important temporal sink and source of MPs. Here, we summarized the distributions of MPs in Arctic snow, sea ice, seawater, rivers, and sediments, to illustrate their potential sources, transport pathways, storage and release, and possible effects in this sentinel region. Items concentrations of MPs in snow and ice varied about 1–6 orders of magnitude in different regions, which were mostly attributed to the different sampling and measurement methods, and potential sources of MPs. MPs concentrations from Arctic seawater, river/lake water, and sediments also fluctuated largely, ranging from several items of per unit to >40,000 items m^{-3}, 100 items m^{-3}, and 10,000 items kg^{-1} dw, respectively. Arctic land snow cover can be a temporal storage of MPs, with MPs deposition flux of about (4.9–14.26) $\times$ 10^8 items km^{-2} yr^{-1}. MPs transported by rivers to Arctic ocean was estimated to be approximately 8–48 ton/yr, with discharge flux of MPs at about (1.65–9.35) $\times$ 10^8 items/s. Average storage of MPs in sea ice was estimated to be about 6.1×10^{18} items, with annual release of about 5.1×10^{18} items. Atmospheric transport of MPs from long-distance terrestrial sources contributed significantly to MPs deposition in Arctic land snow cover, sea ice and oceanic surface waters. Arctic Great Rivers can flow MPs into the Arctic Ocean. Sea ice can temporally store, transport and then release MPs in the surrounded environment. Ocean currents from the Atlantic brought high concentrations of MPs into the Arctic. However, there existed large uncertainties of estimation on the storage and release of MPs in Arctic cryosphere owing to the hypothesis of average MPs concentrations. Meanwhile, representatives of MPs data across the large Arctic region should be mutually verified with in situ observations and modeling. Therefore, we suggested that systematic monitoring MPs in the Arctic cryosphere, potential threats on Arctic ecosystems, and the carbon cycle under increasing Arctic warming, are urgently needed to be studied in future.

1. Introduction

The cryosphere is defined as the part of Earth's layer characterized by the low temperatures and the presence of frozen water, which is vital for the regulation of the planets fragile ecosystems (Fountain et al., 2012; Qin et al., 2017). The Arctic cryosphere (e.g., Greenland Ice Sheet, permafrost, sea ice, snow cover) plays an important role on Arctic climate warming (IPCC, 2021), the storage and release of anthropogenic pollutants (e.g., persistent organic pollutants, mercury) (Zolkos et al., 2020; Hawkings et al., 2021). Meanwhile, winter loss of Arctic sea ice over the subpolar North Atlantic can intensify aerosol transport from South Asia toward the Tibetan Plateau (the Third Pole) in April

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(Li et al., 2020) and also influence the climate extremes in mid-latitudes (Cohen et al., 2014). During past half century, the Arctic has warmed (by +3.1 °C during 1971–2019) about three times faster than the global average (AMAP, 2021b; IPCC, 2021). Under such rapid warming, the melting of Arctic cryosphere, including declined sea ice extend (AMAP, 2021b), enhanced land ice melting (IPCC, 2021), and accelerated permafrost thawing (Natali et al., 2021), has been altering the transport, deposition and biogeochemical cycles of pollutants in this region (Li et al., 2020; AMAP, 2021a; IPCC, 2021). Although the Arctic is far from the direct sources of anthropogenic pollutants, these pollutants have been found almost everywhere in the Arctic (AMAP, 2021c).

As an emerging anthropogenic pollutant, microplastic particles are now prevalent in the global marine and terrestrial environments (Lusher et al., 2015; Peeken et al., 2018; Allen et al., 2019; Bergmann et al., 2019; Mai et al., 2020; MacLeod et al., 2021; Zhang et al., 2021), which may persist in the environment for centuries due to their persistent nature. Microplastics are a variety of unique chemical compounds, which are defined with a particle size of <5 mm (longest dimension) (Rochman et al., 2019). They originate from either primary or the secondary sources, with diverse colors and shapes (e.g., spheres, fragments, films, and fibers) (Li et al., 2018; Hartmann et al., 2019; Hale et al., 2020; Lim, 2021). In particular, the study of atmospheric microplastic transport has shifted to a global outlook (Horton and Dixon, 2018; Bank and Hansson, 2019; Brahney et al., 2020; Wright et al., 2021). The Arctic may be of particular concern as microplastics widely distributed in the Arctic marine and terrestrial environment, considering the relative minor anthropogenic activities (Bergmann et al., 2019, 2022; Eriksen et al., 2020; Evangeliou et al., 2020). Microplastics have different pathways of entry into the Arctic environments, mainly including transported by ocean and atmospheric currents, and biota from both distant and local sources, making it complicated to pinpoint their particular sources (Hale et al., 2020; Mishra et al., 2021; Bergmann et al., 2022). In Arctic, the sources can be divided into two origins of local and long-range; however, the pathways to Arctic, and eventual fates of these microplastic particles are hot topics that require a thorough examination.

The role of sea ice as a transport medium for contaminants has been recognized, which also plays a profound role in centrating and diluting exposures to chemical contaminants (Wang et al., 2017). Recently, the Arctic sea ice has been identified as a temporal sink and means of transport for microplastics (Peeken et al., 2018; Huserbråten et al., 2022). The previous studies indicated that the sea ice had potentials to release the former stored microplastics in the melting season, resulting it an important local source of microplastics to the surrounded Arctic seawater (von Friesen et al., 2020). Abundant microplastics have been reported in Arctic snow, highlighting that atmospheric transport and deposition can be an important pathway for microplastics to Arctic regions (Bergmann et al., 2019; Evangeliou et al., 2020). Arctic glacier and Greenland ice sheet melting increased runoff to the ocean, and released the formerly stored pollutants (e.g., Hg) to Arctic Ocean (Hawkings et al., 2021). Great Arctic Rivers are also considered to be primary freshwater sources of microplastics or other contaminants (e.g., Hg) to the Arctic Ocean (Zolkos et al., 2020; Frank et al., 2021a). Besides, permafrost can be an important sink of atmospheric pollutants, including microplastics (Chen et al., 2021). However, until now, no substantial published data of microplastics from Arctic permafrost were reported.

Despite growing concerns on microplastics in the Arctic, most published literatures on microplastics have focused on the marine or terrestrial environment. These previous studies highlighted an increasing microplastic burden in Arctic ecosystems, and mostly showed the current pollution status of microplastics in Arctic and their transportations (Eriksen et al., 2020; Mishra et al., 2021; Bergmann et al., 2022). They also gave some suggestions on monitoring guidelines and mitigation strategies to reverse the rising plastic pollution in the region (PAME, 2019; Eriksen et al., 2020; AMAP, 2021a). However, nearly no efforts have been made on their status and potential impacts focusing on the Arctic cryospheric components (especially the sea ice and snow cover) from a comprehensive perspective. In order to understand microplastics within Arctic cryosphere and their linkage with other environment matrices, this review is intended to address the current status and the identification of key challenges of microplastics related studies in Arctic region. Based on the comprehensive analysis of microplastics from Arctic sea ice, seawater, snow cover (and glaciers), rivers, and marine deep-sea or coastal sediments (Fig. 1a), we will summarize the characteristics of microplastics and briefly illustrate their distributions in the Arctic region. Meanwhile, we will elucidate the potential sources and transport pathways of microplastics to and in the Arctic. Combined the published microplastic data in the Arctic cryosphere with related modeling, we further evaluate the impacts of cryospheric melting on microplastics storage and release into the Arctic multiple environments. Also, we will discuss the limitations of these estimations. Finally, we will further highlight the perspectives and challenges of microplastics studies in Arctic cryosphere under climate warming in future.

2. Studies of microplastics in the Arctic cryosphere

In this review, geographical extent of the Arctic region is based on that adopted by the Arctic Monitoring and Assessment Programme (AMAP, https://www.amap.no/) (Supplementary Data Fig. S1). In brief, the region essentially includes the terrestrial and marine areas north of the Arctic Circle (66°32′ N). Meanwhile, the region is also modified to include the north of 62°N in Asia and 60°N in North America, the marine areas north of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea. However, for certain discussions in this review, there may have been some deviation from this extent depending on the cryosphere component covered (especially for the land snow cover). Cryosphere is referred to aspect of polar and high altitude regions on Earth, usually with low temperature and within water in its frozen state (Qin et al., 2017; Gaffey and Bhardwaj, 2020). In the Arctic, the cryospheric components mainly include snow cover, mountain glaciers, the Greenland ice sheet, permafrost (including sub-sea permafrost), river and lake ice, and sea ice. Rapid warming in the Arctic during recent decades has caused the cryosphere melting, and cryospheric changes have great significance on climate and environment, not just for the Arctic, but for the Earth as a whole (AMAP, 2021b; IPCC, 2021).

Based on the Web of Science dataset, we performed the search updated in June 2022 using the ‘‘topic” categorical search function concerning the terms of Arctic, microplastics, and microplastic pollution. We also added the word ‘‘sea ice”, ‘‘snow”, ‘‘glacier”, ‘‘lake” and ‘‘river” to the search to estimate the element-specific trends. The number of Arctic microplastics related published literature in peer-reviewed journal has increased rapidly during past two decades (Supplementary Data Fig. S2a). The related studies investigated or mentioned the related terms since 2004, when the term microplastics was first used to report plastics in the ocean (Thompson et al., 2004). Microplastics in Arctic sea ice and their potential impact on the marine ecosystem has been focused as an important and hot issue since 2014. Until 2014, studies focused on microplastics in Arctic sea ice indicated that microplastics had accumulated even in polar sea ice (Obbard et al., 2014). Researchers then started to look for microplastics in seawater and sediments in Arctic. The first publication data of microplastics in

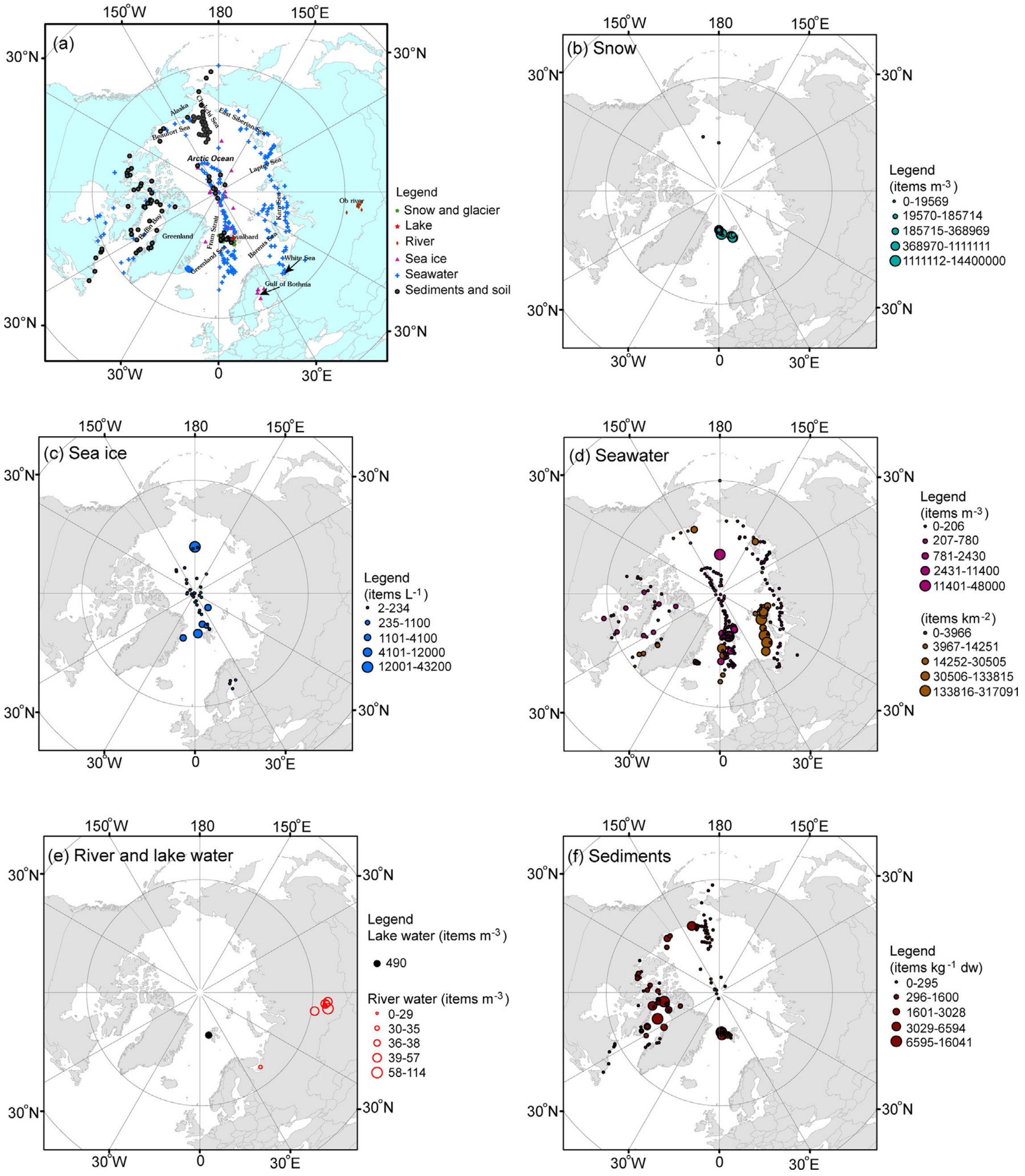

Fig. 1. The distributions of the sample types and sampling locations of existing data on microplastics studies in the Arctic region (a) and the microplastic abundance in (b) Arctic snow, (c) Arctic sea ice, (d) Arctic seawater, (e) river & lake water and (f) sediments. (Microplastics data can be referred to the Supplementary Data Tables S1 – S6).

Arctic snow cover and their atmospheric transport were until 2019 (Bergmann et al., 2019). Almost no studies were found on microplastics in Arctic glaciers or Greenland ice sheet. The trends of publication citations through time also indicated rapid increases (Supplementary Data Fig. S2b), confirming that the microplastic issue attracted wide concerns for the Arctic region. The above analysis shows the increasing studies on microplastics in the Arctic, specifically focusing on their features in the Arctic cryosphere and the need for further investigation. Meanwhile, microplastics studies in Arctic have infiltrated terrestrial and aquatic systems, with interactions between the cryosphere and atmosphere. Mostly recently, an increasing microplastics burden in Arctic ecosystems were noticed (AMAP, 2021a; Bergmann et al., 2022).

3. Microplastics in Arctic cryosphere

3.1. Microplastics in snow and sea ice

Research of plastic pollution in Arctic has increased the understanding of the global plastic cycle (Stubbins et al., 2021). Microplastic concentrations in Arctic snow are only reported recently at the Fram strait, Svalbard, and Canadian Archipelago coast (Fig. 1b). Substantial microplastics (0 to 14.4×10^3 items L^{-1}) have been identified in Arctic snow by using Fourier transform infrared (FTIR) imaging with detected size $\geq$ 11 μm (Bergmann et al., 2019) (Supplementary Data Table S1). The study reveals that the dominant size of detected microplastics is $\leq$ 100 μm (98%); the numbers of plastic particles decrease with increasing size; varnish, rubber, polyethylene, and polyamide are the dominant polymer compositions (Bergmann et al., 2019). Their estimation indicates that annual microplastic deposition is about 8.8±7.9 items m^{-2} yr^{-1} in the Fram Strait, and 1.4±0.4 items m^{-2} yr^{-1} in Svalbard (Bergmann et al., 2019). In snow of Canadian Archipelago coast and Greenland northern coast, the total microplastic concentration is averaged at about 870 items m^{-3}, an order of magnitude lower than those in sea ice cores in the same study (Kim et al., 2021). However, until June 2022, there is no available microplastic data from the Greenland ice sheet, which has an important role in Arctic climate and environment due to its large ice volume.

Arctic sea ice thickness and extent have experienced rapid decrease during past decades (Supplementary Data Fig. S3). Such rapid changes played a critical role to the ongoing warming (Jansen et al., 2020; IPCC, 2021). Besides, changes of Arctic sea ice can alter the pollutants transport and fate, which have potential consequences on the exposure and health of Arctic ecosystems (Wang et al., 2017; AMAP, 2021c). Microplastic concentrations in sea ice range from several items L^{-1} to more than 10^4 items L^{-1} among different studies (Obbard et al., 2014; Geilfus et al., 2019; Kanhai et al., 2020; von Friesen et al., 2020; Kim et al., 2021) (Fig. 1c), with fibers as the dominant shape and with varying colors. The most evident finding is that the microplastic abundant in Arctic sea ice is higher than those in surrounding seawater (Obbard et al., 2014). von Friesen et al. (2020) also found the highest concentration of microplastics was identified in sea ice followed by seawater in the central part of Kongsfjorden (Svalbard). Total microplastic particle load of the various sea ice cores indicate highest abundance occurred at the Fram Strait from data reproduced by the previous studies. The microplastic abundance reported by Peeken et al. (2018) with size $\geq$ 11 μm in entire sea ice cores at five different locations along the Transpolar Drift are two to three orders of magnitude higher than studies in Central Arctic. In terms of colors, the majority of microplastics recorded in the sea ice cores are blue (Supplementary Data Table S2). However, no consistent dominant size category is reported among different studies. Meanwhile, sea ice studies show that the microplastics have no uniform polymer composition possibly due to the growth region and drift paths of the sea ice (Bergmann et al., 2017; Peeken et al., 2018). These large differences in concentrations can be largely explained by different methodology used and detected size limitations.

3.2. Microplastics in Arctic seawater

Microplastics are now likely to be a permanent part of the marine environment and may potentially influence marine biogeochemical and ecological processes (Ryan, 2015; Ferreira et al., 2019; Lim, 2021; Lima et al., 2021; Mishra et al., 2021). For instance, Rogers et al. (2020) indicated that microorganisms influence the fate of marine microplastics through several passive or active processes, including the microbe mediate the transport of microplastics, microorganisms mediate microplastic exposure and impacts in the food web, and microbial processes can degrade plastic-polymer. The estimated floating microplastics in the global oceans is estimated to be ~6000 items m^{-3} (Lima et al., 2021) or span from <1 to 1890 μg L^{-1} for microplastic size from 100 to 5000 μm (Beiras and Schonemann, 2020). Although it is remote from human activities, the Arctic Ocean is now considered as a potential accumulation zone of marine microplastics (Woodall et al., 2014; Kanhai et al., 2019; Lima et al., 2021). Abundant microplastics in Arctic seawater are reported from the surface (or sub-surface) water to water column (Supplementary Data Table S3). Due to different sampling (manta net, bongo samples, or pump water) and analytical methods (stereomicroscope, FTIR, or Raman) used, significant differences in microplastic characteristics are observed mainly due to the different microplastic size cutoff, with abundance ranging from 0 to >10 thousand items m^{-3} in seawater samples (Fig. 1d), and with relatively higher concentrations observed from water columns (Tekman et al., 2020; von Friesen et al., 2020). The median concentrations of microplastics are 142 items m^{-3} in west Greenland seawater (pump) (Rist et al., 2020), comparable to results from the Fram Strait (113–262 items m^{-3}) (Tekman et al., 2020). From another previous study, microplastics concentrations are found to be relatively higher around the Novaya Zelma, with an estimated 963 thousand items per square kilometer (Tošić et al., 2020). The simulation results based on the Nucleus for European Modeling of the Ocean (NEMO) and the dynamics-thermodynamics sea ice model also reveal microplastics invading the Arctic sea ice south of the Novaya Zelma from February to March (Mountford and Morales Maqueda, 2021). Meanwhile, plastic debris is abundant and widespread in the Greenland and Barents seas, with average concentrations of 63,000 items km^{-2} (Cózar et al., 2017). These results reveal that high concentrations of microplastics is observed in surface water of Atlantic origin (Yakushev et al., 2021). Microplastics in subsurface waters of the Canadian Arctic Archipelago range from 0 to 282 items m^{-3} (with average at 31±17 items m^{-3} with microplastic size >50 μm), with the dominant shape of fibers and 71% of polyester and acrylics (Jones-Williams et al., 2021). Average microplastic concentrations in sub-surface water in the Northeast Greenland are 2.4 items m^{-3} with detected microplastics size >700 μm (Morgana et al., 2018). The study also reports that relatively higher concentrations of microplastics are detected in Arctic sea ice (158±155 items L^{-1}) than that in seawater, implying that microplastics identified in seawater of the marginal ice zone are to a large extent likely released during the melting of sea ice (von Friesen et al., 2020). Meanwhile, microplastics in marine water increase between 2005 and 2014 in the Greenland Sea, linking to the increasing plastic production and usage or the lower sea ice extent in 2014 (Amélineau et al., 2016).

3.3. Microplastics from river water and lakes

Around by large rivers (e.g., Yenisey, Lena, Kolyma, Indigirka, Pechora and Dvina (Siberia), Ob, Mackenzie, Yukon, and Nelson (Canada)) (Supplementary Data Fig. S4), the Arctic Ocean receives >10% of the global river discharge, and has a drainage area which encompassed many industrial and agricultural regions (https://arcticgreatrivers.org/). These large rivers can be as a potential source of environment pollutant (e.g. mercury) or nutrients into the Arctic Ocean (McClelland et al., 2016; Fabre et al., 2019; Mu et al., 2019; Zolkos et al., 2020). Rapid changes within the Arctic ecosystem as a consequence of global warming (IPCC, 2019; AMAP, 2021b) make it challenging to establish a contemporary baseline of fluvial export for the pollutants. The abundance and morphology of microplastics in surface water of the Ob River and Yenisey River in Siberia have been recently studied by Frank et al. (Frank et al., 2021a; Frank et al., 2021b). They show that microplastic abundance range from 44–88 items m^{-3} (Fig. 1e and Supplementary Data Table S4), with dominant size <1 mm (93.5%); microplastic fragments are the predominant shape (47%), following by fibers (22%), films (21%) and spheres (10%). Microplastics from discharge plumes of the Great Siberian Rivers show high concentrations, indicating Siberian river discharge is an important source of microplastics input into the Arctic Ocean (Yakushev et al., 2021). Main drift pathways of European riverine microplastics through the Arctic Mediterranean indicate that riverine European microplastics can transport along the Eurasian continental shelf, across the North Pole, and then they can back into Nordic seas; meanwhile, the Nansen basin, the Laptev Sea and the ocean gyres of the Nordic Seas are found to be the accumulation zone of microplastics (Huserbråten et al., 2022). Currently, microplastics in Arctic lakes are only reported from Svalbard Archipelago (Fig. 1e and Supplementary Data Table S5) (González-Pleiter et al., 2020). The average concentration of anthropogenic litter at this location is 400 microparticles m^{-2}; most of the sampled microparticles are fibers (>90%) (acknowledging the limit of detection constraint on analyzed particle size).

3.4. Microplastics in sediments

From a global view, the amount and distributions of litter and microplastics in the ocean and other watercourses are comprehensively synthesized by LitterBase (https://litterbase.awi.de/), including the Arctic beach and seafloor, showing litter quantities varied strongly within certain region (e.g., in East Asia and Southwest Pacific). Litter pollution in Polar regions are still little known compared to that in certain areas (for example, the Mediterranean Sea). In this review on Arctic regions, microplastics in marine sediments have been reported from Bering and Chukchi Seas, Canadian Arctic, Svalbard, and Arctic Central Basin (Fig. 1f and Supplementary Data Table S6). The abundances of microplastics (>100 μm) in sediments of Bering and Chukchi Seas range from 0 to 68.78 items kg^{-1} dry weight (dw) of sediment, with fibers the most common shapes (51.5%) (Mu et al., 2019). A latest study of five years through three voyages in 2016, 2018 and 2020 reveal that the microplastics levels (~21–105 items kg^{-1} dw) in sediments from the Chukchi Sea are lower than those from the Eastern Arctic Ocean (Fang et al., 2022). Canadian Arctic-wide study has found that microfibers (>125 μm) account for 82% of all the detected microplastics, with concentrations ranged from 40 to 3200 items kg^{-1} dw; while the other microplastics (fragments, foams, films and spheres) concentrations range from 0 to 1600 items kg^{-1} dw (Adams et al., 2021). In a remote Arctic fjord of Svalbard, an average of 3.3 items of anthropogenic particles per kg of surface sediments are found and analyzed using Raman and FTIR; fibers dominate among these anthropogenic particles (Collard et al., 2021). In the Arctic deep-sea sediments within the HAUSGARTEN observatory in 2340–5570 m depth in the summer of 2016, microplastics are widely distributed with concentrations of about 42–6595 items kg^{-1} (Bergmann et al., 2017); meanwhile, at HAUSGARTEN observatory in the summer of 2016, average microplastics in sediments are about 4730 items kg^{-1} (Tekman et al., 2020). Canadian Arctic sediment samples has been found to have much lower concentrations of microplastics compared with findings from the Fram Strait (Bergmann et al., 2017; Huntington et al., 2019), with the mean abundance of microplastics of 4360 items kg^{-1} dw and of 1950 items kg^{-1} dw, respectively (Supplementary Data Table S6). Although, it has been reported that relatively higher concentrations of microplastics are observed closer to human activities in coastal sediments (von Friesen et al., 2020), microplastics concentrations range from 2 to 26 items kg^{-1} dw (with mean of 11 items kg^{-1} dw and detected size >100 μm) in coastal sediments of western Svalbard (Carlsson et al., 2021). Another study also indicates that microplastics in surface sediments of Svalbard archipelago is observed to be 2.87 items kg^{-1} dw with size ranging from 55 μm to 381 μm (Ramasamy et al., 2021). In coastlines of Arctic Canada and West Greenland, anthropogenic plastic litter has been observed with a mean density of 1.0±1.7 items·m^{-2} (~10^6 items km^{-2}) along sandy/gravel beaches, predominantly fragments, fibers and films (Mallory et al., 2021), with fibers dominating the microplastic particle morphology in the Canadian Arctic sediment (~57%) (Huntington et al., 2019). These results, however, cannot be directly compared because microplastic abundance was size depend, which indicates more than nearly 80% of the microplastic particles are ≤ 25 μm in size and 99% <150 μm (Bergmann et al., 2017; Tekman et al., 2020). Microplastics in coastal sediments in the Arctic fjords of western Svalbard reveal that fibers are the most common shape (71%, LOD 100 μm) (Carlsson et al., 2021). Synthetic fragments present the most frequent occurring particle types in sediments collected from Svalbard (LOD 30 μm) (von Friesen et al., 2020). Meanwhile, a high diversity of colors has been found in sediments in Arctic regions, with transparent, blue and black as the common colors. Despite the different methodologies used in the above different studies, the relatively high abundance of microplastics in Arctic deep-sea sediment is striking, which may influence the global/regional microplastic cycle (Bergmann et al., 2017).

4. Microplastics storage and release from Arctic cryosphere

4.1. Methods for the estimation

Microplastic deposition fluxes (M_{snow}) from Arctic land snow cover can be calculated by the Eq. (1) as following:

$$M_{snow} = C_{snow} \times SD \times \rho \tag{1}$$

where, C_{snow} is miroplastic concentration in snow cover. SD is the snow depth. ρ is the snow density. In this study, data of C_{snow} referred to the previous study by Bergmann et al. (2019). Data of SD cited from Zhong et al. (2018), and ρ data referred to Dou et al. (2019).

Then, the microplastic storage in sow cover (ST_{snow}) is calculated by the Eq. (2) as following:

$$ST_{snow} = M_{snow} \times S_{snow} \tag{2}$$

where, S_{snow} is the area of snow cover. In this study, Arctic land snow cover areas used ranged from 4×10^6 to 8×10^6 km^2 based on the data from Supplementary Data Table S7 (IPCC, 2019).

When estimating the riverine plastic outflow (M_{out}), a model equation is used by Mai et al. (2019) (Eq. (3)) as following:

$$M_{out} = C_{river} \times Q \tag{3}$$

where, C_{river} is the riverine plastic concentration, Q is the daily riverine water discharge. Based on Eq. (1), discharge of Arctic Great Rivers (Q), and microplastics concentration (C) in the river water (Yang et al., 2014; Frank et al., 2021a) (Supplementary Data Tables S4 and S8), the calculated riverine input of total microplastics from Arctic Great Rivers to Arctic Ocean ranges from 8 ton/yr (14 billion N/day) by Kolyma river to 48 ton/yr (81 billion N/day) by Yenisey. The discharge flux of microplastics ranges from 1.65×10^5 to 9.35×10^5N/s.

Microplastic storage (ST_{ice}) in Arctic sea ice is estimated by the Eq. (4) as following:

$$ST_{ice} = C_{ice} \times V_{ice} \tag{4}$$

where, C_{ice} is the microplastic concentration in sea ice, V_{ice} is the volume of sea ice.

4.2. Deposition and storage of microplastics in Arctic land snow cover

Atmospheric microplastic transport and deposition in the Arctic is a frontier in microplastic research, with field studies and atmospheric modelling illustrating atmospheric transport potentially as an important component of marine plastic pollution via atmospheric transport (Allen et al., 2020; Brahney et al., 2020; Evangeliou et al., 2020). Microplastic deposition fluxes from snow can be calculated based on the microplastic concentration in snow, snow depth and snow density (method referred to section 4.1). Mean microplastic concentration in snow cover has been reported in the Arctic (Svalbard, Greenland northern coast and the Canadian Archipelago coast) ranging from 0.87±0.36 items L^{-1} to

$1.76\pm1.58\times10^3$ items L^{-1} (Bergmann et al., 2019; Kim et al., 2021). Snow depth in the Arctic varies primarily due to different climatic regions and conditions. There have been long-term increases in winter snow depth over northern Scandinavia and Eurasia, but a significant decline over the North American Arctic and northern Canada during past 60 years (AMAP, 2011). The current average snow depth is ~22 cm from the CMIP6 data and ~18 cm from field observations (Zhong et al., 2018, 2022). Arctic snow density is analyzed during the Chukchi Sea Barrow expedition and the spatial variation of snow density is not significant. Snow density ranges from 250 to 320 kg m^{-3} (average of 300 kg m^{-3}) (Dou et al., 2019). SWAIP2011 indicated that the average Arctic snow density remained close to 300 kg m^{-3} over much of the snow season, but snow depth and properties can exhibit strong local variation with many exposed areas, drifts, dunes, and sastrugi (sharp irregular ridges on the snow surface formed by wind erosion and deposition) (AMAP, 2011). It is noted that snow fall is not the only way of snow microplastic deposition; while snow may act as a scavenging force in the atmosphere, dry deposition of atmospheric microplastics into snow also occurs (Materic et al., 2021). Limited study differentiates between dry and wet atmospheric deposition (globally and within the Arctic), thus the proportion of Arctic snow microplastics that occurs due to dry deposition is currently unknown.

Based on the methods and data (Supplementary Data Tables S1 and S7), the calculated microplastic deposition flux in Arctic land snow cover has been estimated with range from 4.90×10^8 to 14.28×10^8 items km^{-2} yr^{-1} (Supplementary Data Table S7). Based on the snow cover area (ranged from 4×10^6 to 8×10^6 km^2), the microplastic storage in Arctic terrestrial snow cover has been estimated to be 1.96×10^{17} to 1.14×10^{18} items yr^{-1}. The results indicate that when snow melt occurs, the formerly deposited abundant microplastics in snow cover can be released again to the Arctic terrestrial surface, flowing to the river or lakes and finally to the Arctic Ocean. We have to note that microplastics deposited onto the surface snow of glaciers or Greenland ice sheet can accumulate in glaciers and some of microplastics will move away along glacial surface runoff discharge due to the melting. We should further identify the mechanism of microplastics transport from snow cover or glaciers in the future.

4.3. Riverine release of microplastics into Arctic Ocean

Rivers can carry plastic waste from the terrestrial environment to the sea, making them major contributors to ocean plastic pollution (Mai et al., 2020; Yakushev et al., 2021). About 4.8–12.7 million tons of plastic has been estimated to end up in the world's oceans every year; approximately 80% of which come from the world's rivers, serving as direct conduits for high intensity city sourced plastic waste to the marine environment (Mai et al., 2020; UNEP, 2021). However, modelled and extrapolated ocean plastic concentrations and estimations of river contributions to oceanic plastic varies significantly. For example, Lebreton et al. (2017) estimated that between 1.15 and 2.41 million tons of plastic waste entered the ocean every year from rivers, with over 74% of emissions occurring between May and October. The Arctic Ocean receives 10% of global river discharge by the six Arctic Great Rivers (the Mackenzie, Yukong, Kolyma, Lena, Yenisey, and Ob' river) (Supplementary Data Fig. S3; Shiklomanov et al., 2021). The six Arctic Great Rivers can export an average of 20,000 hg/yr of total mercury to the Arctic Ocean at present (Zolkos et al., 2020).

Based on the Mai et al. (2019)'s methods of riverine plastic discharge (method referred to Section 4.1), our calculated riverine input of total microplastics from the Arctic Great Rivers to the Arctic Ocean ranges from 8 ton/yr (5.2×10^{12} items yr^{-1}) by Kolyma river to 48 ton/yr (3×10^{14} items yr^{-1}) by Yenisey river (Supplementary Data Table S8). The estimated discharge flux of microplastics ranges from 1.65×10^5 to 9.35×10^5 items/s. Therefore, based on the massive annual discharge of Arctic Great Rivers (~2100 km^3) (Yang et al., 2014; Magritsky et al., 2018), the estimation of riverine microplastics input into Arctic Ocean is about 180 ton/yr (or about 1.1×10^{14} items yr^{-1}). However, it should be noted that the estimation contains large uncertainties due to the very limited microplastic measurements from Arctic river waters. From a global view, there is significantly greater field data for non-Arctic rivers plastic concentration and oceanic discharge. For example, microplastics from Pearl River of China range from 0.005 – 0.7 items m^{-3} and 0.004–1.28 mg m^{-3} and these values positively correlate with water discharge. The annual riverine input of microplastics from the Pearl River Delta has been estimated as 39 billion particles or 66 tons (Mai et al., 2019). Brahmaputra and Meghna rivers (Ganges watershed) could release up to 1–3 billion (10^9) items microplastics into the Bay of Bengal (north-eastern portion of the Indian Ocean) every day (Napper et al., 2021). For Japanese rivers, the average microplastics is widely distributed over four orders of magnitude, ranging from 0.03 to 63.89 items m^{-3} (0.00008 to 16.15 mg m^{-3}), with mean values of 4.34 items m^{-3} (0.79 mg m^{-3}); the number and mass microplastics emissions are 1.27–1.67 trillion (10^{12}) particles or 204 – 294 ton/yr, respectively, from rivers to the sea (Nihei et al., 2020). The lower input of microplastics from the Arctic Great rivers further indicates that the available plastic waste in rivers is influenced by the population density, and solid waste generation (Mai et al., 2019).

It should also be noted that river contributions of plastic are not the single mechanism or vector of Arctic plastic pollution. Beyond river plastic transport and discharge of plastic, Arctic plastic pollution also occurs directly from sea-based sources such as ships, offshore oil platforms, and fishing fleets (UNEP, 2021) as well as atmospheric transport and deposition, potentially comprising 20% of oceanic plastic pollution.

4.4. Temporal storage and release of microplastics from sea ice

Sea ice thickness in the central Arctic Ocean declined by 65% over the period 1975–2012, from an average thickness of 3.6 m to 1.3 m (AMAP, 2017; Marcianesi et al., 2021). Sea ice extent has varied widely in recent years but continued a long-term downward trend (AMAP, 2017), with the greatest sea ice decline found in September, corresponding to a sea ice loss of 3×10^6 km^2 between 1978 and 2013 (Simmonds, 2015), an overall sea ice coverage decreasing from >60% to <40% (Perovich et al., 2020). Average ice volume decline is estimated to be 3.1×10^3 km^3 per decade; and using a combination of observational data and model results, it has been estimated that sea-ice volume has reduced by two-thirds between 1980 and 2013 (Overland and Wang, 2013). Within these boundaries, the Arctic Ocean covers a fixed area of approximately 7.23×10^6 km^2, a current (2020) sea ice volume of 4627 km^3 – 18,785 km^3 (Perovich et al., 2020), with a 4 year (2010–2014) average ice volume of 6819 km^3 in October and 16,369 km^3 in May (Kwok and Cunningham, 2015). For the first year sea ice zone, the average seasonal 2010–2014 growth in volume was recorded from 3203 to 13,627 km^3. This contrasted to the decrease in multi-year ice zone from 3616 to 2769 km^3 during 2011–2014 (Kwok and Cunningham, 2015). Conversely, the transition from multi-year sea ice (perennial sea ice, defined as ice that has survived at least one melt season, usually with density of 917 kg m^{-3}) to first-year sea ice (defined as floating ice of no more than one year's growth developing from young ice, usually with density of 882 kg m^{-3}) is strong in recent years (Kwok and Cunningham, 2015; AMAP, 2017), making the previously frozen microplastic in sea ice to be rapidly released to the Arctic Ocean.

It has been estimated that the maximum microplastic storage in Arctic sea ice is approximately 6.1×10^{18} items, ranging from

9.8×10^{16} to 6.8×10^{19} items due to large differences in the microplastic concentrations (method referred to Section 4.1). For the first-year sea ice, the temporal storage of microplastics can be 5.1×10^{18} items, which is almost five times the mean microplastic storage in the multi-year sea ice (9.9×10^{17} items) (Supplementary Data Table S9). The annual release of microplastics from first-year sea ice melting is estimated to be 5.1×10^{18} items. Due to the decline in multi-year sea ice volume of 210–320 km^3/yr (Overland and Wang, 2013; Kwok and Cunningham, 2015), the decreased microplastic storage from multi-year sea ice is to be approximately 10^{17} items yr^{-1}.

5. Microplastics transport to and within Arctic cryosphere

5.1. Atmospheric transport of microplastics to the Arctic

Very little of anthropogenic plastic is recycled or incinerated in waste-to-energy facilities (PlasticsEurope, 2020). Much of plastics (~79%) ends up in landfills or the natural environment, where it may take up to 1000 years to decompose, leaching potentially toxic substances into the soil and water (Geyer et al., 2017; Hale et al., 2020). A large quantity of microplastics originate in the terrestrial environment (including land-based, rivers and lakes, and atmosphere), which find their way into oceans through rivers, sewage system discharge, surface erosion, atmospheric entrainment and transport (Fig. 2) (Hale et al., 2020; Xu et al., 2020; Bergmann et al., 2022).

Long-range atmospheric transport and deposition is an important pathway of microplastics to remote regions (Allen et al., 2019, 2021; Bergmann et al., 2019; Zhang et al., 2019; Evangeliou et al., 2020). The microplastics, from tire wear and brake wear particles, concentrated in the eastern US, Northern Europe and large urbanized areas of Eastern China, Middle East and Latin America where vehicle densities were highest, were simulated to have high transport efficiencies to remote regions, and modelling suggested that the Arctic may be a particularly sensitive receptor region (Evangeliou et al., 2020). Even in the remote U.S. conservation areas, urban centers and resuspension from soils or water were principal sources for wet-deposited plastics (Brahney et al., 2020; Brahney et al., 2021). From the Picdu Midi Observatory at 2877 m above sea level, the study indicates microplastics presence in the free troposphere would facilitate transport over greater distances and thus the potential to reach more distal and remote parts of the planet (Allen et al., 2021). Abundant microplastics in Arctic snow further evidence that atmospheric deposition can be notable pathways for microplastics to remote areas (Bergmann et al., 2019). These studies emphasize that microplastics from the terrestrial environment close to human activities can be effectively transported to the Arctic region. Atmospheric transport has been considered as an important transport vector in the microplastic cycle in the Earth's environment (Bank and Hansson, 2019; Hale et al., 2020), and therefore be a significant transport mechanism for microplastics entering Arctic regions (Fig. 2) (Obbard, 2018; Bergmann et al., 2019). Previous studies indicate that snow deposition and melting are drivers of polychlorinated biphenyls and organochlorine pesticides in Arctic rivers and lakes (Cabrerizo et al., 2019). Microplastics stored in snow can be also released when snow melt occurred during a short period. As estimated in section 4, Arctic land snow cover can temporally store and release large amount of microplastics every year into the Arctic environment.

5.2. Microplastic sources to and in the Arctic marine environment

5.2.1. Ocean currents transport and local sources

The potential sources of microplastics in Arctic seawater have been posited to predominantly originate from long-range transport due to surface (and atmospheric) circulations. A review of published data illustrated high concentrations of plastic debris in the Greenland and Barents seas (compared to other Arctic sea study locations). Based on the Arctic Ocean large scale circulations and observed data (Cózar et al., 2017; Peeken et al., 2018; Bergmann et al., 2022), the published studies showed that the poleward branch of the Thermohaline Circulation transferred floating debris

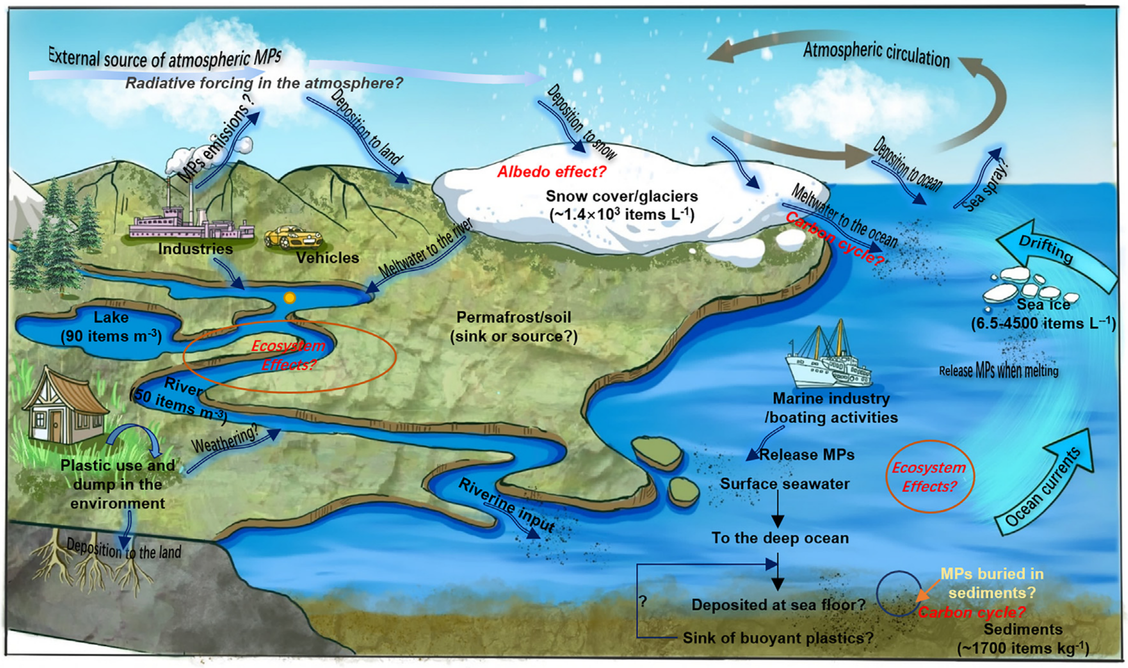

Fig. 2. Sketch map of microplastic potential sources and transport in the Arctic cryospheric regions. Microplastics deposition and storage in Arctic land snow cover, storage in sea ice, and export from Arctic rivers were calculated. Question marks indicate microplastic studies without published estimates and the key challenges.

from the North Atlantic to the Greenland and Barents seas, which indicated that the Arctic Ocean could be a dead end (deposition or storage zone) for this plastic conveyor belt (Supplementary Data Fig. S5). This is supported by Russian Arctic sea findings, where floating marine plastic has been identified in waters of Atlantic marine origin which have travelled via the Barents Sea (Pogojeva et al., 2021). Central European marine plastic has been illustrated to be transported to the Arctic via oceanic drift, with this process taking a year for plastic pollution particles to reach the Arctic (Strand et al., 2021). A latest study further evidenced that Arctic *trans*-polar drift-pathways can transport of buoyant microplastic from northern European rivers to the high Arctic (Huserbråten et al., 2022). The simulation results indicated that the widespread dispersal microplastics along the Eurasian continental shelf, across the North Pole, and back into the Nordic Seas; with accumulation zones over the Nansen basin, the Laptev Sea, and the ocean gyres of the Nordic Seas (Huserbråten et al., 2022). Meanwhile, the local source of regional fishing activities and emissions in Arctic Ocean cannot be overlooked (Lusher et al., 2015; Strand et al., 2021). Sources of microplastics in Svalbard can be divided into two origins: local and long-range. Local sources included human activities' emissions (e.g. industrial activities, tourism, domestic activities); long-range sources of microplastics were transported through both atmospheric and ocean currents and therefore have a diverse and diffuse distal source(s) (Obbard, 2018). In Arctic Canada and West Greenland, anthropogenic floating litter quantities were significantly greater for sites within 5 km of communities than more distal and remote locations, suggesting that much of this macro litter near remote communities may come from local sources (Mallory et al., 2021). The results indicated that local and distal sources were both important components of microplastics in Arctic waters (Lusher et al., 2015). The Arctic Ocean sea spray through the process of bubble burst ejection and wave action on the sea surface may be another important source of atmospheric microplastics to remote Arctic atmosphere, sea ice and terrestrial locations (Allen et al., 2020). However, studies on microplastic transported by sea spray are still limited, therefore constraining the estimation of their impact on atmospheric microplastics is needed for further study.

5.2.2. Arctic sediments as a temporal sink

It has been suggested that microplastics may be accumulating in the deep sea sediments through vertical settling or coastal sediments within the Arctic Ocean (Bergmann et al., 2017; Huntington et al., 2019; Tekman et al., 2020). Illustrating high concentrations of microplastics (~1000 items per kg, Supplementary Data Table S6), deep sea sediments of the Arctic central basin have also been hypothesized as an important temporary sink of plastic debris (Cózar et al., 2017; Kanhai et al., 2020). In marine sediments of the Canadian Arctic, microfibers and microplastics are reported to range from 600 to 4700 items kg^{-1} dw, indicating Canadian Arctic as a sink for microplastics (Adams et al., 2021). This recent study demonstrates that the spatial distribution and fate of microplastics in seafloor is strongly influenced by near-bed thermohaline currents (bottom currents), which can control the distribution of microplastics and created hotspots of up to 1.9 million items m^{-2} (Kane et al., 2020). Until now, the process and mechanism of microplastic transport to deep sea sediments remained largely unknown and required systematic and long-term investigations.

5.2.3. Microplastics transported by sea ice

Sea ice is considered to be a temporal sink of man-made particulates, including microplastics (Obbard et al., 2014; Peeken et al., 2018). Microplastic concentrations in Arctic Sea ice have been found several orders of magnitude greater than those previously reported in surface waters (Supplementary Data Tables S2 and S3). On the one hand, this is because the sea ice can entrap the suspended particles in seawater when it forms (Wang et al., 2017; Alice et al., 2021). On the other hand, microplastic incorporation into sea ice can also potentially occur during its drift across the central Arctic (Kanhai et al., 2020). Atmospheric dry and wet deposition on sea ice can further bring microplastic deposition (Bergmann et al., 2019), as can bubble burst ejection transfer microplastics from the marine (sea) to ice surface (Allen et al., 2020). However, the contributions of different sources of microplastics to the Arctic sea ice is complex and yet to be quantified. The movement or transport of microplastic within the ice flow, vertically, is yet to be defined. When sea ice melting occurs, caused by seasonal or climate induced warming, the formerly entrapped microplastics can be subsequently released again into the Arctic Ocean, resulting in relatively abundant microplastics in the receiving seawater (Lusher et al., 2015). Therefore, sea ice can be considered as the secondary source of microplastics to seawater, especially considering current rapid Arctic warming (Obbard et al., 2014; AMAP, 2021b).

Sea ice as a transport medium for contaminants has been recognized since at least the early 1990s (Wang et al., 2017), and it is thought to play an important role on the transport of microplastics across the Arctic Ocean (Fig. 2) (Obbard et al., 2014; Obbard, 2018; Kim et al., 2021). Kanhai et al. (2020) suggested that microplastics in sea ice of the central Arctic possibly came from the Siberian shelves, western and central Arctic. Backtracking of drift ice trajectories can identify potential origins and the transport pathways of microplastics in sea ice. Peeken et al. (2018) revealed that Arctic sea ice containing abundant microplastics may have originated in the Kara and Laptev seas and the Central Arctic Ocean, transported south across the Barents Sea and the north of Svalbard as well as by the Transpolar Drift toward the Fram Strait (Peeken et al., 2018; Kim et al., 2021). These findings were supported by a recent modelling study identifying sea ice as an important transport vector of microplastics and seasonal microplastic sinks (Mountford and Morales Maqueda, 2021). The extent and depth variations of Arctic sea ice may further alter the concentration of microplastics trapped in sea ice, as well as the surrounding seawater and atmospheric microplastic concentration and availability.

6. Perspectives

The Arctic is a large area that encompasses diverse ecosystems and species connected through complex biogeochemical and ecological pathways. The Arctic cryosphere plays an important role in the temporal sink, source and transport of microplastics in the Arctic terrestrial and marine environments. In 2021, Arctic Monitoring & Assessment Programme released the Monitoring Plan on microplastics in the Arctic, which will document the presence of a range of size classes of microplastics in the environment and to improve the understanding of underlying processes. We believe under this program, new understandings on the microplastic distributions, transport pathways, and their impacts in the Arctic environments will be addressed. The program will also provide data for future Arctic-specific modeling scenarios. The future focuses are suggested currently as following.

6.1. Microplastics pose potential threat to Arctic ecosystems

As a growing tide of plastic production and pollution, microplastics pose an existential threat to marine ecosystems, to marine producers but also to the organisms occupying higher trophic level of food web (Rochman, 2015; Mishra et al., 2021). Microplastic ingestion has been found in Arctic birds/fish/invertebrates/polar bears/walrus/whale/reindeer and caribou, and benthic invertebrate species (Bråte et al., 2016; Fang et al., 2018; Kühn et al., 2018; Moore et al., 2020; Carlsson et al., 2021; Collard and Ask, 2021; Bergmann et al., 2022). Arctic microplastic pollution may threaten Arctic species feeding behavior, habitat, and breeding. There are limited marine or terrestrial Arctic species (eco)toxicity or behavioral impact studies under environmental conditions (Collard and Ask, 2021). Two species of zooplankton have been studied in environmental conditions and were found to ingest microplastics in the open ocean (Long et al., 2015). A further study on Arctic marine zooplankton suggests microplastics may not act as a vector of polycyclic aromatic hydrocarbons in Arctic marine food webs after oil spills; but, at high concentrations (20 items mL^{-1}), microplastics can trigger behavioral stress responses to oil pollution in zooplankton (Almeda et al., 2021).

6.2. Impacts of cryospheric changes on the behavior of microplastics

The Arctic has been experiencing increasing temperatures, approximately-three times the rate of the global warming, resulting in rapid cryosphere melting in recent years (permafrost thawing, loss of seasonal snow cover, ice sheet, glaciers, and reduction of Arctic sea ice) (AMAP, 2021b). The melting cryosphere, as a temporal source of microplastic particles, will release the stored microplastics into the Arctic environment. Climate change may further accelerate microplastics accumulation or transport to the Arctic (Adams et al., 2021). For example, high concentrations of microplastics in East Baffin Bay adjacent to west coast of Greenland may be linked to the recent warming of the subsurface waters along the coast (Holland et al., 2008); the surface melting of the Greenland ice sheet will increase runoff into the surrounding ocean (Hanna et al., 2013), causing microplastic release (Obbard et al., 2014; Zhang et al., 2022). High microplastics concentrations in seawater have been found close to melting Arctic sea ice (von Friesen et al., 2020) and in sediments close to glaciers (Huntington et al., 2020). Modeling has demonstrated the considerable differences between the abundance of neutrally buoyant plastics in the Arctic surface waters and the rest of the water column (Mountford and Morales Maqueda, 2021). There are several studies quantifying the vertical distribution of microplastics within the sea ice depth, with microplastics ranging from 33 to 75,143 items L^{-1} in the vertical profiles of Arctic sea ice cores. However, distribution of neutrally buoyant plastics within Arctic sea ice shows no vertical trend and requires further analysis (Peeken et al., 2018; Kanhai et al., 2020). A comparison between the modeling and observations is essential to verify the simulation of ice floe uptake and transport within the Arctic. Ice nucleation by microplastics and potential exclusion of nanoplastics in the formation of sea ice is another area requiring investigation, along with the effects of algae as found by Alice et al. (2021).

6.3. Possible relationships between microplastics and carbon cycle

Arctic warming has substantially altered the terrestrial and marine carbon cycle in Arctic region (IPCC, 2021). Plastic production consumes large amounts of oil, and boosts the continued production of substances that drive climate change, exacerbating the impacts on the environment (UNEP, 2021). Plastics are considered an emergent component of Earth's carbon cycle. The quantities of plastics presented in some ecosystems comparable to the quantity of natural organic carbon (Stubbins et al., 2021). For example, the permafrost in Arctic regions is rich in soil organic carbon. Permafrost degradation under climate warming will release the deposited microplastics, resulting the permafrost from a sink to a source (Chen et al., 2021), indicating that most of microplastics in permafrost would eventually migrate from the soil into water bodies. This process may be also affected by the microbial activities, which might change the global microplastics and carbon cycle. Therefore, microplastics in permafrost should be paid much attention in the future. Besides, microplastics in ocean provide surfaces for microbial growth and biofilm production, which can increase the production of organic carbon and its aggregation into gel particulates (Galgani et al., 2019). Microbial community grown on microplastic particles in the environment may affect greenhouse gas cycling; however, early results have shown a low contribution to the global gasses surface inventories (Cornejo-D'Ottone et al., 2020). Meanwhile, abiotic and biotic processes in aquatic environment driven by microorganisms are intricately associated with plastic debris, which can influence the biogeochemical cycles of microplastics, including the exposure of consumers to micropalstics, plastic degradation products, and the environmental fate of microplastics (Rogers et al., 2020). Microplastic also affect the composition and function of ocean sedimentary microbial communities, and carbon cycling (Seeley et al., 2020). A major effort is required to understand the pervasive effects of microplastics on the functioning of permafrost or glacial/snow ecosystems; importantly, the study also need to capture the immense diversity of microplastic particles with size distributions, shapes, chemical compositions, and weathering.

6.4. Nanoplastics in Arctic cryosphere

Compared to microplastics, less is known about the abundance and fate of nanoplastics in the Arctic cryosphere. Nanoplastics are usually defined as the plastic particles smaller than 1 μm (Alimi et al., 2018; Gigault et al., 2018). The extraction and quantification of nanoplastics in the environment are difficult due to the technological limitations and dilution effects (Piccardo et al., 2020). As similar to microplastics, nanoplastics have primary (manufactured) and secondary (originated from degradation) sources. Due to their small size and the large surface area per unit mass, the nanoplastic size and surface energy may affect, for example, surface functionalization, grafting, adsorption, homo- and heteroaggregation, reactivity, interaction between other nanoparticles, and their interaction with the environment (Mattsson et al., 2018). Nanoplastics play various adverse effects on organism and inhibit microbial growth and metabolism revealed in marine environment (Fu et al., 2018; Hollóczki and Gehrke, 2019; Gonçalves and Bebianno, 2021). The early studies suggest that nanoplastics can be transported through long-range transport and be present in various environments (Materic et al., 2021; Materic et al., 2022). Currently, less studies have been reported in remote regions. In Siberia lake, river and ponds surface water, nanopalstics have been detected to be about 51 μg L^{-1} (Materic et al., 2022). Therefore, in order to fully understand the nanoplastic sources and fate in Arctic regions, it is urgent to determine the levels and compositions of nanoplastic pollution present in Arctic different ecosystems, which also helps to illustrate the deposition and removal processes of nanopalstics in the environment.

7. Conclusions

Arctic cryosphere is under rapid changing due to climate warming in recent decades, which may profoundly change the biogeochemical cycles for the typical pollutants (including microplastics) and pose potential threats to the related marine and terrestrial ecosystems. In this work, we synthesized the characteristics of microplastics, their possible sources and transport pathways in the Arctic cryospheric environments. Microplastic concentration distributions in snow cover, sea ice, Arctic seawater, river/lake water, and sediments vary significantly, partially due to the differences in sampling and analytical methods. These distributions indicate the possible impacts of different transport pathways or different sources of microplastics to and within Arctic regions. Based on the microplastics data and related parameters, we evaluate the storage and release of microplastics in different cryospheric components. Generally, microplastics deposited in the Arctic land snow cover ranges from 0 to 14.4×10^{3} items L^{-1}, with a storage of 1.96×10^{17} to 1.14×10^{18} items yr^{-1}. Arctic Great River has been estimated to discharge a notable quantity microplastics (~180 ton/yr) every year to the Arctic Ocean, making river runoff and discharge an important source of microplastics into the Arctic Ocean. The maximum storage of microplastics in Arctic sea ice is estimated to be approximately 10^{19} items, with annual microplastics release of 7×10^{18} items yr^{-1}. Microplastics in permafrost and the impacts of permafrost thawing need to be studied further in future.

Microplastics accumulate in the Arctic regions from multiple sources. Long-range atmospheric transport of microplastics from the terrestrial environment plays an important role on the microplastics deposition to the Arctic terrestrial or oceanic surface. We suggest the atmospheric transport can be an important way of microplastics to Arctic environment. Ocean currents from the Atlantic Ocean can convey microplastics to the Arctic Ocean. Microplastics trapped within sea ice can be transported across and within the Arctic Ocean, for example to the Fram Strait, illustrating sea ice as a long range microplastic transport vector for distal sources of microplastic together with local sources of microplastics from human activities (fishing, tourism).

In summary, the changing Arctic cryosphere may be particularly vulnerable to microplastic pollution. It is important to develop a full understanding of the particular threat of microplastic pollution in this sentinel region, and to monitor changes over time. The potential impact of microplastic in the Arctic carbon cycle needs to be further studied. Especially under Arctic warming, the cryosphere has been experiencing rapid melting, and microplastics in the Arctic cryosphere will be released again into multi-environments with potentially increased effects on ecosystems. In particular, the degradating and thawing of permafrost may further influence the microplastics cycle, which should be strengthened in future. Meanwhile, nanoplastis in Arctic should be strengthened in future due to their small size and adverse impacts on the ecosystems. Therefore, a long-term and systematic monitoring plan on microplastics and nanoplastics in the Arctic is urgently required to address the transport, fate, and effects of microplastics in Arctic cryospheric regions.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2023.101566.

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