Microplastic contamination in the Canadian Arctic, Iqaluit, Nunavut

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ABSTRACT

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Microplastics are intricate plastic particles (<5 mm in length) with complex chemical mixtures that are pervasive globally. Nonetheless, our understanding of microplastic contamination in the Canadian Arctic is limited. Therefore, this thesis aimed to investigate the concentration and characteristics of microplastics in and surrounding the community of Iqaluit, Nunavut. Our findings suggest Iqaluit is a local source of microplastics in the Arctic based on their concentration in road dust (2.83 ± 3.72 µg/g). Microplastic concentrations were comparable to those in metropolitan areas and given their abundance in parking lots it is suggested that these are temporary reservoirs for microplastics and tire wear particles. Further, lakes predominately upwind of Iqaluit had a greater concentration of microplastics (134 ± 204 µg/L) than lakes downwind (30.8 ± 55.5 µg/L). These findings underscore the importance of assessing both local-scale and long-range sources when examining microplastic contamination in the Arctic.

Keywords: Plastic pollution, Atmospheric microplastics, Canadian Arctic, Biomonitoring, Fourier-transform Infrared Spectroscopy (FTIR)

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Chapter One: General Introduction

Plastics

Plastics are one of the most transformational inventions to date. Their physical properties are versatile, they are lightweight and durable, they are resistant to water and chemicals, and cost-efficient. In 2021, over 450 million tonnes of plastics were manufactured worldwide for unique purposes. The majority of annual manufactured plastic is for packaging (36%), often consisting of materials that are immediately disposed of following consumption or use. These include water bottles and dispensing containers, cutlery and cups, shampoo bottles, bags, food packaging film, and hot drink cups.

Plastics are synthetic materials, and they are created through the process of polymerization. Two common processes involved in plastic manufacturing are addition and condensation polymerization (Wang et al., 2019). Addition polymerization involves the rearrangement of carbon bonds to allow monomers to directly link with one another (Wang et al., 2019). Condensation polymerization involves carbon-heteroatom bond formation, such as with oxygen or nitrogen (Wang et al., 2019). Plastics are also associated with chemical additives, such as di-2-ethylhexyl phthalate (DEHP) which is a plasticizer that enhances the flexibility of the plastic material (Maddela et al., 2023). Further, stabilizers are added to preserve the plastics' physical integrity, such as from ultraviolet degradation. While dyes are added to provide plastic with unique pigments.

The polymer composition of plastics separates them into thermoplastics and thermoset plastics (Rochman et al., 2019). Thermoplastics are plastics that can be melted and reformed multiple times without undergoing chemical change. They are beneficial because of their versatility, and range of physical properties (Biron, 2016). Common thermoplastics include (high-density and low-density) polyethylene, polypropylene, polystyrene, polyvinyl chloride, and polyethylene terephthalate (Biron, 2016). In contrast, polyurethane is a thermoset plastic, and it undergoes a chemical change when heated (Biron, 2016).

Given the broad application of plastics in modern Western society, the production of plastic materials has exponentially increased (MacLeod et al., 2021). However, a majority of plastic materials have an end life in the environment (ECCC, 2019). Therefore, plastics have reached nearly every surface on Earth in the form of macroplastics (>5000 µm in length), microplastics (1–5000 µm), and nanoplastics (<1 µm). As such, plastics may be one of the most pervasive and complex environmental contaminants of the century.

Microplastics

Microplastics is a catch-all term for plastic particles 1 µm to 5 mm in length (Cole et al., 2011; Rochman et al., 2019). Primary microplastics are manufactured to be micro-size, including micro-beads used as exfoliants in personal care products and pre-production pellets and nurdles (Rochman et al., 2019). Secondary microplastics form in the environment when plastic debris undergoes physical (i.e., wave action, vehicle traffic), chemical (i.e., ultraviolet radiation), or biological (i.e., microbial activity) fragmentation (Rochman et al., 2019).

Microplastics are unique and intricate plastic particles, and they are generally characterized by their shape (e.g., fiber, film, foam, fragment, bead), size, and polymer composition (Rochman et al., 2019). Briefly, (1) fibers are cylindrical often with an equal diameter and either blunt, fray, or pointed ends; (2) foams are cloud-like and compressible when poked with a dissecting instrument; (3) fragments are irregular and rigid and may appear round, angular, or subangular in shape; (4) films are flat, thin, and malleable; and (5) beads are spherical (Rochman et al., 2019). Microplastic shapes can help determine source contributors, and they influence how microplastics behave in the environment, such as in the atmosphere (Preston et al., 2023; Ward et al., 2024). The shape is also used to report mass concentrations of microplastics, by simplifying the particle to a three-dimensional shape (i.e., fibres are considered cylindrical).

Finally, microplastics are composed of synthetic polymers. The polymer types are associated with different densities, and knowing particle density can help develop methods for extracting microplastics from environmental media. Further, coupled with the length and width, the mass of microplastics can be estimated (with limitations). Reporting the mass concentration of microplastics (in addition to count concentrations) builds on our understanding of the quantity of plastic contamination in the environment. Understanding polymer density is also important when considering the fate of microplastics in diverse environments (e.g., sedimentation of microplastic particles in freshwater).

Microplastics also exist in a range of colours, such as blue, green, red, orange, yellow, and white (Rochman et al., 2019). However, quantifying particle colour is subject to personal bias. Microplastics are often multi-coloured, or the colour is difficult to identify (e.g., purple vs dark blue). Colour is also often not reported because microplastics in the environment are subjected to bleaching (Zhao et al., 2022).

The majority of microplastic research has focused on thermoplastics, and only recently has research expanded to include elastomers, such as tire wear particles (Wagner et al., 2018). Tire wear particles form through abrasive forces between vehicle tires and road surfaces, and their presence is gaining increasing attention due to their persistence in urban environments (Kovochich et al., 2021). However, there are controversial opinions on whether tire wear particles are microplastics or micro-rubbers. Throughout this thesis tire wear particles will be assessed separately from traditional primary and secondary microplastics due to the controversial definition and because source contributors are easily distinguished as vehicle tire wear.

Microplastics in the Atmosphere

During the past decade, the number of peer-reviewed publications on microplastic contamination in marine environments has increased exponentially (Wang et al., 2023). Nonetheless, reporting on microplastic contamination in the atmosphere remains limited. Microplastics are emitted into the atmosphere from various sources, including landfills, construction sites, land-based biosolid applications, and from dryer vents during synthetic textiles laundering. Once microplastics are emitted into the atmosphere they may be deposited into local or long-range environments through processes of dry (settling due to gravity) or wet (removal from the atmosphere in rain or snowfall; “scavenging”) deposition (Zhang et al., 2020). Once deposited, microplastics may become incorporated into the system they were deposited into, or they may be resuspended into the atmosphere (and follow the cycle of potentially depositing in local or long-range environments).

The shape (i.e., fibre, fragment, film, foam, bead, etc.) of the microplastic particle has a strong influence on its behaviour and ability to distribute in the atmosphere (Bergmann et al., 2019; Munyaneza et al., 2022; Zhang et al., 2020). For instance, microplastic fibres have the potential to travel greater distances from their source compared to non-fibrous microplastics (i.e., fragments, foams, films, and beads). This is because microplastic fibres have a greater surface area relative to mass ratio and experience more drag in the air compared to non-fibrous microplastics (Preston et al., 2023; Tatsii et al., 2024). Microplastic fibres also experience dissimilar aerodynamic behaviour than non-fibrous microplastics, resulting from their irregular movement (tumble or float) and orientation (horizontal versus vertical).

Although the shape of a microplastic particle plays a role in the transport of microplastics in the atmosphere, the size may also influence the distance it can travel. For instance, the length range of microplastic particles in snow samples from an urban environment ranged from 0.3 mm to 4 mm (Zhang et al., 2020), while particles in snow samples from a remote environment were less than 0.025 mm (Bergmann et al., 2019). The detection of varying particle sizes between urban and remote environments may be a result of sampling and analytical methods, however, it is also possible that small microplastics (of equivalent shape) remain in the atmosphere longer and travel further distances than larger particles (Ward et al., 2024).

Passive and active sampling methods have been used to understand atmospheric microplastics. Passive sampling methods include bottle and funnel, road dust, and biological monitoring. The use of passive sampling methods is advantageous as they are inexpensive, require little effort to deploy and retrieve, and require no electricity, making them an efficient method for examining microplastics in remote environments (such as the Arctic). Due to these factors more samples can be collected thus increasing the spatial coverage. The bottle and funnel method collects microplastics that settle (through dry and wet deposition processes), and it is a common passive sampler to estimate microplastics in total atmospheric deposition. Whereas road dust and moss biomonitoring are novel approaches to estimate atmospheric microplastics. Road dust is composed of media from multiple sources, including atmospheric deposition. The collection of road dust requires minimal field equipment, and the simplicity of field methods allows the collection of samples over a greater spatial area. Biological monitors, such as lichen and moss species have been collected to estimate the accumulation of microplastics from atmospheric deposition (Bertrim & Aherne, 2023; Jafarova et al., 2022; Loppi et al., 2021; Roblin & Aherne, 2020). In contrast to passive sampling, active sampling requires electricity at a secure location, which is a challenge in remote environments and reduces the ability to cover a large spatial area. However, active sampling enables the collection of wet-only precipitation, and filtering air using a vacuum pump. This allows researchers to better understand how atmospheric processes (such as wet deposition) influence microplastic deposition.

Microplastics in Freshwater Lakes

Only recently have lakes gained increasing attention for the presence of microplastic contamination. Microplastics have been detected in freshwater bodies globally (Nava et al., 2023), and their concentration and characteristics are often positively correlated to anthropogenic infrastructures, such as proximity to urban centers and wastewater treatment plants (Liu et al., 2019a). Indicating that freshwater systems near urban environments are vulnerable to microplastic pollution (Nava et al., 2023). Studies have identified microplastics in freshwater catchments isolated from anthropogenic infrastructures, indicating atmospheric microplastic deposition is a pathway for microplastics to isolated regions. Freshwater systems can have a high retention time for microplastics making them reservoirs (accumulators) of microplastic contamination (Nava et al., 2023). There are various methods for sampling microplastics in freshwater, two common methods include (a) volume-reduced sampling using a plankton net or sieve and pump (100–1000 L), and (b) bulk samples (10–50 L) – both of which may additionally involve digesting and filtering to extract microplastics.

Lakes are widespread across the Canadian Arctic and reflect spatial and temporal responses to both natural processes and human activities at a catchment scale (Adrian et al., 2009). Catchment-scale studies have been widely used to assess the fate of atmospheric pollutants (Brown, 2023; Karl 2023; Roblin, 2019, Windsor et al., 2019). Further, biological monitoring has been widely used to assess atmospheric pollutant deposition (Bertrim & Aherne, 2023; Clough, 1975; Harmens et al., 2011, 2013; Olmstead & Aherne, 2019; Roblin & Aherne, 2020).Since the early 1960's, mosses have been sampled to investigate atmospheric contaminants, such as trace elements (Berg et al., 1995; Halleraker et al., 1998), nitrogen (Harmens et al., 2011; Olmstead & Aherne, 2019), persistent organic pollutants (Harmens et al., 2013), particulate matter (Clough, 1975) and microplastics (Bertrim & Aherne, 2023; Roblin & Aherne, 2020). Mosses have a high surface area and can accumulate microplastics deposited from the atmosphere. Further, lake water and sediment can act as reservoirs at the catchment scale integrating ecosystem responses over time (Adrian et al., 2009).

In aquatic systems, microplastics infiltrate the food chain and may have adverse physical effects on organisms when ingested such as accumulating in stomachs and causing blockages (Liu et al., 2020). Microplastics are also associated with chemical additives (e.g., polycyclic aromatic hydrocarbons, petroleum hydrocarbons, and phthalates) that can leach into surrounding environments (Andjelković et al., 2021; Teuten et al., 2009) and have adverse effects on aquatic organisms (Gunawardana et al., 2012). Despite the environmental presence and potential ecological effects of microplastics in freshwater bodies globally, few studies have evaluated microplastics in Arctic lakes (AMAP, 2021).

Microplastics in the Arctic

Microplastics in Arctic marine environments have gained increasing attention; they have since been detected in Arctic surface water (Huntington et al., 2020; Lusher et al., 2015), the water-column (Andrady, 2011; Lusher et al., 2015; Tekman et al., 2020), invertebrates (Bos et al., 2023; Jamieson et al., 2019), fish (Kögel et al., 2023; Morgana et al., 2018), deep-sea sediment (Bergmann et al., 2017; Huntington et al., 2020; Tekman et al., 2020), sea-algae (Bergmann et al., 2023), sea-ice (Kanhai et al., 2020; Obbard et al., 2014; Peeken et al., 2018), and sea-birds (Hamilton et al., 2021; Provencher et al., 2014).

Further, microplastic research in Arctic regions has primarily focused on the role of long-range transportation (i.e., ocean currents or atmospheric transport). For instance, the North Atlantic branch of the Thermohaline Circulation is known to support the transport of microplastics from distant sources to the Arctic through ocean currents (Cózar et al., 2017), in addition to the transport and melting of sea ice (Obbard et al., 2014). Atmospheric circulation is also a significant transport mechanism that aids the transport of microplastics from distant sources to Arctic regions (Ward et al., 2024), while seabirds aid in transporting microplastics within the Arctic (Hamilton et al., 2021).

Microplastics have since been classified as contaminants of emerging Arctic concern (AMAP, 2021), however, there is a paucity of research on microplastics in terrestrial Arctic environments. The Arctic Monitoring and Assessment Program (AMAP) acknowledges these knowledge gaps and has declared immediate baseline monitoring of microplastic contamination in Arctic freshwater and the atmosphere (AMAP, 2021).

Thesis Objective

As noted, there are knowledge gaps concerning the concentration and characteristics of microplastics in terrestrial Arctic environments and the contribution of local sources to microplastics in the Arctic. The objective of this thesis was to investigate the concentration and characteristics of microplastics within the community of Iqaluit, Nunavut, and surrounding environments (i.e., lakes upwind and downwind of Iqaluit) to better understand how Iqaluit contributes to microplastic contamination. Iqaluit is the largest community in Nunavut, and it was selected as a study region due to pre-existing research relationships. There are four research chapters in the thesis to address the primary objective.

The first research chapter assessed Iqaluit as a local contributor to atmospheric microplastics in the Arctic, using road dust as an indicator for atmospheric microplastic deposition. In this study, road dust was collected and processed from commercial (n = 8) and industrial (n = 8) areas of Iqaluit. It was predicted that commercial sites would be dominated by microplastic fibres due to the abundance of people in these areas compared to industrial regions. Further, microplastic concentrations were predicted to be less than concentrations reported in the literature from metropolitan cities due to the low population density of Iqaluit.

The second research chapter investigated the concentration and characteristics of microplastics in Arctic lakes (n = 19; upwind and downwind) using a catchment-based approach. Lake water and sediment was collected to determine the fate of microplastics in the freshwater system, while stair-step moss was collected to biologically monitor microplastics in atmospheric deposition. Given that the community influences the concentration and characteristics of microplastics, it was predicted that lakes downwind of Iqaluit would have a greater concentration and diversity of microplastic characteristics.

The third research chapter investigated how sample collection methods influence the estimated concentration and characteristics of microplastics in Arctic lake water. In this chapter a volume-reduced and a bulk sampling method were performed at 19 lakes and ponds surrounding Iqaluit. It was predicted that there would be a greater abundance of non-fibrous microplastics in the volume-reduced water samples, as the pore size of a plankton net results in the loss of fibrous microplastics (due to their narrow diameter).

The final research chapter evaluated the presence of atmospheric microplastics over the Arctic Ocean in the High Arctic. In this study, air was sampled along 12 transects through the Canadian Archipelago of Nunavut on the Canadian Coast Guard Ship Amundsen in September 2023. This study provided insight into the potential long-range transport of microplastics in the atmosphere in addition to potential local sources, such as scientific activities on the vessel.

The following four research chapters are presented as standalone manuscripts; therefore, some text (e.g., laboratory and analytical methods) may be repeated across chapters to fulfill manuscript requirements. All studies follow a design that involved sample collection, analytical procedures to extract microplastics from sample media, visual analysis to quantify microplastic shape and size, polymer analysis using Fourier-Transform Infrared spectroscopy to determine polymer type, and data acquisition and analysis. Mass and count concentrations are reported for microplastics and tire wear particles across all studies to enhance our understanding of environmental concentrations.

Chapter Two: Microplastic and tire wear particles in Arctic road dust, Iqaluit, Nunavut

2.0 Introduction

The exponential growth in plastic production since the 1950's coupled with the mismanagement of waste has resulted in a plastic pollution crisis, exemplified by the ubiquity of microplastics (plastic particles 1 µm to 5 mm in length; MacLeod et al., 2021). Microplastics are complex contaminants generally characterized by their physical and chemical attributes, including shape, size, and polymer composition (Cole et al., 2011; Rochman et al., 2019). Primary microplastics are manufactured to be micro-size (e.g., plastic microbeads as exfoliants in personal care products and pre-production pellets or nurdles; Rochman et al., 2019). Secondary microplastics form from chemical, physical, and biological fragmentation of plastic material, including the shedding of synthetic textiles (Rochman et al., 2019). Microplastics have various sources, and they enter the wider environment through several pathways, including atmospheric transport and deposition (Allen et al., 2019; Dris et al., 2016; Roblin et al., 2020; Welsh et al., 2022b).

Atmospheric microplastics are plastic particles that have been directly emitted or resuspended into the atmosphere. In major urban environments, atmospheric microplastics have received increasing attention during the past decade, as they are significant sources of microplastics (Dris et al., 2016; Wright et al., 2020). Nonetheless, the contribution of Arctic communities to atmospheric microplastics remains understudied (AMAP, 2021). Despite the recognition that microplastics are emerging contaminants of Arctic concern, there is a paucity of studies that investigate atmospheric microplastics especially in Arctic communities (AMAP, 2021).

Road dust is present in every urban environment, and it is composed of organic and inorganic materials (e.g. silica, clay, silt, brake pad dust, asphalt, tire wear particles, etc.) that arise from diverse sources, including atmospheric deposition (Gunawardana et al., 2012), and provides a snapshot of local atmospheric deposition. Road dust has been widely used as a passive indicator of microplastic and tire wear atmospheric deposition (Dehghani et al., 2017; O'Brien et al., 2021; Patchaiyappan et al., 2021) as it facilitates spatial assessments, making it possible to monitor trends across a region.

The objective of this study was to investigate the concentration, characteristics, and deposition of microplastics and tire wear particles in an Arctic community, using road dust as an indicator of atmospheric microplastic deposition. During the summer of 2022, road dust was collected from commercial and industrial areas in Iqaluit (ᐃᖃᓗᐃᑦ), Nunavut, and assessed for microplastics and tire wear particles. Herein, tire wear particles are presented separate from traditional microplastics (i.e., non-rubber fibres, fragments, films, foams, and beads), despite the recognition that tire wear particles have been previously categorized as a microplastic (Knight et al., 2020).

2.1 Methods

2.1.1 Study Area and Site Selection

Iqaluit, Nunavut (63.7467° N, 68.5170° W), is located in Koojesse inlet of Frobisher Bay in northern Canada. It is the largest community in Nunavut with an area of 52.5 km^2 and a population of approximately 8,000. The community has few paved roads, no traffic lights, no stormwater drains, and <8,000 registered vehicles (dominated by trucks, all-terrain vehicles, and snowmobiles). Iqaluit is surrounded by barren land with low vegetation and has a polar tundra climate that is influenced by the Labrador Current. The average summer temperature during 2020–2022 was 6.1°C (June to September) with an average wind speed of 3.6 m/s from the south-east (ECCC, 2023). In contrast, the average winter temperature during 2020–2022 was –18.9°C (December to March) with an average wind speed of 4.3 m/s from the northwest (ECCC, 2023). The average annual precipitation in Iqaluit was ~217 mm between 2020–2022 (ECCC, 2023). Before the study period (14–15 July 2022), the highest precipitation event was on 24 June 2022 (0.6 mm) and the last precipitation event before sampling was 6 July 2022 (0.05 mm; Figure S1; ECCC, 2023).

The study sites were randomly selected from commercial and industrial areas in Iqaluit (Figure 2.1; Table 2.1). This was accomplished by subdividing commercial and industrial regions into equal area sampling units using k-means clustering of 10 m by 10 m land cover classified grids (Spatial Coverage Sampling and Random Sampling from Compact Geographical Strata; Version 0.4-2;

Walvoort et al., 2010). A total of eight commercial sites were selected from parking lots (n = 4) and roadsides (n = 4), and eight industrial sites were selected from roadside locations (n = 8), due to the lack of paved parking lots in Iqaluit. Commercial sites were located within the downtown core of the community, while the industrial sites were clustered to the northwest of the community (due to limited paved surfaces in industrial regions; Figure 2.1). Commercial areas consisted of storefronts, recreational centers, and hotels. Industrial areas consisted of construction enterprises, fuel depots, automobile shops, and storage yards.

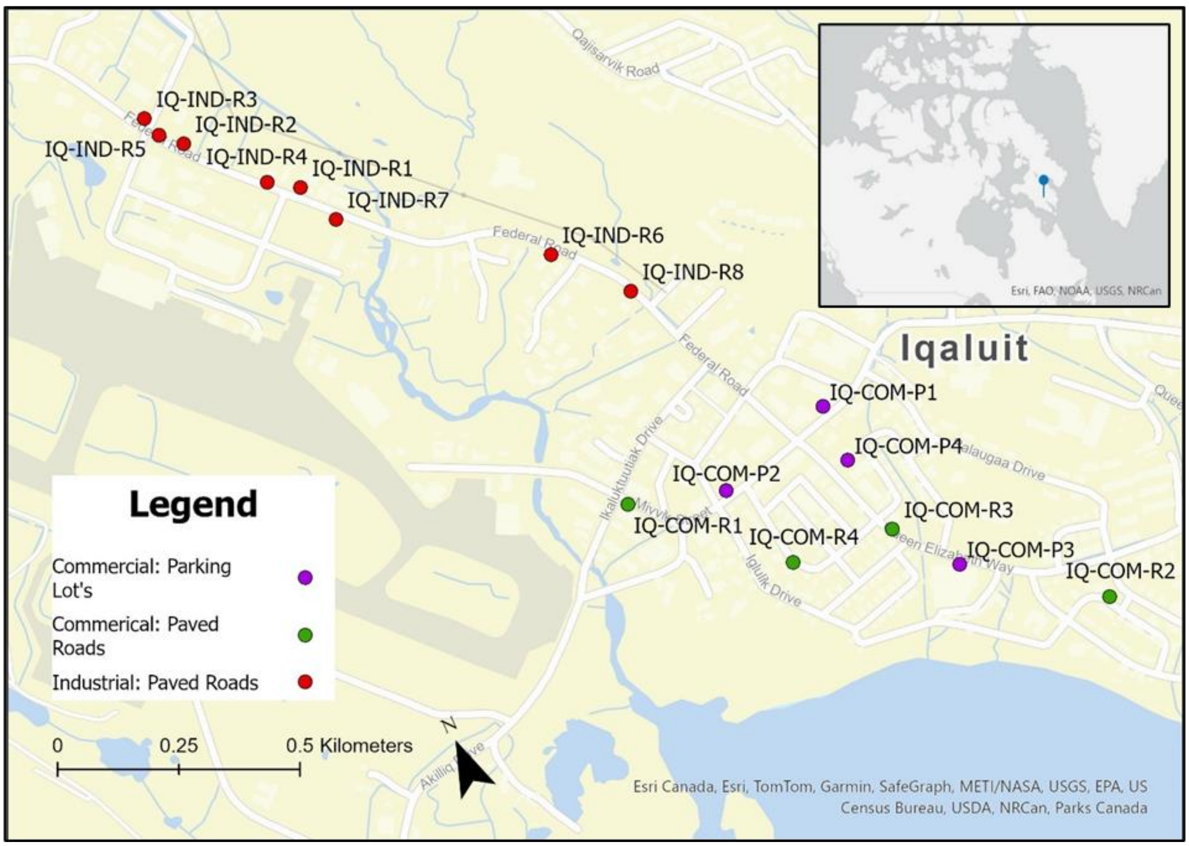

Figure 2.1. Location of study sites in commercial parking lots (IQ-COM-P; n = 4), commercial roadsides (IQ-COM-R; n = 4), and industrial roadsides (IQ-IND-R; n = 8), Iqaluit, Nunavut (ArcGIS Pro, Version 3.1.1).

2.1.2 Quality Assurance and Quality Control

Strict quality assurance and control is vital to ensure estimated microplastic values accurately reflect environmental concentrations. Given their ubiquity, all solutions (i.e., reverse osmosis water, 30% hydrogen peroxide, and lab grade sodium bromide) were filtered through a glass-fibre filter (Fisherbrand™ Glass Filter Circle, 1.6 µm pore diameter, G6, filter diameter 4.25 cm). In the laboratory, a 100% cotton laboratory coat was worn, and hands/gloves were periodically rinsed with filtered reverse osmosis (FRO) water. Metal and glass equipment were used where possible, and all equipment was triple rinsed with FRO water before and in between the handling of environmental samples to keep tools clean. Laboratory blanks (n = 2) were performed in sequence with environmental samples and consisted of running solutions through the same laboratory processes as environmental samples (i.e., digestion and density separation) to capture microplastics unintentionally added during the extraction process. Open-air laboratory blanks (n = 2) were collected by exposing a glass-fibre filter in a petri dish beside the microscope to capture indoor microplastic deposition.

Field blanks (n = 6) were performed at a random subset of commercial and industrial study sites, and mimicked field methods by sweeping microplastic-free road dust (250 g pre-baked at 500°C for 12 h) from a cork board into the sampling containers. The purpose of field blanks was to capture microplastics or tire wear particles that potentially contaminate the sample during the collection process (e.g., atmospheric deposition, improper cleaning of field equipment). A known concentration of polyethylene (PE) beads (size ranges 75–90 µm and 212–250 μm) were also added to field blanks prior to the extraction process to assess recovery and limits of detection; field blanks were processed in sequence with environmental samples. The limit of detection (LOD) refers to the lowest concentration of microplastics that can be reliably detected using a specific analytical method. In this study the LOD was estimated as the mean microplastic count in field blanks plus three times their standard deviation (Bertrim & Aherne, 2023).

Table 2.1. SiteID, sampling date (July 2022), longitude (decimal degree; dd), latitude (decimal degree; dd), transect length (meters; m), mass of total road dust swept (grams; g), microplastic (count; #), and tire wear particle (count; #) at each study site (n = 16; commercial, COM; industrial, IND) in Iqaluit, Nunavut.

SiteID	Date	Latitude	Longitude	Transect	Road dust	Microplastic	Tire wear
		dd	dd	m	g	#	#
IQ-COM-R1	14	63.74968	-68.52949	30	45.2	1	31
IQ-COM-R2	14	63.74444	-68.51241	10	158.0	2	23
IQ-COM-R3	14	63.74725	-68.51968	10	22.9	5	29
IQ-COM-R4	14	63.74743	-68.52410	30	71.8	3	13
IQ-COM-P1	14	63.74987	-68.52027	10	217.0	12	453
IQ-COM-P2	14	63.74917	-68.52545	10	378.0	11	81
IQ-COM-P3	14	63.74613	-68.51767	10	137.0	9	186
IQ-COM-P4	15	63.74877	-68.52023	10	84.2	2	66
IQ-IND-R1	15	63.75760	-68.53675	30	8.4	1	18
IQ-IND-R2	15	63.75924	-68.54053	30	2.0	6	36
IQ-IND-R3	15	63.75997	-68.54162	30	44.4	6	109
IQ-IND-R4	15	63.75794	-68.53795	30	85.6	2	74
IQ-IND-R5	14	63.75957	-68.54134	10	183.0	15	99
IQ-IND-R6	14	63.75455	-68.52820	30	50.2	7	17
IQ-IND-R7	14	63.75678	-68.53593	30	15.5	0	35
IQ-IND-R8	14	63.75331	-68.52574	30	30.4	9	48

2.1.3 Sample Collection

During 14–15 July 2022, road dust was collected using a natural-fibre brush and metal dustpan (O'Brien et al., 2021). Briefly, each road site was swept along a transect (10–30 m in length depending on the quantity of road dust available) against the direction of the wind and following a minimum of five days without precipitation under stable weather conditions (wind speed less than 4 m/s). All contents in front of the metal pan (43.2 cm in diameter) were collected using a slow sweeping motion to minimize the resuspension of microplastic particles. Road dust contents in the dustpan were sieved at 2 mm to remove large mineral debris and the <2 mm fraction was retained in an aluminum dish (pre-baked at 400°C for 4 hr), which was subsequently covered with aluminum foil and stored in a brown paper bag. Prior to sampling, the metal dustpan, natural-fibre brush, and sieve were cleaned using a 100% cotton cheesecloth and sprayed with compressed air to prevent contamination across study sites.

2.1.4 Extraction of Microplastics and Tire Wear Particles

Road dust samples were oven-dried at 45°C for 48 h, homogenized by gently stirring (~1 min), and 1 g of road dust from each site was processed in 0.5 g aliquots to optimize the analytical procedure (i.e., a total of 8 g each for commercial and industrial areas). Organic matter was removed using wet oxidation; in a 250 mL Erlenmeyer flask, 40 mL of 30% filtered hydrogen peroxide was added to each sample and digested at 45°C for 24 h (Hurley et al., 2018). Following digestion, samples were wet sieved (20 µm), and the residue was retained in a 100 mL tall glass beaker. The filtrate from a subset of samples (n = 8) was retained to determine if there was particle loss from the sieving process; no microplastics or tire wear particles were visible in the filtrate. Microplastics and tire wear particles were subsequently extracted from the residue using one water and two sodium bromide (NaBr; density ≥1.5 g/cm^3) density separations, each with a settling time of 24 h. Following each settling time, the supernatant was decanted and filtered onto a glass-fibre filter, and filters were stored in clear polystyrene petri dishes until visual analysis.

2.1.5 Identification of Microplastics and Tire Wear Particles

Filters were visually analyzed for microplastics and tire wear particles using a stereomicroscope (AmScope version x64) under brightfield and using a 540 nm blue light (NightSea Stereo Microscope Fluorescence Adapter). The entire filter surface was analyzed for microplastics, and these were identified using the following set of criteria: (1) unnaturally coloured relative to the sample, and appeared homogeneous in material and texture with no visible cellular structures, (2) remained intact when compressed or poked with dissection instruments, and (3) had a shiny or glossy appearance; while fibres additional a consistent width throughout, (3) and shared no similarities to natural fibres with limited fraying (Kosuth et al., 2018). Given the abundance of tire wear particles, a quarter of the filter surface was analyzed and scaled up by multiplying the counts by four. Tire wear particles were identified as being (1) black, (2) elongated/cylindrical in shape, (3) with a rough surface texture, and (4) spongy when poked with a dissection instrument but remained intact (Leads & Weinstein, 2019).

All suspected microplastics or tire wear particles that met at least two visual identification criteria was photographed (AmScope MU100 camera, 3584 × 2748 pixels). Suspected microplastics were then touched with a heat source (400°C; Beckingham et al., 2023), while suspected tire wear particles were not touched with a heat source as they do not melt even at high temperatures. The length and width of all suspected microplastics that melted and 95% of tire wear particles were measured using the photo taken prior to melting in AmScope (Version 4.11.22004.20230115). In general, visual identification is limited to particles >50 µm, but where possible, particles down to ~20 µm were also identified, albeit a small proportion (~5%).

Fourier-Transform Infrared spectroscopy (FTIR; LUMOS II, Brucker) was performed on a subset of particles (30% microplastics and 22% tire wear particles) using attenuated total reflectance (ATR) to determine polymer type. The diameter of the ATR crystal (Germanium; diameter of tip = 100 µm) generally limited polymer analysis to larger particles (>100 µm); fibrous microplastics were particularly challenging due to their narrow diameter. For all particles, a scan time of 16 seconds was used under low pressure. Subsequently, tire wear spectra were corrected for ‘Black Rubber’ in OPUS (Version 8.7). Despite correcting for ‘Black Rubber’ it is important to note there are limitations to using ATR-FTIR for spectral identification of tire wear particles as their dark nature only reflects a small amount of light (Kang et al., 2022). All spectra were uploaded to OpenSpecy to identify polymer type (Cowger et al., 2021). The plastic polymer with the highest Pearson’s Correlation was selected as the polymer associated in the suspected particle, with a minimum correlation value of >0.5 due to the challenges of spectroscopic analysis of aged microplastics and tire wear particles.

2.1.6 Data Analysis

Study sites were grouped into industrial roadsides (IQ-IND-R), and commercial sites (IQ-COM) with the latter comprising commercial parking lots (IQ-COM-P) and commercial roadsides (IQ-COM-R). The count concentration of microplastics and tire wear particles (n/g) per gram dry weight of road dust was estimated at each site by summing the counts from each duplicate and dividing by the sum of road dust analyzed (~1 g). The concentration of microplastics and tire wear particles were corrected by multiplying the count concentration by the proportion of particles that were identified as plastic by ATR-FTIR. It is important to note that the estimated concentration of microplastics and tire wear particles represent particles that range from 20–2000 µm, however, visually identifying microplastics and tire wear particles <50 µm were challenging due to their small size.

Mass concentrations (µg/g) were estimated for microplastics and tire wear particles using the volume of each particle and average polymer density (Simon et al., 2018). Briefly, the volume of microplastic and tire wear particles at each site was summed by particle shape (Table S1) and multiplied by the average density for shape-specific polymers (Table S2). Further, deposition was calculated by dividing the total mass (g) of road dust collected at each site (Table 2.1) by the sampling area (area (m^2) = width of dustpan × transect length) and multiplying that value by the concentration of microplastics or tire wear particles per gram of road dust analyzed (n/m^2 or $\mu g/m^2$). It is presumed that the concentration and deposition represent an accumulation of atmospheric microplastics and terrestrial particles directly emitted from their sources (such as tire wear particles). Hereafter, concentration and deposition (± standard deviation) are reported as per gram dry weight of road dust and per square metre, respectively.

To determine if there was a statistical difference in concentration, characteristics, and deposition between commercial and industrial areas a Kruskal–Wallis test was used with a confidence interval of 95%, followed by a pairwise Mann–Whitney U test if there was statistical significance. All figures and statistical analyses were carried out in Past (Version 4.12; Hammer et al., 2001).

2.3 Results

2.3.1 Quality Assurance and Quality Control

No microplastics were found in the laboratory blanks and open-air blanks. Given the overall low concentration of microplastics (0.17 n/g) in the field blanks and that all observed concentrations were greater than the limit of detection (1.4 n/g), microplastic observations were not blank corrected. No tire wear particles were detected in blank samples (process or field). The proportion of plastic polymer hits with a Pearson's correlation >0.5 was 75% for microplastics and 87% for tire wear particles (Table S3). The recovery for spiked PE beads from the field blanks (n = 4) ranged from 70–100% (average = 83%) for sizes 75–90 µm and 90–100% (average = 98%) for sizes 212–250 µm, which is consistent with reported recovery rates (Dimante-Deimantovica et al., 2024).

2.3.2 Microplastics in Arctic Road Dust

2.3.2.1 Concentration and Deposition

In total, 91 microplastic particles (Figure 2.2; Table S4 for count by shape) were identified at 15 of the 16 study sites (Table 2.1). The mean concentration of all microplastics (excluding tire wear) was 2.83 ± 3.72 µg/g (3.91 ± 3.02 n/g). The concentration was 1.93 ± 2.56 µg/g (3.90 ± 3.18 n/g) in industrial sites and 3.73 ± 4.61 µg/g (3.91 ± 3.08 n/g) in commercial sites, ranging from 0.47 ± 0.48 µg/g (1.89 ± 1.09 n/g) in commercial roadsides to 7.00 ± 4.58 µg/g (5.93 ± 3.17 n/g) in commercial parking lots (Table 2.2). There was a significant difference across groups (Kruskal–Wallis, $p < 0.05$); microplastic concentration in commercial parking lots were statistically greater than both commercial and industrial roadsides (Mann–Whitney U, $p < 0.05$; Figure 2.3; Figure S2 for n/g).

Microplastic deposition followed the same pattern; the mean across all sites was 45.8 ± 41.3 µg/m^2 (53.8 ± 49.0 n/m^2) with deposition of 2.98 ± 4.92 µg/m^2 (10.4 ± 19.6 n/m^2) in industrial sites and 90.2 ± 127 µg/m^2 (75.3 ± 104 n/m^2) in commercial sites, ranging from 1.27 ± 0.97 µg/m^2 (9.12 ± 9.47 n/m^2) in commercial roadsides to 133 ± 118 µg/m^2 (142 ± 118 n/m^2) in commercial parking lots (Table 2.3). Further, there was a significant difference in microplastic deposition across groups (Kruskal–Wallis, $p < 0.05$); deposition was significantly greater in commercial parking lots than in both commercial and industrial roadsides (Mann–Whitney U, $p < 0.05$; Figure 2.3; Figure S2 for n/m^2). There was also a significant difference in the deposition of films across groups (Kruskal–Wallis, $p < 0.05$);

the deposition of films was significantly greater in commercial parking lots than in both commercial and industrial roadsides (Mann–Whitney U, $p < 0.05$).

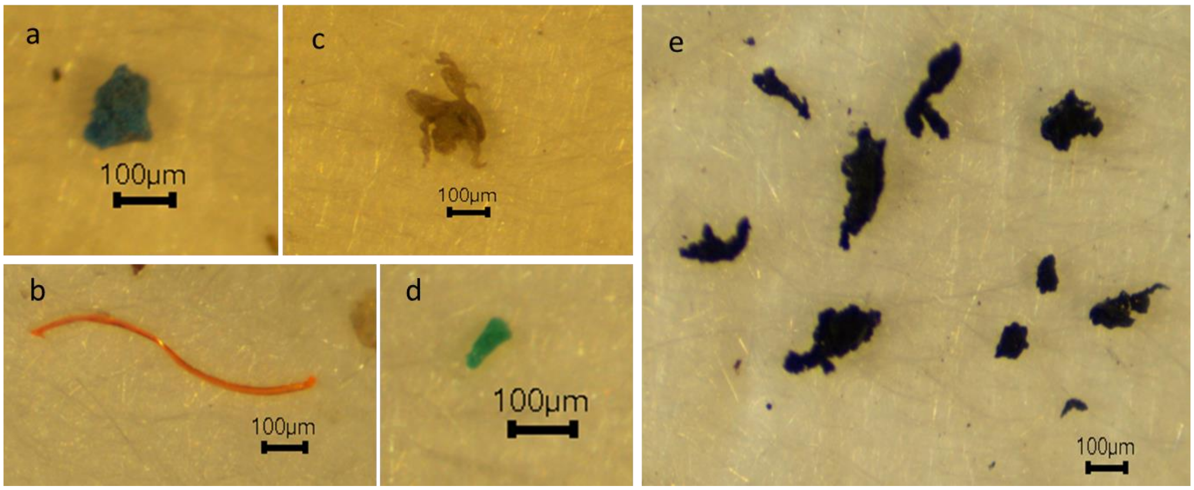

Figure 2.2. Microscope images of microplastics identified in road dust samples collected from commercial parking lots, commercial roadsides, and industrial roadsides in Iqaluit, Nunavut; a) blue foam, b) pink fibre, c) grey film, d) green fragment, and e) tire wear particles.

2.3.2.2 Characteristics (Shape, Size, and Polymer Composition)

Based on microplastic counts, commercial parking lots and industrial roadsides were dominated by fragments (51% and 95%, respectively), and commercial roadsides were dominated by fibres (86%; Figure S3). Based on mass, commercial parking lots had a greater proportion of films (49%), while commercial and industrial roadsides remained dominated by fibres (50%) and fragments (42%), respectively (Figure 2.4). Overall, there was a greater proportion of non-fibrous microplastics in commercial parking lots and industrial roadsides, while commercial roadsides had a greater proportion of fibrous microplastics.

Table 2.2. Microplastic concentration (n/g or µg/g dry weight) and deposition (n/m² or µg/m²) in road dust across commercial parking lots (IQ-COM-P), commercial roadsides (IQ-COM-R), industrial roadsides (IQ-IND-R), and commercial areas (IQ-COM) in Iqaluit, Nunavut.

	Units	**IQ-COM-P**	**IQ-COM-R**	**IQ-IND-R**	**IQ-COM**
Land class	–	Commercial	Commercial	Industrial	Commercial
Surface	–	Parking lot	Roadside	Roadside	Parking lots and roadsides
Site number	n	4	4	8	8
Count (number)					
Microplastics	n	34	16	46	50
Fibre	n	11	7	7	18
Fragment	n	13	3	32	16
Film	n	8	1	6	9
Foam	n	2	0	1	2
Count concentration					
Microplastics	n/g	5.93 ± 3.17	1.89 ± 1.09	3.90 ± 3.18	3.91 ± 3.08
Fibre	n/g	1.91 ± 2.14	1.22 ± 0.36	0.60 ± 0.56	1.57 ± 1.47
Fragment	n/g	2.27 ± 1.86	0.51 ± 0.63	2.73 ± 2.43	1.39 ± 1.60
Film	n/g	1.39 ± 1.00	0.16 ± 0.33	0.49 ± 0.75	0.78 ± 0.95
Foam	n/g	0.35 ± 0.41	–	0.09 ± 0.26	0.18 ± 0.32
Count deposition					
Microplastics	n/m²	142 ± 118	9.12 ± 9.47	10.4 ± 19.6	75.3 ± 104
Fibre	n/m²	22.1 ± 37.1	7.57 ± 10.4	1.55 ± 2.63	27.9 ± 40.6
Fragment	n/m²	56.4 ± 68.3	1.18 ± 1.46	7.14 ± 2.45	28.8 ± 53.6
Film	n/m²	27.9 ± 23.3	0.37 ± 0.75	1.70 ± 4.08	14.1 ± 21.2
Foam	n/m²	9.0 ± 12.2	–	0.006 ± 0.02	4.5 ± 6.1
Mass concentration					
Microplastics	µg/g	7.00 ± 4.58	0.47 ± 0.48	1.93 ± 2.56	3.73 ± 4.61
Fibre	µg/g	0.76 ± 0.84	0.23 ± 0.18	0.44 ± 1.10	0.50 ± 0.63
Fragment	µg/g	1.83 ± 2.70	0.07 ± 0.09	0.91 ± 1.50	0.95 ± 2.00
Film	µg/g	3.22 ± 3.01	0.17 ± 0.34	0.48 ± 0.72	1.70 ± 2.57
Foam	µg/g	1.19 ± 1.64	–	0.11 ± 0.30	0.59 ± 1.24
Mass deposition					
Microplastics	µg/m²	133 ± 118	1.27 ± 0.97	2.98 ± 4.92	90.2 ± 127
Fibre	µg/m²	19.0 ± 19.9	1.14 ± 1.23	0.64 ± 1.21	10.1 ± 10.6
Fragment	µg/m²	30.8 ± 35.6	0.16 ± 0.23	1.91 ± 2.94	15.5 ± 17.9
Film	µg/m²	90.7 ± 132.9	0.38 ± 0.77	1.42 ± 3.12	46.1 ± 66.9
Foam	µg/m²	37.1 ± 63.1	–	0.01 ± 0.02	18.6 ± 31.6

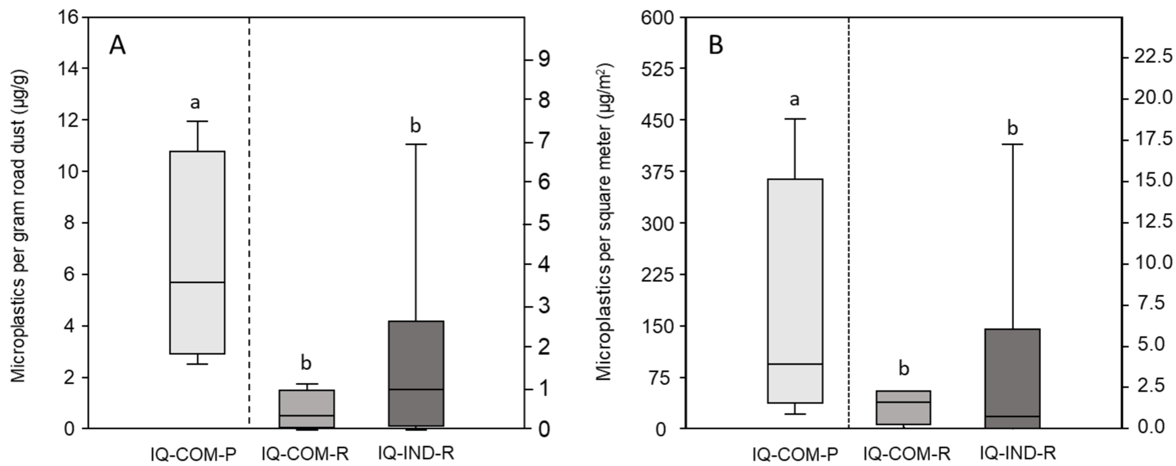

Figure 2.3. Box plots presenting the A) mass concentration of microplastics (µg/g) and B) mass deposition of microplastics (µg/m^2) in commercial parking lots (IQ-COM-P; n = 4), commercial roadsides (IQ-COM-R; n = 4), and industrial roadsides (IQ-IND-R; n = 8) across Iqaluit, Nunavut. Lowercase letters indicate statistical significance (Kruskal–Wallis, $p < 0.05$). The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

The mean (range) length of fibrous microplastics were not significantly different ($p > 0.05$) across the study area, ranging from 792 ± 346 µm (339–1264 µm) in commercial parking lots, to 798 ± 642 µm (201–1695 µm) in industrial roadsides, and 819 ± 329 µm (365–1183 µm) in commercial roadsides. The mean (range) length of non-fibrous microplastics ranged from 105 ± 42.3 µm (67.1–151 µm) in commercial roadsides, to 119 ± 82.1 µm (19.2–316 µm) in industrial roadsides, and 280 ± 333 µm (62.1–1223 µm) in commercial parking lots. There was a significant difference in the length of non-fibrous microplastics across groups (Kruskal–Wallis, $p < 0.05$), non-fibrous microplastics in commercial parking lots were significantly longer than industrial roadsides (Mann–Whitney U, $p < 0.05$; Figure 2.5).

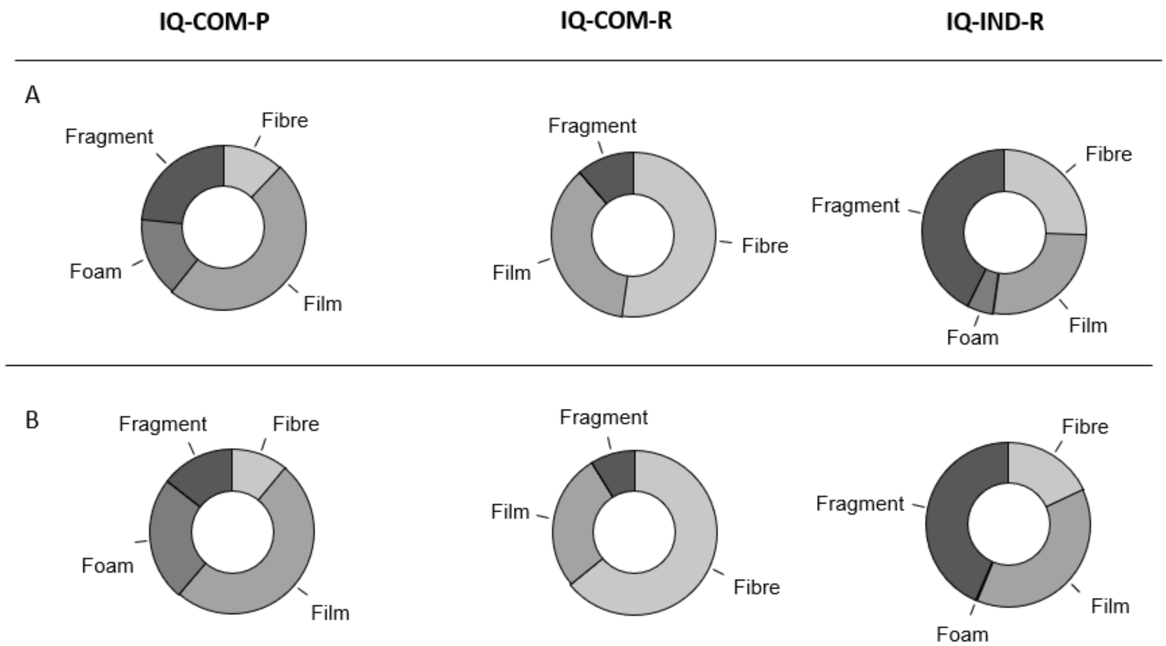

Figure 2.4. Donut charts presenting microplastic shapes by mass (µg) A) per gram road dust (g) and B) per square meter (m^2) in commercial parking lots (IQ-COM-P; n = 4), commercial roadsides (IQ-COM-R; n = 4), and industrial roadsides (IQ-IND-R; n = 8) across Iqaluit, Nunavut.

Various polymers were identified across commercial parking lots (6 types), commercial roadsides (3 types), and industrial roadsides (2 types). Polyester (40%) was the dominant polymer for fibrous microplastics, polymethyl acrylate (50%) was the dominant polymer for fragments, polystyrene (100%) was dominant for films, and polyvinyl butyral, polyurethane, and polyvinyl chloride were equally dominant for foams (Table 2.3).

2.3.3 Tire Wear Particles in Arctic Road Dust

2.3.3.1 Concentration and Deposition

Tire wear particles were pervasive across the study area; in total 1,318 tire wear particles were quantified across all sites (Table 2.1). The mean concentration of tire wear particles was 146 ± 230 µg/g (231 ± 302 n/g), with a concentration of 31.7 ± 18.3 µg/g (152 ± 92.9 n/g) in industrial sites and 259 ± 289 µg/g (309 ± 417 n/g) in commercial sites, ranging from 62.0 ± 50.5 µg/g (69.7 ± 21.4 n/g) in commercial roadsides to 459 ± 294 µg/g (549 ± 501 n/g) in commercial parking lots. Despite this range, there was no significant difference in mass concentration of tire wear particles across groups ($p > 0.05$; Figure 2.6). In contrast, commercial parking lots had a significantly greater count concentration of tire wear particles than commercial roadsides (Figure S4 for n/g).

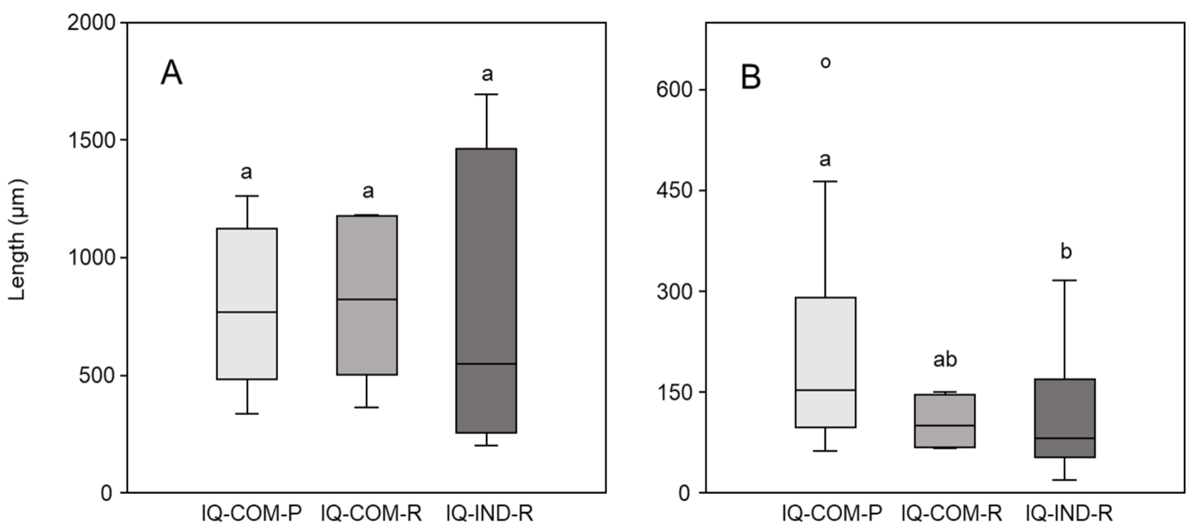

Figure 2.5. Box plots presenting the length (µm) for A) fibrous and B) non-fibrous (fragment, film, foam) microplastics in commercial parking lots (IQ-COM-P; n = 4), commercial roadsides (IQ-COM-R; n = 4), industrial roadsides (IQ-IND-R; n = 8) across Iqaluit, Nunavut. Lowercase letters indicate statistical significance (Kruskal–Wallis, $p < 0.05$). Two outliers (1222.8 µm and 1146.9 µm) in commercial parking lots for non-fibrous microplastics are not visible on the plot. The box represents

the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

The deposition of tire wear particles followed the same pattern, with a mean deposition of 74.1 ± 128 µg/m^2 (372 ± 561 n/m^2) in industrial sites and 5,430 ± 7,660 µg/m^2 (5,780 ± 9,340 n/m^2) in commercial sites, ranging from 247 ± 194 µg/m^2 (417 ± 529 n/m^2) in commercial roadsides to 10,600 ± 8,080 µg/m^2 (12,800 ± 12,900 n/m^2) in commercial parking lots. There was a significant difference between groups (Kruskal–Wallis, $p < 0.05$), deposition of tire wear particles was significantly greater in commercial parking lots than in both commercial and industrial roadsides (Mann-Whitney U, $p < 0.05$; Figure 2.6; Figure S4 for n/m^2).

Table 2.3. Proportion of microplastic polymers for fibres, films, foams, and tire wear particles in road dust across commercial parking lots (n = 4), commercial roadsides (n = 4), and industrial roadsides (n = 8) in Iqaluit, Nunavut.

Shape Type	Polymer Type	Proportion (%)
Fibre	Polyester	40
	Polymethyl acrylate	20
	Polyethylene	20
	Polyethylene terephthalate	20
Fragment	Polymethyl acrylate	50
	Polyethylene terephthalate	25
	Polystyrene	25
Film	Polystyrene	100
Foam	Poly(vinyl butyral)	33
	Polyurethane	33
	Polyvinyl chloride	33
Tire wear	Rubber	27
	Polypropylene	20
	Polyethylene	18
	Polystyrene	16
	Polyvinyl chloride	12
	Nitrile	2
	Poly(vinyl butyral)	1
	Polyester	1
	Polymethyl acrylate	1
	Polyethylene terephthalate	1
	Polyacrylate nitrile	<1
	Low-density polyethylene	<1
	Polyurethane	<1

2.3.3.2 Characteristics (Size and Polymer Composition)

The mean (range) length of tire wear particles was not significantly different between groups and ranged from 132 ± 78.1 µm (51.8–505 µm) in commercial roadsides to 139 ± 71.4 µm (54.5–476 µm) in industrial roadsides, and 157 ± 143 µm (27.0–1859 µm) in commercial parking lots. A total of 13 plastic polymers were identified across sites, rubber (27%) was dominant, followed by polypropylene (20%; Table 2.3); however, this may reflect the challenges of spectroscopic analysis of tire wear particles.

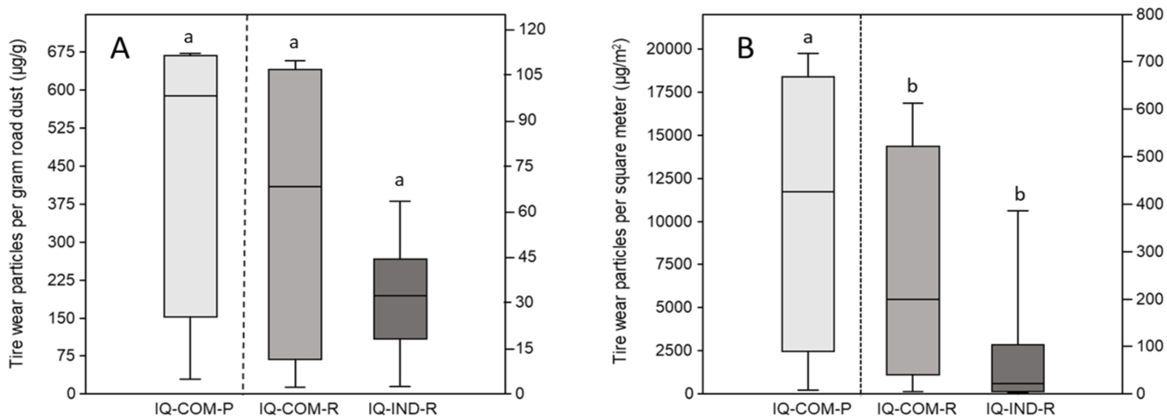

Figure 2.6. Box plots presenting the A) mass concentration of tire wear particles per gram dry weight road dust (µg/g) and B) mass deposition of tire wear particles per square meter (µg/m^2) in commercial parking lots (IQ-COM-P; n = 4), commercial roadsides (IQ-COM-R; n = 4), and industrial roadsides (IQ-IND-R; n = 8) across Iqaluit, Nunavut. Lowercase letters indicate statistical significance (Kruskal–Wallis, $p < 0.05$). The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

2.4 Discussion

Commercial and industrial areas in Iqaluit, Nunavut, had concentrations of microplastics and tire wear particles in road dust comparable with metropolitan cities (and notably higher in commercial parking lots). Given the low population density of Iqaluit, microplastic concentrations in road dust were expected to be lower, as microplastic concentrations are positively correlated with population density (Yukioka et al., 2020). In contrast, the count concentration of microplastics in road dust from Iqaluit (3.91 ± 3.02 n/g) was similar to Chennai, India (2.28 ± 0.89 n/g; population = 6.7 million; Patchaiyappan et al., 2021), Kathmandu, Nepal (3.90 n/g; population = 856,000; Yukioka et al., 2020), Da Nang, Vietnam (4.10 n/g; population = 1.1 million; Yukioka et al., 2020), and Kasatsu, Japan (2.50 n/g; population = 139,000; Yukioka et al., 2020). However, microplastic count concentrations in Iqaluit road dust were lower than Goyang City, South Korea (~505 n/g; population = 1.1 million; Kang et al., 2022), and mass concentrations were lower than in Brisbane, Australia (500–6000 µg/g; population = 1.2 million; Table S5; O'Brien et al., 2021).

The deposition of microplastics across Iqaluit (53.8 ± 49.0 n/m^2) was comparable to Kusatsu, Japan (2.00 ± 1.60 n/m^2; population = 139,000), Kathmandu, Nepal (12.5 ± 10.1 n/m^2; population = 856,000), and Da Nang, Vietnam (19.7 ± 13.7 n/m^2; population = 1.1 million; Table S5; Yukioka et al., 2020). The similarities and differences in microplastic concentrations in Iqaluit road dust, compared with more densely populated cites, may reflect differences in sampling methodologies; for example, Yukioka et al. (2020) used a vacuum cleaner to collect road dust, and samples were sieved at 75 µm, which may have resulted in the loss of fibrous microplastics that have a narrow diameter (10–20 µm). Nonetheless, the observations in Iqaluit are within the same order of magnitude as studies within numerous metropolitan areas (Table 2.5); suggesting that the microplastics are likely sourced from the community.

Dominant microplastic shape also varied across studies; a greater proportion of fibrous microplastics was reported in road dust in Bushehr City, Iran (76%; population = 220,000; Abbasi et al., 2017) using a plastic brush and pan, which was similar to commercial roadside findings in the current study. In contrast, our findings are more similar to a study in Ma'anshan City, China (population = 2.1 million; Wang et al., 2022), which identified fragments (50%) as the dominant microplastic shape in road dust collected using a wooden brush and steel shovel. A higher proportion of fragments (68–81%) was also observed in road dust sampled from Kusatsu, Japan, Da Nang, Vietnam, and Kathmandu, Nepal (Yukioka et al., 2020); however, as noted above it is likely that the field methods used by Yukioka et al. (2020) favoured the collection of non-fibrous microplastics.

It is challenging to compare the concentration and deposition of tire wear particles in road dust to other studies. Tire wear particles are generally grouped with microplastic fragments or excluded from studies altogether due to the challenges of visual and spectroscopic analysis. Dehghani et al., 2017 investigated tire wear in road dust from Tehran, Iran (population = 7.7 million), and suggested a concentration of 16.6 n/g road dust. In the current study, the average concentration of tire wear across the study area was 231 n/g. The higher concentration of tire wear particles in Iqaluit may be a result of sampling and analytical techniques. It is also possible that the composition of vehicle tires is different between the study areas; for instance, winter vehicle tires are composed of a soft rubber material and may shed more particles than all-year or summer tires. Further, rubber compounds harden at lower temperatures which may also increase particle shedding through wear and tear. In contrast, tire wear particles in Goyang city, South Korea (~1210 n/g; Kang et al., 2022) were greater than concentrations in the current study. A study in Norway that investigated the accumulation of tire wear particles in roadside snowbanks identified an average concentration of 10,600 ± 2,200 mg/m^2 (Rødland et al., 2022). The higher concentration of tire wear particles in snowbanks is likely a result of the greater accumulation period throughout the winter (several months), in contrast to road dust that reflects accumulation following the most recent wash out event (approximately 7 days in the current study).

The concentration and deposition of microplastics and tire wear particles were significantly greater in parking lots than on roadsides. This may indicate that parking lots serve as a temporary sink for microplastics and tire wear particles. Parking lots had a greater quantity of dust per square meter (Table 2.1), indicating parking lots have a greater accumulation of dust compared to roadsides. The retention of dust in parking lots likely reflects the slower vehicle velocity, which would reduce resuspension.

Road dust reservoirs may facilitate the transport of microplastic and tire wear particles to the wider environment, and therefore understanding their concentrations and characteristics are crucial. Microplastics and tire wear particles in road dust can become re-entrained into the atmosphere by wind or vehicle traffic, and subsequently deposited in local or longer-range environments (Evangeliou et al., 2020). Microplastics in suspended dust may be inhaled, and their associated risks are not well established (Baensch-Baltruschat et al., 2020). Road dust also facilitates the transport of microplastics and tire wear particles to aquatic systems through stormwater drainage following precipitation washout events (Monira et al., 2021). Moreover, microplastic and tire wear particles have been observed in Arctic sediments close to communities but not in more remote locations, suggesting that communities are a source of these contaminants to surrounding environments (Adams et al., 2021; Huntington et al., 2020). The particles that enter aquatic environments can have adverse effects, such as infiltrating the aquatic food chain and causing physical harm to aquatic species when ingested (Lim, 2021). Further, the associated chemical additives (e.g., polycyclic aromatic hydrocarbons, petroleum hydrocarbons, and dyes) that that are associated with microplastics and tire wear particles leach into surrounding environments (Andjelković et al., 2021; Teuten et al., 2009). Such additives also have adverse effects on aquatic species, for instance, 6PPD (N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine) improves the durability of tires but its oxidation product 6PPD-quinone is highly toxic to some aquatic organisms (Tian et al., 2022).

Lastly, we acknowledge there are limitations to our study that may influence the estimated concentration and deposition of microplastic and tire wear particles in road dust. The detection limit for microplastics and tire wear particles in this study was >20–2000 µm, which may have resulted in the loss of larger particles between 2–5 mm in length. The recovery of spiked PE beads may not reflect environmental fibres, films, foams, fragments, and tire wear particles due to their physical characteristics. Finally, the mass concentrations are an estimate based on two measurements (longest length and width); this may skew the estimated mass of microplastic and tire wear particles given they are intricate three-dimensional particles with complex physical structures.

2.5 Conclusion

In this study, we shed light on the presence of microplastics and tire wear particles in Arctic road dust. The mean concentration of microplastics was 2.83 ± 3.72 µg/g (3.91 ± 3.02 n/g) and tire wear particles was 146 ± 230 µg/g (231 ± 302 n/g) in road dust across Iqaluit, Nunavut. This study suggests the concentration of microplastics in Arctic road dust are comparable with observations in metropolitan areas. The high magnitude of microplastics and tire wear particles in commercial parking lots also suggests they are temporary reservoirs (accumulation zones) for microplastics and tire wear particles. Further investigation of atmospheric microplastics in Iqaluit, and microplastics in urban ponds and Frobisher Bay may indicate the fate of microplastics and tire wear particles in Arctic road dust.

Chapter Three: Microplastics in Arctic freshwater lake catchments on Baffin Island, Nunavut

3.0 Introduction

Microplastics (plastic particles less than 5 mm in length) are physical and chemical contaminants divided into two types, primary and secondary particles. Primary microplastics are manufactured to be micro-sized; for instance, microbeads are widely added to personal care products, while pellets and nurdles are used in the production of plastic material (Rochman et al., 2019). Secondary microplastics are derived from the fragmentation of plastic debris, including the shedding of synthetic textiles. It is widely recognized that microplastics are a contaminant of emerging concern given their pervasiveness across every environment. Nonetheless, few studies have investigated microplastic contamination across Arctic environments. As such, microplastic contamination in Arctic freshwater lakes has been identified as a high priority for the AMAP and Canada’s Northern Contaminants Program.

Only recently have lakes gained increasing attention for the presence of microplastic contamination. Microplastics have been detected in freshwater bodies globally (Nava et al., 2023), and their concentration and characteristics are often positively correlated to anthropogenic activities, such as proximity to urban centers and wastewater treatment plants (Liu et al., 2019a). In addition, microplastic contamination is also pervasive in lakes isolated from direct anthropogenic inputs (Free et al., 2014). The presence of microplastic contamination in remote and pristine lakes suggests that atmospheric transport and deposition is a pathway for microplastic contamination to lake catchments.

Lakes are widespread across the Canadian Arctic and reflect spatial and temporal responses to both natural processes and human activities at a catchment scale (Adrian et al., 2009); and catchment-scale studies have been widely used to assess the fate of atmospheric pollutants (Brown, 2023; Karl 2023; Roblin, 2019, Windsor et al., 2019). Further, biological monitoring has been widely used to assess atmospheric pollutant deposition (Bertrim & Aherne, 2023; Clough, 1975; Harmens et al., 2011, 2013; Olmstead & Aherne, 2019; Roblin & Aherne, 2020). Since the early 1960's, mosses have been sampled to investigate atmospheric contaminants, such as trace metals (Berg et al., 1995; Halleraker et al., 1998), nitrogen (Harmens et al., 2011; Olmstead & Aherne, 2019), persistent organic pollutants (Harmens et al., 2013), particulate matter (Clough, 1975) and microplastics (Bertrim & Aherne, 2023; Roblin & Aherne, 2020). Mosses have a high surface area and can trap and accumulate microplastics deposited from the atmosphere. While, lake water and sediment act as a reservoir at the catchment-scale by integrating ecosystem responses over time (Adrian et al., 2009).

The objective of this study was to assess the abundance and characteristics of microplastics in lake catchments surrounding Iqaluit, Nunavut. To achieve this, lake water and sediment samples were collected to assess the fate of microplastics, while stair-step moss (*Hylocomium splendens*) was collected as a biological monitor of atmospheric microplastic deposition. Using a catchment-scale approach, the study addresses knowledge gaps on microplastic contamination in Arctic lakes.

3.1 Methods

3.1.1 Study Area and Sites

The lake catchments (n = 19) in this study were located on southern Baffin Island, surrounding Iqaluit, Nunavut (63.7467° N, 68.5170° W; Figure 3.1; Table 3.1), and were selected based on their size (>1 ha) and proximity to Iqaluit (i.e., walking distance). There were two distinct clusters of catchments, i.e., to the north (n = 10) primarily upwind of Iqaluit, and east (n = 9) primarily downwind of Iqaluit. The catchments to the north had a slightly higher average elevation (163 m) and larger surface area (167,250 m^2) than the catchments to the east (149 m, 45,143 m^2. respectively; Table 3.1). Further, lakes to the east were closer to Iqaluit (3.2 km) compared with lakes in the north (5.5 km). The annual dominant wind direction was from the northwest, except between July and September when the dominant wind direction was from the southeast (Figure 3.2).

3.1.2 Field Sampling

3.1.2.1 Lake water

In the summer of 2023, ~7.8 L of lake water (at 5 cm depth) was collected from one location at each catchment (n = 19) using a 1-gallon HDPE jug (refilled once). Lake water was subsequently filtered in the field across multiple (n = 8) glass-fiber filters (Fisherbrand™ Glass Filter Circle, G6, 1.6 µm pore diameter, 4.7 cm filter diameter) using a portable Nalgene filtering apparatus and hand pump (Figure S5). Filters were transferred to a clear polystyrene petri dish and wrapped in aluminum foil. Following the last refill, the HPDE jug and the Nalgene apparatus were triple rinsed with FRO water to capture adhered particles and filtered onto a separate filter. The volume of water that passed through each filter was measured at a subset of lakes (n = 7) using a 1 L graduated cylinder.

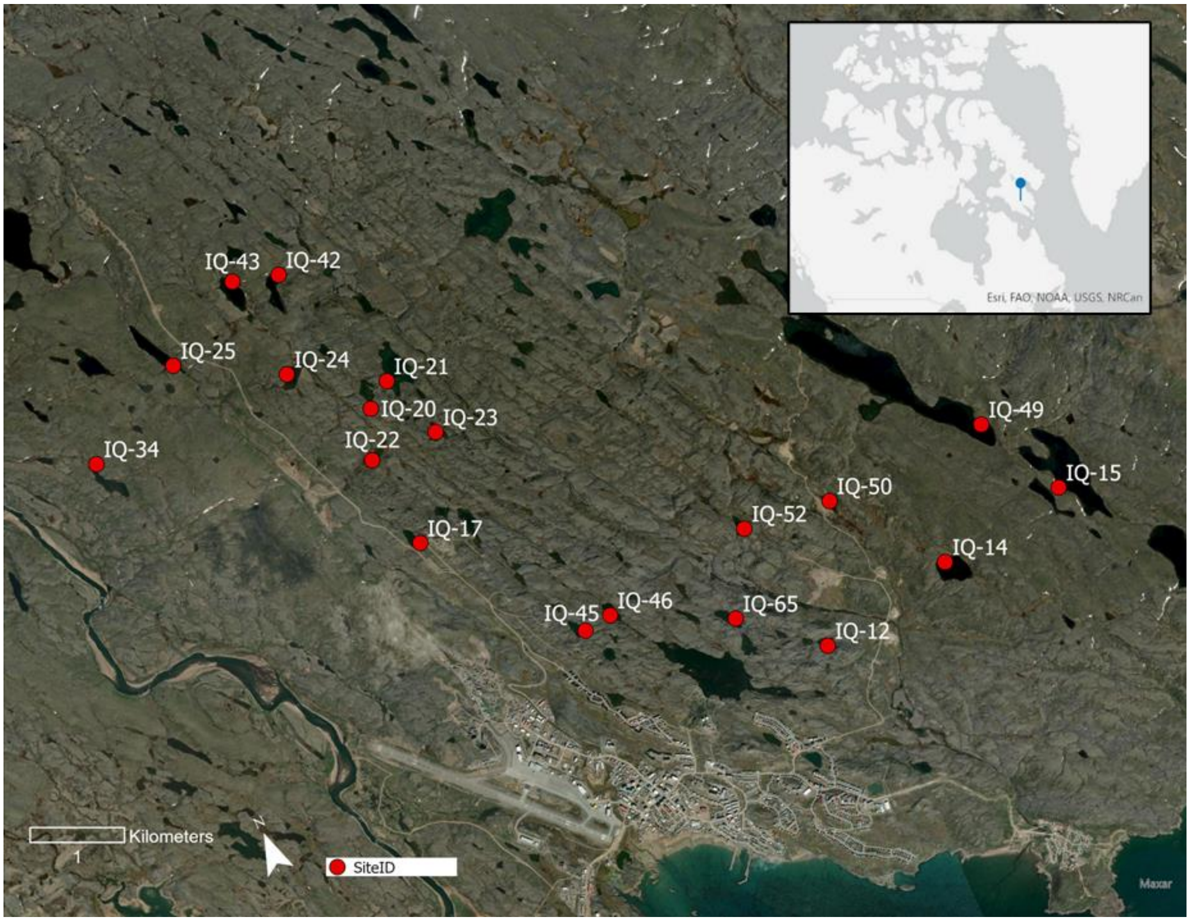

Figure 3.1. Study sites (n = 19) surrounding Iqaluit, Nunavut are indicated by the red circles. Inet map shows the location of Iqaluit in northern Canada. Map made in ArcGIS Pro (Version 3.1.1) by Kelly Evans.

3.1.2.2 Sediment

In the summer of 2022, surface sediment (~200 g; depth = 5 cm) was collected from the shoreline at two locations (randomly selected based on availability of sediment) at each study site (n = 19) using a metal ladle fixed to a metal pole. Sediment was decanted into unlined paint tins and the ladle was rinsed with FRO. Upon arrival at Trent University, sediment was transferred into 1 L glass mason jars and stored at 4°C.

Table 3.1. Site ID, **l**ongitude and latitude (decimal degree; dd), elevation (meters above sea level; m a.s.l.), surface area (m^2) of the lake and the distance of the lake to urban center (m) was measured in ArcGIS Pro (Version 3.1.1). Location is the direction of the catchment from Iqaluit, Nunavut (see Figure 3.1).

SiteID	Latitude	Longitude	Elevation	Surface area of lake	Distance to urban center	Location
	dd	dd	m	m^2	m	
IQ-12	63.756	-68.476	121	11996	2334	East
IQ-14	63.759	-68.445	165	82742	3887	East
IQ-15	63.761	-68.416	222	322648	5344	East
IQ-17	63.781	-68.548	208	16667	3587	North
IQ-20	63.795	-68.546	171	32286	4500	North
IQ-21	63.797	-68.540	181	106423	5138	North
IQ-22	63.790	-68.550	157	20564	4559	North
IQ-23	63.790	-68.535	170	14373	4387	North
IQ-24	63.801	-68.559	165	35365	5860	North
IQ-25	63.806	-68.581	135	72269	6802	North
IQ-34	63.800	-68.605	100	43828	6633	North
IQ-42	63.810	-68.552	177	50713	6742	North
IQ-43	63.811	-68.562	162	58947	6993	North
IQ-45	63.767	-68.523	137	18608	1740	East
IQ-46	63.767	-68.516	121	19102	1804	East
IQ-49	63.769	-68.425	209	999824	5167	East
IQ-50	63.769	-68.462	130	8819	3512	East
IQ-52	63.770	-68.482	112	16396	2838	East
IQ-65	63.762	-68.492	122	25114	1911	East

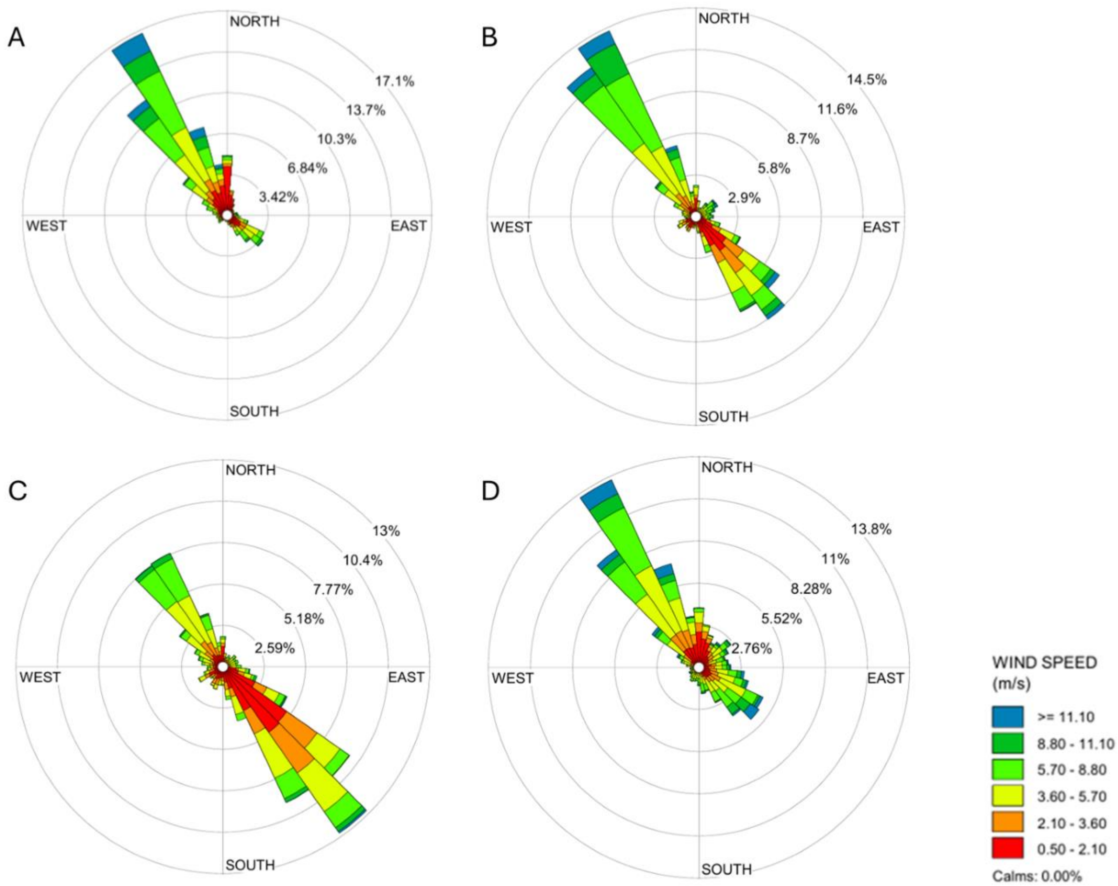

Figure 3.2. Wind roses during the months of (A) January to March, (B) April-June, (C) July-September, (D) October-December in 2020–2022, Iqaluit, Nunavut. Data obtained from Iqaluit Climate Air Monitoring Station (URL: climate.weather.gc.ca). Wind roses were made in WRPLOT View™ (Version 8.0.2).

3.1.2.3 Stair-step moss

In the summer of 2022 and 2023, stair-step moss (~5 g; *Hylocomium* splendens; Figure 3.3) was collected following sampling guidelines in the International Cooperative Programme on Vegetation monitoring manual (ICP Vegetation, 2020). Briefly, living moss tissue (representing the last 2–3 years of growth) was sampled by hand from ~5 random locations in a 50 m^2 plot in each catchment. Before sample collection, hands were rinsed with FRO water to reduce microplastic contamination, and moss was also collected away from lemming dens, geese feces, and four-wheel trails to capture a sample representative of microplastics in atmospheric deposition. Samples were stored in brown-paper lunch bags prior to analysis.

Figure 3.3. Photograph of stair-step moss (*Hylocomium splendens*) on Baffin Island, Nunavut (Kelly Evans, 2022).

3.1.3 Quality Assurance and Quality Control

To avoid contamination of microplastics all samples were collected against the direction of the wind. Field blanks were collected for water samples by mimicking field sampling methods using 1 L filtered tap water. All solutions (reverse osmosis water, hydrogen peroxide, Fenton's reagent, and sodium bromide) were filtered through a glass-fiber filter (Fisherbrand™ Glass Filter Circle, G6, 1.6 µm pore diameter, 4.25 cm filter diameter) prior to adding them to environmental samples. A 100% cotton coat was worn in the laboratory, and hands/nitrile gloves were rinsed periodically with filtered reverse osmosis (FRO) water throughout the extraction. Metal and glass equipment were used where possible, all equipment was tripled-rinsed with FRO water before and in between the handling of environmental samples, and samples were covered with aluminum foil when not being analyzed to prevent procedural contamination.

Laboratory blanks that mimicked laboratory processes (i.e., digestion, density separation) were completed for sediment (n = 4) and stair-step moss (n = 4) to obtain a limit of detection (LOD). Further, polyethylene (PE) beads (n = 10–15 per size; 46–56 µm, 75–90 µm, and 212–250 µm) were used to assess the recovery of microplastics using these procedural methods. For water samples (n = 4), PE beads were added to a 1-gallon high-density polyethylene (HDPE) jug with 3.8 L of FRO water and filtered mimicking field methods. The PE beads were also added to sediment laboratory blanks (100 g wet weight; n = 4) prior to the first density separation. No recovery procedure was completed for stair-step moss. Open-air blanks were collected by placing an exposed glass-fiber filter in a petri dish in the laboratory and by the microscope to capture indoor atmospheric microplastic deposition (n = 2), and at each study site (n = 19) to capture outdoor atmospheric microplastic deposition.

3.1.4 Microplastic Extraction

3.1.4.1 Sediment

Sediment samples were homogenized by gently stirring (~2 min) and analyzed in duplicates (100 g wet weight). Microplastic particles were extracted using three sodium bromide (NaBr) density separations (density = 1.4 g/cm^3) by filling 300 mL tall beakers to the 250 mL line and gently stirring (2 minutes) before settling for 24 hr at ambient temperature. Following the settling time, the beaker walls were carefully rinsed with filtered NaBr and the supernatant was decanted onto a glass-fiber filter, which was stored in a clear polystyrene petri dish until visual analysis. The percent moisture of sediment at each site was calculated by subtracting the dry weight of the sediment from the wet weight, dividing the value by the wet weight, and multiplying by 100. The dry weight of sediment was determined by weighing >2 g of sediment before and after oven drying at 50°C for 72 hr.

3.1.4.2 Stair-step moss

Stair-step moss samples were oven-dried at 45°C for 48 hr in brown-paper bags. After drying, moss was analyzed in 1 g triplicates following modified methods outlined by Roblin and Aherne (2020). Briefly, moss was digested in 1 L glass beakers with 40 mL filtered 30% hydrogen peroxide (i.e., wet oxidation) at 45°C for 24 hr. Following the digestion time, four aliquots of 10 mL Fenton's reagent (0.005 Molar Iron (II) catalyst) were added in 10 min intervals. The temperature of the solution was monitored carefully with a thermometer, and if the solution exceeded 50°C the beakers were placed in an ice bath. One hour after the last aliquot of Fenton's reagent, FRO water (volume = 200 mL) was added to dilute the solution, and sample digested for an additional 24 hr at ambient temperature. Samples were subsequently filtered onto three to five glass-fiber filters and stored in clear polystyrene petri dishes until visual analysis.

3.1.5 Microplastic Identification

All filters were visually analyzed for microplastics using a stereomicroscope (AmScope version x64) and followed the same methods outlined in Chapter Two. Fourier-Transform Infrared spectroscopy (FTIR; LUMOS II, Brucker) was performed on a subset of suspected microplastic particles (43%, water; 65%, sediment; 24%, *H. splendens*) following methods outlined in Chapter 2. All spectra obtained were uploaded to OpenSpecy to identify polymer type (Cowger et al., 2021), and the plastic polymer with the highest Pearson's Correlation coefficient (>0.5) was selected; however, particle hits were on average >0.7.

3.1.6 Data Analysis

The concentration of microplastics in lake water (n/L) was calculated by dividing the count of microplastics by the volume of water sampled. For the subset of lakes where water volume was not measured (n = 12), the average volume of water (7.8 L) was used to estimate concentrations of microplastics in lake water. The concentration of microplastics in sediment (n/kg) was calculated by dividing microplastic counts by the dry weight of the sediment analyzed (Table S6) and converted to counts per kilograms. The concentration of microplastics in stair-step moss (n/g) was calculated by dividing the total count of microplastics by the mass of moss analyzed and averaged between 2022 and 2023 concentrations. To calculate the deposition of microplastics (n/m^2) using stair-step moss, the surface area of moss shoots (n = 11; randomly selected) were measured using threshold analysis and Region of Interest manager tools in ImageJ (Version 1.54b). The mean leaf mass per meter square for moss (62.6 g/m^2) was determined by dividing the mass of the shoots by the combined surface area of the shoots and averaging across sites (n = 13).

The mass concentration of microplastics were estimated for lake water (µg/L), sediment (µg/kg), and stair-step moss (µg/g and $\mu g/m^2$) using modified methods outlined in Chapter Two. Hereafter, the count and mass concentration and deposition of microplastics across media are reported as a mean ± standard deviation.

To determine if concentrations and characteristics of microplastics between catchments located to the east and north of Iqaluit were statistically significant a Mann–Whitney U test was used with a confidence interval of 95%. Spearman's rank-order correlation analysis was performed to determine if the lake's surface area and the distance to Iqaluit were correlated with microplastics in lake water. All figures and statistical analyses were carried out in Past (Version 4.12; Hammer et al., 2001).

3.2 Results

3.2.1 Quality Assurance and Quality Control

No microplastic particles were detected in laboratory blanks for sediment and stair-step moss samples. Microplastics were detected in lake water field blanks, therefore, concentrations were blank corrected by colour and shape (0.6 blue fibres/L). Lake water and sediment concentrations were corrected based on only 94% and 82% of particles identified as plastic by ATR-FTIR, respectively. The recovery of all PE beads from water samples was 100%. For sediment, the recovery of PE beads was 70%, 83%, and 80% for sizes 46–56 µm, 75–90 µm, and 212–250 µm, respectively.

No microplastics were detected in open-air blanks in the laboratory. One blue microplastic fragment was detected in one open-air field blank. However, no microplastics in environmental samples shared similar characteristics to the one identified in the blank; therefore, samples were not corrected based on open-air field blanks.

3.2.2 Lake water

All lake water samples (n = 19) contained microplastic particles. The concentration of microplastics in lake water ranged from 0.22–619 µg/L (0.12–4.94 n/L), with a mean concentration of 79.7 ± 151 µg/L (1.21 ± 1.37 n/L) across study lakes. The mean concentration in lake water ranged from 30.8 ± 55.5 µg/L (0.94 ± 1.34 n/L) in lake water north of Iqaluit to 134 ± 204 µg/L (1.62 ± 1.13 n/L) in lake water to the east of Iqaluit (Figure 3.4). There was a significant difference between the two groups; lakes to the east had a greater microplastic count concentration than the north (Mann–Whitney, $p < 0.05$). There was no significant difference in mass concentrations between the two groups ($p > 0.05$). There was no correlation between microplastic concentration (mass or count) and lake area or distance to the community of Iqaluit.

Microplastic fibres were the dominant shape identified in lake water across the study area (east, 92%; north, 96%; Figure 3.5). The mean concentration of microplastic fibres ranged from 0.22–611 µg/L (0.13–3.97 n/L), with a mean concentration of 29.5 ± 52.2 µg/L (0.74 ± 0.26 n/L) in lakes to the north to 123 ± 199 µg/L (1.21 ± 0.95 n/L) in lakes to the east. The mean concentration of non-fibrous microplastics ranged from 0.00–56.4 µg/L (0.00–1.41 n/L), with a mean concentration of 1.28 ± 3.37 µg/L (0.19 ± 0.19 n/L) in lakes to the north to 11.3 ± 19.1 µg/L (0.43 ± 0.36 n/L) in the east. The mean concentration of fibrous and non-fibrous microplastics were overall greater in lakes to the east than north, however, there was no significant difference between groups ($p > 0.05$).

The mean length of microplastic fibres were not significantly different between lakes in the east (783 ± 777 µm) and north (1030 ± 773 µm) of Iqaluit (Figure 3.6). The mean length of non-fibrous microplastics were also not significantly different between north (171 ± 109 µm) and east (400 ± 799 µm) lakes (Figure 3.6). Across the study lakes, polyester (60%) was the dominant polymer for microplastic fibres; while non-fibrous were equally dominated by high-density polyethylene, polyamide 6, polyester, polysulfone, polyurethane, and styrene acrylonitrile (Table 3.2).

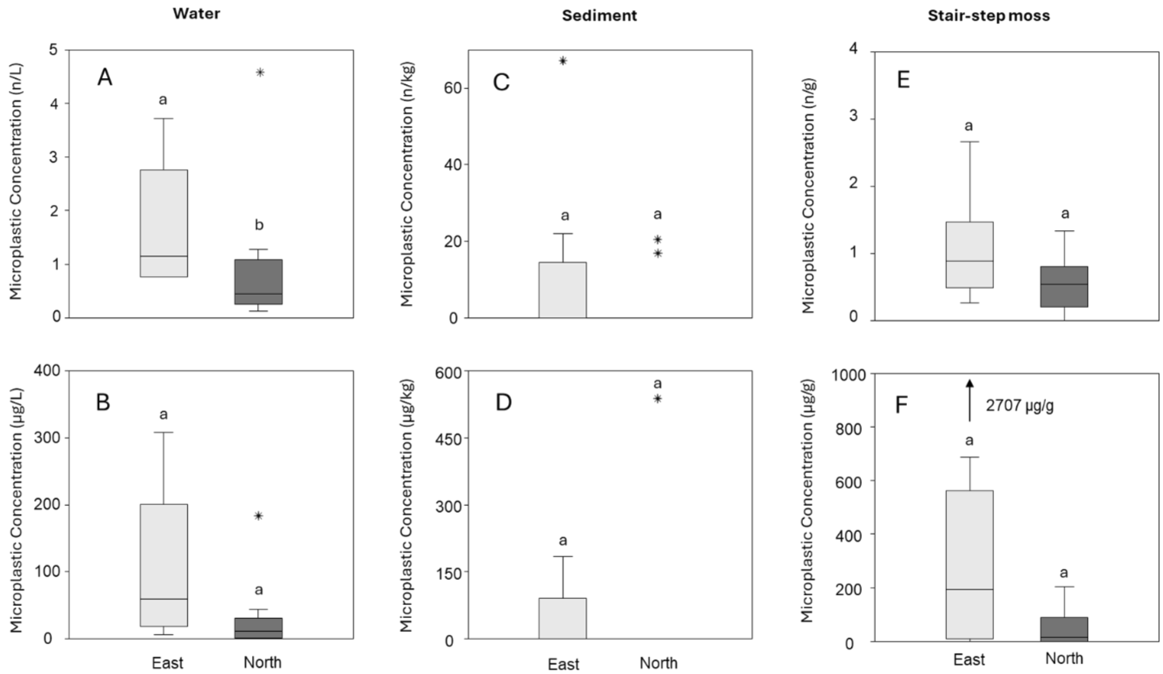

Figure 3.4. Box plot representing A) count concentration of microplastics in lake water (n/L), C) count concentration of microplastics in lake sediment (n/kg), E) count of microplastics in stair-step moss (*Hylocomium splendens*; n/g), B) mass concentration of microplastics in lake water (µg/L), D) mass concentration of microplastics in lake sediment (µg/kg), F) mass concentration of microplastics in stair-step moss (µg/g; outlier at 2707 µg/g in east lakes is not visible in the plot) in lakes (n = 19) to the east and north of Iqaluit, Nunavut. The lowercase letters represent a significant difference between groups (Mann-Whitney, $p < 0.05$). The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

Figure 3.5. Stacked box plot illustrating the proportion of microplastics by shape in lake water, sediment, and stair-step moss (*Hylocomium splendens*) in eastern and northern lakes (n = 19) surrounding Iqaluit, Nunavut.

3.2.3 Sediment

In total, 17 microplastic particles were detected in sediment at 4 of the 19 lake catchments (1 in the north and 3 in the east). The concentration ranged from 0.00–538 µg/kg (0.00–67.1 n/kg), with a mean concentration of 42.8 ± 128 µg/kg (6.67 ± 16.0 n/kg) across lake sediment. The mean concentration ranged from to 44.8 ± 155 µg/kg (3.40 ± 7.61 n/kg) in sediment to the north to 59.1 ± 78.6 µg/kg (10.7 ± 22.4 n/kg) in sediments to the east (Figure 3.4). Across the study sites, microplastic fibres (65%) were the dominant shape identified in sediment, followed by films (25%) and fragments (10%). Overall, the proportion of fibrous microplastics was greater in lake sediments to the north (83%) than the east (40%; Figure 3.5).

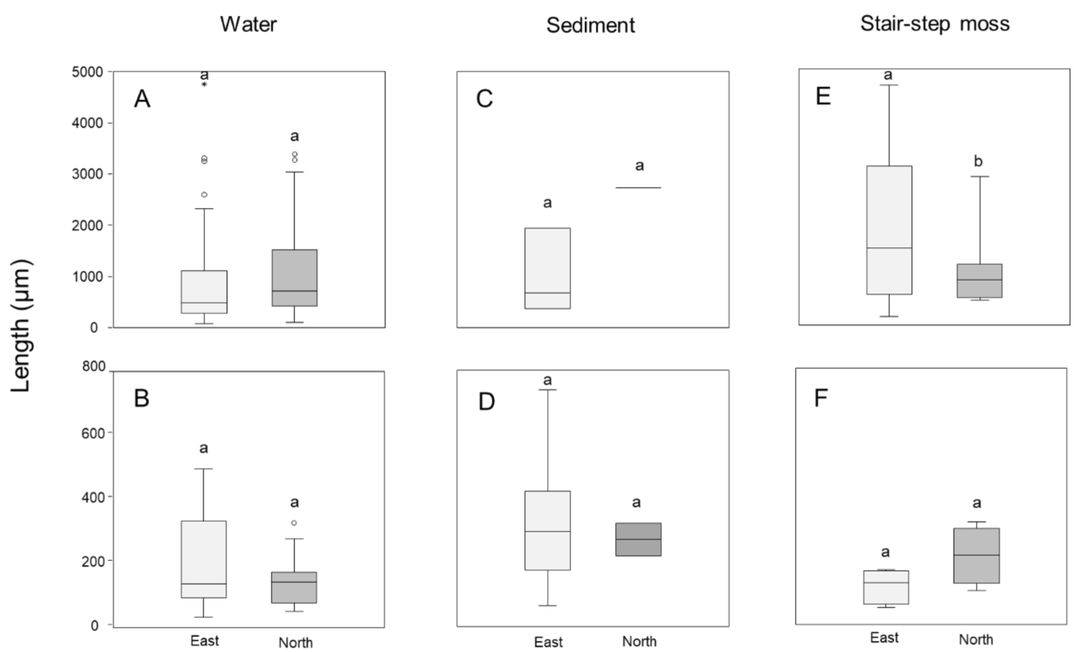

Figure 3.6. Box plots representing the length (µm) of microplastic fibres (A, C, E) and non-fibres (B, D, F) in lake water, sediment, and stair-step moss (*Hylocomium splendens*) from lake catchments (n = 19) located to the east and north of Iqaluit, Nunavut. The lowercase letters represent a significant difference between groups (Mann-Whitney, $p < 0.05$). The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

Table 3.2. Proportion (percent; %) of plastic polymers identified for fibrous and non-fibrous microplastics in lake water, sediment, and stair-step moss (*Hylocomium* splendens) samples from lake catchments (n = 19) surrounding Iqaluit, Nunavut.

Sample media	Microplastic type	Polymer type	Proportion
Water	Fibrous	Polyester	60
		Polyamide	40
	Non-fibrous	High-density polyethylene	16.66
		Polyamide 6	16.66
		Polyester	16.66
		Polysulfone	16.66
		Polyurethane	16.66
		Styrene acrylonitrile	16.66
Sediment	Fibrous	Polypropylene	100
	Non-fibrous	Polypropylene	72
		Polystyrene	14
		Polyethylene	14
Stair-step moss	Fibrous	Polyester	100
	Non-fibrous	Polystyrene	75
		Polypropylene	25

The mean length of microplastic fibres ranged from 997 ± 830 µm in sediment to the east to 2730 µm in the north of Iqaluit (Figure 3.6). The mean length of non-fibrous microplastics ranged from 282 ± 71.6 µm in the north to 343 ± 205 µm in the east (Figure 3.6). Further, polypropylene was the dominant polymer identified in sediment samples across the study area for microplastic fibres (100%) and non-fibres (50%; Table 3.2).

3.2.4 Stair-step moss

In total, 58 microplastic particles were detected in stair-step moss at 17 of the 19 study sites. Microplastics were detected in moss at all sites to the east (n = 9) and at 8 of the 10 north sites. The mean concentration of microplastics in moss across sites was 264 ± 619 µg/g (0.69 ± 0.48 n/g) and ranged from 49.6 ± 66.9

μg/g (0.41 ± 0.30 n/g) in the north to 503 ± 858 μg/g (0.81 ± 0.56 n/g) in the east (Figure 3.4). The mean deposition of microplastics per square meter of moss across the study area was 4.22 ± 9.90 μg/m^2 (0.01 ± 0.008 n/m^2) and ranged from 0.79 ± 1.07 μg/m^2 (0.007 ± 0.005 n/m^2) in the north to 8.03 ± 13.7 μg/m^2 (0.01 ± 0.009 n/m^2) in the east. There was a significant difference between the two groups, microplastic deposition (μg/m^2) was greater in catchments to the east than the north (Mann-Whitney, $p < 0.05$). Further, the count and mass concentration and deposition of microplastics in moss was significantly correlated to the count concentration of microplastics in lake water ($p < 0.05$).

The dominant microplastic shape identified in moss across the study sites were fibres (east, 70%; north, 77%; Figure 3.5). The mean length of microplastic fibres in moss ranged from 1100 ± 723 μm in the north to 2520 ± 2390 μm in the east (Figure 3.6). There was a significant difference between the two groups, microplastic fibres to the east were longer than those in the north (Mann–Whitney U, $p < 0.05$). The mean length of non-fibrous microplastics were similar between the two groups and ranged from 215 ± 88.8 μm in the north to 223 ± 356 μm in the east (Figure 3.6). In moss, polyester (100%) was the dominant polymer for microplastic fibres, and polystyrene (75%) was the dominant polymer for non-fibrous microplastics (Table 3.2).

3.3 Discussion

Microplastic particles were identified at each lake catchment in this study. It is likely that atmospheric microplastic deposition was a dominant source for microplastic contamination to these catchments as suggested by the correlation between microplastic concentrations in lake water and moss, which is a biological monitor of atmospheric microplastic deposition (Roblin & Aherne, 2020). Further, microplastic fibres were the dominant shape identified across the three environmental media; in general, fibres are a dominant shape identified in atmospheric studies due to their lower settling velocity (Preston et al., 2023).

Despite the dominance of microplastic fibres across the study area, the lake water to the east had a greater diversity of fibrous and non-fibrous microplastics than the lakes to the north (Figure S6), suggesting the lakes to the east and north are not equally exposed to microplastic sources (Tatsii et al., 2024; Ward et al., 2024). This finding suggests that Iqaluit may have a greater influence on microplastic contamination in the lakes to the east, since urban communities tend to have a greater diversity of microplastic particles than remote areas (due to the presence of human activities and infrastructure). Unlike the lakes to the east, the lakes to the north of Iqaluit are predominantly upwind of anthropogenic sources; therefore, they have a lower atmospheric connectivity to the community. This is reflected by the low concentration and diversity of microplastic particles in the north compared with the east.

There are challenges when comparing microplastic concentrations and characteristics across studies due to the lack of standard collection and analytical methods. A study in the remote polar region of the Kola Peninsula in northwest Russia identified a range from 1.50–4.17 fibers/L and 0.42–1.60 fragments/L in nine isolated freshwater lakes (Kaliszewicz et al., 2023), which are similar to the findings of our study. In contrast, a study that investigated microplastics in the

Svalbard Archipelago (78°N, 11°E) detected no microplastics in lake water sieved at 0.5 mm (González-Pleiter et al., 2020). The detection of zero microplastics by González-Pleiter et al. (2020) is likely a result of the large mesh size of the sieve used in their study, which would likely result in the loss of small plastic particles, including fibres which have a narrow diameter (10–20 µm). The methods in the current study were similar to Welsh et al. (2022a) who suggested a mean concentration of 1.78 n/L in headwater lakes with minimum anthropogenic input in southern Ontario.

Microplastic fibres were the dominant shape identified in the current study (>90%), as well as in northwest Russia (76%; Kaliszewicz et al., 2023) and in headwater lakes in southern Ontario, Canada (>70%; Welsh et al., 2022a). This trend indicates that synthetic textiles are a major source for microplastic contamination in lake catchments.

The concentration of microplastics in sediment samples in the current study was less than the mean concentration (3660 n/kg) of microplastics in sediment from freshwater in southern Ontario (Welsh et al., 2022a). There was a rare occurrence of microplastics in lake sediment within the current study (4 out of the 19 lakes), so these data results are conservative.

One other study investigated microplastic fibers in stair-step moss and found a mean of 3.12 n/g across three lake catchments in western Ireland (Roblin and Aherne, 2020), which was approximately three times greater than the current study. The length of microplastic fibres identified by Roblin and Aherne (2020) observed shorter microfibers in moss from lake catchments further in distance from urban environments, which followed a similar trend to the current study.

We acknowledge there are limitations to our study; bulk water sampling for microplastic contamination typically involves the collection of 10–50 L, whereas in the current study we filtered an average of 7.8 L. Further, a greater mass of sediment was required for analysis due to the rare occurrence of microplastics detected across the study area. The sample size of 100 g (wet weight) was likely too small. In addition, the sample size of stair-step moss was likely too little too.

3.4 Conclusion

This study suggests that atmospheric transport and deposition is a dominant pathway for microplastics to freshwater lake catchments surrounding Iqaluit, Nunavut. Using a catchment-based sampling approach we identified the concentration, characteristics, and distribution of microplastic particles in lake water, sediment, and moss; the results suggest that Arctic freshwater lakes are vulnerable to atmospheric microplastic contamination from local communities. Overall, the freshwater lake catchments to the east of Iqaluit had a greater concentration, longer particles, and a greater diversity of microplastic compared to lakes in the north. The results from this study underscore the importance to better understand how local Arctic communities contribute to microplastics in wider environments. The results of this study contribute to baseline data on microplastic concentrations in Canadian Arctic freshwaters.

Chapter Four: Sampling method influences estimated microplastic concentrations and characteristics in Arctic lake water

4.0 Introduction

Microplastics are plastic particles <5 mm in length, and a contaminant of emerging Arctic concern (AMAP, 2017). These contaminants are intricate physical particles with complex chemical structures often associated with chemical additives (Rochman et al., 2019). Microplastic particles are generally characterized by shape (e.g., fiber, foam, fragment, film, and bead), size (e.g., length and width), and chemical composition (Cole et al., 2011; Rochman et al., 2019). Sources of microplastic contamination include personal care products, synthetic textiles, and plastic debris; and they enter the wider environment through pathways, such as wastewater effluent (Herzke et al., 2021), road surface wash off (Monira et al., 2021), and atmospheric transport and deposition (Dris et al., 2016; Wright et al., 2020). Microplastic contamination in freshwater systems has gained attention during the past decade (Nava et al., 2023), however, there is no standard method for sample collection (Hung et al., 2021).

Two common methods to estimate microplastic concentrations and characteristics in lake water are (a) volume-reduced, and (b) bulk sampling. Volume-reduced sampling often involves pumping a large volume of water (100–1000 L) through a plankton net or sieve (mesh sizes ranging from 50 to 300 µm) and only analyzing the residue. This method reduces the total volume of water into a manageable quantity for analysis and tends to represent a diversity of microplastics (Sharma et al., 2024). However, microplastic fibres and small particles are generally under-quantified due to the diameter size of the net or sieve. In contrast, bulk sampling retains the full volume of the sample, therefore, the method retains majority of microplastics (typically dominated by microplastic fibres) depending on the pore size of the filter (0.1–10 µm). In contrast to volume-reduced sampling, a smaller volume (10–50 L) of lake water is typically collected in bulk sampling and this reduces the diversity of microplastics characterized. Both methods are commonly followed by a series of analytical techniques to extract microplastic particles from the sample, including digestion (e.g., wet oxidation using hydrogen peroxide) and filtration (0.1–10 µm pore size filter).

In this study, we assessed how the sampling method influenced the concentration and characteristics of microplastics in 19 lakes surrounding Iqaluit, Nunavut. In 2022, lake water was collected using a volume-reduced method by pumping ~150 L of surface water through a 53 µm plankton net and filtering (pore size 1.6 µm) the contents retained in the cod end in the laboratory. In 2023, the lakes were revisited, and a bulk sample was collected by filtering ~8 L surface water in the field onto a 1.6 µm filter. The results of this study provide valuable insight into how the sampling method influenced microplastic concentration and characteristics.

4.1 Methods

4.1.1 Study Sites

The freshwater lakes (n = 19) in this study were located around Iqaluit, Nunavut (63.7467° N, 68.5170° W), on southern Baffin Island (Figure 3.1; Table 3.1). The lakes have a mean elevation of 156 m above sea level and a mean surface area of 103 km^2. They are located in a walking proximity (8 km radius) to the community.

4.1.2 Quality Assurance and Quality Control

Strict quality assurance and control measures were implemented to ensure the estimated values reflect environmental concentrations. Given their ubiquity, all solutions were filtered through a glass-fibre filter (Fisherbrand™ Glass Filter Circle, 1.6 µm pore diameter, G6, filter diameter 4.25 cm). In the laboratory, a 100% cotton laboratory coat was worn, and hands/gloves were periodically rinsed with filtered reverse osmosis (FRO) water. Metal and glass equipment were used where possible, and all equipment was kept clean by periodically triple rinsing with FRO water. Laboratory blanks (n = 2) were performed in sequence with environmental samples and consisted of running solutions through the same laboratory processes as environmental samples to capture microplastics unintentionally added during the extraction process. And open-air laboratory blanks (n = 2) were collected by exposing a glass-fibre filter in a petri dish beside the microscope to capture indoor microplastic deposition.

An equipment blank was carried out for the volume-reduced method by pouring 1 L FRO into the plankton net and retaining the contents in the cod end. However, due to the logistical limitations of carrying >10 L of FRO water into the field, field blanks for the volume-reduced method were not carried out. To obtain a limit of detection (LOD) for the bulk method, field blanks were performed at random lakes (n = 5) and involved filtering 1 L FRO water in the field using a 500 mL portable Nalgene apparatus.

Laboratory blanks were carried out for the volume-reduced method, with involved filtering ~250 mL of FRO from a beaker. No laboratory methods were carried out for the bulk method because samples were filtered in the field. Open-air blanks were collected by placing an exposed glass-fiber filter in a petri dish in the laboratory and by the microscope to capture indoor atmospheric microplastic deposition (n = 2). Further, air blanks were collected at each study lake (n = 19) by placing an exposure filter to outdoor atmospheric deposition.

4.1.3 Field Sampling and Sample Processing

4.1.3.1 Volume-reduced method

In the summer of 2022, lake water was collected from one location at each lake and pond (n = 19), the site was selected based on safety and avoided areas with visible plastic debris. The plankton net was pre-conditioned (downstream of the sample site) with lake water by rinsing the outside of the plankton net (without the cod end attached) with ~10 L of lake water, and the cod end was triple rinsed with FRO water. Subsequently, lake water (volume = ~150 L, depth = 5 cm) was pumped through the plankton net (53 µm pore diameter) using a Sea Bulge pump and white polyethylene tubbing. Once the sample was collected, the outside of the plankton net was rinsed with an additional ~10 L of lake water to wash down particles that adhered into the cod end. The contents in the cod end were decanted into an unlined paint tin, and the cod end was triple rinsed with FRO water into the same paint tin. Upon arrival at Trent University, lake water samples were filtered onto a glass-fiber filter using a vacuum pump, and the paint tin was triple rinsed with FRO water and filtered onto the same filter.

4.1.3.2 Bulk Method

In the summer of 2023, ~7.8 L of lake water (at 5 cm depth) was sampled from one location at each catchment (n = 19) using a 1-gallon HDPE jug (refilled once). Lake water was filtered in the field at each study site across multiple (n = 8) glass-fiber filters using a portable 500 mL Nalgene apparatus and hand pump. Filters were transferred to a clear polystyrene petri dish using clean tweezers and the petri dish was wrapped in aluminum foil. Following the last refill, the HPDE jug and the Nalgene apparatus were triple rinsed with FRO water to capture the remaining particles and filtered onto a separate filter. The volume of water that passed through each filter was measured at a subset of lakes (n = 7) using a 1 L graduated cylinder.

4.1.4 Microplastic Identification

Filters were visually analyzed for microplastics using a stereomicroscope (AmScope version x64) and followed the same methods outlined in Chapter 2. Fourier-Transform Infrared spectroscopy (FTIR; LUMOS II, Brucker) was performed on a subset of particles (21% for volume-reduced and 43% for the bulk method) following methods outlined in Chapter 2. All spectra were uploaded to OpenSpecy to identify polymer type (Cowger et al., 2021), the plastic polymer with the highest Pearson's Correlation coefficient (>0.5 due to the suspected aging of the particles) was selected. Particle hits were on average >0.7.

4.1.5 Data Analysis

The count concentration of microplastics in lake water was calculated by dividing the number of microplastics counted by the volume sampled. Mass concentrations were estimated using modified methods from Simon et al. (2018) by calculating the volume of each particle based on their shape (Table S1), summing particle volume by shape across each study site, and multiplying the volume sum by the average polymer density for shape-specific particles. Hereafter, microplastic count and mass concentration are reported as mean Hereafter, microplastic count and mass contaminations are reported as mean (± standard deviation) per Liter lake water. Microplastic concentrations were also corrected by multiplying the count and mass concentration by the proportion of particles determined to be plastic by ATR-FTIR. To determine if concentration and characteristics of microplastic particles between the two methods were statistically significant a Mann–Whitney U test was used with a confidence interval of 95%. All figures and statistical analysis were carried out in Past (Version 4.12; Hammer et al., 2001).

4.2 Results

4.2.1 Quality Assurance and Quality Control

Microplastics were detected in the equipment blanks (Table S8). However, since field blanks were not performed concentrations were not blank corrected. All suspected particles from volume-reduced sampling were all (100%) identified as plastic by ATR-FTIR. Bulk lake water samples were corrected using the limit of detection by microplastic shape and colour (0.6 blue fibres/L) and based on 94% of particles identified as plastic by ATR-FTIR.

No microplastics were detected in the laboratory blanks for volume-reduced sampling. Further, no microplastics were detected in open-air blanks. One blue fragment was detected in an open-air blank at one field site; however, no microplastic particles in environmental samples shared the characteristics to the one identified in the blank. Therefore, environment samples were not corrected based on outdoor open-air blanks.

4.2.2 Volume-reduced Method

In total, 1454 microplastic particles were quantified in lake water samples using the volume-reduced method (Table S9). The concentration of microplastics in lake water ranged from 0.0003–0.24 µg/L (0.07–1.29 n/L) across the study lakes, with a mean concentration of 0.02 ± 0.04 µg/L (0.50 ± 0.41 n/L; Figure 4.1).

Fragments (52%) were the dominant microplastic shape identified by the volume-reduced method, followed by films (21%), fibres (16%), and foams (10%; Figure 4.2). The length range of fibrous and non-fibrous microplastics was 79.9–4878 µm and 15.3–3523 µm, respectively. The mean length of fibrous microplastics was 1418 ± 1013 µm and the mean length of non-fibrous microplastics was 170 ± 257 µm (Figure 4.3). Across the study lakes, polyester (56%) was the dominant polymer for fibrous microplastics, and polyvinyl chloride (27%) was the dominant polymer for non-fibrous microplastics (Figure 4.4).

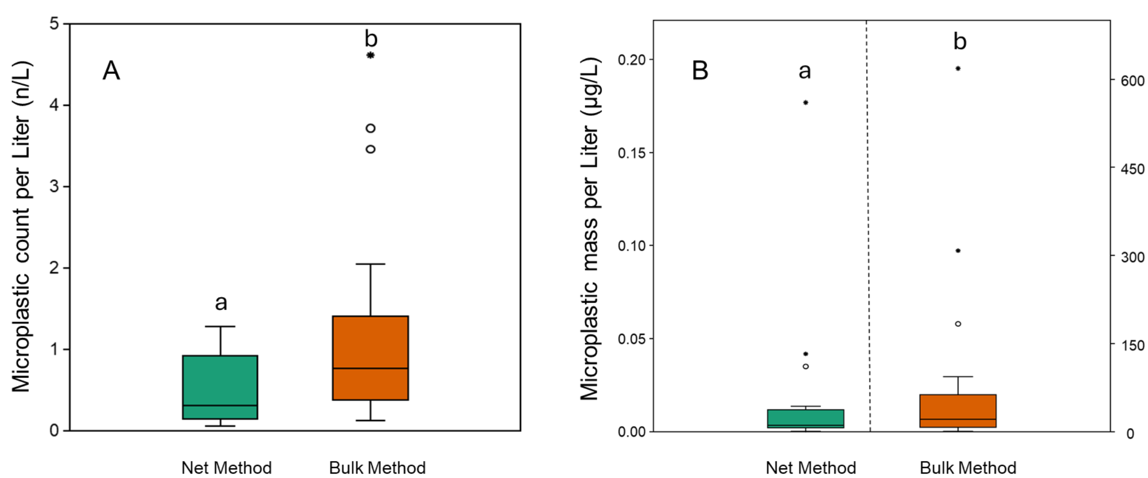

Figure 4.1. Box plot representing A) count concentration per liter (n/L) and B) mass concentration per liter (µg/L) of microplastics in lake water (n = 19) on Baffin Island, Nunavut, using volume-reduced (i.e., "net method") and bulk sampling methods. The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range. The lowercase letters represent a significant difference between groups (Mann-Whitney, $p < 0.05$).

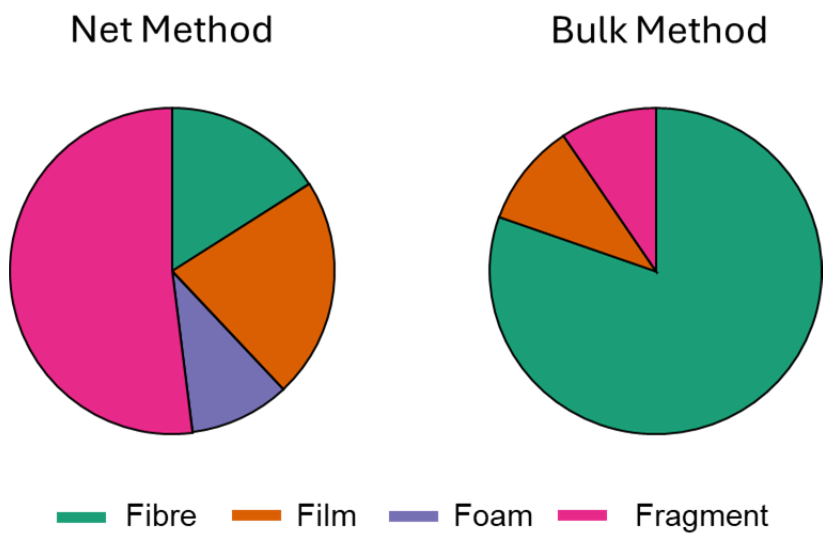

Figure 4.2. Pie charts illustrating the proportion of microplastic shapes identified in Arctic lake water using volume-reduced method (i.e., “net method”) with 53 µm plankton net and bulk sample method (n = 19) on Baffin Island, Nunavut.

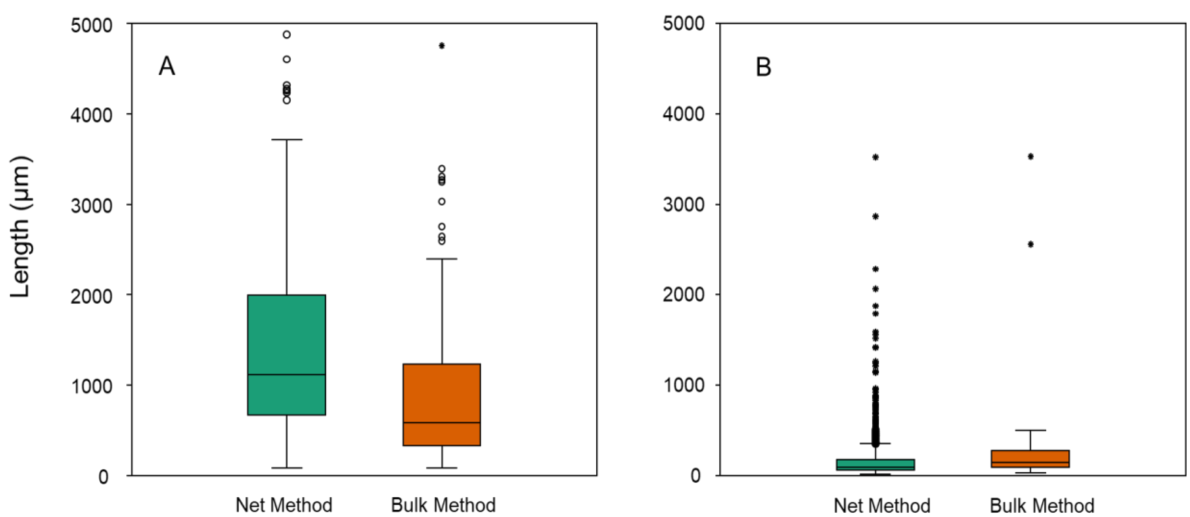

Figure 4.3. Box plots presenting the length (µm) of A) fibrous and B) non-fibrous microplastics in Arctic lake water samples using volume-reduce method (i.e., “net method”) with a 53 µm plankton net and bulk method across lakes (n = 19) on Baffin Island, Nunavut. The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

4.2.3 Bulk Method

In total, 246 microplastic particles were quantified in lake water samples using the bulk method (Table S10). The concentration of microplastics in lake water ranged from 0.22–619 µg/L (0.12–4.94 n/L) across the study lakes, with a mean concentration of 79.7 ± 151 µg/L (1.21 ± 1.37 n/L; Figure 4.1). Microplastic fibres (80.4%) were the dominant shape identified by the bulk method, followed by films (10.2%), and fragments (9.4%; Figure 4.2); no foams were detected. The length range of fibrous and non-fibrous microplastics was 80.7–4750 µm 32.1–3530 µm, respectively. The mean length of fibrous microplastics was 882 ± 782 µm and the mean length of non-fibrous microplastics was 313 ± 637 µm (Figure 4.3). Across the study lakes, polyester (61%) was the dominant polymer for fibrous microplastics, while non-fibrous microplastics were equally dominated by high-density polyethylene, polyamide 6, polyester, polysulfone, polyurethane, styrene acrylonitrile (Figure 4.4).

4.3 Discussion

Our study illustrates that sample collection method influenced the estimated concentration and characteristics of microplastics in Arctic lake water. Lake water collected using a bulk sample method expressed a microplastic concentration approximately 2.5 times greater by count, and ~4000 times greater by mass than the volume-reduced method. The volume-reduced method likely underestimated the concentration of microplastics in lake water as the pore size of the plankton net allowed small microplastics and microplastic fibres (due to their narrow diameter;

10–20 µm) to escape. Similar trends have also identified that the method of sample collection influences on the concentration of microplastics in lake water; in general, a larger pore size reduces the concentration of microplastics detected.

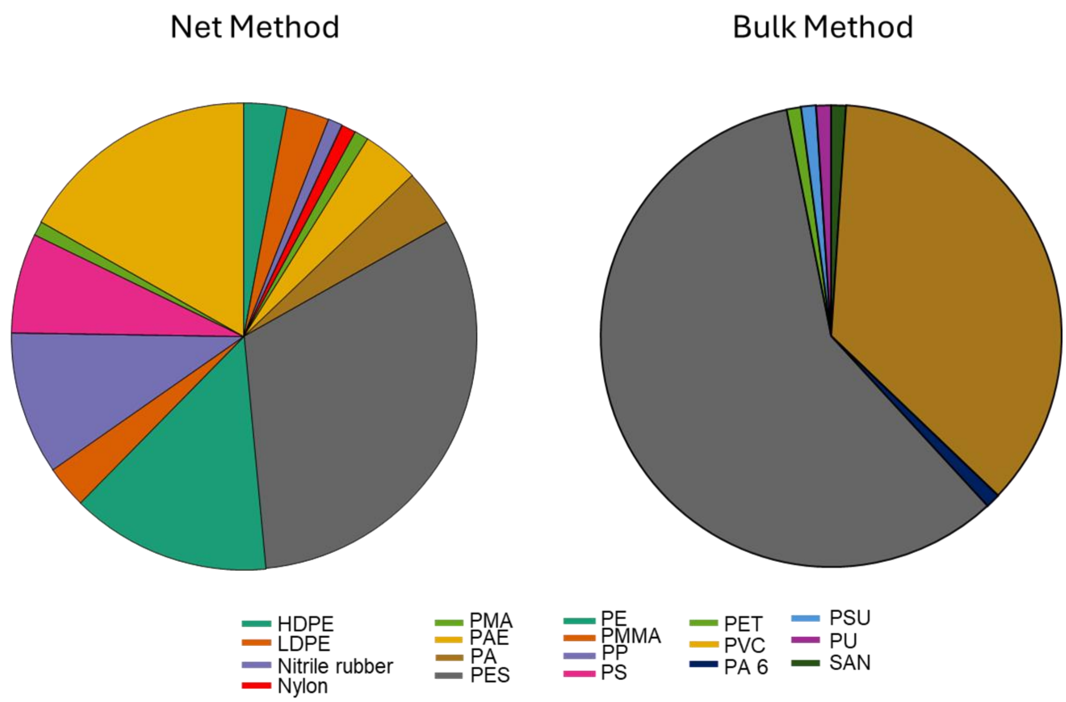

Figure 4.4. Pie charts illustrating the proportion of plastic polymers characterized in Arctic lake water using a volume-reduced method (i.e., "net method") with 53 µm plankton net and bulk sample method across lakes (n = 19) on Baffin Island, Nunavut. HDPE: High-density polyethylene; LDPE: Low-density polyethylene; PMA: Polyacrylamide; PAE: Polyacrylate; PA: Polyamide; PES: Polyester; PE: Polyethylene; PMMA: polymethyl methacrylate; PP: Polypropylene; PS: Polystyrene; PET: Polyethylene terephthalate; PVC: Polyvinyl chloride; PA 6: Polyamide 6; PSU: Polysulfone; PU: Polyurethane; SAN: Styrene-acrylonitrile.

The sample collection method for lake water also influenced the microplastic characteristics identified. A greater proportion of microplastic fibres were identified lake water collected using the bulk method compared with the net method (which was dominated by fragments; 52%). This is likely due to the loss of fibres from the plankton net which had a pore size of 53 µm. The findings in this study are akin to previous studies which also detect a greater proportion of microplastic fibres in bulk samples compared with volume-reduced sampling (De-la-Torre et al., 2022; Hung et al., 2021; Tamminga et al., 2018). Although sampling method influenced the shape of microplastics identified, the size of fibrous and non-fibrous microplastics between bulk and volume-reduced sampling were similar ($p > 0.05$). In contrast, a greater frequency of smaller microplastics was identified using the bulk method than with the volume-reduced method. Further, the volume-reduced method captured a greater diversity of polymer types compared with the bulk method, which results from the large volume of water sampled using the volume-reduced method (~150 L) compared with the bulk method (<8 L).

There are advantages and disadvantages to each method. The volume-reduced method provides a more representative picture of the microplastic polymers present in Arctic lake water, which is vital to understanding source contributors. However, it underestimates microplastic fibres and this influences the estimated concentration. In contrast, the bulk method in this study captures all microplastics (down to 1.6 µm) in lake water. However, due to the small volume of water collected, these samples reflect a low diversity of microplastic polymers and are unable to capture microplastic shapes that are less abundant in the environment. For instance, microplastic foams were only identified in lake water collected using volume-reduced sampling and this is likely because a larger volume of water is required to identify these ‘rarer’ microplastic particles.

Overall, the choice of sampling method for microplastic analysis in lake water should be centered around the research question and the objective of the study. For example, in Chapter 3 of this thesis, the objective was to identify atmospheric transport as a pathway for microplastics to isolated freshwater catchments, and because microplastic fibres are a dominant shape present in the air we elected a sampling method that targeted the collection of microplastic fibres. Alternatively, a method that combines both volume-reduced and bulk sampling may be a solution to capture a representative concentration of fibres and also high diversity of particles.

4.4 Conclusion

In our study, the choice of sampling method influenced the concentration and characteristics of microplastic particles identified in Arctic lake water. The count and mass concentration of microplastics was greater in lake water collected using a bulk method compared with a volume-reduced method. Further, the bulk method captured a greater proportion of microplastic fibres, while the volume-reduced method captured a greater diversity of microplastic polymers. In contrast, the length of microplastics were similar for both methods. This study highlights the importance of detailed sampling and analysis descriptions when reporting microplastic contamination in lake water. It is recommended that the method choice for sample collection reflects the objective of the study. However, it may be advantageous to use a method that combines both volume-reduced and bulk sampling.

Chapter Five: Atmospheric microplastics over the Arctic Ocean

5.0 Introduction

Microplastic (plastic particles <5 mm in length) contamination is pervasive in the environment and considered a contaminant of emerging Arctic concern (AMAP, 2021). Primary microplastics are intentionally produced to be micro- or nano-sized and largely used to form plastic products or as additives to personal care products. Secondary microplastics form in the environment through chemical, physical, and biological fragmentation of large plastic debris (Cole, 2016; Rochman et al., 2019), including the shedding of synthetic clothing and textiles and tire wear particles (Monira et al., 2021). Microplastics are further distributed to the wider environment through biological (e.g., seabirds; Hamilton et al., 2021), hydrological (e.g., rivers; Geng et al., 2023; Lebreton et al., 2017; Strokal et al., 2023, ocean currents; Cózar et al., 2017, and sedimentation; Dimante-Deimantovica et al., 2024), and atmospheric (air currents and deposition; Bertrim & Aherne, 2023; Dris et al., 2016; Evangeliou et al., 2020; Roblin et al., 2020; Ward et al., 2024; Welsh et al., 2022b) transport mechanisms.

Microplastic contamination in Arctic marine environments has been detected in surface water (Huntington et al., 2020; Lusher et al., 2015), the water-column (Andrady, 2011; Lusher et al., 2015; Tekman et al., 2020), invertebrates (Bos et al., 2023; Jamieson et al., 2019; Huntington et al., 2020), fish (Kögel et al., 2023; Kühn et al., 2018; Morgana et al., 2018), deep-sea sediment (Bergmann et al., 2017; Huntington et al., 2020; Tekman et al., 2020), sea-algae (Bergmann et al., 2023), sea-ice (Kanhai et al., 2020; Obbard et al., 2014; Peeken et al., 2018), and sea birds (Hamilton et al., 2021; Provencher et al., 2014). Nonetheless, no studies have evaluated the concentration or characteristics of atmospheric microplastics in remote regions of the High Arctic.

The objective of this study was to identify atmospheric microplastics over the Arctic Ocean to better understand their concentration and characteristics in remote regions of the High Arctic. The study was conducted on the Canadian Coast Guard Ship (CCGS) Amundsen using an active sampler along 12 transects during a scientific expedition in the Canadian Archipelago of Nunavut.

5.1 Methods

5.1.1 Sample Collection

Air was sampled over the Arctic Ocean using an active sampler during a scientific expedition on the CCGS *Amundsen* (R-class research icebreaker; length 98 m; ~80 members on the vessel during the expedition) from 11 September 2023 to 4 October 2023 (Figure 5.1). On the bridge, air was pulled through a glass-fibre filter (Fisherbrand™, 47 mm diameter, 1.6 µm pore diameter) using an aluminum NILU filter holder system designed for microplastic collection and a vacuum pump. The system was deployed vertically with the filter facing up and was sheltered under an aluminum funnel to prevent contamination from wet deposition (i.e., snow or sea spray; Figure S7).

The flow rate of the sampler was calibrated to 20 L/min each deployment, and the flow rate was recorded at deployment and retrieval to obtain an average volume (liters/min) sampled during each 48-hr exposure (n = 12 transects; Table

5.1). Following the deployment period, filters were transferred to a clear polystyrene petri dish using clean stainless-steel tweezers and stored in clear polystyrene petri dishes until visual analysis.

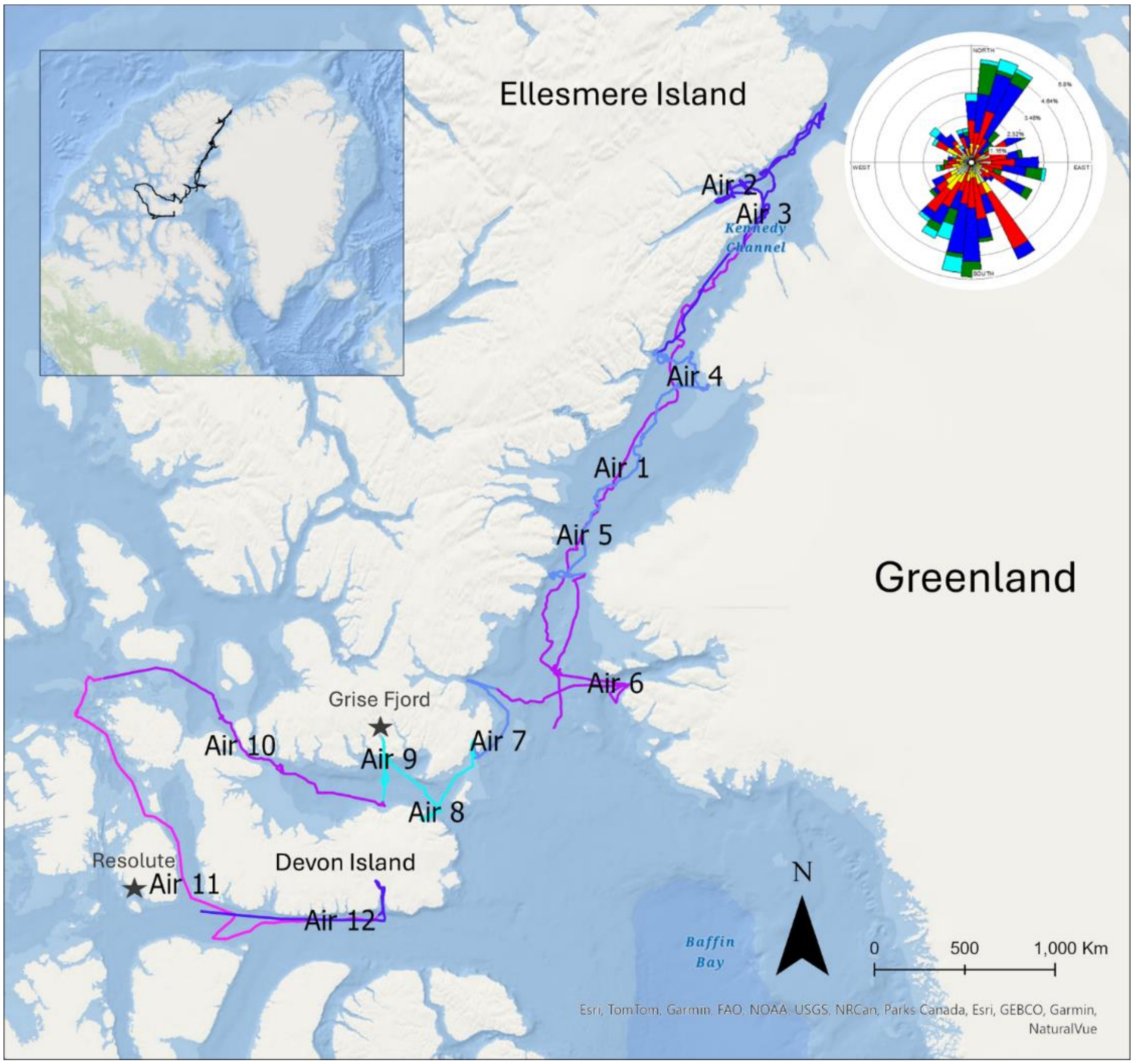

Figure 5.1. The study area in the Canadian Arctic Archipelago of Nunavut showing 12 sampling transects where air was sampled for ambient microplastics from 11 September 2023 to 4 October 2023. The wind rose depicts the wind direction and speed during the study period. The inlet map shows the study area relative to northern Canada and Greenland.

5.1.2 Quality Assurance and Quality Control

A 100% cotton lab coat was worn while loading the NILU filter pack, and the air head cover was wrapped in aluminum foil when not attached to the sampler. The air head cover was sealed to the sampler while transporting air pack from the laboratory to the deployment site on the bridge. To determine the limit of detection (LOD), blanks (n = 4) were performed by mimicking the sample collection methods. This involved (1) loading the air head with a filter in the laboratory, (2) covering the air head with the lid, (3) transporting the air sampler to the deployment area, (4) running the air sampler for 30 seconds, (5) covering and transporting the air sampler back to the laboratory, and (6) unloading the filter into a clear polystyrene petri dish; no microplastics were detected in field blanks.

5.1.3 Microplastic Identification

Filters were visually analyzed for microplastics using a stereomicroscope (AmScope version x64) and followed the same methods outlined in Chapter 2. Fourier-Transform Infrared spectroscopy (FTIR; LUMOS II, Bruker) was performed following methods outlined in Chapter 2. All spectra obtained were uploaded to OpenSpecy to identify polymer type (Cowger et al., 2021), the plastic polymer with the highest Pearson's Correlation was selected, with a cut-off value of 0.5; while a higher correlation (>0.5) is generally favoured, we selected a cut off of 0.5 to allow flexibility for the potential aging of particles.

Table 5.1. SiteID, sampling date, longitude and latitude where the air sampler was turned on, longitude and latitude where the air sampler was turned off, and the average air volume sampled (L/minute) across each sampling transect (n = 12).

TransectID	Date On	Location On	Date Off	Location Off	Volume
		Latitude/ Longitude		**Latitude/ Longitude**	**L/min**
Air 1	10-Sept-23	77° 25.0335' N 75° 09.8842' W	12-Sept-23	81° 27.0529' N 64° 12.6211' W	16.0
Air 2	12-Sept-23	81° 32.3913' N 64° 57.5730' W	14-Sept-23	82° 03.8602' N 61° 30.6880' W	17.0
Air 3	14-Sept-23	82° 03.8602' N 61° 30.6880' W	16-Sept-23	80° 19.1770' N 69° 43.7084' W	17.0
Air 4	16-Sept-23	80° 18.8199' N 69° 43.8436' W	18-Sept-23	79° 35.4791' N 70° 18.4482' W	17.5
Air 5	18-Sept-23	79° 35.4747' N 70° 18.3844' W	20-Sept-23	78° 18.3775' N 73° 26.0232' W	18.5
Air 6	20-Sept-23	78° 17.5421' N 73° 33.4817' W	22-Sept-23	77° 09.7188' N 78° 07.5685' W	20.0
Air 7	22-Sept-23	77° 09.7188' N 78° 07.5685' W	24-Sept-23	76° 29.0722' N 78° 44.4044' W	20.0
Air 8	24-Sept-23	76° 29.0722' N 78° 44.4044' W	26-Sept-23	76° 25.1008' N 82° 55.8126' W	20.5
Air 9	26-Sept-23	76° 25.1008' N 82° 55.8743' W	28-Sept-23	75° 49.8360' N 83° 18.8118' W	21.0
Air 10	28-Sept-23	75° 49.8360' N 83° 18.8118' W	30-Sept-23	76° 55.2499' N 98° 23.9060' W	20.3
Air 11	30-Sept-23	76° 55.2499' N 98° 23.9060' W	02-Oct-23	74° 53.7635' N 83° 35.1757' W	19.0
Air 12	02-Oct-23	74° 53.7258' N 83° 35.2323' W	04-Oct-23	74° 41.3139' N 94° 51.5058' W	18.0

5.1.4 Data Analysis

The microplastic count data were converted to microplastic concentration based on the average volume of air sampled over each 48-hr sample period. If we let *N* represent the number of microplastics quantified, *t* represent the length of sample exposure (hours), and *V* represent the volume (liters) of air sampled per transect, then the microplastic concentration (L; n/m^3) is calculated as:

$$L = \frac{N}{\left[\frac{t \cdot \bar{V}}{1000} \right]}$$

Microplastic mass concentration (μg/m^3) was estimated using modified methods from Simon et al. (2018) by calculating the volume of each particle based on their shape (Table S1), summing particle volume by shape across the transect, multiplying volume sum by the average polymer density for each shape (Table S12), and dividing the mass by the volume of air sampled (m^3). Hereafter, microplastic count and mass contaminations are reported as mean (± standard deviation).

A Grubbs test was used to identify potential outliers. A Spearman's Correlation was calculated to between microplastic variables (i.e., mass and count concentrations, proportion (percent; %) of fibres, and length of fibres) and meteorological and geographical variables (i.e., average air temperature, wind speed, wind direction, longitude, and latitude). The meteorological and geographical data was collected on board and provided by Amundsen Science, and it included variable data for the entirety of the cruise. The mean air temperature (degrees Celsius), longitude (decimal degree), and latitude (decimal degree) for each sampling transect (Table S12) was calculate using the data available from the time of deployment and retrieval in Past (Version 4.12; Hammer et al., 2001). Averaging wind speed and direction requires arithmetically and vector-based approaches, respectively. The average wind speed was calculated by adding the squared values of the average wind speed in the X and Y direction (in radians). Then, square rooting the added value. The average wind direction was calculated by calculating the arctangent of the average wind speed in the X and Y direction and converting the value to degrees. All data analysis and figures were completed in Past (Version 4.12; Hammer et al., 2001). The average wind speed and direction was calculated in Excel (Version 2410).

5.2 Results

5.2.1 Concentration

In total, 31 microplastic particles were quantified in 8 of the 12 sampling transects (Table 5.2). One outlier (Air 1) was removed from analysis based on the results of the Grubbs test. The concentration of microplastics ranged from 0.00–3.64 µg/m^3 (0.00–0.09 n/m^3), with a mean concentration of 0.70 ± 1.07 µg/m^3 (0.03 ± 0.03 n/m^3; Figure 5.2; Table 5.2).

Table 5.2. Count (n) and concentration (n/m^3 and µg/m^3) of microplastics across the sampling transects (n = 12).

TransectID	**Counts**		**Concentration**			
	Fibres	Fragments	Fibres	Fragments	Fibres	Fragments
	n	*n*	*n/m^3*	*n/m^3*	*µg/m^3*	*µg/m^3*
Air 1	10	1	0.22	0.02	8.21	4.28E-02
Air 2	0	0	0.00	0.00	0.00	0.00
Air 3	2	0	0.04	0.00	0.74	0.00
Air 4	1	0	0.02	0.00	0.25	0.00
Air 5	3	0	0.06	0.00	3.64	0.00
Air 6	3	1	0.05	0.02	0.71	2.29E-01
Air 7	0	0	0.00	0.00	0.00	0.00
Air 8	3	2	0.05	0.03	1.19	6.52E-02
Air 9	2	1	0.03	0.02	0.52	7.22E-03
Air 10	2	0	0.03	0.00	0.35	0.00
Air 11	0	0	0.00	0.00	0.00	0.00
Air 12	0	0	0.00	0.00	0.00	0.00

5.2.2 Characteristics (Shape, Size, Polymer Composition)

Microplastic fibres (84%) were the dominant shape identified ($p < 0.05$), followed by fragments (16%); no beads, foams, or films were identified (Figure 5.3). Fibres ranged from 205–2863 µm in length with a mean (median) length of 1093 ± 822.8 µm (1046 µm), the mean length of fibres was longest in Air 5 (1807 µm) and shortest in Air 10 (628.5 µm). The length of fragments ranged from 70.4–394 µm with a mean (median) length of 204.3 ± 132.9 µm (184 µm; Figure 5.2). The length of microplastic fibres were significantly longer than non-fibrous microplastics ($p < 0.05$; Table 5.3). Polyester was the dominant polymer identified for fibrous (46%) and nonfibrous (40%) microplastics (Figure 5.3).

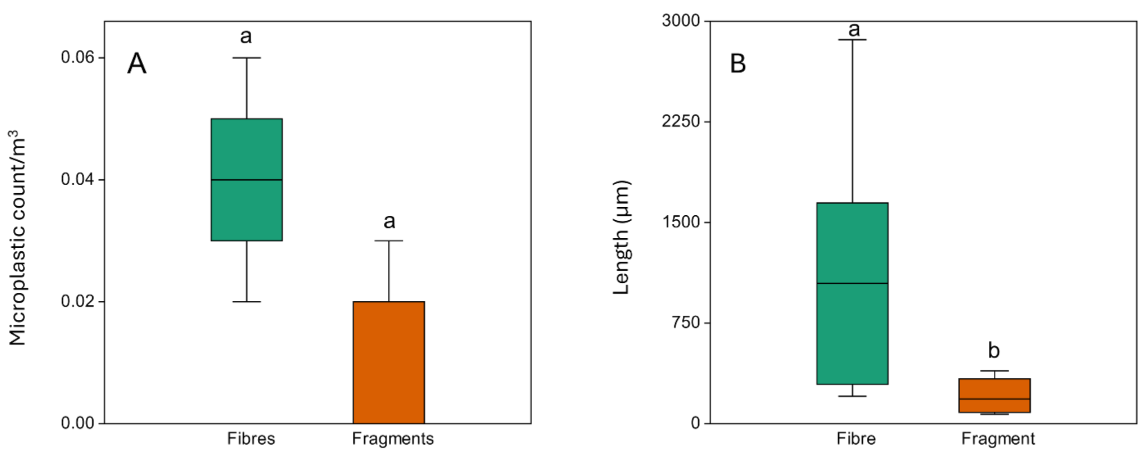

Figure 5.2. Box plots presenting (A) microplastic counts per cubic meter (n/m^3) for fibres and fragments across the study area and (B) length (µm) of detected microplastic fibres and fragments. The lower-case letters represent a statistical difference (Mann-Whitney; $p < 0.05$). The box represents the 25th and 75th percentile, the horizontal line represents the median and the whiskers represent the interquartile range.

5.3 Discussion

Comparing the concentration and characteristics of atmospheric microplastics across studies is problematic due to the lack of standardized sampling and analytical methodologies. Nonetheless, despite potential method differences, the results in the current study are consistent with previous studies that investigate microplastics over marine waters (Table 5.4); i.e., microplastics ranged between 0.02 ± 0.02 n/m^3 and 0.04 ± 0.04 n/m^3 over the South China Sea (Ding et al., 2021; Wang et al., 2021), and 0.06 ± 0.16 n/m^3 over the Pacific Ocean (Liu et al., 2019b). The dominance of microplastic fibres is consistent with observations over the South China Sea (Ding et al., 2021) and Pacific Ocean (Liu et al., 2019b).

Table 5.3. Mean, median, minimum, and maximum length (µm) for microplastics detected across sample transects (n = 12).

Transect ID	Mean	Median	Minimum	Maximum
	µm	*µm*	*µm*	*µm*
Air 1	993	561	184	2703
Air 2	-	-	-	-
Air 3	1061	1061	294	1827
Air 4	1110	1110	1110	1110
Air 5	1807	2337	220	2863
Air 6	623	375	286	1458
Air 7	-	-	-	-
Air 8	664	291	70.4	1434
Air 9	930	876	98.0	1814
Air 10	628	628	213	1044
Air 11	-	-	-	-
Air 12	-	-	-	-

Polyester was the dominant polymer identified for atmospheric microplastics over the northwest South China Sea (29%; Ding et al., 2021) and East Indian Ocean (50%; Wang et al., 2020). These characteristics indicate synthetic textiles were a significant contributor to Arctic marine atmospheric microplastics, suggesting they have a greater tendency for long-range atmospheric transport (Preston et al., 2023). In the current study, red fragments were detected in three air samples (comprising 63% of the fragments in these samples); these particles matched the colour of the CCGS *Amundsen*. Although we cannot confirm that the vessel was the source of contamination, it indicates that shipping vessels may be a local contributor to marine atmospheric microplastics. The similar microplastic concentrations and characteristics (i.e., dominated by microplastic fibres and polyester) across studies may reflect textiles and particles released from shipping and research vessels and crew members. Unfortunately, previous studies do not report the vessel size or the number of crew members making a comparison challenging. There were no correlations between microplastics and meteorological and geographical identified. This trend was also identified in previous studies, highlighting the need for further investigation of the factors that influence the transport of atmospheric microplastics to marine environments (Wang et al., 2020, Wang et al., 2021).

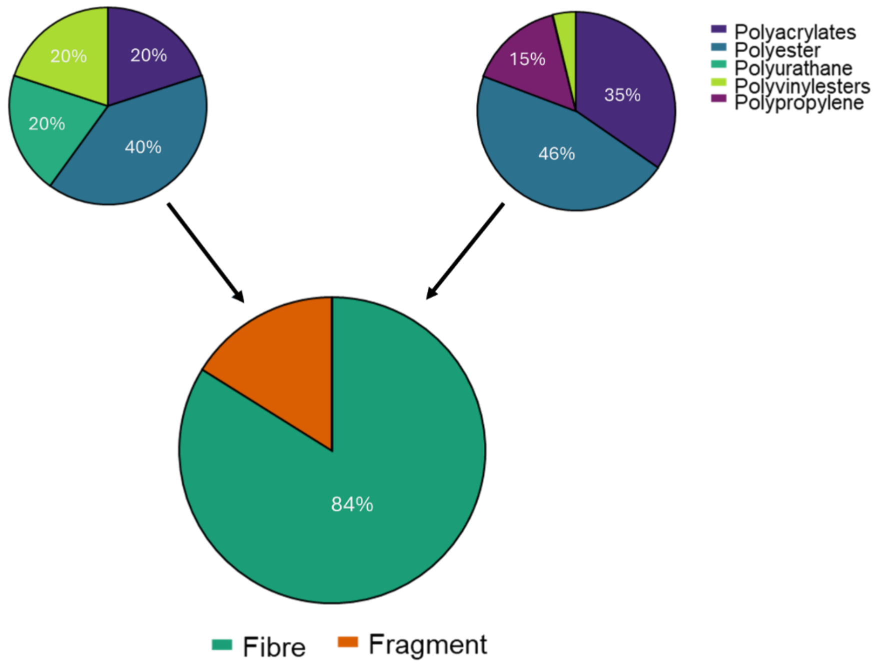

Figure 5.3. Pie charts illustrating the proportion of microplastics by shape and polymer composition in air sampled off the Amundsen icebreaker in September 2023.

The concentration of atmospheric microplastics over the Arctic Ocean in the current study was 28 times lower than concentrations in a metropolitan city (Shanghai, China; Liu et al., 2019c). Further, Dris et al. (2017) reported a concentration of microplastic fibres that ranged from 0.13–1.50 n/m^3 in outdoor air (Paris, France), which is 25 times greater than the range of microplastic fibres (0.00–0.06 n/m^3) in the current study. The greater concentration of microplastics in metropolitan environments compared with remote environments indicates that atmospheric microplastics are associated with human activities. This suggests that activities occurring on a vessel may contribute (as a local source) to marine atmospheric microplastics.

5.4 Conclusion

In this study, we report for the first time the presence of microplastics in the atmosphere over the Arctic Ocean throughout the Canadian Archipelago of Nunavut. The mean concentration of microplastics was 0.70 ± 1.07 $\mu g/m^3$ (0.03 ± 0.03 n/m^3), dominated by polyester fibres, which is consistent with the count concentration and characteristics of microplastics observed in the atmosphere over the South China Sea and Pacific Ocean. Shipping vessels likely serve as a local point source of atmospheric microplastics over marine environments based on the characteristics of fragments detected in three samples in the current study. As shipping channels in the Arctic increase due to melting sea-ice, shipping vessels may become a more dominant direct source of microplastic contamination to these remote environments.

Table 5.4. Summary of atmospheric microplastic concentration (n/m³), shapes identified, and polymers identified from similar studies.

Study Area	Microplastic concentration (n/m³)	Microplastic shapes identified	Polymers identified	Reference
Arctic Ocean	0.03 ± 0.03	Fibre, Fragment	PES, PAK, PU, PVA, PP, PVE	Current Study
South China Sea	0.02 ± 0.02	Fibre, Fragment, Film, Foam, Granule	PP, RY, PE, PA, PES, PS, PHE	Ding et al. (2021)
East Indian Ocean	0.04 ± 0.04	Fibre, Fragment, Film	PET, PMMA, EVA, PE, Others	Wang et al. (2020)
South China Sea	0.04 ± 0.04	Fibre, Film, Fragment	PHE, PP, PMMA, PET, PS, PE, EVA	Wang et al. (2021)
Pacific Ocean	0.06 ± 0.16	Fibre, Fragment, Granule	PET, PE, PE, PP, PS, ALK, EP, PA, PAN, PHE, PMA, PP, PES, PVA, PVC	Liu et al. (2019b)
Shanghai, China	1.42 ± 1.42	Fibre, Fragment, Granule	PET, PE, PES, PAN, PAA, RY, EVA, EP, ALK	Liu et al. (2019c)

PES: Polyester; PAK: Polyacrylate; PU: Polyurethane; PVA: Poly(vinyl acetate); PP: Polypropylene; RY: Rayon; PVE: Polyvinyl ether; PE: Polyethylene; PA: Polyamide; PS: Polystyrene; PHE: Phenoxy resin; PMMA: Polymethyl methacrylate; PET: , Polyethylene terephthalate; EVA: Ethylenevinyl acetate; PAN: Polyacrylonitrile; PVC: Poly(vinyl chloride); PAA: Poly(N-methyl acrylamide); EVA: Ethylene vinyl acetate; ALK: Alkyd resin; EP: Epoxy resin

Chapter Six: General Conclusion

Microplastics and tire wear particles in Arctic road dust, Iqaluit, Nunavut

In this study, we bring light to the presence of microplastics and tire wear particles in Arctic road dust. The mean concentration of microplastics and tire wear particles was 2.83 ± 3.72 μg/g (3.91 ± 3.02 n/g) and 146 ± 230 μg/g (231 ± 302 n/g), respectively, from 16 locations across Iqaluit, Nunavut. The results of this study suggests the concentration of microplastics in Arctic road dust are comparable to observed concentrations in metropolitan areas (Patchaiyappan et al., 2021; Yukioka et al., 2020). In Iqaluit, commercial and industrial areas were similar, however, microplastics and tire wear particles were an order of magnitude higher in parking lots compared with roadsides. This finding suggests parking lots are temporary reservoirs for microplastics and tire wear particles. Overall, sample collection was challenging due to the vehicle activity during the day. I am thankful to Kayla who tolerated being in the field at late hours to avoid traffic. I thank Harriet Walker for assisting with the development of the extraction method in Chapter 2.

Microplastics in Arctic freshwater lake catchments, Baffin Island, Nunavut

This study evaluated the concentration, characteristics, distribution, and fate of microplastics in freshwater lakes surrounding Iqaluit, Nunavut. Microplastics were detected at each study catchment, indicating Arctic freshwater systems are vulnerable to microplastic contamination.

Sampling method influences estimated microplastic concentrations and characteristics

The sampling method influenced the concentration and characteristics of microplastics identified in Arctic lake water. Using two methods to quantify the concentration and characteristics of microplastics we were able to capture a diverse picture on the microplastics present in the lakes. The volume-reduced method captured a greater abundance of non-fibrous microplastics and various polymer types, while the bulk method captured a greater abundance of microplastic fibres predominately dominated by polyester. As observed in comparable studies, the count and mass concentration of microplastics was greater in samples collected using a bulk method compared with the volume-reduced method. In contrast, the length of microplastics were similar between the bulk and volume-reduced methods. Both methods provide valuable results, and it is recommended that the method choice for sample collection reflects the objective of the study or use a combination of volume-reduced and bulk sampling.

Atmospheric microplastics over the Arctic Ocean

The time I spent on the CCGS Amundsen was the most rewarding experience of my education. The concentration of atmospheric microplastics in the High Arctic was comparable to concentrations over the South China Sea and Pacific Ocean, and significantly lower than concentrations in a major metropolitan city. Fibrous microplastics were the dominant shape identified, which was expected due to fibrous particles having a longer atmospheric residence time than non-fibrous microplastics. To improve this study in the future, it would be beneficial to only run the air sampler while the vessel is moving/in transit to avoid sampling air circulating around the ship.

Overall Significance

Microplastics are an emerging contaminant of concern, particularly due to their association with toxic chemical additives. Canada's Plastic Science Agenda recognizes the need for research that identifies their source regions and their fate in the environmental (ECCC, 2019). Although gaining recent attention, microplastics in the atmosphere remain a relatively understudied environmental compartment. In an Arctic context, there is limited knowledge of the environmental concentrations of atmospheric microplastics. The first, second, and fourth research chapters add value to this knowledge gap.

Further, the Arctic Monitoring and Assessment Program recognizes the need for characterizing microplastics in Arctic freshwater, given the paucity of published investigations in Canadian freshwater bodies. Our second study addressed this knowledge gap by investigating the fate of microplastics in freshwater lake catchments. Our results indicated that inland freshwater lakes are temporary reservoirs for microplastic contamination. Further, our third study investigated how the sampling method can influence microplastic concentrations and characteristics and illustrated the value of standardizing sampling methods for microplastic analysis. Overall, the four studies add valuable data to microplastic concentrations in the Arctic.

Personal Conclusion

What a journey it has been! I am taking a moment to bring light to everything accomplished throughout the master's degree. As there is more to it than four final manuscripts. The fieldwork was interesting (to say the least). I am thankful Kayla tolerated sampling late at night to avoid daily vehicle traffic in the community. The laboratory components were extremely rewarding and given the ubiquity of microplastics, I worked hard on perfecting quality assurance and control measures to prevent sample contamination. I spent months looking at intricate plastic pieces using a stereomicroscope and photographing and measuring them using software packages. I became proficient in using Fourier-Transform Infrared spectroscopy for polymer analysis. I synthesized data and presented results using figures and tables, and I since have written four individual manuscripts which were presented above. I completed a required graduate-level course that allowed me to become more familiar with the writing process as this is something I have always struggled with. I also completed a graduate-level reading course that allowed me to further develop skills in Geographical Information Systems by developing land use regression models associated with microplastic accumulation in moss bags; I found this course particularly rewarding. I feel satisfied with the research I've completed over the last two years; however, I recognize there are limitations to my research and there is always room for improvement.

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