Arctic Plastification: Climate-driven amplification of plastic pollution through accumulation and fragmentation

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Abstract: Rapid warming of the Arctic, known as Arctic Amplification, is reshaping ice, ocean, and coastal systems in ways that alter how plastic pollution accumulates and transforms in the region. As global plastic emissions continue to rise, more debris is transported northward by rivers and ocean currents. At the same time, the loss of sea ice, coastal erosion, and the formation of new shorelines are creating new accumulation zones where plastics can build up. These processes also expose plastic debris to stronger sunlight, waves, and freeze–thaw cycles, accelerating its fragmentation into smaller particles. Together, these conditions mean that the Arctic is not just a passive sink for global plastic waste but an active and dynamic environment where macroplastics are broken down into secondary microplastics, increasing risks for ecosystems and human health.

Here, we synthesize these interconnected processes under the new concept of *Arctic Plastification* – a physical geography–based framework that links Arctic Amplification with the mechanisms that enhance both plastic accumulation and fragmentation, offering a structured basis for identifying where and how these processes interact across cryospheric, coastal, and oceanic systems. Recognizing this transformation reframes the Arctic from a remote endpoint of plastic transport into an active interface that shapes plastic fate and impact. Based on our framework we outline an interdisciplinary research agenda to quantify Arctic plastic accumulation and fragmentation dynamics under accelerating climate change. Understanding Arctic Plastification is essential for predicting how a warming planet will redistribute and transform plastic pollution worldwide.

Keywords: Arctic Amplification; macroplastic fragmentation dynamics; secondary microplastic formation; mechanical and biochemical degradation; plastic accumulation dynamics; Arctic plastic pollution

1. Introduction

The exponential growth of plastic production has resulted in its pervasive and widespread dispersal into the environment, elevating plastic pollution to a critical global problem (MacLeod et al., 2021; Stubbins et al., 2021). A significant proportion of this plastic pollution reaches the world's oceans, where it is transported over long distances and then accumulates unevenly across marine and coastal systems (Bergmann et al., 2017; Cózar et al., 2017). Despite its remoteness and sparse human population, plastic is now found across a wide range of Arctic environments from sea ice and fjords to remote beaches. The sources of this plastics have been recognized to comes from local land-based sources (Mallory et al., 2021; Strietman et al., 2021) and over long distances (Cózar et al., 2017) by ocean currents, as indicated by large-scale modelling and observational records of floating debris (e.g., van Sebille et al., 2012).

The Arctic Ocean accounts for only 3% of the global ocean surface and receives about 11% of global river discharge. The rivers flowing into the Arctic Ocean are heavily polluted and field observations reveal that plastic constitutes up to 80% of all debris along Arctic shorelines (Meijer et al., 2021; Meyer et al., 2023; Haarr et al., 2024). Moreover the poleward branch of the thermohaline circulation has been documented to function as a conveyor belt, channelling floating plastic debris from the equatorial Atlantic Ocean into the Arctic Ocean (Cózar et al., 2017). Considering the physical geographical conditions of the Arctic, which favour the delivery and accumulation of plastics, together with the projected increase in global plastic waste emissions, the region is likely to become particularly vulnerable to future risks from plastic pollution.

While the recent rise in plastic pollution is alarming in itself, its coincidence with the Arctic's rapidly changing climate adds a new layer of complexity. On one hand, it contributes to the formation of potential new accumulation zones – such as newly exposed coastlines and isostatically rebounding islands – where altered nearshore circulation and sediment dynamics may promote debris retention (Kavan et al., 2025; Irrgang et al., 2022). On the other, it fosters conditions that may accelerate macroplastic degradation and production of secondary microplastics in these areas, including high seasonal air temperature variability, freeze–thaw cycling, episodic storm events and strong winds. While multi-decadal projections suggest an overall increase mean UV-B at high latitudes by 2100 (Bais et al., 2011), localised springtime anomalies associated with ozone variability, snow/ice albedo and prolonged daylight can still temporarily enhance photodegradation (Fig. 1). This combination of physico-geographical factors imply that the Arctic is not merely a passive recipient of plastic debris–it is becoming an active agent in its transformation into secondary microplastic, finally increasing the related risks to biota and human health.

The convergence of increasing global plastic emissions (Borrelle et al., 2020), the formation of new climate-driven Arctic coastlines (Ziaja et al., 2019, 2023) that can act as plastic accumulation zones (Bergmann et al., 2017; Haarr et al., 2024), and the simultaneous intensification of processes accelerating plastic fragmentation (e.g. Bernhard et al., 2020; Zhang et al., 2023; Ma et al., 2024) underscores the need for a new conceptual framework to guide future data collection. Here, we propose the concept of Arctic Plastification – a physical geography–based (Liro and Zielonka, 2025) framework designed to systematize how and where plastic pollution accumulates and transforms under Arctic conditions. This framework links climate-driven processes with plastic transport, accumulation, and fragmentation, arguing that the system-level phenomenon of Arctic Amplification not only enhances the region's capacity to act as a macroplastic sink but also accelerates the fragmentation of plastics into microplastics. Finally, we emphasize the importance of understanding the Arctic's evolving role within the global plastic cycle (Kvale et al., 2024).

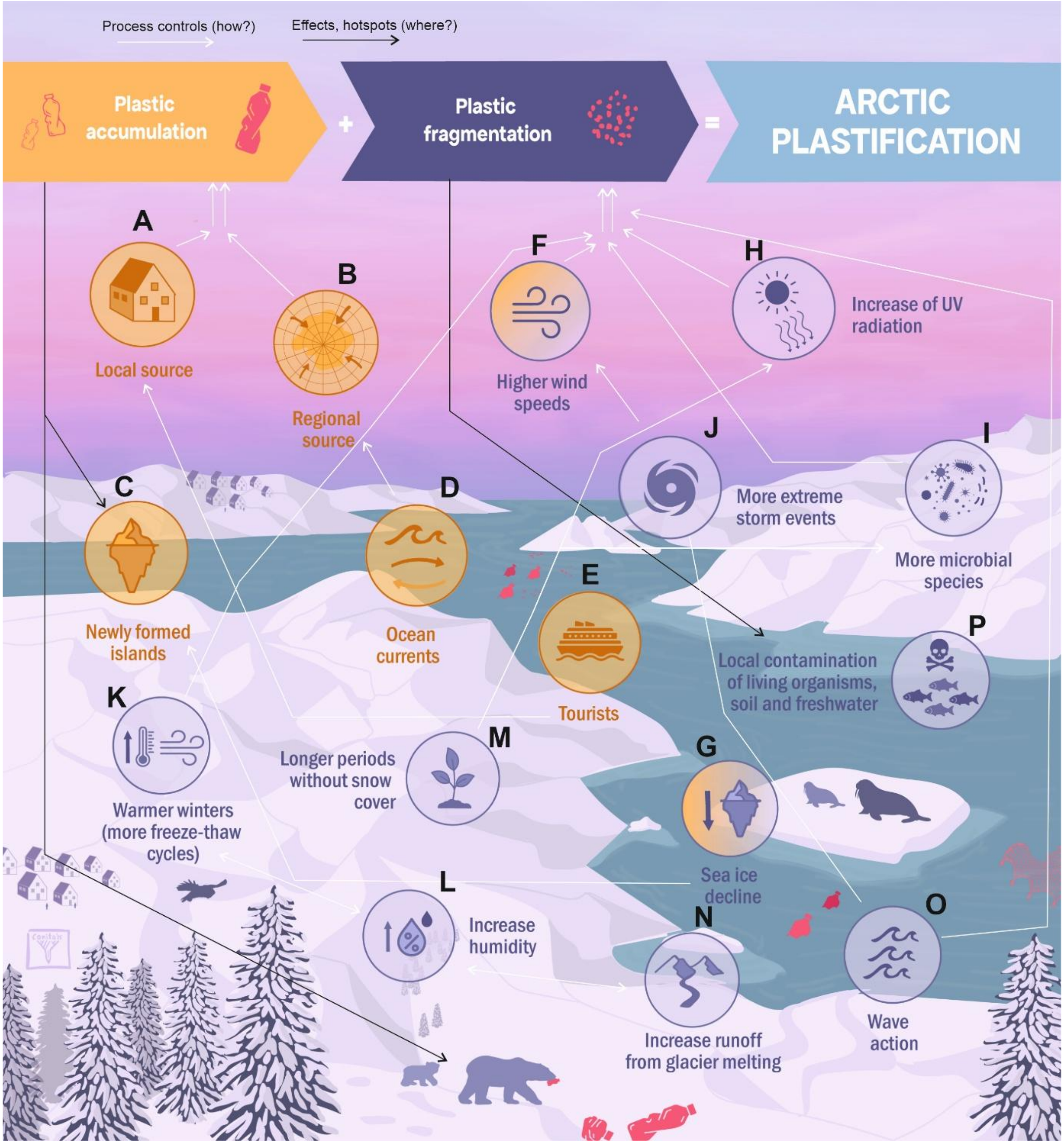

Fig. 1. A conceptual framework showing the links between plastic pollution (accumulation and fragmentation) and Arctic Amplification leading to Arctic Plastification. The increase in plastic accumulation results from plastic pollution and Arctic Amplification, which together enhance plastic fragmentation and microplastic production. Plastic accumulation factors (A–G): A – local sources (Mallory et al., 2021; Strietman et al., 2021), B – regional sources (Mallory et al., 2021; Meyer et al., 2023), C – newly formed islands (Ziaja et al., 2009; Ziaja and Ostafin, 2019; Kavan et al., 2025), D – ocean currents (Cózar et al., 2017; Lima et al., 2021), E – tourist activity

(Runge et al., 2020; Taylor et al., 2020), F – higher wind speed (Davis et al., 2023), and G – sea ice decline (Petty et al., 2018; Post et al., 2019). Plastic fragmentation factors (H–O): H – increased UV radiation (Williamson et al., 2014; Bernhard et al., 2020), I – higher microbial diversity (Zettler et al., 2013; Węsławski and Kotwicki, 2018; Rüthi et al., 2023), J – more frequent extreme storm events (Vermaire et al., 2013; Parker et al., 2022; Zhang et al., 2023), K – warmer winters (enhanced freeze–thaw cycles) (Ma et al., 2024), L – increased humidity (Wang et al., 2024), M – longer snow-free periods (Bokhorst et al., 2016), N – intensified glacier melt runoff (Błaszczyk et al., 2013; Hasholt et al., 2018; Geyman et al., 2022), and O – wave action (Corcoran et al., 2009; Zbyszewski and Corcoran, 2010). Plastic pollution (P): P – local contamination of living organisms, soil and freshwater (Collard and Ask 2021; Seewoo et al., 2024).

2. Arctic Plastification: How Arctic Amplification Is Turning the Arctic into a Microplastic Factory

Arctic Plastification refers to the growing interaction and spatial convergence between plastic accumulation and fragmentation processes occurring under rapidly changing Arctic conditions. Below, we synthesize current knowledge on key aspects of Arctic Amplification processes and, drawing on existing research on plastic pollution, highlight their links with plastic accumulation and fragmentation dynamics. Closely linked to the Arctic Amplification, the region's accelerated warming that reshapes cryospheric, oceanic, and coastal systems, this concept emphasizes how climate-driven transformations influence both where plastic debris build up and how they break down. Existing studies show that Arctic Amplification simultaneously increases macroplastic inflow (e.g., via ocean currents) and exposure along both existing and newly emerged coastlines, while also accelerating plastic breakdown into microplastic through physical and biochemical forces (Fig. 1). Recent evidence indicates that this transformation is rapidly enhancing microplastic bioavailability and their infiltration into Arctic food webs and, ultimately, human populations (Bergmann et al., 2022).

Newly formed Arctic straits and islands (Ziaja and Ostafin 2019; Kavan et al., 2025) are emerging as potential accumulation zones for macroplastic debris (C in Fig. 1). At the same time, changing ocean currents are carrying plastics into previously isolated areas (D in Fig. 1). Growing tourism, shipping, and fishing are also adding more plastic waste from local sources (E in Fig. 1) (Bergmann et al., 2017; Taylor et al., 2020; Meyer et al., 2023). The Arctic has become both a terminal basin and a convergence zone for plastic pollution, combining distant ocean currents, local inputs, and human activity across rapidly changing environments. Coastal communities in Greenland and Canada are key examples. They are now at the forefront of landscape and environmental changes, experiencing rising plastic inflows and urgent need for monitoring and effective waste management. Understanding where, how, and from whom plastic accumulates and how Arctic-specific processes accelerate its transformation remains a critical frontier in global pollution research.

2.1. Plastic accumulation in the Arctic

The Arctic Ocean has emerged as a convergence zone for macroplastic transported by oceanic and fluvial pathways. The poleward branch of the thermohaline circulation acts as a conveyor belt, delivering floating plastic debris from lower latitudes. Estimates for floating plastic in ice-free Arctic waters range from 100 to 1200 tonnes, or up to 300 billion items, exceeding levels in tropical oceans by a factor of three (Cózar et al., 2017).

These trends coincide with climate-driven changes to sea ice extent and ocean circulation (Fig. 2), which can redistribute floating debris and reshape deposition zones. Models predict macroplastic hotspots along the Russian Arctic (mainly Novaya Zemlya) and west Greenland coasts, underlining the role of both oceanic inflow and localized conditions. Simultaneously, local communities especially in west Greenland and northern Canada contribute to shoreline litter via open landfills and limited waste infrastructure. In contrast, east Greenland is mainly affected by long-range transported plastics, illustrating the dual nature of Arctic pollution sources (Mallory et al., 2021).Empirical data confirm substantial plastic accumulation across Arctic shorelines (Haarr et al., 2024). For example, plastics constitute 73–80% of all beach debris in areas like Svalbard and northern Canada, with polymer types such as polyethylene (PE) and polypropylene (PP) dominating (Mallory et al., 2021). These materials fragment more easily than denser polymers like PET, and can further be considered as potential sources of secondary microplastic (Liro et al., 2023).

Other anthropogenic pressures are also intensifying. For example, Arctic tourism has surged (E in Fig. 1) quadrupling in summer and increasing 600% in winter between 2006 and 2016 (Runge et al., 2020). As sea ice declines, cruise ship activity has expanded rapidly, raising the likelihood of waste leakage. Fishing remains a dominant source of macroplastic, especially abandoned or discarded gear (ALDFG), which accumulates in remote coastal zones like the Barents Sea (Bergmann et al., 2017). Non-fishing maritime traffic is also a concern, though less well quantified. The discovery of household plastics on remote beaches points to shipboard sources from galleys and domestic waste. The expansion of Arctic maritime traffic, as documented in the Arctic Ship Traffic Database, further underscores the need for comprehensive governance and waste management.

Glacial systems represent another emerging vector for macroplastic processing. Meltwater-fed rivers with high flow energy and sediment loads facilitate mechanical fragmentation, especially near settlements (N in Fig. 1). Seasonal discharge peaks in spring (snowmelt) and summer (ice melt) correspond with increased plastic mobilization. Settlements near glacierized areas–such as the Greenlandic towns of Qaqortoq, Nuuk and Ilulissat, and towns along the Alaskan coast– are particularly relevant, whereas Russian Arctic populations are more industrial and distanced from glacier-influenced zones (Fig. 2).

Concurrently, the Arctic coastline is physically transforming due to glacial retreat, isostatic rebound, and sediment redistribution. Over 40 new islands have emerged in Greenland and the Russian Arctic over recent decades (Fig. 2) (Ziaja and Haska, 2023), in addition to the ongoing evolution of coastal depositional landforms such as sand spits, isthmuses, tombolos, and shoals These newly exposed landforms may act as novel accumulation zones and fragmentation hotspots, while changing sea ice extent and isostatically rebounding may alter nearshore circulation and sediment dynamics and thereby promoting longshore drift and debris accretion (Fig. 2). The dynamic nature of these coastlines, combined with increasing storm surge frequency and shoreline erosion, which exceeds 1.4 m yr^{-1} in some regions (Irrgang et al., 2022), raises the likelihood of physical stress on stranded plastics.

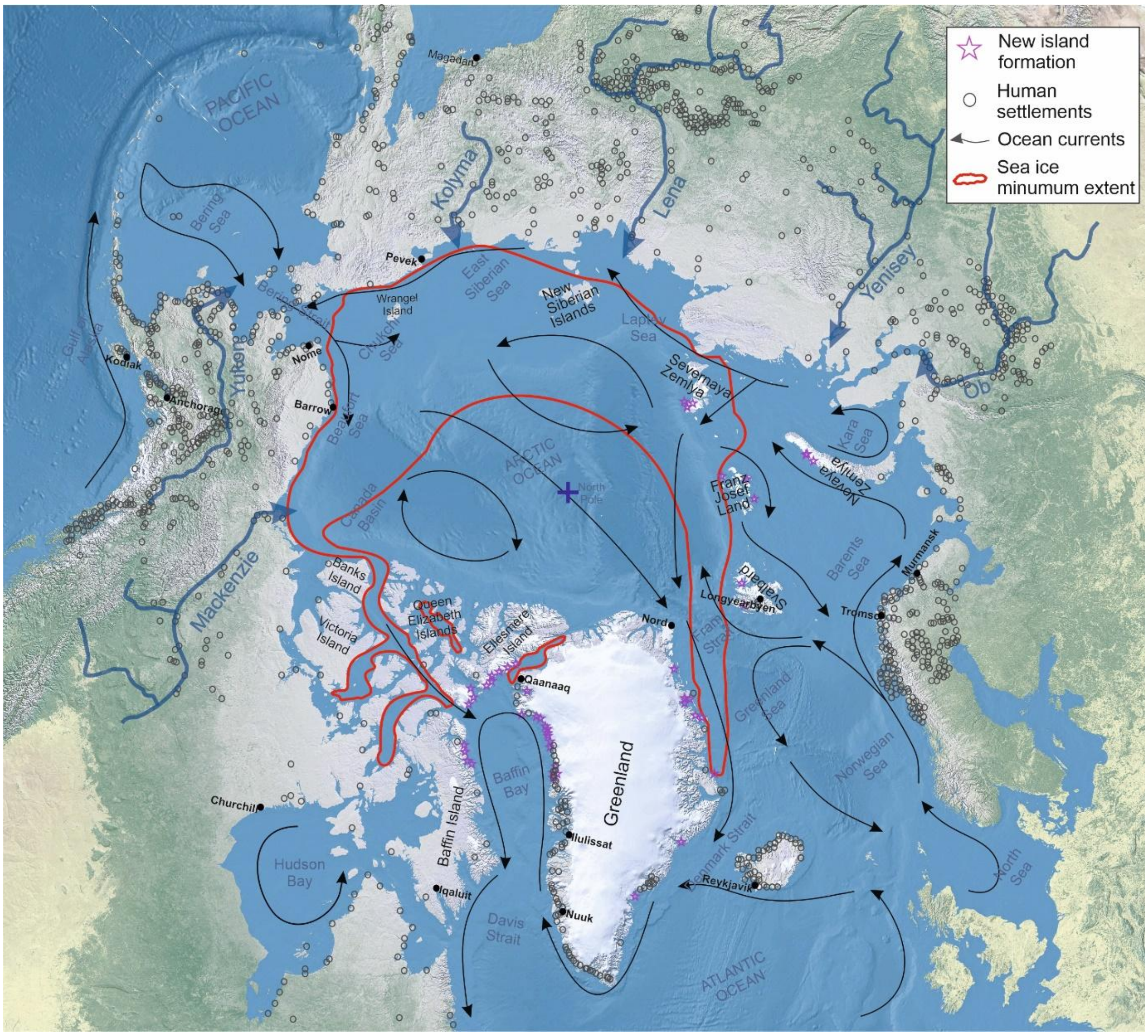

Fig. 2. Pathways of plastic debris transport and accumulation in the Arctic. Ocean current data is adapted from Macdonald et al. (2005). Data on human settlements within the Arctic are from Nordregio (2024) and based on National Statistical Institutes and for Alaska from the Department of Labor and Workforce. Extent of highest sea ice loss (1979–2023) are derived from C3S/ECMWF/EUMETSAT/MET Norway. Information on newly formed islands is from Kavan et al. (2025), Ziaja and Haska (2023). In the Canadian Arctic, the locations of new islands were identified based on regions with the most significant glacial recession, as reported by Cook et al. (2019).

2.2. Plastic fragmentation in the Arctic

UV radiation is a critical driver of fragmentation (Andrady, 2015). Amplified by sea ice loss, Arctic UV-B levels are expected to increase up to tenfold by 2100 compared to the 1950s (Williamson et al., 2014). This shift enhances photodegradation, particularly for blue, green, and red plastics, which absorb more radiation than black or white variants. Seasonal patterns further modulate this effect. For example, springtime UV anomalies and continuous summer daylight intensify exposure to UV light, accelerating polymer breakdown (H in Fig. 1).

Biological processes also shape plastic degradation (Węsławki and Kotwicki 2018). Biofilms on macroplastics can shield against UV while enabling microbial breakdown (I in Fig. 1). In low-energy Arctic coastal lakes and lagoons, biofilms may thrive; in high-energy coasts, abrasion may reduce their persistence. Incorporating these microbial interactions into the Arctic Plastification framework provides a more complete understanding of how environmental and biological mechanisms collectively control the pace of plastic transformation in polar systems.

Weather extremes–especially intensified winter warm spells (K in Fig. 1) and cyclonic activity–are reshaping macroplastic fragmentation dynamics. Rising storm frequency and intensity (J in Fig. 1) mobilize plastic debris from land to sea and vice versa, often subjecting it to physical fragmentation along dynamic coastal fronts. Storm surges combined with strong onshore winds promote inland transport of plastics (Fig. 3), which can extend exposure to freeze–thaw cycles and wind abrasion (F in Fig. 1). The spatial variability of these forces adds complexity to modelling plastic fate across the region.

Temperature and humidity play further roles. Laboratory studies demonstrate that plastics subjected to repeated freeze–thaw cycles become brittle (Koutnik et al., 2022), fragmenting more readily. As warming accelerates, these cycles become more frequent in Arctic winters. Elevated humidity, linked to fog deposition, exacerbates internal stress in polymers, promoting microcrack formation (Kablov et al., 2021). These abiotic stressors work synergistically to advance macroplastic degradation in ways unique to the Arctic (K, L in Fig. 1).

The age and origin of plastic debris significantly influence its fragmentation potential (Sorasan et al., 2022). Long-range transported plastics typically exhibit more advanced weathering and fragment more rapidly, releasing micro- and nanoparticles. Locally sourced plastics, though less degraded, may persist near communities, increasing local exposure. Understanding degradation pathways requires comparing polymer types under differing environmental histories such as age, transport distance, and local conditions.

The toxicological implications of this degradation are profound. Fragmented plastics introduce both physical and chemical hazards to Arctic biota. In shoreline zones, animals such as polar bears, foxes, seabirds, seals, and whales encounter microplastics through ingestion and environmental contact (N in Fig. 1). Secondary exposure via contaminated seafood is a growing concern for Arctic communities reliant on marine resources, and although Bergmann et al. (2022) synthesised Arctic microplastic records, they did not analyse multi-decadal trends; regional datasets suggest possible increases, but robust pan-Arctic trends cannot yet be established. Microplastics and associated additives such as BPA and phthalates have been linked to reproductive and metabolic disruptions in mammals, reinforcing the need for preventive action.

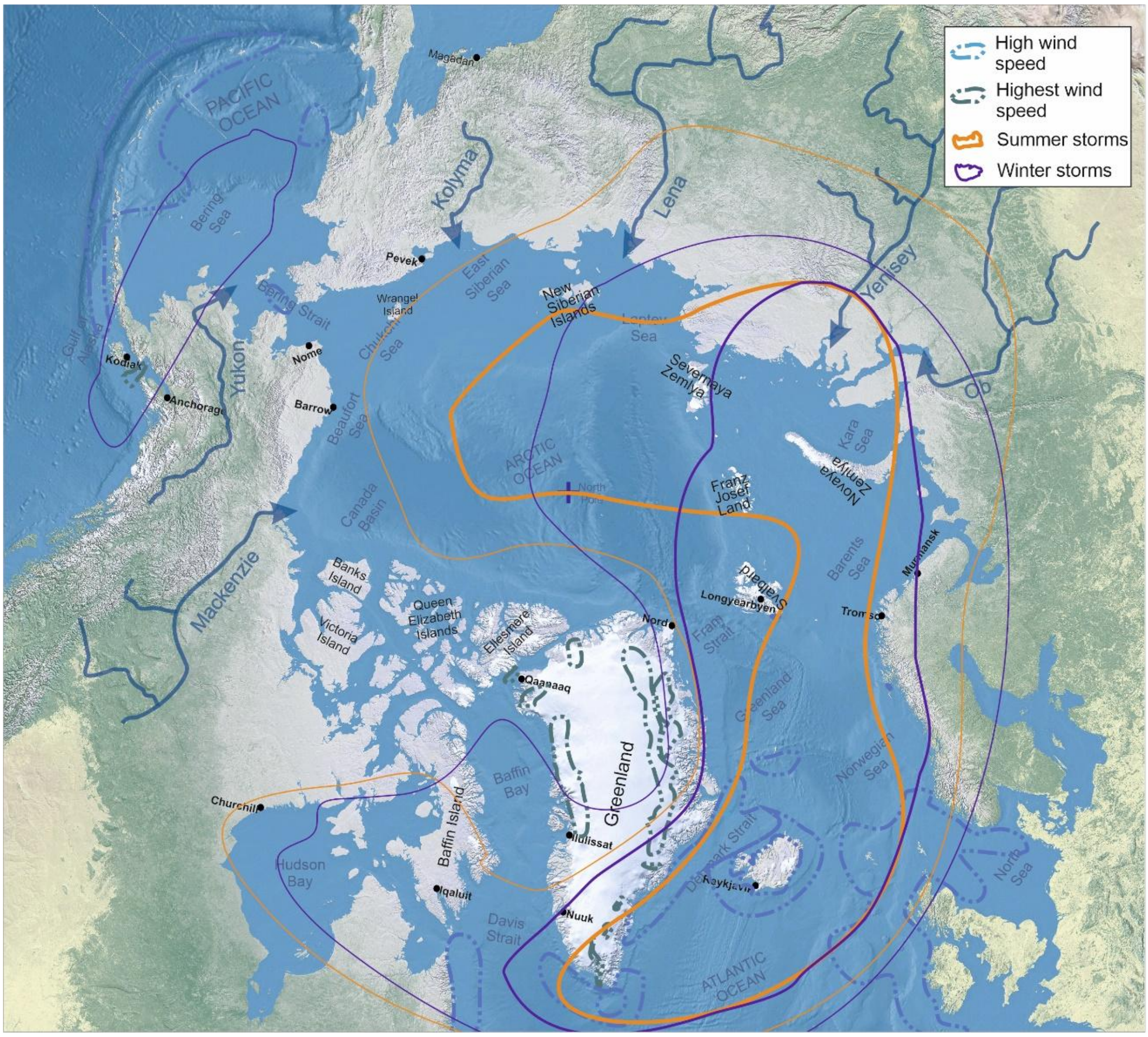

Fig. 3. Pathways of selected plastic fragmentation controls in the Arctic. Storm frequency data (1986–2021) adapted from Zhang et al., (2023). Wind speed data (thresholds: high wind speeds >8 m s^{-1} and highest wind speeds >10 m s^{-1} at 10 m above sea level) are sourced from the Global Wind Atlas (Davis et al., 2023). The spatial coverage of data related to UV radiation and freeze–thaw cycles is not uniform across the Arctic and has therefore not been included on the map.

Outlook: A Strategic Agenda for Arctic Plastification Research

Arctic Plastification marks a pivotal shift in the global plastic cycle from viewing the Arctic merely as a remote endpoint of plastic transport to recognising it as a potential transformation interface shaped by oceanic, cryospheric and climatic drivers. We suggest that fragmentation can be key mechanism linking accumulation to secondary sourcing, turning the Arctic from a passive recipient into an active transformer of macroplastics into microplastics. Recognising this transition reframes the Arctic as a critical interface between continental and oceanic plastic fluxes, where climate-driven processes govern both accumulation and fragmentation. Amplified by climate change, rapid environmental transitions such as sea ice retreat, altered currents, and extreme weather–are accelerating both macroplastic accumulation and fragmentation. These dynamics elevate risks to Arctic biodiversity and human communities and warrant urgent scientific attention. Addressing this emergent phenomenon demands a transdisciplinary, globally integrated research strategy that bridges empirical evidence, mechanistic modelling, and policy engagement. We propose a tiered agenda structured around foundational, integrative, and translational priorities.

Foundational priorities: process quantification and environmental controls

At the core lies the need to quantify the physical and biochemical fragmentation regimes operating across Arctic environments. Research must isolate the roles of UV exposure, freeze–thaw cycling, wave-induced mechanical stress, and biofilm-mediated degradation across diverse polymer types. Standardized protocols should be deployed across mapped hotspot zones (Fig. 3) including glacial river mouths, rebounding islands, and newly exposed coastlines affected by the Arctic amplification. These sites concentrate aged, fragmentation-prone macroplastics. Capturing seasonal extremes and episodic disturbances (e.g., cyclonic storm surges or sea-ice-free events) is critical for generating robust, field-calibrated rates of accumulation and breakdown.

Integrative priorities: coordinated monitoring and model incorporation

Establishing interoperable observatories along both eastern and western Arctic coasts is essential. These should combine remote sensing, in situ tracking of polymer aging, and engagement with Indigenous communities to co-design monitoring. Collaborative frameworks – such as UNEP's Global Partnership on Marine Litter and the Arctic Council's Expert Groups– should guide integration. Critically, Arctic-specific parameters (e.g., UV flux, freeze–thaw dynamics, microbial action) must inform global plastic fate models (e.g., Lebreton et al., 2017; Meijer et al., 2021), which currently underrepresent Arctic transformation pathways. Doing so will improve projections of secondary microplastic production and redistribution in subpolar and polar ecosystems.

Translational priorities: risk, governance, and policy relevance

Plastification poses escalating threats to Arctic wildlife, food security, and health. Sentinel marine species – seabirds, seals, whales – are susceptible to microplastic ingestion and toxic exposure, with cascading impacts on Indigenous communities dependent on marine resources. Research must align with frameworks such as the Stockholm Convention and AMAP while respecting knowledge sovereignty through equitable partnerships. This conceptual bridge between science and governance underscores the Arctic's emerging role as a laboratory for understanding and managing plastic transformations under a warming climate. Our mapped hotspots (Figs. 2, 3) offer a roadmap for science-based policy and local engagement, ensuring that risk assessments translate into actionable strategies tailored to Arctic realities.

Only by addressing these interconnected priorities – scientific, infrastructural, and ethical – can we begin to understand and mitigate the far-reaching consequences of Arctic Plastification in the Anthropocene.

Acknowledgment

We gratefully acknowledge discussion and feedback with dr Tim van Emmerik during the writing process of the manuscript. Figure 1 was designed by Carmen Cañizares (@canitanatura), based on the authors' concept.

Author contributions

A.Z. conceived the idea, compiled the literature, and wrote the manuscript with substantial contributions from M.L. and J.C.Y.; A.Z. and M.L. conceptualized the overall structure of the work and prepared the figures. All authors reviewed, revised, and approved the final version of the manuscript.

Competing interests

The Authors declare no competing interests.

Additional information

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