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Microplastics and PMT plastic-associated chemicals as co-contaminants in ice shaving waste from an urban ice rink

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Ice hockey, curling, and skating are popular recreational activities across Canada's nearly 8000 ice rinks, yet potential contamination of rink ice shaving waste remains understudied. This study investigated the presence of emerging contaminants, including microplastics and persistent, mobile, and toxic (PMT) plastic-associated chemicals as co-contaminants in ice shaving from the Mattamy Athletic Centre (formerly Maple Leaf Gardens) located in the City of Toronto. Microplastics were detected at high concentrations ranging from 59 to 2063 particles per 100 mL of melted ice shaving, with particle sizes between 11 and 494 μm (median 38 μm) in diameter. Among 124 screened PMT plastic-associated chemicals, significantly higher levels were detected in ice-shaving water than ice-making source water, implicating the ice rink infrastructure and/or skater equipment as sources of contamination. These findings represent the first documented evidence of microplastics and PMT chemicals in ice shavings from an ice rink. They are significant because ice-shaving waste is disposed of *via* drainage to sanitary sewers and/or outdoor dumping, both of which are pathways for potential environmental contamination. Given the scale of ice rink operations nationwide, the results highlight a need for comprehensive multi-facility assessments, source identification, targeted contaminant monitoring, and improved waste-management practices, including accessible treatment technologies.

Environmental significance

Millions of litres of ice-shaving waste generated annually from Canadian ice rinks are routinely discharged to sewers or dumped outdoors, yet their role as a source of emerging contaminants has remained largely unexamined. This is important because recreational facilities are widespread urban infrastructure and may contribute overlooked microplastic and chemical emissions to aquatic environments. This study provides the first evidence that ice-shaving waste contains high concentrations of microplastics together with persistent, mobile, and toxic (PMT) plastic-associated chemicals originating from on-ice activities and rink infrastructure. The findings identify ice rinks as a previously unrecognized source of contaminant mixtures and highlight the need for targeted monitoring, improved meltwater management, and treatment strategies to reduce contaminant release.

1 Introduction

Ice hockey, curling, and figure skating are among Canada's most beloved sports, with between 400 000 and 700 000 registered hockey players as well as over 100 000 registered curling players in any given year[1,2] and innumerable hobby players who use the almost 8000 ice rinks in Canada.[3] Especially in professional hockey, ice quality is critical to player performance.[4,5] According to the 2018 National Hockey League (NHL) Sustainability Report, approximately 320 million gallons of water are utilized each season for ice rink preparation and maintenance, with community rinks across North America reflecting similar consumption patterns.[6] Ice shaving waste (the layers of ice removed from the rink surface by an ice resurfacer during maintenance) is commonly managed by emptying it into a 'melt pit' within the arena – when available – which drains into the sanitary sewer system, or alternatively disposed of outdoors where it melts and drains into storm sewers or adjacent pervious areas (*e.g.*, lawns). Melt pits are more common in large multi-rink arenas, while outdoor disposal is more common in single- or double-rink community arenas, with some facilities using both disposal methods. Despite growing interest in rink sustainability,[7] the potential emissions of emerging contaminants from ice rink operations and activities remain underexamined.[8] Contaminants, such as microplastics and persistent, mobile, and toxic (PMT) plastic-associated chemicals, could be released from synthetic materials in ice maintenance

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equipment (*e.g.*, resurfacer cloth), athletic gear (*e.g.*, jerseys, sticks, pucks), and rink infrastructure (*e.g.*, boards, kick plate).[9] For example, a 2023 Finnish study estimated that approximately 20 g of microplastics were generated from a single hockey game.[9] The ice surface is a potential receptor for these contaminants, given the nature of ice hockey, figure skating and curling activities.

Microplastics are typically defined as solid plastic particles ranging from 1 μm to 5 mm in size.[10] Primary sources include intentionally manufactured micro-sized particles, such as microbeads found in personal care products like toothpaste, while secondary sources, generally recognized as the predominant contributors, involve the environmental degradation of larger plastic products into smaller fragments.[11] Since the introduction of the term "microplastics" in 2004,[12] extensive research has identified their presence across various environmental compartments, including oceans, lakes, rivers, soils, food, and air.[13] Exposure to microplastics poses potential risks to ecosystems and human health through both physical interactions, such as ingestion, and chemical pathways involving the leaching of polymer constituents and chemicals used in plastic manufacturing and final products.[14] Of particular concern for water-use intensive activities (such as ice production for hockey) are recent reports of the widespread use of water-soluble PMT substances in a variety of plastic products in Canada.[15] These plastic-associated chemicals have variable toxicity profiles[15] and many have been associated with potential harmful effects on aquatic and human health.[16] The resulting mixtures of plastic-associated chemicals and microplastics require investigation in order to understand the potential environmental and human health risks associated with their release and exposure to these complex contaminant mixtures.

Co-contamination of PMT plastic-associated chemicals and microplastics is of particular urgency due to their high recalcitrance in water and low adsorption to organic matter, making them challenging to remove using conventional water treatment processes.[17] It has been argued that PMT chemicals pose environmental risks comparable to persistent, bioaccumulative, and toxic (PBT) substances,[18] yet regulatory oversight remains insufficient. In Canada, compliance frameworks primarily address PBT substances, not PMT chemicals.[19]

Given the scarcity of research on the occurrence of emerging contaminants mixtures and co-contaminant issues of microplastics and PMT plastic-associated chemicals in integrated ice shaving waste associated with rinks during routine operation, the objectives of this study were to: (i) characterize the microplastic and PMT plastic-associated contaminant profiles in ice shavings and source water used for ice making at a professionally used hockey rink and (ii) to compare the detected ice shaving microplastics and PMT contaminant loads and profiles to their concentrations and profiles in surface water collected in the same area to investigate potential rink contributions to the natural environment. The aim of this research was to provide initial insight into the potential contribution of ice rink operations and activities to the release of plastic contaminant mixtures into the environment, and to inform best practices for ice waste management and more sustainable ice rink operations.

2 Materials and methods

2.1 Materials and chemicals

Benchmark standards included three organophosphate standards (d15-triethyl phosphate [dTEP], d21-tripropyl phosphate [dTPrP], d21-triphenyl phosphate [dTPP]; > 98%, 50 μg mL^{-1}) from Wellington Laboratories and $^{13}C_6$-6PPD-quinone (>98%, 100 μg mL^{-1}) from Cambridge Isotope Laboratories (Tewksbury, MA, USA) and acetamionphen-d_4 (>98%, 100 μg mL^{-1}) from Millipore Sigma (Burlington, MA, USA).

Acetonitrile (HPLC plus grade) and formic acid (98–100%) were purchased from Millipore Sigma (Burlington, MA). All laboratory water (referred to as Milli-Q water) used in the work is ultrapure water (conductivity $\leq$ 0.056 μS cm^{-1}) prepared using a Millipore Direct-Q® 8 UV Water Purification System.

Amber glass LC vials (2 mL), pre-slit caps, and glass fiber/nylon membrane syringe filters (0.22 μm, 25 mm, Agilent Technologies, Santa Clara, CA) were used during sample preparation for LC-QTOF-MS analyses. A vacuum filtration assembly with a 25 mm filter diameter with glass support (Millipore Sigma, Burlington, MA), polycarbonate filters (15 μm, 25 mm, Sterlitech, Auburn, WA), and polyester aluminum-coated membrane filters (0.8 μm, 25 mm, 100/0 nm coating, i3 Membrane, Germany) were used for microplastic analysis preparation.

2.2 Sample collection

Samples were collected from an indoor ice rink at the Mattamy Athletic Centre in Toronto, ON. Thirteen ice-shaving samples were collected at approximately weekly intervals from October 2024 through February 2025, immediately after the full ice resurfacing with a Zamboni© following scheduled on-ice activities such as hockey practices and games. Sampled sessions were primarily hockey practices, with one sampling event conducted following a hockey game (Week 2). Ice shaving samples were taken from multiple points within the snow pile discharged by the Zamboni before it was shovelled into the melt pit, and the collected shavings were combined. A single Zamboni was used for all sampling events except Week 2, during which two machines were in operation for a hockey game; however, the sample was collected only from the snow pile discharged by the same machine. A clean metal bucket (maximum capacity 3 L) and scoop were pre-washed with methanol (10 mL) and Milli-Q water (3 × 20 mL), then rinsed twice with ice shavings prior to sample collection. Filled buckets were covered with aluminum foil and transported promptly to the laboratory. Melted ice shavings were transferred into an amber glass bottle (1 L) for microplastics and PMT substances analyses. Thirteen ice-making source water samples were simultaneously collected as a control and are hereafter referred to as "source water". At each sampling event, source-water and ice-shaving samples were collected on the same day and treated as paired field samples for subsequent comparison. The source water is reverse osmosis (RO) treated water blended with Toronto municipal water to achieve a total dissolved solids concentration of approximately 80 mg L^{-1}. All samples were stored at 4 °C prior to analysis and were processed within 1–2 weeks following collection.

To contextualize the ice rink findings, ten surface water samples were collected from the lower reaches of the major stream systems draining the Greater Toronto Area (both separated and combined sewer systems occur in the watersheds where sample sites are located). The samples were collected approximately 1–3 km upstream of the stream outlets into Lake Ontario, collectively representing watersheds that include 214 hockey rinks (Fig. SA1, SI A). Approximately 1 L of surface water was collected in a glass bottle, pre-washed as described above, and stored at 4 °C until analysis, with all samples processed within 1–2 weeks after collection. The surface water samples were analysed for the same suite of contaminants as the ice shavings.

2.3 Sample preparation and instrumentation

2.3.1 Microplastics analysis. Water samples (25 mL) were filtered onto polycarbonate filters (15 μm, 25 mm). Particles were resuspended into clean glass tubes using Milli-Q water (2 × 10 mL) and subsequently filtered onto polyester aluminum-coated membrane filters (0.8 μm, 25 mm). The initial filtration onto the 15 μm polycarbonate membrane was used for sample collection and transfer preparation, while particle sizing was based on the Laser-Directed Infrared Spectroscopy (LDIR) Agilent 8700 Chemical Image analysis of particles present on the final 0.8 μm aluminum-coated membrane. Analysis was performed using LDIR over the spectral range of 1800–975 cm^{-1}. Particles (10–500 μm) were identified using the automated Particle Analysis module and the Microplastics Starter 2.0 library, with a hit-quality index threshold set at >0.88. Microplastic sizes in ice-shaving samples were characterized based on particle width (major axis), height (minor axis), and diameter. Shape classification was based on conservative criteria, with circularity > 0.9 used for spheres, aspect ratio > 5 for fibres and fibre-like particles, and all remaining particles classified as fragments.

2.3.2 PMT plastic-associated chemicals screening. The screening was conducted on a LC-QTOF-MS system (Agilent Technologies, Santa Clara, CA), including a 1290 Infinity II Multisampler (G7167A) with analytical head (100 μL), 1260 Infinity II quaternary pump (LC pump, G7104C) for the mobile phase delivery, a 1260 Infinity II column oven (G4227A), and a 6546 QTOF system equipped with a Jet Stream Electrospray ionization (ESI) source.

The PMT plastic-associated chemicals screening method was adopted from Fries and Sühring (2023).[20] The water samples were filtered through a glass fiber/nylon membrane syringe filter (0.22 μm, 25 mm) and 1 mL of filtrate was transferred to a glass LC vial. Subsequently, a benchmark standard solution (100 ng mL^{-1}, 20 μL) containing dTEP, dTPrP, dTPP, $^{13}C_6$-6PPD-quinone and acetaminophen-d_4 was added to each sample. These compounds were selected as benchmark standards to represent a range of chromatographic and physicochemical behaviour within the suspect-screening method and to provide a consistent basis for monitoring analytical performance across samples. As they were not compound-matched surrogates for all analytes in the suspect library, the resulting PMT responses were interpreted comparatively on a semi-quantitative basis. The samples (injection volume of 50 μL) were chromatographically separated on an Agilent InfinityLab Poroshell 120 EC-C_{18} column (3.0 × 100 mm, 2.7 μm) with a guard column of matching stationary phase and were analyzed by LC-QTOF-MS ESI positive mode. Full scan data were acquired over the mass range of 50 to 1000 m/z. The details of the instrumental methods are summarized in Text SA1. The suspect screening was performed in MassHunter Qualitative Analysis 10.0 software against an in-house library containing 124 PMT plastic-associated chemicals.[15] The details of suspect screening workflow are presented in Text SA2, and a full list of 124 PMT plastic-associated chemicals is listed in Table SB1 (SI B).

2.4 QA/QC and data analysis for microplastics analysis

A thoroughly rinsed glass filtration assembly was used for pre-processing samples for microplastics analysis and pure cotton lab coats were worn by the analyst during sample preparation. Given the relatively simple nature of the samples and to minimize particle loss during sample preparation, no density separation or digestion was applied.

Detection limits (DLs) for microplastic particle counts were defined as the average blank plus three times the standard deviation (3 × SD) of five Milli-Q water aliquots of 100 mL each (quality index > 0.88) for detected particles. A DL of one particle per 100 mL was defined for every polymer in the Microplastics Starter 2.0 library due to no observation, except for polyamide (4 particles per 100 mL), polycarbonate (5 particles per 100 mL) and polypropylene (8 particles per 100 mL). Source waters were dominated by polycarbonate (2–48 particles per 100 mL) and polypropylene (52–196 particles per 100 mL), with trace occurrences of acrylonitrile butadiene styrene, polyamide, polyethylene, polyethylene terephthalate, polymethyl methacrylate, polystyrene, and polyurethane at low frequencies (1–4 particles across all blanks). Spike recovery check was conducted during the method development showing no substantial particle loss due to sample preparation. However, the tests did not cover the full range of particle sizes, particularly the smaller size range.

To distinguish microplastics originating from ice, ice-shaving samples were corrected by subtracting the average particle counts of the source waters for each polymer type and size range.

2.5 QA/QC and data analysis for PMT plastic-associated chemicals screening

Appropriate quality assurance measures were employed to minimize the contamination of samples with plastic-associated chemicals from the laboratory environment. Acid-washed and oven-baked glassware and solvent-washed glass syringes were used for the PMT plastic-associated chemicals screening.

For the PMT plastic-associated chemicals screening, blanks (Milli-Q water) were included to account for background contamination from sample preparation and/or the instrument. Samples were spiked with benchmark standard solution to account for variations in sample volumes and instrument performance.

For PMT plastic-associated chemicals without detectable blanks, the DL were set at a signal-to-noise ratio (S/N) of 3. In the 15 method blanks analyzed, 32 distinct PMT plastic-associated chemicals were detected, with each blank containing between 8 and 23 PMT substances (median = 12). For these detected PMT plastic-associated chemicals, the DL were calculated as the mean blank relative peak area (RPA) plus 3 times its SD. All sample RPAs were then corrected by subtracting the corresponding blank value. Here, RPA is defined as the ratio of an analyte's peak area to that of the benchmark standard with the most similar retention time.

Peak integration for PMT plastic-associated chemicals was performed using Agilent MassHunter (Qualitative Analysis and Quantitative Analysis software 10.0). Statistical analyses included linear mixed-effect modelling and were conducted in R version 4.3.0 (R Core Team, 2024) with a critical α-level of 0.05. Mixed-effect models were used for statistical analysis with the lme4 package.[21] This approach is ideal for this sampling design, as it accounts for the non-independence of measurements taken within the same rink by treating sampling time as random effects. Fixed effects included water type: source water and ice shavings. The lmerTest package[22] was used to calculate *p*-values for fixed effects, employing Satterthwaite's degrees of freedom method for reliable statistical significance testing. The residuals were assessed *via* Q–Q plots for normality. However, due to the small sample size, residual normal distribution and homoscedasticity could not be thoroughly verified, therefore results were interpreted with this limitation in mind.

A fold-change (FC) of abundance of PMT plastic-associated chemicals in ice shaving to source water (FC = instrument response for analyte in ice shavings/instrument response for the same analyte in the paired source water) was used to assess relative changes in ice shaving samples compared with source water and identify which PMT substances were introduced to the ice through on-ice activities and/or ice operations rather than source water. A value of FC > 1 indicates that the compound had a greater abundance in the ice shaving than in the source water.

3 Results and discussion

To aid interpretation of the results presented in this section, microplastics data are reported at the individual-sample level to describe particle occurrence and polymer composition in the ice-shaving waste, whereas PMT plastic-associated chemicals data are reported as semi-quantitative detection patterns and relative fold changes between source-water and ice-shaving samples.

3.1 Microplastics in rink ice shavings: abundance, polymers, and size distribution

Microplastic concentrations in melted rink ice shaving samples ranged from 59 to 2063 particles per 100 mL with an average of 770 ± 685 particles per 100 mL (scatter with line in Fig. 1). The substantial variability in microplastic concentrations suggested an impact of in rink use and on-ice activities, such as player numbers and activity type (hockey practices and games). In addition, replicate field collections and replicate sample-preparation analyses were not performed in this study; therefore, analytical variability could not be independently separated from field-level variability. Importantly, the results suggested a high potential for microplastic release from the rink. At the study rink, a single resurfacing process generated on average around 94 L of melted water, based on the Zamboni model 526 and assuming 10% snow-to-water conversion.[23] Based on the microplastic numbers detected in our analyses, this would correspond to between 0.06–1.9 million microplastic particles per resurfacing event. With around 3000 resurfacing events per year (based on 11 months of operation and approximately 65 resurfacing events per week),[24] the annual microplastic load from this single hockey rink would be between 0.2–5.8 billion particles. While these numbers are not representative of every hockey rink or even every season, they indicate that hockey rinks may release microplastic particles in numbers similar to wastewater treatment plants, which are widely regarded as important sources of contamination.[25]

In contrast, microplastic concentrations in surface water samples from across the Greater Toronto Area were steadily below the DL (1–8 particles per 100 mL based on polymer types). This was consistent with previous studies reporting low microplastic concentrations in surface waters in the study region. For example, microplastic concentrations in local rivers ranged between 2.3 and 29.4 particles per liter (>125 μm).[28] Despite low concentrations, a recent study on a large urban river in the City of Toronto, which considered a range of flow conditions, found that approximately 522 billion microplastic particles are transported to Lake Ontario annually.[26] Given the ice rink upper load estimate (5.8 billion particles per year) and the number of ice rinks across the Greater Toronto Area (Fig. SA1), the ice shaving microplastic concentrations found in this study suggest that ice rinks could be a significant source of microplastic loading to urban rivers in the region.

Polypropylene (PP) was the predominant polymer type detected in 64% of samples, while polyethylene (PE) dominated the remaining samples (Fig. 1). Within individual samples, PP and PE had average detection frequencies of 34% and 37%, respectively. Polyurethane (PU, 12%) and polyethylene terephthalate (PET, 10%) were also frequently identified. Together, these four polymer types accounted for over 89% of all particles in all samples, except Week 6, where they comprised around 79%. Hietanen and Sutinen (2023)[9] reported that polyisoprene rubber and PE together comprised 61% of the total microplastic mass recovered from samples collected from a single ice hockey game. Although rubber with a high quality index (>0.88) was absent, the high level of PE was consistent with their findings. In addition, other types of polymers detected in the present work, including PET, PP, PMMA, PA, PC, PS and ABS, mirror the diversity of microplastic polymer types documented by Hietanen and Sutinen (2023).[9]

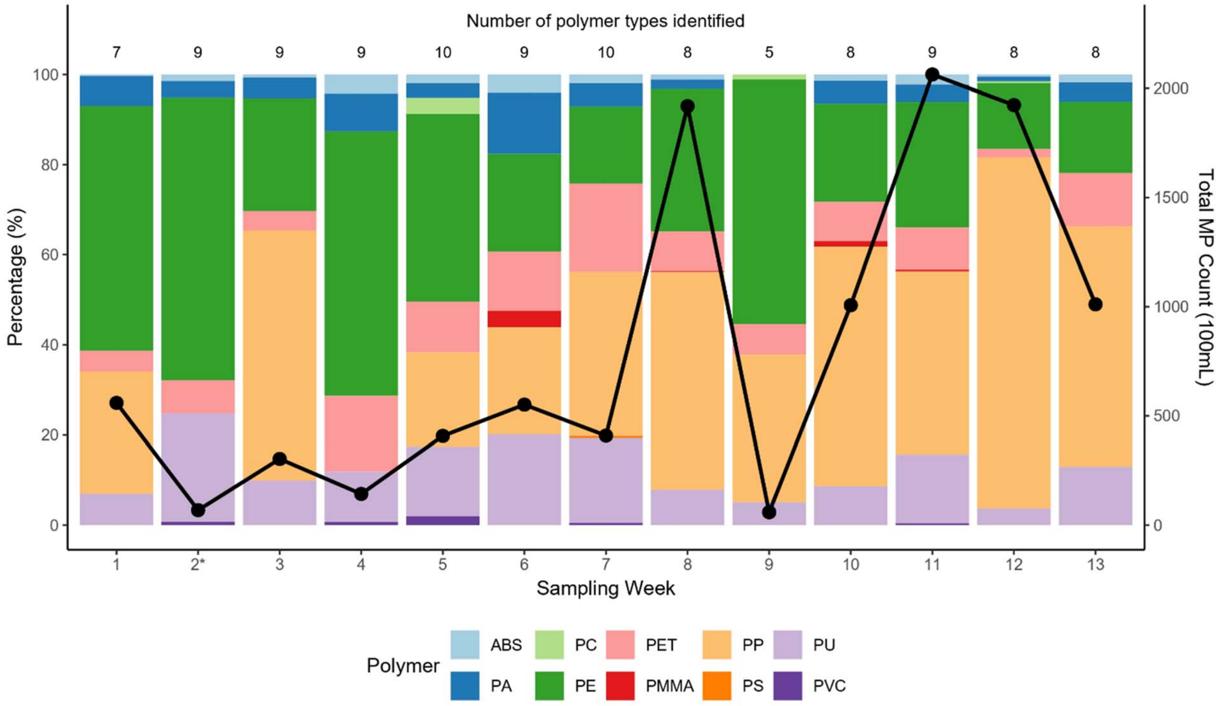

Fig. 1 Percentage of different microplastic polymer types in each weekly sample, with the total microplastic (MP) particle counts per 100 mL of melted ice shavings overlaid. The number of unique polymer types found in each weekly sample is listed at the top of the plot. Acrylonitrile butadiene styrene (ABS), polyamide (PA), polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), polypropylene (PP), polystyrene (PS), polyurethane (PU), polyvinyl chloride (PVC). Week 2*, marked with an asterisk, represents sampling during a hockey game while all other weeks correspond to hockey practice sessions.

Interestingly, the number of polymers detected varied substantially across different sampling events and did not necessarily correlate with high or low detected particle counts. The Week 9 sample exhibited the fewest microplastic particles and the least variability in polymer types. Conversely, Week 2, despite having similarly low particle counts, contained as many as nine polymer types (Fig. 1). Collected after a hockey game, Week 2 showed a pattern similar to Week 4, which also exhibited few particles but high polymer diversity. However, the Week 4 sample was taken following a hockey practice. These observations suggest no obvious trend between particle counts and polymer type diversity (Fig. SA2), indicating that different on-ice activities, such as games *versus* practices, and their associated complexities (for example, the player density, diverse equipment, exchange frequency, practice format, and foot traffic) likely influence the microplastic composition in ice shavings. The relationship between the type and characteristics of on-ice activities and microplastic concentration and composition in ice shavings, as well as contributions from other rink environment sources, are a future line of inquiry.

Plastic products that are commonly found at ice rinks and are made with the detected polymers are summarized in Table 1. For instance, dasher boards surrounding the ice rink are predominantly made of high-density PE. Repeated impacts from player activities with skates and hockey sticks may cause PE microplastic particles to be shed onto the ice surface. PP microplastics were not detected in Weeks 2 and 4 but were present in all other samples. Their absence in both a game-associated sample and a practice-associated sample suggests that on-ice activity alone does not fully explain this pattern and that additional source pathways may also contribute. Given the widespread use of PP in textiles, packaging, and other consumer materials, inputs from the wider rink environment are also plausible. PP particle counts also showed an overall increase

Table 1 Examples of ice-rink-related products associated with the polymer types identified in the microplastics analysis

Polymer type	Products associated with ice rink[a]
Polypropylene (PP)	Gear bags, packaging, textiles
Polyethylene (PE)	Dasher board (cap rail, puck board, kick plate); pad foam of protective gears
Polyurethane (PU)	Pad foam of protective gears
Polyethylene terephthalate (PET)	Sports activewear
Polyamide (PA)	Hockey pants exterior

[a] Sources identified through online searches of hockey rink equipment, material supplies, and surveys of hockey players' protective gear tags.

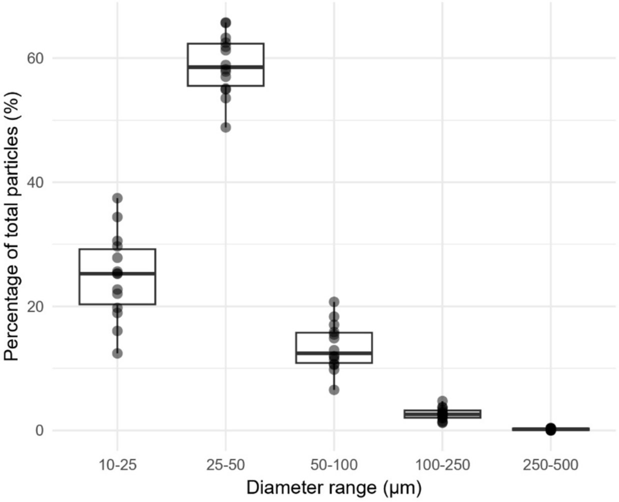

Fig. 2 Size distribution of microplastics in ice shaving samples across 13 sampling events. Box plots depict the percentage of total particles in each size range; boxes represent the interquartile range (25th–75th percentiles), and center lines denote the median.

across the sampling period, consistent with the broader pattern observed for total particle counts. Although this directional change may reflect evolving inputs over the hockey season, including potentially increased wear of PP-containing equipment and materials, it should be interpreted cautiously, as multiple rink-related and surrounding environmental sources may contribute to PP occurrence in the ice-shaving waste.

Microplastic particles sizes ranged from 11 to 494 μm (median 38 μm) in melted rink ice shavings. Most microplastics detected in the ice shavings were concentrated in the smaller diameter range (10–100 μm), particularly within the 25–50 μm range (Fig. 2). Smaller-sized microplastics, with their relatively larger surface areas, present increased risks as sources of contaminants, such as absorbed environmental pollutants and plastic-associated chemicals used in the product from which the microplastic originated.[27]

Size-resolved microplastic data for surface waters in local urban streams are limited, the size distribution of microplastics in the ice shavings appeared to be smaller compared to those reported in Northwestern Lake Ontario,[28] where the most common size range was 200–300 μm, approximately six times as in range of 125–200 μm. It is worth noting that a cut-off size limit of 125 μm was employed in their study[28] due to detection constraints. This means that the majority of the size classes detected in our study were not covered which limits the comparability of the results. A US study in Western Lake Superior, just south of the Canadian border, found that microplastic particles between 5 and 50 μm were most abundant, suggesting a similar pattern in microplastic size distribution as found in the ice shaving samples analysed in this study.[29] These results highlight the need to specifically monitor for smaller-sized microplastics in both suspected source and receiving waters. This is particularly important because smaller microplastics have an increased likelihood of evading removal processes and crossing biological barriers, thereby potentially elevating ecological and health risks.[30]

The distribution of particle sizes was notably associated with polymer types (Fig. 3). Larger particles tended to be composed of PE, PET, and PP material (Fig. 3). Their highly irregular shapes suggest they are secondary microplastics resulting from fragmentation of larger plastic items.[31] Fiber-shaped PET particles aligned with the common usage of PET in the textile industry, which accounts for approximately 60% of global PET production.[32] Such PET fibers are commonly used in ice rink apparel, *e.g.* jerseys and activewear.[33] Similarly, PA particles were present in a fiber-like shape but with a smaller size range compared to PET (Fig. 3). PA polymer fibers are also intensively utilized in sportswear textiles,[34] and a likely source for the

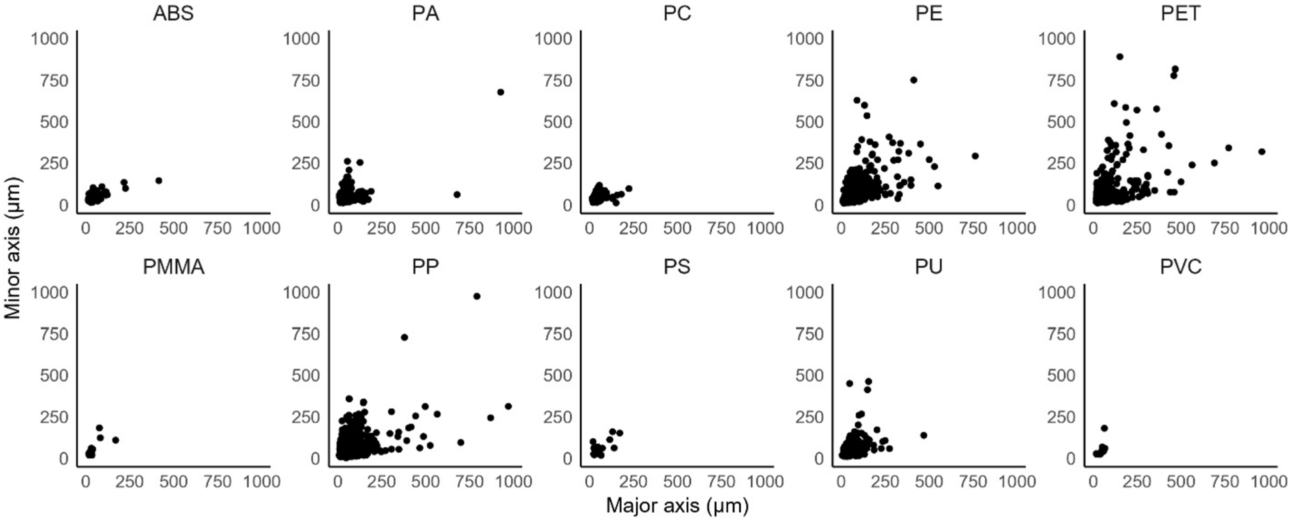

Fig. 3 Size distribution of microplastics detected in the ice shaving waste ($n = 13$) using a two-dimensional framework, where the x-axis and y-axis are the width and height of the particles determined by the LDIR. Each point represents one detected microplastic item with a high hit quality score (>0.88).

observed contamination. The observed size difference between PET and PA fibers possibly relates to product-specific characteristics, warranting further investigation to identify sources more precisely. PE particles exhibited a wide distribution of widths and heights, displaying fewer fiber-like characteristics than PET particles (Fig. 3). These fragments were likely derived from rink dasher boards and kick plates. Rozman, *et al.* (2023)[35] reported that fragments and films generated from PE material by physical alteration were polydispersed, consistent with findings from this study. Overall, fragments were the dominant microplastic shape identified in the ice-shaving samples, whereas fibres and fibre-like particles accounted for only 1–7% of the detected particles and no spheres were detected.

3.2 Co-occurrence of PMT plastic-associated chemicals and microplastics in rink ice shavings and source water

A total of 48 PMT plastic-associated chemicals were detected in ice shavings and source water. A higher number of PMT plastic-associated chemicals were detected in ice shaving samples (11–27 PMT; median = 15) compared to source water samples (3–19 PMT; median = 10, Fig. SA3), with significantly higher amounts (linear mixed-effect model, $\alpha = 0.05$) of eight PMT in ice shavings compared to source water. Similar to the results for microplastics, these results suggested that PMT, including 1,1′-oxybis[2-methoxu-ethane] (diglyme, $p < 0.05$), 1,4-diazabicyclo [2, 2, 2] octane (DABCO, $p < 0.01$), 1,3-diphenylguanidine (DPG $p < 0.01$), 1-methyl-4-nitro-benzene (4-nitrotoluene, $p < 0.05$), nitrobenzene ($p < 0.05$), diphenyl-methanone (benzophenone, $p < 0.05$) tris(2-butoxyethyl) phosphate (TBEP, $p < 0.05$), and tri-(2-chloroisopropyl) phosphate (TCPP, $p = 0.05$) originated from sources in the arena and on-ice activities rather than the water used to make the ice (Fig. 4a). However, while the number of PMT plastic-associated chemicals followed a similar increasing trend as microplastic counts over the sampling duration, the patterns of individual PMT plastic-associated chemicals indicated the presence of more specific contamination sources than an increased presence of players and spectators.

The FC values are discussed as a comparison between source water and ice shaving samples collected and are interpreted on a semi-quantitative basis. Diglyme had FC value of 65, indicating significantly higher input from sources other than the water used to make the ice (Fig. 4), but showed decreasing concentrations over time, with intermittent increases in sampling weeks 4 and 7. The decreasing trends in RPAs over the sampling time indicated that diglyme was used at the start of the season (and likely reapplied in weeks 4 and 7). Likewise, DABCO had fold change value of 276 and intermittently elevated detections, with noticeably higher RPAs in sampling weeks 1, 4, and 7 than during the other sampling occasions. Both PMT plastic-associated chemicals were consistently detected in ice shaving samples, with detection frequencies of 100%. DPG was detected in 100% of ice-shaving samples but was absent in the source water samples. This was similarly the case for 4-nitrotoluene and nitrobenzene, which were each detected exclusively in the ice shaving samples, with detection rates of 62% and 46%, respectively, and no correlation with sampling time or microplastic counts. Benzophenone was detected in 77% of both ice shaving and source water samples, however at a higher level in the ice shaving samples with FC above 2. TBEP was detected in both ice shaving and source water samples, but its detection frequency was higher in ice shaving (54%) than in source water (23%), and the FC value was about 120. Interestingly, TBEP was detectable only in the first half of the sampling, indicating a potential application during the early hockey season. TCPP, meanwhile, was found in 100% of ice shaving samples and exhibited FC value higher than 26. Although samples were stored at 4 °C and analysed within a similar time window of 1–2 weeks after collection, analyte-specific stability during storage was not examined and should be considered when interpreting the observed response patterns.

Potential sources of eight PMT vary due to their versatile applications and functions. Their occurrence should not be interpreted as evidence of plastics as the sole source. Diglyme, commonly used as a solvent in the manufacturing of printing inks,[36] has been identified as a Substance of Very High Concern (SVHC) by the European Chemicals Agency[37] due to reproductive toxicity. Possible sources could be the use in colours and plastic stencils used as markings and team logos within the ice.[38] DABCO is categorized as hazardous by ECHA (CAS 280-57-9)[39] and is widely used in adhesives, sealants, coating products and manufacturing of polymers. DGP is suspected to be toxic to reproduction according to ECHA (CAS 102-06-7).[40] Commonly used in the manufacture of rubber products such as hockey pucks, tires, brake pads, and building flooring. Its concentrations did not seem to follow any discernible trend, suggesting that its occurrence may reflect a combination of variable ongoing inputs, degradation or transformation processes. 4-Nitrotoluene is classified as hazardous, whereas nitrobenzene is toxic to reproduction, suspected to be carcinogenic and under assessment for endocrine-disrupting potential, and has been identified as SVHC by ECHA (CAS 99-99-0).[41] Both compounds serve as intermediates and processing aids in polymer manufacturing. Benzophenone is carcinogenic and used in various consumer products, including washing and cleaning products, inks and toners, polishes and waxes, personal care products, and the manufacturing of plastic products.[42] TBEP is commonly used as a floor polish, which would be applied intermittently and could therefore explain the absence of the compound in the latter half of the samples. TCPP is a widely used flame retardant and has demonstrated moderate toxicity to aquatic organisms and terrestrial plants, and may have reproductive and developmental effects on humans.[43]

Nevertheless, the consistent high detection of a variety of PMT plastic-associated chemicals in ice shavings compared to source water (Fig. 4b–i), paired with the intermittent occurrence and variable levels, suggests multiple and diverse contamination sources that should be investigated further. Given the different functions of the detected PMT plastic-associated chemicals (Table SA2), they may be incorporated into multiple plastic products used in hockey and curling, indicating that microplastics and PMT plastic-associated chemicals should be treated as co-contaminants forming a complex contaminant mixture with a high likelihood for environmental release.

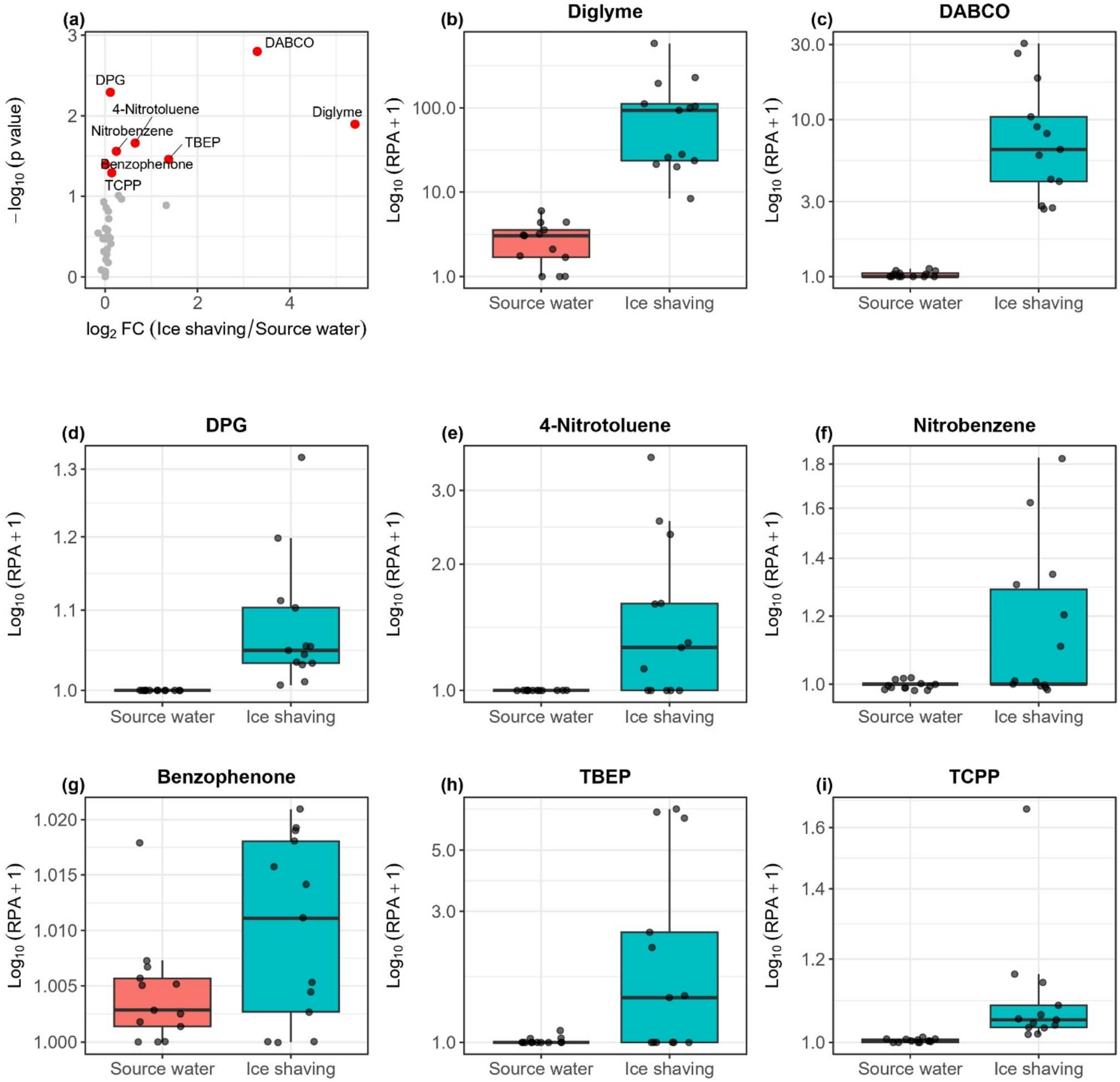

Fig. 4 PMT plastic-associated chemicals identified higher in the ice shaving ($n = 13$) than in the source water samples ($n = 13$). (a) Volcano plot highlighted the significant PMTs with p-values < 0.05 from linear mixed-effect model (equivalently $-\log_{10}$ (p-value) > 1 on y-axis) and fold-change (FC) of PMT plastic-associated chemicals abundance in ice shaving to source water (instrument response intensity) > 1 (equivalently log $_2$fold-change > 0 on x-axis). The comparison between ice shaving and source water RPA are shown for (b) diglyme (1,1′-oxybis[2-methoxu-ethane]), (c) DABCO ((1,4-diazabicyclo [2, 2, 2] octane)), (d) DPG (1,3-diphenylguanidine), (e) 4-nitrotoluene (1-methyl-4-nitro-benzene), (f) nitrobenzene, (g) benzophenone (diphenyl-methanone), (h) TBEP (tris(2-butoxyethyl) phosphate) and (i) TCPP (tri-(2-chloroisopropyl) phosphate)). RPA (relative peak area) = peak area of the analytes relative to the peak area of a benchmark standard which had the closest retention time.

3.3 PMT plastic-associated chemicals profiles in surface water compared to ice shavings

While microplastics were below the DL in all analysed surface water samples, PMT plastic-associated chemicals were detected in all water samples (Fig. 5). In total, 53 PMT plastic-associated chemicals were found in both groups, with approximately 85% (45) detected in ice shaving waste and around 55% (29) in surface water samples. The number of PMT plastic-associated chemicals per surface water ranged from 6 to 15, noticeably lower than in melted rink ice shavings (Fig. SA3). Both groups shared 21 common PMT plastic-associated chemicals, comprising over 72% of PMTs found in the surface water samples (Fig. 5).

Because matrix effects could not be assessed for all PMT chemicals, benchmark standards were used to evaluate matrix effects in surface water and ice-shaving relative to Milli-Q water. Matrix-induced response differences were 17–64% for surface water and 9–37% for ice shaving, indicating potential strong matrix effects in surface water. Therefore, cross-matrix differences should be interpreted as indicative rather than fully quantitative. Nevertheless, noteworthy differences included diglyme, which was detected at concentrations 278-time higher in ice shavings compared to surface water, and DABCO, present consistently in ice shavings but rare in surface water (only at one site, Fig. 5). The lower level or absence of these PMT plastic-associated chemicals in the surface water samples were consistent with the hypothesis that these compounds had specific applications within the hockey ice rink. Conversely, 1,4-dioxane was consistently detected in surface water but absent in ice-shaving samples, indicating sources outside of the ice rinks. The suspected carcinogen 1,4-dioxane[44] can be used as a colourant, filler, intermediate, odour agent, and other processing aids.[15] Moreover, it is primarily used as a solvent in the manufacture of pharmaceuticals and veterinary drugs and can also be present as an impurity from the production of personal care products and detergents.[45] The multi-sector uses of 1,4-dioxane may explain the ubiquitous detection in the surface water

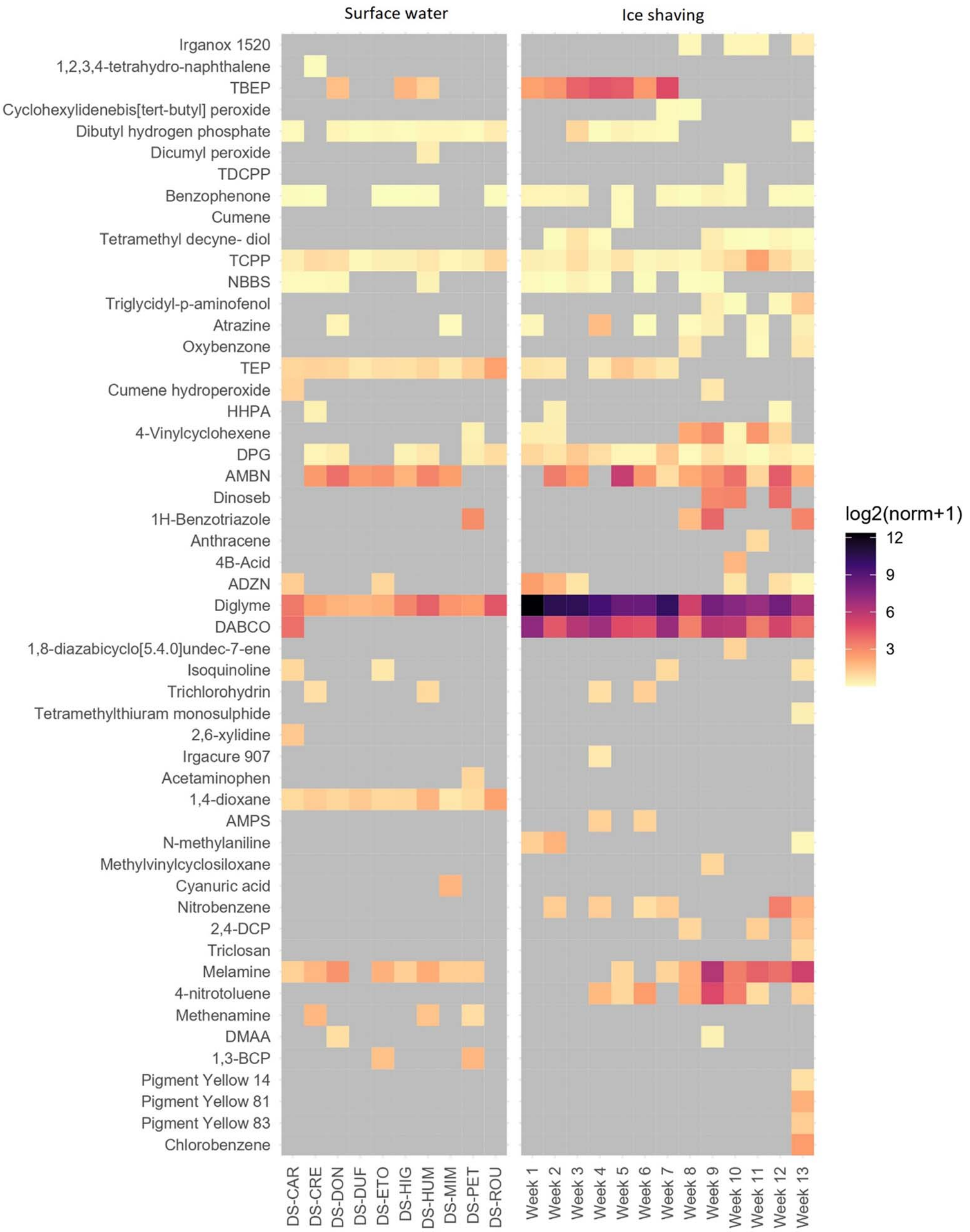

Fig. 5 Comparison of PMT plastic-associated chemicals profile of surface water ($n = 10$, left) and ice shavings ($n = 13$, right). The PMT plastic-associated chemicals are ordered from bottom to top of the y axis based on their increasing retention times. The intensity of color ($\log_2$(Norm RPA + 1)) corresponds to the $\log_2$-transformed size-factor normalized relative peak area (RPA) of each PMT plastic-associated chemical against a benchmark standard (DS = downstream, CAR = Carruthers Creek, DUF = Duffin Creek, PET = Petticoat Frenchman's Creek, ROU = Rouge River, HIF = Highland Creek, DON = Don River, HUM = Humber River, MIM = Mimico Creek, ETO = Etobicoke Creek, CRE = Credit River).

samples, which is impacted by diverse contaminants sources, surfaces and materials as it flows through the urban landscape. While ice shavings from major ice rinks, including the Mattamy Athletic Centre are usually melted onsite in a "snow pit", that drains into the combined sewer system and flow to a downstream wastewater treatment plant, many smaller hockey rinks simply pile the used ice outside of the rink and let it melt naturally. The high overlap between PMT plastic-associated chemicals in ice shavings and surface water samples could indicate potential contributions from rinks, particularly those that discharge ice shaving meltwater into the separated storm sewer system or let the ice waste melt outside. However, the wide variety of PMT plastic-associated chemical applications and use of plastics make it impossible to draw any specific conclusions regarding the sources of PMT plastic-associated chemicals in surface water across Toronto at this point. Future research on melt and surface water close to rinks across the GTA would be useful to better understand the specific contributions of the rinks to the plastic contaminant mixture in the local aquatic environment.

3.4 Practical implications for rink operations

At the studied rink, microplastics were dominated by 10–100 μm particles and polymers consistent with boards, gear, and textiles. Several PMT chemicals were detected more often or at higher levels in ice shavings than in paired source water, indicating rink-internal input. Considering these results, facilities should avoid outdoor dumping and install "snow-pit" filtration targeting small particle range (<100 μm). Where meltwater reuse is possible, for example for cooling-system applications or potential reuse within the facility for ice resurfacing, PMT plastic-associated chemicals and microplastic particles should be considered in treatment selection. Recycling water collected from snow melt pits may offer opportunities to reduce water consumption, although the relevance and required degree of treatment will depend on the intended reuse pathway. Where meltwater is to be reused as ice-making water, more thorough treatment would likely be required, and testing filtration systems with appropriate size ranges could help improve particle removal and reduce recirculation of contaminants within the water source. While filters and strainers can potentially remove microplastic particles, dissolved PMT plastic-associated chemicals would require additional processes such as activated carbon, advanced oxidation, or high-pressure membranes (*e.g.*, nanofiltration, reverse osmosis).[46] However, no single treatment process is likely sufficient because these substances span a broad range of physicochemical properties. Site-specific assessment of contaminant presence and corresponding treatment performance is therefore necessary to determine appropriate treatment strategies and their removal efficiency.

4 Limitation

As an exploratory study, this study has several limitations that should be considered when interpreting its findings. Ice-shaving samples were collected as composite material from multiple points within the bulk snow pile generated during resurfacing to better represent the overall ice-shaving waste stream; however, only an aliquot of the melted composite was analyzed, which may not fully capture heterogeneity within the bulk sample. The relatively small surface-water volume analyzed for microplastics likely reduced detection sensitivity for low-abundance particles and may have contributed to the absence of detected microplastics in those samples. In addition, the microplastics analysis focused on particle occurrence and polymer identity, and additional descriptors such as colour were beyond the scope of the present work. Polymer-specific spike-recovery experiments across particle size ranges, particularly for the smaller size fractions, were not performed; therefore, differences in recovery among particle sizes and morphologies cannot be excluded. Because duplicate field sampling and duplicate laboratory processing were not conducted, some of the observed variation among samples may also reflect methodological uncertainty. For PMT plastic-associated chemicals, the screening workflow was semi-quantitative, and matrix effects could not be fully evaluated because authentic analytical standards were not available for all compounds in the suspect library. Although matrix effects were assessed using benchmark standards, this approach could not provide compound-specific correction for every suspect-list compound. In addition, compound-specific stability during storage was not assessed, and storage-related changes in some analytes may therefore have influenced the measured responses. Accordingly, the results should be interpreted as indicative of occurrence and relative patterns rather than as a fully comprehensive quantitative characterization of microplastics and plastic-associated chemicals across all sampled matrices.

5 Conclusion

This study provides the first documented evidence of microplastics and PMT plastic-associated chemicals in rink ice shavings, highlighting an overlooked source of emerging contaminants from the ice sports sector. Given the large number of ice rink facilities in Canada and worldwide, proactive management strategies should be developed to minimize the transport of contaminants from ice shavings to local receiving waters. Since conventional treatment in wastewater treatment plants cannot fully remove microplastics and PMT plastic-associated chemicals, there is also a need to develop facility-scale water-recycling technologies and waste-disposal guidelines that can effectively capture, treat, and reuse ice shavings to prevent downstream contaminant release and promote sustainable recreational water use without compromising operational efficiency.

Author contributions

Yanan Li: conceptualization, methodology, validation, formal analysis, investigation, visualization and writing – original draft and writing – review & editing; Ryan H. S. Hutchins: methodology, formal analysis and writing – review & editing; Claire Oswald: conceptualization, writing – review & editing, supervision and funding acquisition; Stefania Impellizzeri: conceptualization, writing – review & editing, supervision, project administration and funding acquisition; Roxana Suehring: conceptualization, methodology, writing – review & editing, supervision, project administration and funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting the findings of this study are included in this article and its supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5em01017a.

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References

1 C. Gough, *Total Number of Registered Ice Hockey Players in Canada from 2010/11 to 2023/24*, https://www.statista.com/statistics/282125/number-of-registered-ice-hockey-players-in-canada/, (accessed 10 June, 2025).

2 C. Heritage, *Government of Canada Announces Financial Support for Curling Canada*, Journal, 2022.

3 C. Gough, *Total Number of Ice Hockey Rinks in Canada from 2010/11 to 2023/24*, https://www.statista.com/statistics/282363/number-of-ice-hockey-rinks-in-canada/, (accessed 10 June, 2025).

4 L. Poirier, E. P. Lozowski and R. I. Thompson, Ice hardness in winter sports, *Cold Reg. Sci. Technol.*, 2011, **67**, 129–134, DOI: 10.1016/j.coldregions.2011.02.005.

5 J. H. Lever, A. P. Lines, S. Taylor, G. R. Hoch, E. Asenath-Smith and D. S. Sodhi, Revisiting mechanics of ice–skate friction: from experiments at a skating rink to a unified hypothesis, *J. Glaciol*, 2022, **68**, 337–356, DOI: 10.1017/jog.2021.97.

6 NHL, *NHL Sustainability Report*, https://www.nhl.com/community/nhl-green/, (accessed 23 July, 2024).

7 NHL, *Green*, https://www.nhl.com/community/nhl-green/, (accessed 12 April, 2025).

8 R. H. S. Hutchins, Y. Li, G. Taylor, D. Loverock and S. Impellizzeri, Arena ice quality and perspectives on optimizing performance and addressing emerging challenges, *Sci. Rep.*, 2025, **15**, 13600, DOI: 10.1038/s41598-025-97405-5.

9 J. Hietanen and V. Sutinen, Microplastics generation during an ice hockey game, *Procedia Environ. Sci. Eng. Manag.*, 2023, **10**, 285–300.

10 R. C. Thompson, W. Courtene-Jones, J. Boucher, S. Pahl, K. Raubenheimer and A. A. Koelmans, Twenty years of microplastic pollution research—what have we learned?, *Science*, 2024, **386**, eadl2746, DOI: 10.1126/science.adl2746.

11 M. Cole, P. Lindeque, C. Halsband and T. S. Galloway, Microplastics as contaminants in the marine environment: A review, *Mar. Pollut. Bull.*, 2011, **62**, 2588–2597, DOI: 10.1016/j.marpolbul.2011.09.025.

12 R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle and A. E. Russell, Lost at Sea Where Is All the Plastic?, *Science*, 2004, **304**, 838, DOI: 10.1126/science.1094559.

13 J. Liu and L. Zheng, Microplastic migration and transformation pathways and exposure health risks, *Environ. Pollut.*, 2025, **368**, 125700, DOI: 10.1016/j.envpol.2025.125700.

14 C. Campanale, C. Massarelli, I. Savino, V. Locaputo and V. F. Uricchio, A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health, *Int. J. Env. Res. Public Health*, 2020, **17**, 1212, DOI: 10.3390/ijerph17041212.

15 E. Fries, T. Grewal and R. Sühring, Persistent, mobile, and toxic plastic additives in Canada: properties and prioritization, *Environ. Sci.: Process. Impacts.*, 2022, **24**, 1945–1956, DOI: 10.1039/D2EM00097K.

16 N. R. Maddela, D. Kakarla, K. Venkateswarlu and M. Megharaj, Additives of plastics: Entry into the environment and potential risks to human and ecological health, *J. Environ. Manage.*, 2023, **348**, 119364, DOI: 10.1016/j.jenvman.2023.119364.

17 T. Reemtsma, U. Berger, H. P. H. Arp, H. Gallard, T. P. Knepper, M. Neumann, J. B. Quintana and P. d. Voogt, Mind the Gap: Persistent and Mobile Organic Compounds—Water Contaminants That Slip Through, *Environ. Sci. Technol.*, 2016, **50**, 10308–10315, DOI: 10.1021/acs.est.6b03338.

18 S. E. Hale, H. P. H. Arp, I. Schliebner and M. Neumann, Persistent, mobile and toxic (PMT) and very persistent and very mobile (vPvM) substances pose an equivalent level of concern to persistent, bioaccumulative and toxic (PBT) and very persistent and very bioaccumulative (vPvB) substances under REACH, *Environ. Sci. Eur.*, 2020, **32**, 155, DOI: 10.1186/s12302-020-00440-4.

19 R. Sühring, M. L. Diamond, S. Bernstein, J. K. Adams, J. K. Schuster, K. Fernie, K. Elliott, G. Stern and L. M. Jantunen, Organophosphate Esters in the Canadian Arctic Ocean, *Environ. Sci. Technol.*, 2021, **55**, 304–312, DOI: 10.1021/acs.est.0c04422.

20 E. Fries and R. Sühring, The unusual suspects: Screening for persistent, mobile, and toxic plastic additives in plastic leachates, *Environ. Pollut.*, 2023, **335**, 122263, DOI: 10.1016/j.envpol.2023.122263.

21 D. Bates, M. Mächler, B. Bolker and S. Walker, Fitting Linear Mixed-Effects Models Using lme4, *Journal of Statistical Software*, 2015, **67**, 1–48, DOI: 10.18637/jss.v067.i01.

22 A. Kuznetsova, P. B. Brockhoff and R. H. B. Christensen, lmerTest Package: Tests in Linear Mixed Effects Models, *Journal of Statistical Software*, 2017, **82**, 1–26, DOI: 10.18637/jss.v082.i13.

23 E. C. Ware, D. M. Schultz, H. E. Brooks, P. J. Roebber and S. L. Bruening, Improving Snowfall Forecasting by Accounting for the Climatological Variability of Snow Density, *Weather and Forecasting*, 2006, **21**, 94–103, DOI: 10.1175/WAF903.1.

24 L. Nichols, *Improving Efficiency in Ice Hockey Arenas*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009,.

25 A. Yaseen, I. Assad, M. S. Sofi, M. Z. Hashmi and S. U. Bhat, A global review of microplastics in wastewater treatment plants: Understanding their occurrence, fate and impact, *Environ. Res.*, 2022, **212**, 113258, DOI: 10.1016/j.envres.2022.113258.

26 J. Haney, X. Zhu, M. Long, B. A. Schwenk, T. J. Hoellein, W. M. Wollheim, R. B. Lammers, S. Zuidema and C. M. Rochman, The influence of flow on the amount, retention and loss of plastic pollution in an urban river, *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, 2025, **383**, 20230023, DOI: 10.1098/rsta.2023.0023.

27 I. Chubarenko, A. Bagaev, M. Zobkov and E. Esiukova, On some physical and dynamical properties of microplastic particles in marine environment, *Mar. Pollut. Bull.*, 2016, **108**, 105–112, DOI: 10.1016/j.marpolbul.2016.04.048.

28 J. Grbić, P. Helm, S. Athey and C. M. Rochman, Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources, *Water Res.*, 2020, **174**, 115623, DOI: 10.1016/j.watres.2020.115623.

29 A. Thomas, J. Marchand, G. D. Schwoerer, E. C. Minor and M. A. Maurer-Jones, Size Distributions of Microplastics in the St Louis Estuary and Western Lake Superior, *Environ. Sci. Technol.*, 2024, **58**, 8480–8489, DOI: 10.1021/acs.est.3c10776.

30 V. Kopatz, K. Wen, T. Kovács, A. S. Keimowitz, V. Pichler, J. Widder, A. D. Vethaak, O. Hollóczki and L. Kenner, Micro- and Nanoplastics Breach the Blood–Brain Barrier (BBB): Biomolecular Corona's Role Revealed, *Nanomaterials*, 2023, **13**, 1404, DOI: 10.3390/nano13081404.

31 H. Boettcher, T. Kukulka and J. H. Cohen, Methods for controlled preparation and dosing of microplastic fragments in bioassays, *Sci. Rep.*, 2023, **13**, 5195, DOI: 10.1038/s41598-023-32250-y.

32 A. Majumdar, S. Shukla, A. A. Singh and S. Arora, Circular fashion: Properties of fabrics made from mechanically recycled poly-ethylene terephthalate (PET) bottles, *RCR*, 2020, **161**, 104915, DOI: 10.1016/j.resconrec.2020.104915.

33 R. Shishoo, *Textiles for Sportswear*, ed. R. Shishoo, Woodhead Publishing, 2015, pp. 3–16, DOI: 10.1016/B978-1-78242-229-7.00001-1.

34 V. K. Kothari, *Polyesters and Polyamides*, ed. B. L. Deopura, R. Alagirusamy, M. Joshi and B. Gupta, Woodhead Publishing, 2008, pp. 419–440, DOI: 10.1533/9781845694609.3.419.

35 U. Rozman, B. Klun, A. Kuljanin, T. Skalar and G. Kalčíková, Insights into the shape-dependent effects of polyethylene microplastics on interactions with organisms, environmental aging, and adsorption properties, *Sci. Rep.*, 2023, **13**, 22147, DOI: 10.1038/s41598-023-49175-1.

36 R. Macwan and S. D. Ray, *Encyclopedia of Toxicology*, 4th edn, ed. P. Wexler, Academic Press, Oxford, 2024, pp. 185–191, DOI: 10.1016/B978-0-12-824315-2.00381-X.

37 ECHA, *Bis(2-methoxyethyl) ether*, https://echa.europa.eu/substance-information/-/substanceinfo/100.003.568, (accessed 16 May 2025).

38 International Ice Hockey Federation, *Official Ice Arena Guide*, 2024, pp. 20–24.

39 ECHA, *1,4-Diazabicyclooctane*, https://echa.europa.eu/substance-information/-/substanceinfo/100.005.455, (accessed 20 May 2025).

40 ECHA, *1,3-Diphenylguanidine*, https://echa.europa.eu/substance-information/-/substanceinfo/100.002.730, (accessed 22 July 2025).

41 ECHA, *4-Nitrotoluene*, https://echa.europa.eu/substance-information/-/substanceinfo/100.002.553?_disssubsinfo_WAR_disssubsinfoportlet_substanceId=100.002.553, (accessed 22 July 2025).

42 ECHA, *Benzophenone*, https://echa.europa.eu/substance-information/-/substanceinfo/100.003.943, (accessed 22 July 2025).

43 Health Canada, *Flame Retardants*, https://www.canada.ca/en/health-canada/services/chemicals-product-safety/flame-retardants.html, (accessed 20 May, 2025).

44 ECHA, *1,4-Dioxane*, https://echa.europa.eu/substance-information/-/substanceinfo/100.004.239, (accessed 16 May 2025).

45 Health Canada, *1,4-Dioxane*, https://www.canada.ca/en/health-canada/services/chemical-substances/challenge/batch-7/1-4-dioxane.html, (accessed 16 May, 2025).

46 S. E. Hale, M. Neumann, I. Schliebner, J. Schulze, F. S. Averbeck, C. Castell-Exner, M. Collard, D. Drmač, J. Hartmann, R. Hofman-Caris, J. Hollender, M. de Jonge, T. Kullick, A. Lennquist, T. Letzel, K. Nödler, S. Pawlowski, N. Reineke, E. Rorije, M. Scheurer, G. Sigmund, H. Timmer, X. Trier, E. Verbruggen and H. P. H. Arp, Getting in control of persistent, mobile and toxic (PMT) and very persistent and very mobile (vPvM) substances to protect water resources: strategies from diverse perspectives, *Environ. Sci. Eur.*, 2022, **34**, 22, DOI: 10.1186/s12302-022-00604-4.