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Plastic and anthropogenic microfiber pollution on exposed sandy beaches in Nova Scotia, Canada

Noreen E. Kelly[1], Olga Trela[1], Heidi Gavel[1,2], Alyssa Vander Kuylen[1]

[1]Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth B2Y 4A2, Nova Scotia, Canada.
[2]Department of Environmental Science, St. Mary's University, Halifax B3H 3C3, Nova Scotia, Canada.

Correspondence to: Dr. Noreen E. Kelly, Fisheries and Oceans Canada, Bedford Institute of Oceanography, 1 Challenger Drive, Dartmouth B2Y 4A2, Nova Scotia, Canada. E-mail: noreen.kelly@dfo-mpo.gc.ca

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Abstract

This study aimed to assess the initial presence of microplastics on two sandy beaches along a rugged coastline in the Northwest Atlantic, an area with limited prior investigation. Sediment samples were collected from High, Mid, and Low intertidal zones at two beaches on the eastern shore of Nova Scotia, Canada. Microplastics were isolated from 100 g sediment samples using density flotation with a sodium iodide solution. Particle characterization included size, shape, and color analysis, with polymer identification performed using Fourier Transform Infrared (FTIR) spectroscopy. Results indicated that the predominant microplastics were small (< 1.4 mm) transparent microfibers, primarily composed of polyethylene terephthalate (PET), nylon, or alkyd polymers from paints. Mean concentrations were comparable between the two beaches, averaging 5.08 ± 3.20 and 5.58 ± 4.52 microplastics per 100 g of sediment, respectively. Non-plastic microfibers, including natural and semi-synthetic cellulosic materials, were notably more abundant, with mean concentrations ranging from 75.9 ± 60.1 to 97.7 ± 87.9 per 100 g sediment. Statistical analysis revealed no significant differences in microplastic counts across tidal zones due to high variability over small spatial scales (tens of meters). Sources of microfibers were potentially from high recreational use at these sites. This study highlights the lower-than-expected levels of microplastic pollution compared to earlier research at these sites and global beach studies. Future monitoring efforts could focus on longitudinal studies to track microplastic trends on these exposed sandy beaches.

Keywords: Beach sand, density separation, microplastics, microfibers, cellulosic fibers, Northwest Atlantic, local sources, tourism, recreation

INTRODUCTION

Microplastics (MPs), synthetic polymers ≤ 5 mm in size[1], are ubiquitous marine pollutants found in all regions of the world ocean, from the surface[2] to the seafloor[3], and from the poles[4,5] to the tropics[6,7]. Primary MPs originate from the release of small particles into the environment during industrial manufacture, transportation, or use; secondary MPs, on the other hand, form when larger plastics undergo fragmentation due to chemical and/or mechanical abrasion as they disperse throughout the ocean[8]. The persistence of MP pollution on a global scale, combined with their small size, gives rise to concerns about their impacts on the marine environment and biota across all trophic levels[9], from microbes[10] and plankton[11] to marine mammals[12]. MPs have been shown to pose ingestion hazards to marine biota[13], increase exposure to toxic contaminants[14,15], and provide substrate to harmful microorganisms and/or invasive species[16]. Despite the increase in research on plastic pollution over the last decade[17], major gaps in understanding of baseline plastic concentrations remain, particularly in the Northwest (NW) Atlantic[18,19].

Beaches and intertidal environments are at a heightened risk of MP pollution, due to their proximity to plastic pollution sources and their role as (temporary) sinks for plastic pollution[20,21]. Thus, assessing baseline concentrations and patterns of deposition in intertidal areas is necessary for a better understanding of the fate of MPs along shorelines. To date, there have been numerous studies examining the abundance of MPs on beaches and shorelines around the world, reporting a range of particles typically in the 10 to 100s per kg of dry sediment, and a predominance of fibers over other types of particles[20,22-27]. Polyethylene and polyester are the most commonly reported MPs in marine sediments[28]. However, reporting anthropogenic (human-made) non-plastic particles derived from cellulose separately from synthetic, petroleum-based fibers[29-31] is becoming more common.

In contrast, very little research has focused on temperate areas of the NW Atlantic, particularly in Atlantic Canada[19,32]. The first study to investigate MP pollution in intertidal sediments (mud and sand) in Nova Scotia, Canada, documented notably high MP fiber abundances[33]. However, in 2012, Mathalon and Hill were unable to validate the identity of their sampled fibers using spectroscopic or other methods[33]. While these methods were not as prevalent in the literature at the time[34], it is now recognized that visual identification alone is insufficient to accurately determine MP concentrations[35,36]. In addition, Mathalon and Hill suspected laboratory contamination of samples, which is now a well-documented issue[33,37-39]. Given the uncertainty in these MP abundance estimates, yet their widespread use in the scientific literature (cited in 556 publications[40]), repetition of their study is clearly warranted.

The region of Atlantic Canada presents an intriguing opportunity for analysing the distribution of MPs, due to its low human population density but a long history of utilizing its coastal and marine environments, particularly for fishing, shipping, transportation, aquaculture, and tourism and recreation[41,42]. In this study, we investigate concentrations of MPs in beach sediments along an exposed coastline in Atlantic Canada, and compare our results to a previous study conducted in the same region[33] through new investigative tools. Our study contributes additional insight into the fate of a persistent environmental pollutant in an understudied region of the global ocean.

METHODS

Study sites and field sampling

Sediment samples were collected at Rainbow Haven beach (44° 38' 46.69" N, 63° 25' 10.131" W) on April 16, 2019 and at Martinique beach (44° 41' 27.86" N, 63° 08' 18.68" W) on April 17, 2019 in Nova Scotia [Figure 1]. Located along the Eastern Shore of Nova Scotia, Rainbow Haven (https://parks.novascotia.ca/park/rainbow-haven-beach) is a 3.2 km long, primarily sand and cobblestone beach, while Martinique (https://parks.novascotia.ca/park/martinique-beach) is a 5 km long crescent white sand beach that is also a protected area for shorebirds and a wildlife refuge for migratory waterfowl. Both beaches are popular swimming and day-use recreational areas and are located eastward along the coast from Halifax Harbour, a major shipping port and population center in the province. The mean tidal range at both beaches is approximately 1.5 m.

On each beach at low tide, four cross-shore transects, approximately 50 m apart, were created, starting just below the wrack line and extending towards low water. On each transect, one sediment core was collected at High, Mid (at the midpoint between High and Low positions), and Low intertidal positions, following Mathalon and Hill[33]. This resulted in a total of 12 cores per beach. Beach sediment cores were collected using 15 cm tall, 750 mL pre-cleaned glass mason jars with metal lids. Immediately prior to collecting each sample, the jar was inverted (with the lid facing downwards), the lid was removed from the jar, and the jar was then driven into the sand until 2.5 cm of space remained within the jar. This covered an approximate depth of 12.5 cm of sediment. A metal trowel was placed underneath the opening of the jar to prevent the contents from falling out as the jar was removed. The jar was turned upright and the lid was quickly secured and the sample was kept in a cooler with ice packs. After returning from the field, the jars were frozen (at -20 °C) until processed.

Laboratory processing

Prior to processing, jars were thawed at 4 °C for a minimum of 72 h. Once thawed, the sediment representing > 5 cm depth was removed from the jar; the remaining sediment in the jar, representing the 0-5 cm depth, was covered with aluminum foil and placed in an oven at 60 °C until dry (~72 h to 1 week). Once dry, the sediment was transferred to a glass beaker and was homogenized by manually mixing the sediment for 1 min in a laminar flow hood. After mixing, a 100.0 g subsample was removed with a metal spoon, and placed in a 500 mL glass beaker for density flotation.

A maximum density sodium iodide (NaI, Sigma Aldrich) solution (mean density of 1.8 ± 0.04 g·cm^{-3}) was prepared, using ultrapure water (Milli-Q®; Millipore Sigma) at 25 °C, to separate plastics from the sediment via floatation[43]. NaI was chosen over other solutions, such as sodium chloride (NaCl), as it can more efficiently extract higher-density MPs, such as polyvinylchloride (PVC, 1.3-1.7 g·cm^{-3}) and polyethylene terephthalate (PET, 1.4-1.6 g·cm^{-3})[34]. In a fume hood, the NaI solution (210 mL) was added to the 500 mL glass beaker containing 100.0 g (~70.0 mL volume) of sediment to attain a 3:1 NaI to sediment volume ratio. The solution was manually stirred for 2 min with a glass stirring rod. After stirring, the rod was rinsed with a small amount of ultrapure water into the solution, and the solution was covered with aluminum foil and allowed to stand for 30 min. The supernatant was decanted and vacuum filtered onto a 47 mm, 20 µm polycarbonate membrane filter (PCTE, Sterlitech). The 500 mL beaker (with the remaining sediment) was rinsed three times with ultrapure water to capture any remaining particles on the sides of the beaker, and the remaining small amount of supernatant was pipetted into the vacuum funnel. The sides of the vacuum funnels were also rinsed three times with ultrapure water to ensure all particles were transferred onto the filter. Filters were carefully removed and transferred to Petri slides (Millipore Sigma) and then dried (covered) in a desiccator overnight. Once dried, the Petri slides were stored at room temperature.

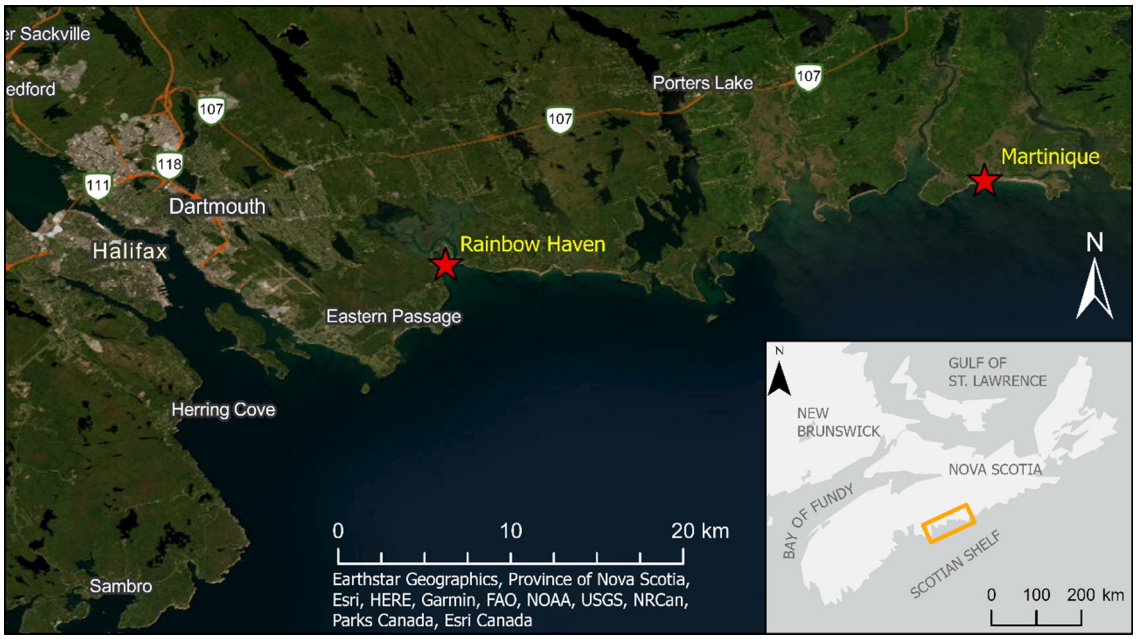

Figure 1. Locations of the two beaches (red stars) sampled in this study. Inset: Sample area (orange box) in relation to the Province of Nova Scotia, Canada.

Particle characterization

Filters were examined under a dissecting microscope at 40-100× magnification. Suspected MPs were removed by hand using ultra fine-tipped jeweler's forceps and placed on double-sided tape in Petri slides. Suspected particles were photographed using a microscope-mounted digital camera (Nikon SMZ-25 fitted with a Di-3 digital camera, Nikon Instruments, Inc.). All suspected particles were classified according to morphology, colour, and transparency, following specific criteria[44-46]. Particle size, measured as the longest dimension, was determined from the microscope photographs using image analysis software (NIS-Elements D, Nikon Instruments, Inc.). We counted all transparent fibers, but only measured the length of a subset of these particles due to their high abundance.

Polymer composition for select particles was identified by Fourier transform infrared (FTIR) spectroscopy at Surface Science Western, University of Western Ontario, London, Ontario, Canada. Selected particles were randomly chosen from each major colour and morphology combination (i.e., transparent fibers, blue fragments, black films, *etc.*), totalling 200 particles or 7% of the dataset. Selected particles were transferred to a diamond compression cell and analyzed by FTIR in transmission mode under the Hyperion 2000 microscope attached to a Bruker Tensor II spectrometer. Particle spectra were matched to a known polymer through manual comparison of individual spectral components using spectral libraries, references, and the knowledge of multiple IR experts; thus, particle matches are considered to be highly certain. For microfibers that had FTIR spectra consistent with a cellulosic material, the method of Cai *et al.* was applied to distinguish between dyed cellulosic textiles (e.g., cottons) and semi-synthetic cellulosic (e.g., regenerated) materials[47]. Each spectrum in question was visually examined for a peak, shoulder, or no peak at ~1,105 cm^{-1}. Particles with spectra that contained a peak at this wavelength were classed as cellulosic fibers; particles with no peak or a shoulder at this wavelength were classed as semi-synthetic fibers. Thus, we report a MP count that includes plastics and alkyds (paints and surface coatings), as well as a separate anthropogenic cellulosic fiber count (following Huntington *et al.*[48]), which includes both cellulosic fibers (i.e., textile fibers made from processed and dyed plant fibers, such as cotton or linen but have been

manipulated for human purposes), and semi-synthetic fibers (i.e., particles comprised of rayon or viscose).

Contamination reduction protocols

Following Dimitrijevic *et al.*, many steps were taken to minimize MP contamination during sample collection and processing[49]. In the field, researchers wore clothing made from natural materials (i.e., not fleece) or non-shedding clothing, wore nitrile gloves, and minimized the amount of time samples were exposed to air during the collection process. Mason jars were pre-cleaned in the laboratory and transported to and from the field sites in pre-cleaned totes, and researchers rinsed their gloves with ultrapure water between taking each sample. In the laboratory, researchers wore yellow coveralls (Tyvek 2000, Dupont) or 100% cotton lab coats, a muslin headscarf, and nitrile gloves, which were all cleaned with a lint roller prior to sample processing. Prior to sample processing, all work surfaces, including the laminar flow hood, fume hood, and microscope work area, were cleaned three times using a distinctly-coloured sponge (yellow or pink) dampened with ultrapure water. The microscope work area was covered with plastic sheeting to limit the amount of airborne contamination[37]. Prior to use in density floatation, the NaI solution was vacuum filtered through a 2.7 μm, 90 mm grade D Whatman glass filter and stored in glass jugs. As much field and laboratory equipment as possible was either made of metal or glass and all were rinsed with ultrapure water three times prior to use.

Background and procedural blanks were collected during the laboratory processing of all samples. Individual background blanks for each sample were created by placing a 47 mm, 3 μm PCTE filter, dampened with ultrapure water, in a Petri slide. The background blank was opened whenever its respective sediment sample was exposed to air during sample processing. A procedural blank was conducted each day of sample processing, corresponding to approximately every three samples processed. Each blank was prepared following the same floatation procedure as the sediment samples, but 70 mL of ultrapure water instead of sediment was used. Background and procedural blank filters were examined under 40X magnification and the morphology and colour of any observed particles were recorded.

Statistical analysis

All calculations and statistical analyses were conducted using the R software environment (version 4.2.1, R Core Team[50]) in RStudio (version 2023.06.0, Posit Software).

Particles found in background and procedural blanks were used to correct the final particle counts by establishing a Limit of Detection (LOD) following Dawson *et al.*[51]. The LOD was calculated as the mean + 3* standard deviation (SD) for each particle colour and morphology combination. Corrective action (subtraction of the LOD across all blanks from the number tallied in the sample) was only taken if an item of the same colour and morphology was found in both the blanks and the samples. If the corrected values were less than zero (i.e., subtraction resulted in a negative number), the value was set to zero. Following the blank correction of samples, particle counts per sample were further adjusted to account for the amount of visual identification errors. Using the results of FTIR spectroscopy, the number of particles in each colour-morphology combination was multiplied by a correction factor to account for the amount of visual identification error[46,52]. Final counts were rounded up to the nearest whole integer (to maintain the nature of count data). See Supplementary Materials for original particle counts, LOD values, correction factors, and corrected data.

We tested the difference in particle counts between Beaches (Rainbow Haven, Martinique) and among Intertidal Positions (High, Mid, and Low tide) using generalized linear models (GLMs). We used a negative binomial error distribution to provide a better fit for our over-dispersed count data (number of particles per standard 100 g samples). GLMs for anthropogenic cellulosic fiber counts and MP counts were conducted

separately, using the glm.nb function in the MASS package[53]; Tukey post-hoc testing was conducted using the emmeans function in the emmeans package[54]. Model assumptions were assessed from plots of residuals and normal quantiles using the DHARMa package[55].

RESULTS

Background blanks that accounted for airborne laboratory contamination contained a mean of 4.2 ± 5.7 SD particles per sample. Particles found on background blanks were primarily transparent, blue, brown, and black fibers. Procedural blanks that accounted for particle contamination during sample processing contained a mean of 3.6 ± 3.4 SD particles per sample. Particles found on procedural blanks were primarily transparent, red, and blue fibers [Supplementary Materials].

MPs were found in 23 of 24 samples from High to Low intertidal positions, with counts ranging from 0-14 particles per 100 g of sediment. The overall mean concentration was 5.08 ± 3.20 SD and 5.58 ± 4.52 SD MPs per 100 g of sediment at Rainbow Haven and Martinique beaches, respectively. The mean counts of MPs per 100 g of sediment were generally greater at Mid than at High or Low intertidal positions, and High intertidal positions had greater mean counts than Low intertidal positions [Figure 2A]. However, there was no statistically significant difference in mean MP counts per 100 g of sediment detected between Beaches (GLM Likelihood ratio $X^2 = 0.25$, $df = 1$, $P = 0.62$), nor a significant interaction between Beach and Intertidal Position (GLM Likelihood ratio $X^2 = 0.97$, $df = 2$, $P = 0.61$), but there was a significant difference detected in Intertidal Position (GLM Likelihood ratio $X^2 = 6.22$, $df = 2$, $P = 0.045$). Across both beaches, mean MP counts were significantly greater at Mid than Low intertidal position ($P = 0.047$), although there was no significant difference between High and Low ($P = 0.73$) nor High and Mid ($P = 0.23$) intertidal positions [Figure 2A].

At both beaches, anthropogenic cellulosic fibers were up to 19 times more abundant than MP particles, ranging from 1-270 particles per 100 g sediment. The overall mean concentration was 75.9 ± 60.1 SD and 97.7 ± 87.9 SD anthropogenic fibers per 100 g sediment at Rainbow Haven and Martinique beaches, respectively. Mean counts of anthropogenic fibers per 100 g of sediment at Martinique Beach followed the same general pattern across the intertidal zone as for MPs [Figure 2B]. In contrast, at Rainbow Haven, mean anthropogenic cellulosic fiber counts were greatest at the Mid intertidal position, followed by Low and then High intertidal position, respectively [Figure 2B]. Overall, these differences between Beaches (GLM Likelihood ratio $X^2 = 0.94$, $df = 1$, $P = 0.33$), among Intertidal Position (GLM Likelihood ratio $X^2 = 3.89$, $df = 2$, $P = 0.14$), and their interaction (GLM Likelihood ratio $X^2 = 1.38$, $df = 2$, $P = 0.50$), were not statistically significant.

Across all samples combined ($n = 2{,}220$ particles), 99.2% of all particles extracted from beach sediments were fibers, with the remaining fraction composed of films (0.36%), fragments (0.27%), and foams (0.18%), respectively. Of the subset of particles identified by FTIR spectroscopy ($n = 200$), 93.5% were of anthropogenic cellulosic origin (88% natural, 5.5% semi-synthetic), 5% were plastics [3% were PET, 1% nylon (polyamide), and 1% alkyds], and the remaining 1.5% were either natural particles (i.e., plants) or unable to be identified (i.e., no match in spectral library).

The characteristics of particles (both anthropogenic and plastic) were markedly similar between beaches [Supplementary Figure 1], and thus were compared among intertidal positions for the beaches combined. Particle morphology did not vary among intertidal positions, with fibers dominating at all three tidal heights [Figure 3A]. Transparent particles dominated at all intertidal positions, but yellow, red, blue, and black particle colours were also observed, with the occasional brown, green, and grey coloured-particles

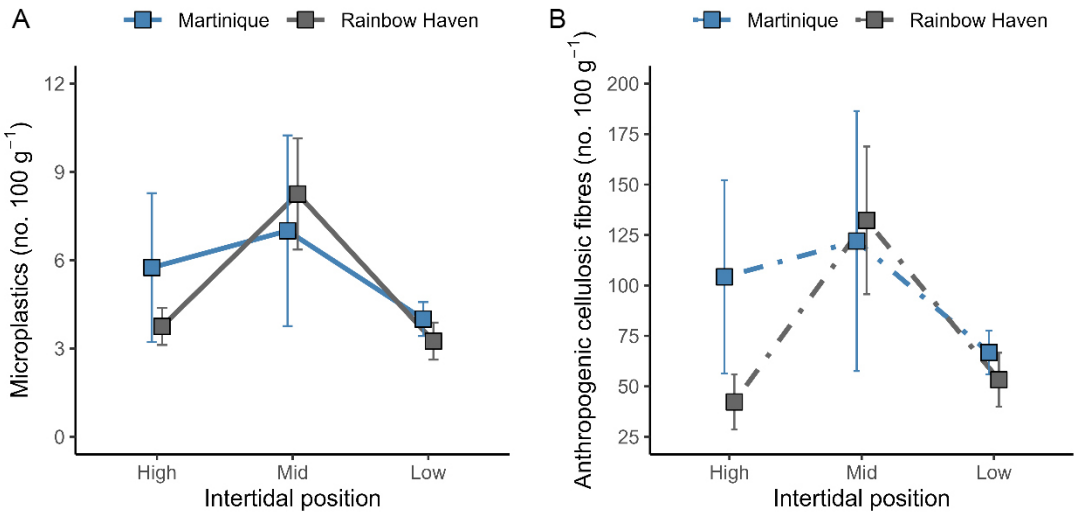

Figure 2. Mean (± SE) (A) MPs and (B) anthropogenic fiber counts (no. particles 100 g^{-1} sediment) by intertidal position sampled at Martinique (blue line) and Rainbow Haven (grey line) beaches. Note the difference in vertical axis scales between panels. MPs: Microplastics.

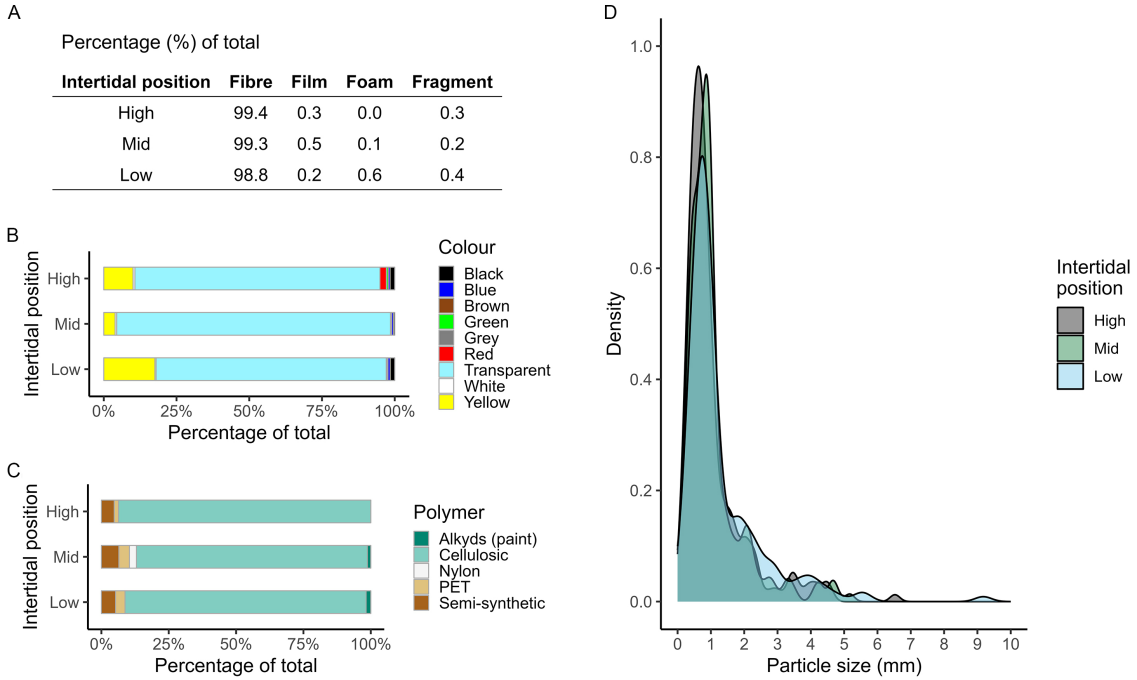

Figure 3. Characteristics of MPs and anthropogenic particles by intertidal position, collected from Martinique and Rainbow Haven beaches combined. (A) Particle shape and (B) colour, as a percentage of all particles found (*n* = 2,220); (C) polymer composition as a percentage of all particles identified using FTIR spectroscopy (*n* = 200); and (D) size, measured as the longest dimension (in mm). See Materials and Methods for further details. PET: Polyethylene terephthalate; MPs: microplastics; FTIR: Fourier transform infrared.

[Figure 3B]. Yellow particles at Low intertidal positions, and red particles at High intertidal positions, were slightly more abundant than elsewhere. However, we suspect a few of the yellow fibers were actually transparent cellulosic fibers stained from the NaI salts used in the extraction process, suggesting our counts of yellow-coloured fibers may be slightly overestimated.

Of the particles analyzed using FTIR spectroscopy, cellulosic particles were the most common at all tidal heights, followed by semi-synthetic celluloses and PET [Figure 3C]. Alkyds (as paints or surface coatings) were found only at Mid and Low intertidal positions, while nylon (polyamide) fibers were found only at Mid intertidal positions [Figure 3C]. Sodium benzoate was a common secondary contaminant found on 24 (or ~14%) of the anthropogenic cellulosic fibers as identified from FTIR spectroscopy.

While particle sizes ranged from 65-9,176 μm, most anthropogenic and plastic particles were small, being ≤ 1.4 mm (1,400 μm) in longest dimension [Figure 3D]. At Low intertidal positions, there were slightly fewer particles < 1.4 mm and slightly more particles between 1.8-3 mm; otherwise, the distribution of particle lengths was very similar among intertidal positions.

DISCUSSION

In this study, we demonstrate a high abundance of anthropogenic microfiber pollution in the intertidal sediments of two exposed sandy beaches along the Eastern Shore of Nova Scotia. Transparent anthropogenic cellulosic fibers ≤ 1.4 mm in size were the most commonly encountered particle type across the intertidal, being up to 19 times more abundant than MP pollution. Globally, fibers are the dominant MP morphology found on beaches, accounting for 90% of all particles[20,28]. However, in recent years, more attention has been given to documenting human-made, non-plastic microfibers (e.g., anthropogenic celluloses) in addition to synthetic and semi-synthetic textile fibers[29-31]. Similar to our findings, small (≤ 1 mm) non-plastic, cellulosic microfibers have been previously documented to comprise a large portion of sediment samples collected from beaches worldwide, ranging from 19%-93.8% of extracted particle types[20,25,26,56]. Such fibers have also been reported to occur in other marine habitats[31,57], as well as ingested by marine species[58-60], suggesting their distribution is as widespread as other types of plastic pollution. Although the relative rate of degradation is faster for anthropogenic cellulosic fibers than for plastics in marine environments[61] - potentially reducing their persistence in the environment compared to plastics - many anthropogenic celluloses are treated with a range of colourants (dyes, pigments) and finishes (flame retardants, antimicrobial agents, stabilizers, softeners) that may leach into the environment[62,63]. As anthropogenic cellulosic fibers may have similar toxicological impacts as plastics to marine biota once ingested[64], additional research is needed to determine the ecotoxicological risk of anthropogenic microfiber pollution to intertidal fauna in Atlantic Canada and elsewhere.

MP contamination at Rainbow Haven and Martinique beaches was towards the lower end of the range of particles reported by studies in other areas of the globe [Table 1], suggesting low MP pollution at our sites. We identified plastic polymers of nylon, alkyds, PET, and non-plastic semi-synthetic celluloses (e.g., viscose, rayon). Once deposited on the beach, the higher density of these polymers compared to seawater (e.g., nylon = 1.13-1.15 g·cm^{-3}; PET = 1.29-1.40 g·cm^{-3}; viscose/rayon = 1.53 g·cm^{-3}, cellulose = 1.5 g·cm^{-3}; alkyds = 1.2-1.7 g·cm^{-3}; seawater = 1.027 g·cm^{-3}) may make them more likely to be retained within the sediments along this wave-exposed coastline. Further, turbulent mixing of beach sediments during high wave action may bury MPs within the sand, and protect them from washing back into the water column[21]. PET is frequently used in the construction of food packaging, beverage bottles, and clothing, while nylon is widely used in textiles, nets and ropes, and sportswear[49,70]. Fragments of alkyd plastics, frequently used in paints and other surface coatings, suggest an urban or marine source for these particles, possibly from fishing or recreational boats[7,25,46]. However, in combination with the high abundance of anthropogenic celluloses in our samples, some of which were contaminated with sodium benzoate (a widely used antifungal and antimicrobial agent in foods and cosmetics, including sunscreens), it suggests that certain MP sources might be local rather than arriving from distant locations (i.e., from wear and tear of textiles, such as swimsuits, beach towels, blankets, clothing, *etc.*, and fragmentation of plastic containers discarded on the beach).

Table 1. Comparison of MP abundance in sandy sediments reported from other published studies around the globe

Location	MP abundance (no. kg^{-1} d.w. sediment)	Source
Atlantic coast, Canada	50.8 ± 32.0 to 55.8 ± 45.2[a]	Our current study
Atlantic coast, Canada	2,000-8,000[a,b]	Mathalon and Hill[33]
Bay of Fundy, Canada	268 ± 208.7[c]	Forsythe[65]
Atlantic coast, USA	63.8 ± 19.1 to 126.3 ± 43.2	Whitemire and Van Bloem[66]
Pacific coast, USA	38.8 ± 7.2 to 140.0 ± 24.8	Whitemire and Van Bloem[66]
Pacific coast, Mexico	179 ± 50	Piñon-Colin *et al.*[27]
Pacific coast, Gulf of California	76 ± 12	Piñon-Colin *et al.*[27]
Baja California, Mexico	135 ± 92	Piñon-Colin *et al.*[27]
Pacific Islands, USA	98.8 ± 27.7 to 187.5 ± 22.4	Whitemire and Van Bloem[66]
Alaska, USA	21.3 ± 4.3 to 128.8 ± 36.1	Whitemire and Van Bloem[66]
Bohai Sea, China	102.9 ± 39.9 to 163.3 ± 37.7	Yu *et al.*[25]
India	45 ± 12 to 220 ± 50	Tiwari *et al.*[67]
Arabian Gulf	13.5 (range 6-38)	Abayomi *et al.*[56]
Europe, Mediterranean coast	291 ± 62	Lots *et al.*[26]
Slovenia coast	133.3 (median)	Laglbauer *et al.*[68]
Baltic coast	14-532[b]	Stolte *et al.*[24]
Baltic coast	88.10 (median)	Hengstmann *et al.*[69]
Europe, Baltic coast	270 ± 90	Lots *et al.*[26]
Belgian coast	92.8 ± 37.2	Claessens *et al.*[23]
Europe, Atlantic coast	190 ± 35	Lots *et al.*[26]

Values are means ± SD unless otherwise indicated. [a]units converted to no. kg^{-1} sediment to enable inter-study comparison; [b]reported as fibers only; [c]intertidal mud and sand. MP: Microplastic.

Tourism has been implicated as a large contributor of MPs at beaches worldwide[24,25,27,71,72]. Due to their proximity to urban centers, Rainbow Haven and Martinique beaches are popular recreational sites throughout the year[73], lending further support to local tourism as the source of some microfiber pollution in this area.

Combining the results of two previous regional studies[33,65] with our current findings on MP pollution in intertidal zones can shed light on the distribution of this pervasive environmental pollutant on Atlantic Canadian coastlines. Compared to our 0-1.4 MPs per 10 g sediment, Mathalon and Hill documented 20-80 MP fibers per 10 g sediment at Rainbow Haven beach[33]. Given that our sample processing methods differed (Mathalon and Hill used a chemical digestion and short density floatation with NaCl compared to our longer NaI floatation only[33]), it is difficult to directly compare absolute values of MP concentrations between studies. However, at the time, Mathalon and Hill could not validate the identity of their sampled fibers using spectroscopic or other methods, and laboratory contamination of samples was also suspected, suggesting their MP fiber estimates were overestimated by 1-2 orders of magnitude[33]. More recently, Forsythe[65] examined MPs (validated using FTIR) in the intertidal zone at various locations in the Bay of Fundy, an area known for its dynamic tidal range[74], documenting a mean concentration of 268 ± 208.7 MPs per 1 kg sediment, of which 89% were fibers. As in our study, Mathalon and Hill[33] and Forsythe[65] did not find any significant differences in MP quantities across tidal ranges. Collectively, these results suggest MPs and anthropogenic microfibers are evenly distributed along intertidal gradients in the sandy sediments around Nova Scotia. However, the high variability within beaches among samples and transects taken over small spatial scales (10 s of meters) documented in our and these studies also stresses the need for caution when extrapolating to identify broader spatial patterns of pollution in the intertidal zones of Atlantic Canada. More research is clearly needed before the fate of MP pollution is fully understood in these wave-

and tidal-dominated systems.

Blue, black, and other brightly coloured MPs are the most frequently detected particles in sediments worldwide[24,28], due to the high global production of plastics with these colours, and/or the ease of visually distinguishing particles of these colours from sediment during sampling[75]. The distribution of colours we report herein may be an indicator of the residence time of these microfibers on Nova Scotia beaches, as the high load of transparent microfibers suggests significant exposure of these particles to UV solar radiation[76]. As we sampled in April before the height of the recreational and tourism season, it is possible that the majority of microfibers were deposited the previous year and lost their colour over the fall and winter through environmental exposure[7]. Future sampling to examine the seasonal deposition of microfibers along the coastline of Nova Scotia would provide additional insight into the sources and residence time of anthropogenic pollution to Atlantic Canadian coastlines. For example, targeted sampling before, during, and after summer could test not only for seasonal changes in plastic loading, but also whether the sources of contamination and MP types change with seasonal recreational use.

Our study documented MP and anthropogenic (non-plastic) microfiber pollution along exposed beaches in Atlantic Canada, and added new investigative tools (e.g., FTIR, contamination control protocols) to refine previous estimates in this understudied region. While our sampling design replicated that of Mathalon and Hill[33] in order to enable a regional comparison, the design shares similarities to those recommended by other monitoring programs for beach litter assessments[77,78]. However, since our results suggest MPs (and anthropogenic microfibers) are patchily distributed over small spatial scales (10 s of m) in this region, many more replicates would be needed to detect differences in the spatial patterns of MP distribution and attribute potential differences to environmental or anthropogenic factors. With additional sampling effort comes increased costs and time, making monitoring potentially less feasible to conduct. Fisner *et al.* suggest that time series assessments may be more realistic than aiming for estimates of absolute particle density[79]. We suggest future work in this region could target Rainbow Haven beach as a focal point for time series analysis of MP change on exposed sandy beaches.

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Authors' contributions

Made substantial contributions to the conception and design of the study and performed data analysis and interpretation: Kelly NE, Gavel H
Performed data acquisition, as well as providing administrative, technical, and material support: Kelly NE, Trela O, Vander Kuylen A
Wrote paper: Kelly NE
Provided comments and review: Gavel H, Trela O, Vander Kuylen A

Availability of data and materials

The dataset for this research is included in the Supplementary Materials attached to this publication.

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All authors declared that there are no conflicts of interest.

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