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Measuring atmospheric microplastic composition and concentration from an uncrewed aerial system

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Article

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Title: Measuring atmospheric microplastic composition and concentration from an uncrewed aerial system

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Abstract (200 words)

Airborne microplastic (MP) particles are transported through the atmosphere, yet direct measurements at altitude remain scarce. We developed a novel uncrewed aerial system (UAS)-based method for in situ MP sampling near the air-sea/air-land interface or along the vertical axis within and above the atmospheric boundary layer, motivated by evidence that sea spray injects MPs into the marine boundary layer and by documented long-range MP transport. In this proof-of-concept study, we deployed the UAS at 80–100 m above ground level in Colorado, USA, during fall 2024, collecting particles larger than 1 µm at two sites with high anthropogenic activity using an environmental cyclone sampler. Plastic-like particles were isolated, counted by optical microscopy, and identified by Raman microscopy with automated spectral analysis (OpenSpecy). MPs were detected at both sites, with plastic-like particle concentrations of 10.09 ± 4.13 m^{-3} for particles 3–10 µm. These estimates should be considered conservative upper bounds. Hetero-aggregates dominated the samples, consistent with traffic-related material, with compositional differences between sites reflecting local human activity. This proof of concept demonstrates the feasibility of UAS-based atmospheric MP sampling and establishes a framework adaptable for ocean-surface, high-altitude, and remote environment monitoring.

Introduction

Research on atmospheric micro- and nanoplastics (MNPs) has grown substantially in recent years, with the number of studies tripling between 2022 and 2024 (Habibi et al., 2022; Zheng et al., 2024). Nevertheless, compared with other environmental plastic research fields, such as those focused on oceans, freshwater systems, and soils, the number of peer-reviewed articles addressing atmospheric MNPs remains relatively limited (Allen et al., 2022). Detecting and characterizing MNPs is particularly challenging: microplastics (1 µm–5 mm) are already difficult to distinguish from other airborne particles, while nanoplastics (1 nm–1 µm) present even greater analytical complexities. These challenges, coupled with the long-standing assumption that airborne plastic particles are too scarce to warrant investigation, may explain the initial lack of attention to the atmosphere.

The recent surge in publications suggests a turning point in atmospheric MNP research, with advances ranging from the determination of particle size distributions to assessments of ecological and human health impacts (Nafea et al., 2024; Nene et al., 2025). This progress is especially timely, given ongoing efforts by the United Nations to establish a legally binding international agreement on plastic pollution (Intergovernmental Negotiating Committee on Plastic Pollution). From an air quality perspective, most attention has focused on human health, with particle collection typically carried out on urban rooftops (Morioka et al., 2024) or indoors at breathing height (Bhat & Gaga, 2024). However, the need to quantify atmospheric MNPs in terms of size, shape, and concentration extends beyond health concerns. For example, studies have raised the potential influence of MNPs on cloud microphysics (Aeschlimann et al., 2022) and radiative forcing (Revell et al., 2021).

Evidence for long-range transport is clear, as airborne MNPs have been detected in remote regions including the Arctic (Bergmann et al., 2022; Chen et al., 2024; Cai et al., 2026) and isolated alpine glaciers (Jukschat et al., 2025). Deposition measurements from the free troposphere at Pic du Midi (Allen et al., 2021) further confirm that MNPs can be transported to high altitudes. Yet, very few studies have reported direct observations of MNPs in the atmospheric column between the surface and cloud level. The only airborne in situ measurements above the boundary layer to date were reported by González-Pleiter et al. (2021), who detected limited plastic particles larger than 10 µm.

From a climate and cloud-formation perspective, recent laboratory studies have demonstrated that MNPs can be more hygroscopic than previously assumed (Mao et al., 2024), largely due to atmospheric aging processes (Raincrow et al., 2024). This property suggests that MNPs may act as cloud condensation nuclei (CCN) or ice-nucleating particles (INP). Laboratory experiments have shown that microplastics exhibit ice-nucleating activity comparable to that of mineral dust (Busse et al., 2024). Furthermore, modeling work with FLEXPART has estimated that MPs could contribute more than 40% of total INP number concentrations in some regions (Tatsii et al., 2025). Together, these findings underscore the urgent need to identify and quantify atmospheric MNPs at cloud altitudes.

The ocean has already been recognized as a source of atmospheric MPs through bubble bursting and wave breaking (Trainic et al., 2020). Yet, studies focusing on oceanic emissions remain geographically and temporally limited (Allen et al., 2020; Grossmann et al., 2023). Global modeling studies estimating atmospheric MPs based on secondary re-emission from oceans tend to diverge when addressing the relevance of re-suspension to atmospheric loading. Evangeliou et al. (2022) presented the ocean as a non-negligible source, while still recognizing terrestrial emissions as the main origin of atmospheric MPs. Yang et al. (2025) concluded that oceanic sources make a minor contribution compared to the terrestrial ones, based on oceanic emission flux. It should be noted that MP air-sea exchanges were constrained by observational data; however, the datasets provided limited MP inventories, with concentration differences of up to three orders of magnitude reported at the same location (Yang et al., 2025). Sea-spray

aerosolization transfers MNPs from seawater to air, with enrichment influenced by particle size, polymer type, and seawater characteristics; smaller, denser polymers show higher enrichment, relevant for Arctic sea ice and melt dynamics (Bucci et al., 2024). As a result, MNP sources should not be limited to land-based origins, and oceanic sources should also be examined in order to fully understand the extent of MNPs in the atmosphere.

Multiple emission sources and transport pathways are particularly relevant when considering remote areas. As climate change has significantly affected the Arctic, this polar region has drawn considerable attention from the research community, not only regarding the impacts of Arctic warming (Jahn et al., 2024), but also its influence on mid-latitude climate and weather (Zhang et al., 2023; Yang et al., 2023). Atmospheric MP studies have provided a glimpse of the pollution from long-range transport (MacDonald et al., 2025), raising concerns about the scale of the problem and its impacts on ecosystems. Plastic emission dominance in high Arctic aerosols has been highlighted during light spring (Chen et al., 2024), with sea-spray aerosols as a key oceanic source of MNPs to the atmosphere, explaining high concentrations in remote areas (Trainic et al., 2020; Bucci et al., 2024; Lambert et al., 2024). As connections between the changing Arctic and mid-latitude climate have become better established, studying atmospheric MNP in the Arctic is essential, both to characterize pollution in this remote region (Muir et al., 2025), and to evaluate and anticipate the broader global climate repercussions of this relatively new form of contamination.

In this study, a tailored method to investigate atmospheric microplastics (MPs) was developed. To our knowledge, this work represents the first successful in situ measurements of airborne MPs using a small uncrewed aerial system (sUAS). sUAS platforms are ideally suited for sampling across a range of altitudes in the lower atmosphere, both above and below the boundary layer (Lappin et al., 2023; Reuder et al., 2012), and can also operate near the ocean surface to assess aerosol contributions from breaking waves and sea spray (Bousquet et al., 2021), critical for MP flux at the air-sea interface, as prior collections via aircraft and balloons overlook this. The use of sUAS in meteorology, boundary-layer research, and aerosol studies is well established (Pinto et al., 2021; Hamilton et al., 2022; Sanchez et al., 2017). Early applications relied on large fixed-wing aircraft (Roberts et al., 2008; Cassano et al., 2016), but the emergence of commercially available small multicopters (Segales et al., 2020; Hervo et al., 2023) has greatly facilitated operations. For this study, a hexacopter was selected to carry newly developed lightweight instrumentation designed specifically to collect MPs in the lower atmosphere, up to several hundred meters above ground level. The following sections describe the instrumentation and sampling approach, detail the procedures used for MP processing, including collection, treatment, contamination-control protocol, and polymer identification, and present results from multiple flights at 80 and 100 m a.g.l. (above ground level) over distinct environments in Colorado, USA. Finally, the limitations of this proof-of-concept study are discussed, and pathways are outlined for advancing airborne MP sampling and analysis.

Methods and materials

a. Instrumentation

Environmental cyclones are widely used for aerosol monitoring (Cauda et al., 2014). The principle of the cyclone geometry constraining the air stream can be found in Kenny et al. (2000). For a given geometry and a specific air flow, the cut-point diameter indicates that more than 50% of the particles larger than this diameter will be retained in the side chamber of the cyclone, while particles smaller than the cut-

point diameter will pass through (Su et al., 2012). For this study, the Alaric Model AE2.5V cyclone is implemented and follows the same specificities as the BGI VSCC 2.946 cyclone. Following the spreadsheet from the constructor (BGI, 2014), the calibration curves to determine the flow rate as function of the differential pressure and the cut-point diameter are reproduced in Figure 1.

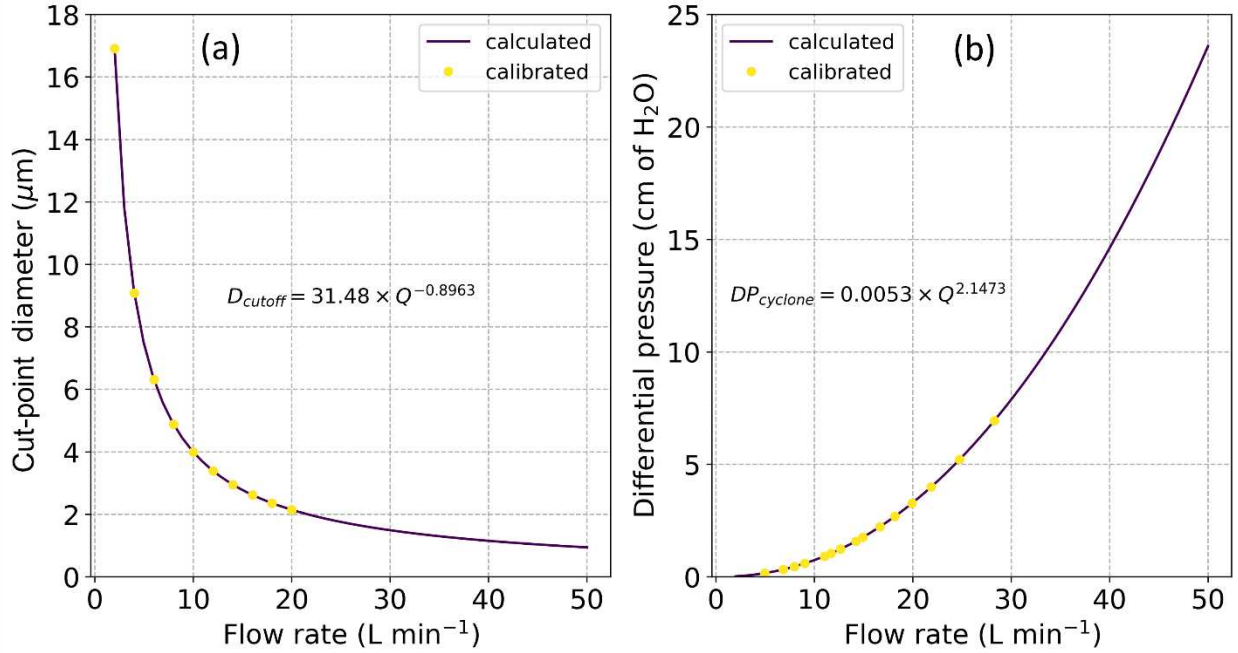


Figure 1. Calibrations and mathematical models for the environmental cyclone (a) flow rate vs cut-point diameter, (b) flow rate vs differential pressure. Reproduced with permission from Mesa Labs. © Mesa Labs. All rights reserved.

As rapid sampling of large air volumes within short sUAS flight durations was required, the cyclone was operated at 43 L min^{-1}, enabling collection of ~1 m^3 of air in 25 minutes (Fig. 1a). Particles larger than the cut-point diameter of 1.10 µm were retained in the side chamber for subsequent MP identification. The cyclone was positioned above the influence of the sUAS rotor downwash, meaning that the inflow was drawn from air at the altitude of the platform rather than from the downward rotor jet recirculation. Airflow was provided by a Nidec TF037E micro blower and regulated with a Seeduino XIAO microcontroller connected to a differential pressure sensor. The micro blower was set to perform at a pressure drop of 17.1 cm of H_2O to generate the required high flow rate (Fig. 1b). A proportional–integral–derivative (PID) control loop maintained stable flow under varying dynamic pressures in flight. Flow data were logged at 1 Hz to calculate sampled air volume. Details of the calculations from measured differential pressure to volume of air sampled during a sUAS flight are detailed in Supplemental Material S1. The payload was mounted on a DJI hexacopter powered by a 6S 24 V, 23,000 mAh battery and controlled via a PixHawk autopilot (Fig. 2). Table 1 summarizes the sUAS flights and the volume of air sampled during each hovering in altitude. The uncertainty associated with the volume of air was obtained from the error propagation on the flow rate measurements (Supplemental Material S2) and remained below 4 % for this experiment.

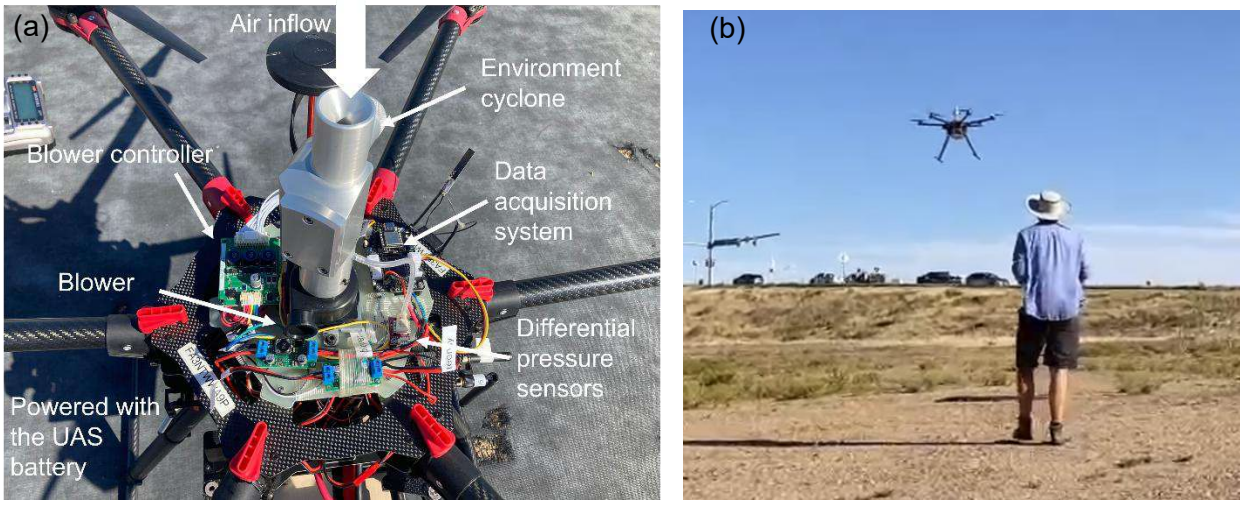


Figure 2. (a) Designed instrumentation with the environmental cyclone, the blower, the differential pressure sensors, and the microcontroller board (data acquisition system). (b) DJI sUAS with onboard instrumentation during a flight at Erie, Colorado.

Table 1. sUAS flights, locations, and volume of air sampled

Flights	Date (local time)	Location	Altitude (m a.g.l.)	Duration (min)	Flow rate (L min^{-1})	Volume of air (m^3)	Volume uncertainty (m^3)
FL 1A	2024-09-19 15:33	Erie, CO	80	11	56.72	0.648	0.008
FL 1B	2024-09-19 15:45	Erie, CO	80	10	42.81	0.428	0.005
FL 1C	2024-09-19 16:13	Erie, CO	80	28	42.79	1.213	0.043
FL 2A	2024-09-20 11:20	Arvada, CO	80	24	41.78	1.038	0.036
FL 2B	2024-09-20 12:10	Arvada, CO	80	26	42.81	1.122	0.038

FL 3A	2024-10-02 11:50	Arvada, CO	100	27	42.77	1.180	0.044
FL 3B	2024-10-02 12:26	Arvada, CO	100	27	42.82	1.195	0.039
FL 4A	2024-10-03 10:30	Erie, CO	100	29	42.78	1.249	0.045

160

161 b. Microplastics sample processing procedures

162 Aerosols with diameters larger than 1.1 µm were collected in the cyclone side chamber. Following each
163 flight, particles were transferred to fiberglass filters (Whatman GF/F, 47 mm or 25 mm, 0.7 µm pore size).
164 To ensure complete transfer and minimize particle loss, the chamber was rinsed with more than 1 L of
165 deionized water (DIW) and 75% ethanol, which reduced surface tension and concentrated particles onto
166 the filter (Peeken et al., 2018). The suspension was then passed through a syringe into a glass fiber filter
167 (Fig. 3). The majority of organic matter was removed by immersing the filter in 35% H_2O_2 overnight
168 (Peeken et al., 2018). This approach efficiently removes much of the organic matrix but does not fully
169 digest all forms of refractory organic material, especially hetero-aggregates of biogenic particles and
170 exopolymer-rich debris that can be strongly imprinted onto the filter surface during filtration (Peeken et
171 al., 2018). Aggressive high-temperature digestion (Rodrigues et al., 2023) was not applied in order to avoid
172 potential damage to the glass-fiber substrate. The following day, filters were rinsed thoroughly with DIW,
173 dried, and stored in glass Petri dishes for transport and subsequent analysis.

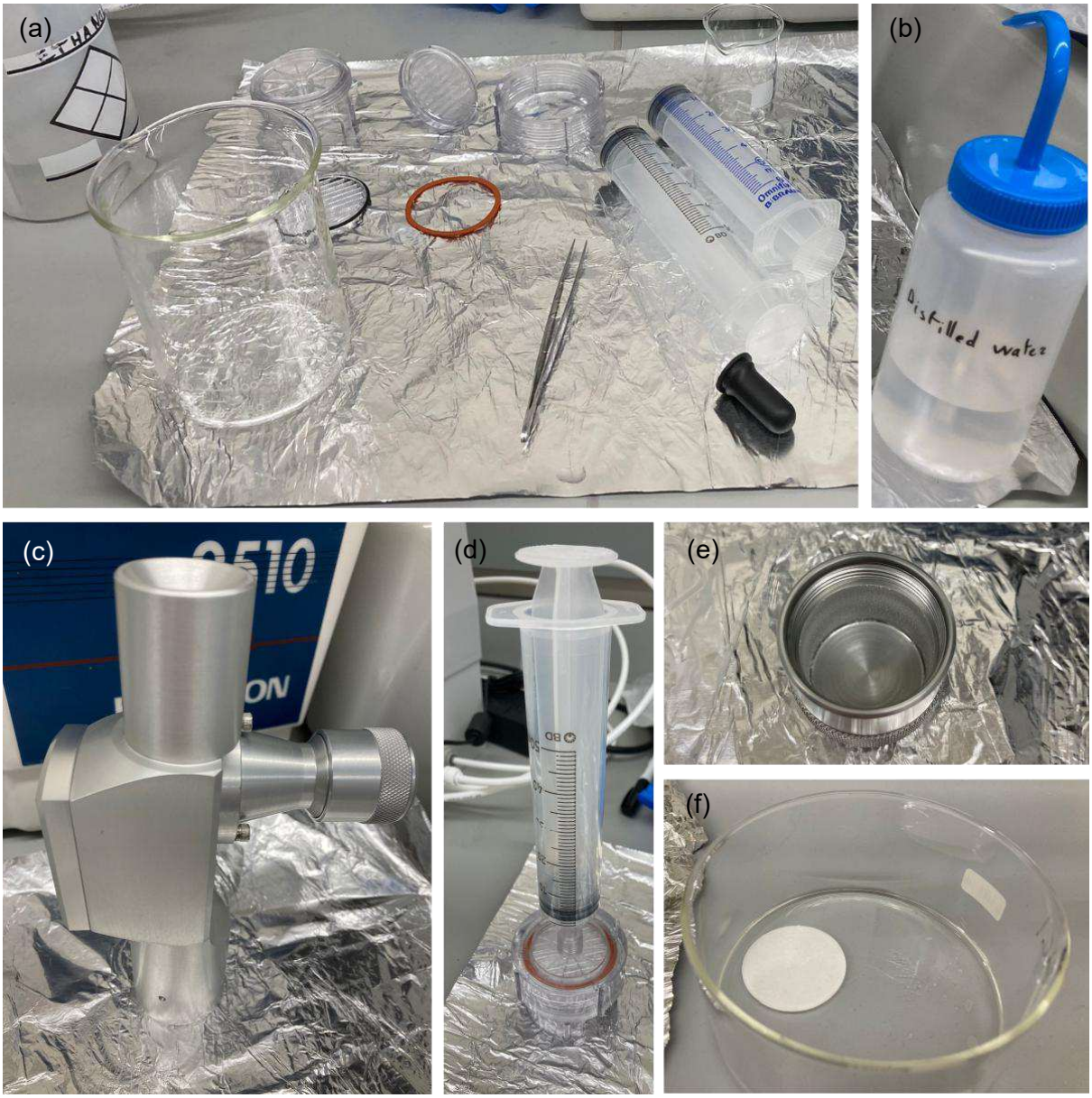


Figure 3. (a) materials used to transfer the particles, (b) a large quantity of DIW is used for the transfer, (c) environmental cyclone, (d) particle transfer using a syringe and a filter holder, (e) unscrewed side chamber of the environmental cyclone, (f) filter with particles sitting overnight in hydrogen peroxide.

c. Contamination-control protocol.

Sampling and processing were conducted under conditions designed to minimize plastic contamination. All glassware was cleaned with DIW and 75% ethanol prior to use. Operators wore non-fibrous clothing, and samples were handled within a clean aluminum foil mat. Blank samples were prepared in both field and laboratory settings. For each flight and each day of laboratory analysis, a blank sample was processed following the same transfer and storage procedures as flight samples, thereby providing controls for unavoidable background contamination.

To characterize background variability, we also pooled all blank filters and used their particle counts to derive class-specific contamination metrics (see Section e.), following recent recommendations for microplastic quality assurance and quality control (Dawson et al., 2023).

d. Microplastic sample analysis

The concentration of microplastics (C_MP, m^{-3}) was calculated from the plastic-like particle count (N_MP) and sample volume (V). Counts obtained from blank samples (Control) from the corresponding flight and laboratory day were subtracted from N_MP to correct for background contamination, according to:

$$C_{MP} = \frac{N_{MP} - Control}{V}$$

Particle enumeration and classification were performed at 100× magnification, enabling enumeration of particles larger than 3 µm by using optical microscopy at the Campbell Lab, University of Rhode Island (Graduate School of Oceanography). Each particle was categorized by shape (filament, fragment, or bead) and measured for size. Representative particles, along with those suspected to be plastic, were selected for polymer identification using Raman microscopy at the Rhode Island Consortium for Nanoscience and Nanotechnology (RIN2) (Araujo et al., 2018).

Spectra were pre-processed in OpenSpecy using the same pipeline applied to the reference library, including smoothing, baseline correction, range restriction and flattening, intensity conversion, wavenumber alignment, and min–max normalization. Polymer and mineral identities were then assigned in batch mode by comparison to the onboard OpenSpecy reference library, which aggregates more than six published spectral collections for environmental particles (Cowger et al., 2020). The matching algorithm calculates Pearson correlation coefficients between raw spectra (and their first and second derivatives) and a reference database, yielding a composite similarity score from 0 to 1 (Primpke et al., 2020). To ensure analytical rigor while accommodating weathered or degraded plastic limitations, a minimum threshold correlation score of 0.5 was adopted (Fig. S1, Table S1). Spectra scoring below this threshold were considered unknown polymers, hence excluded from positive identification. In addition, OpenSpecy provides a *signal_to_noise* metric that quantifies spectral quality: higher values indicate cleaner spectra with clearer peaks, whereas lower values denote noisier spectra (Table S1). Optical fragment counts were biased upward because some mineral particles were misclassified as microplastics prior to spectroscopic confirmation. Raman/OpenSpecy analysis indicated that this issue affected both blanks and samples, so the final corrected concentrations still represent conservative estimates of airborne microplastics.

e. Robustness test based on limits of detection.

To assess the robustness of our airborne microplastic counts against background contamination, we re-evaluated the dataset using a limit-of-detection/limit-of-quantification (LoD/LoQ) framework as proposed by Dawson et al. (2023). For filaments and fragments separately, we calculated LoD and LoQ values from the pooled blank counts as:

$$LoD = mean_{blank} + 3 * SD_{blank}$$

$$LoQ = mean_{blank} + 10 * SD_{blank}$$

With *SD* corresponding to the standard deviation from the blank samples, yielding LoD values of 0.37 particles for filaments and 0.39 particles for fragments with corresponding LoQs that were also <1 particle (Table S2). For each sample and particle class, we compared the flight/day-specific blank-corrected counts to the corresponding LoD. Counts at or below LoD were treated as non-detects and set to zero; while all non-zero counts that exceeded both LoD and LoQ and were retained unchanged and then normalized by sample volume to obtain MP concentration.

This supplementary LoD screening follows the control-based correction strategies shown by Dawson et al. (2023) to reliably remove ≥95% of contamination in MP datasets and provides an independent check on the robustness of our blank-corrected airborne microplastic concentrations. All non-zero blank-corrected counts in our dataset exceeded the LoD thresholds, indicating that reported concentrations were clearly above the variability observed in blanks (Table S2).

Results

a. sUAS flights

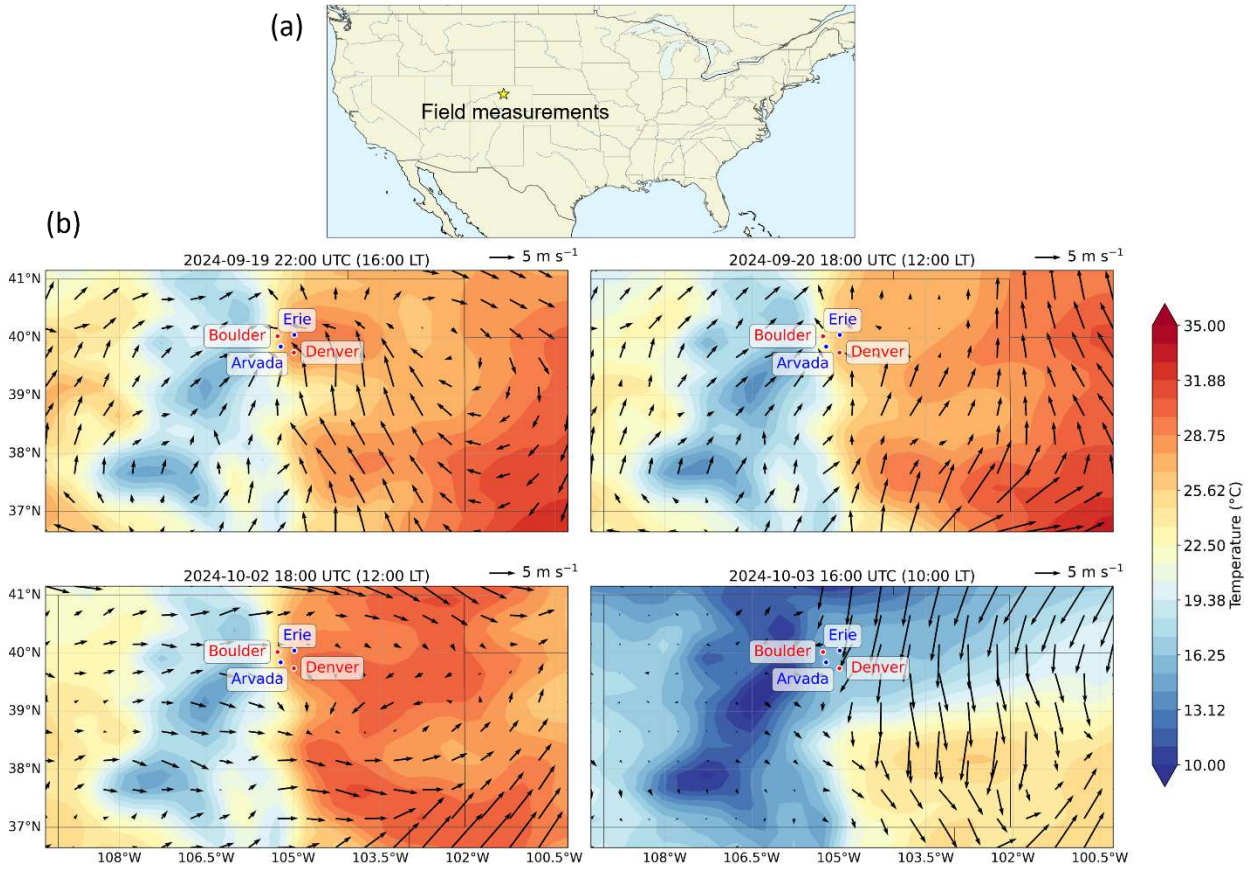


Figure 4. (a) USA map with the location of the sUAS field measurements in Colorado. (b) ERA5 reanalysis for 2-m temperature and 10-m wind speed and direction. UAS flights were conducted in Erie, CO and Arvada, CO. Boulder and Denver locations are provided as reference on the Colorado state map.

Two sites in Colorado, USA, were selected for sUAS measurements due to their potential for elevated airborne MP concentrations (Fig. 4a). Looking at the regional meteorological context, the ERA5 Reanalysis (Hersbach et al., 2023) was used to provide 2-m temperature and wind speed and direction at 10 m at the time when the UAS flights occurred (Fig. 4b). Measurements took place at Erie, CO and Arvada, CO, in the Front Range, where 2-m temperatures were still above 20 °C. The Rocky Mountains to the West were characterized by colder temperatures, where the Great Plains to the East showed temperatures close to 35 °C. The regional wind changed in intensity and direction over the four days of measurements. However, wind speed was below 3 m s^{-1} at the flight sites when the sUAS flew. The last flight day, 2024-10-03 16:00 UTC, was characterized by colder temperatures and increased wind speed from the north.

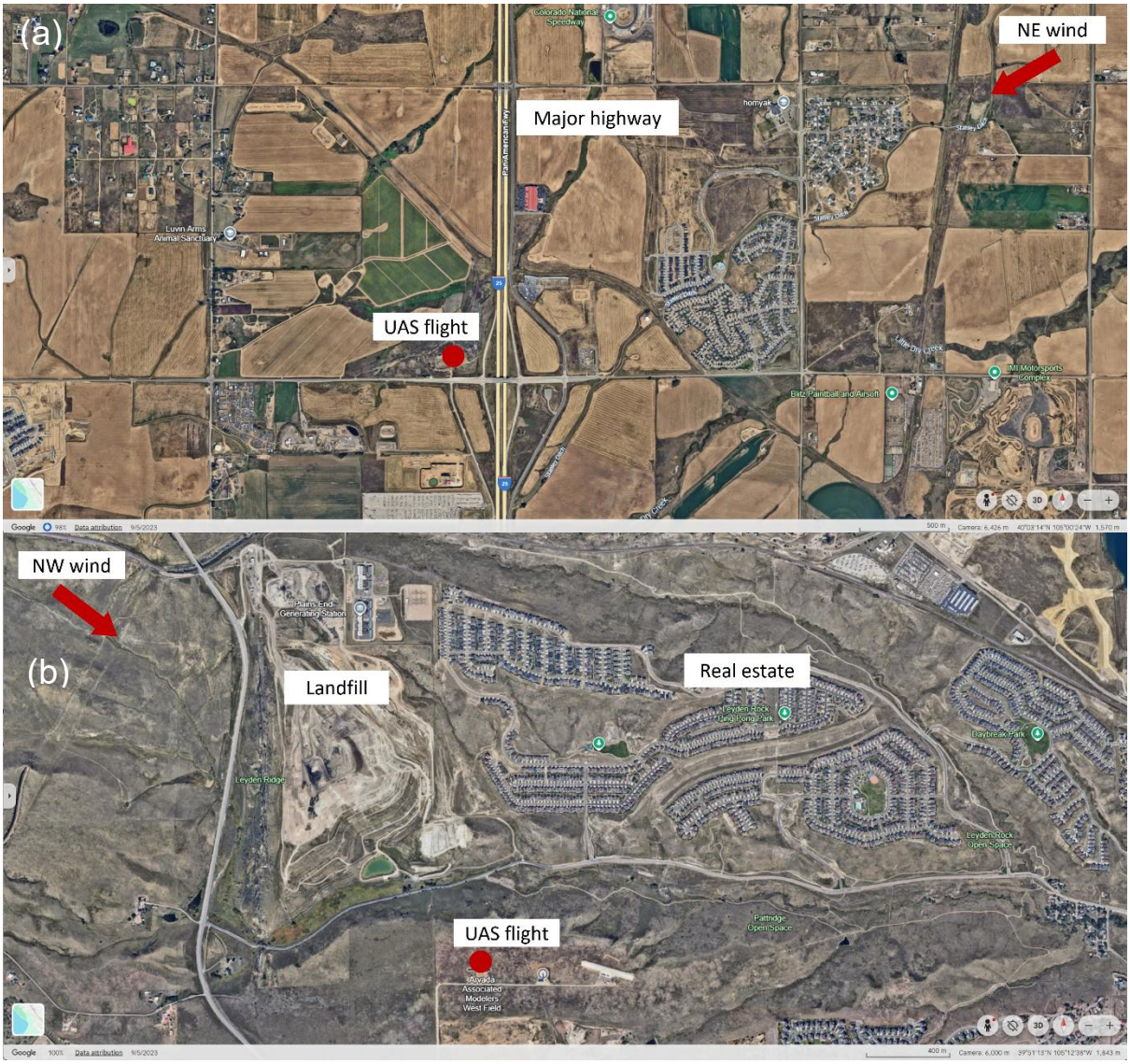


Figure 5. (a) Erie sUAS flight location characterized by a major highway. (b) Arvada sUAS flight location characterized by the proximity of a large landfill and dense neighborhoods.

At Erie, CO, flights were conducted near a heavily trafficked highway, while at Arvada, CO, sampling took place a few hundred meters from a landfill and large residential areas (Fig. 5). During the flights, wind speed was very low. The platform was localized downstream of the local anthropogenic activities

generating MPs. sUAS operations were carried out at 80 m and 100 m a.g.l. Each flight involved a rapid ascent to the target altitude, followed by hovering for approximately 25 minutes until low battery indication. The sUAS then landed for a battery exchange and repeated the procedure for an additional 25 minutes. In total, each sampling session represented ~50 minutes of flight time, corresponding to ~2.3 m^3 of air sampled at a flow rate of 43 L min^{-1}.

As the instrumentation was still undergoing testing, occasional technical issues (i.e., the blower remained off) resulted in reduced air volumes for some flights. Nevertheless, MPs were successfully detected at both Erie, CO, and Arvada, CO, at both altitudes (80 m and 100 m a.g.l.). Additional test flights were conducted at Boulder airfield, a location relatively isolated from major human activity and road traffic. However, as the system was still in its evaluation phase, results from these filters were inconclusive and were excluded from the analysis.

b. MPs concentration and composition

Table 2. Concentration of plastic-like particles per filter at the flight sites for particle larger than 3 µm

Location	Filter number	Plastic-like particle number N_{MP}		Blank (*control*)		Plastic-like particle corrected	Volume of air (m^3)	Plastic-like particle concentration C_{MP}(m^{-3})
		Filaments	Fragments	Filaments	Fragments			
Arvada	Filter 1	4	28	1	19	12	2.16	5.56
	Filter 2	18	23	4	9	28	2.38	11.79
Erie	Filter 3	8	25	1	16	16	2.29	6.99
	Filter 4	6	28	4	10	20	1.25	16.01

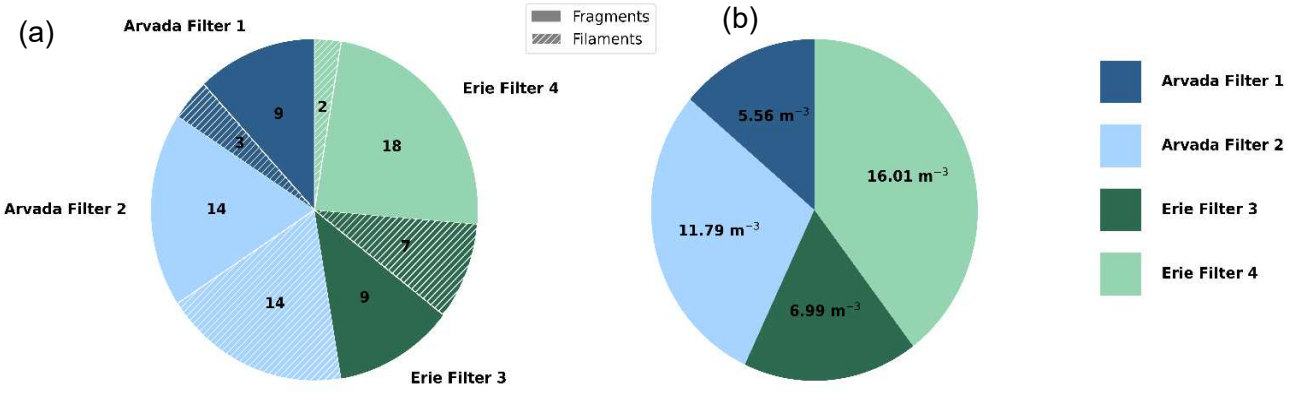


Figure 6. (a) Plastic-like particle numbers for fragments and filaments at Arvada, CO (blue) and Erie, CO (green), for each filter. (b) Concentration of plastic-like particles per filter. Number and concentration are given for particles larger than 3 µm.

Plastic-like particle concentrations at Arvada and Erie were within the same order of magnitude, averaging 10.09 ± 4.13 m^{-3} (Table 2). Filter 4 at Erie exhibited a larger concentration. Arvada showed a slightly higher number of putative MP than Erie, with one filter displaying a particularly large number of filaments (Fig. 6a). However, optical classification showed that fragments dominated the particle pool and were likely enriched in mineral particles rather than polymers, while filaments were less common. Because Raman/OpenSpecy analysis showed that many visually plastic-like fragments were minerals, the optical counts likely overestimated microplastic fragments abundance in both samples and blanks, and the blank-corrected concentrations should be interpreted as conservative upper-bound estimates.

Polymer composition differed between the two sampling sites (Fig. 7). Across the 135 visually plastic-like particles, 33 spectra with match values ≥ 0.5 were confidently classified, and these were dominated by minerals at both Arvada and Erie, with only a minor fraction assigned to polymers and organic matter.

Spectroscopically confirmed polymers were limited to polyethylene, poly(tetrafluoroethylene), and a few polyhaloolefins (including PVC-like materials). In Arvada, the non-mineral fraction was mainly organic matter and polyhalolefins (vinylhalides), whereas Erie showed a more polymer-enriched composition, including poly(ethylene) and poly(tetrafluoroethylene). These polymers are widely used in packaging, construction materials, and technical components, so their occurrence is consistent with diffuse emissions from urban infrastructure, transport activities, and industrial/technical applications in the surrounding area rather than a single point source. Given the small number of confirmed polymer particles, these sources attributions should be regarded as qualitative and indicative rather than quantitative.

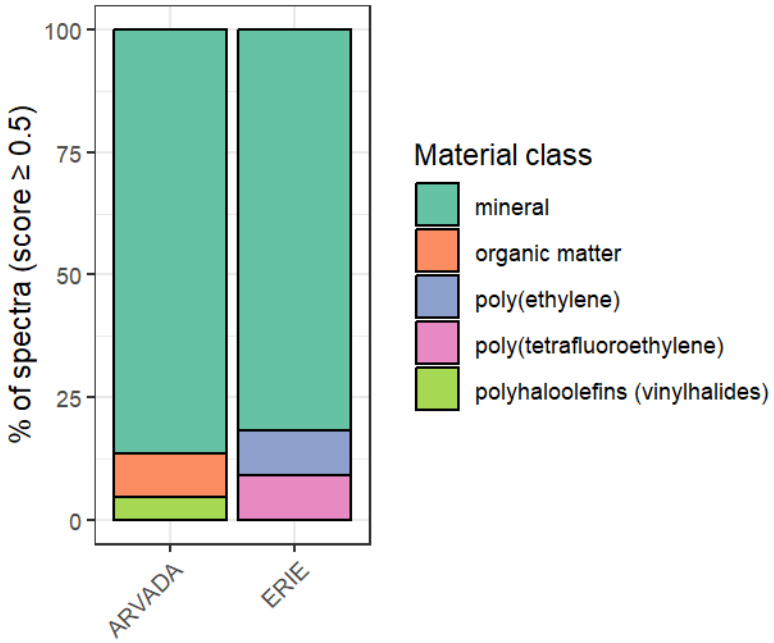


Figure 7. Material class (%) of plastic-like particles with spectra above the OpenSpecy quality threshold (≥0.5) at Arvada, CO, and Erie, CO, sites (N=33).

For a direct comparison between plastic-like airborne particles and environmentally weathered tire particles, old tire parts lying on the road side at Erie, CO, were gathered and brought back to the lab to undergo the same sample processing as the sUAS flight samples (Fig. S2). Spectroscopically analysis showed minerals, polyphenylethers, and polyester-like signatures (Fig. S3). Environmental and tire-wear samples were similar as both containing a strong mineral component and only a limited number of non-mineral matches. The main difference was compositional: the tire-wear particles were characterized by polymer classes consistent with tire-associated residues, while the airborne particles showed a broader mix that included mineral-dominated spectra and more varied minor classes, indicating a less specific and more heterogeneous particle assemblage.

c. Conclusions

The few spectroscopically confirmed polymers (polyethylene, poly(tetrafluoroethylene), and PVC-like polyhaloolefins) are widely used in packaging, construction materials, and technical components. At Erie, the polymer signal was more pronounced than in Arvada, consistent with diffuse inputs from traffic and associated urban activities along the adjacent highway, confirmed by the surface tire sample analysis; whereas at Arvada, the particles were dominated by mineral spectra and showed only minor polymeric and organic matches, likely reflecting emissions from the nearby landfill and surrounding residential areas. This pattern is broadly consistent with inputs from urban activities and road-related debris at Erie, including the tire-wear reference particles, whereas the Arvada assemblage appears more heterogeneous and less clearly polymer-enriched. However, given the small number of confirmed polymer particles and the potential for regional and long-range atmospheric transport, these sources inferences should be considered qualitative rather than definitive.

Discussions

a. Proof-of-concept study to collect in situ atmospheric microplastics (MP).

This study represents the first successful in situ collection of atmospheric MPs aloft at 100 m a.g.l. using a sUAS and demonstrating the ability to adjust the platform altitude based on the research questions. A custom-built sampling system was specifically developed for this purpose, incorporating an environmental cyclone operating at 43 L min^{-1}. The system effectively captured particles larger than 1.1 µm in diameter. Collected particles were transferred to filters, treated to remove organic matter, and analyzed microscopically. Optical microscopy at 100× magnification enabled enumeration of particles larger than 3 µm, and concentrations were calculated by combining particle counts with the sampled air volume.

Raman microscopy provided spectral identification of polymers by comparison with reference libraries. sUAS flights confirmed the presence of MPs between 3 and 10 µm at both 80 m and 100 m a.g.l. over sites influenced by human activity, meeting the core objective of this proof-of-concept. Even with limited sampling, plastic-like particle concentrations were within the same order of magnitude. Comparing fragment and filament concentrations, filaments were present in lower numbers, likely due to their shorter atmospheric residence times given their larger and elongated shapes. Identification of particle material classes revealed a high occurrence of minerals in the samples, with distinct polymer compositions

between the two sites. These compositional differences highlight variability in local microplastic inputs and degradation processes across locations. The correlation between changes in weather conditions and the higher concentration observed for one filter (Erie Filter 4, 2024-10-03) suggests that atmospheric plastic-like particle concentrations at 100 m a.g.l. are impacted by larger-scale atmospheric circulation. However, due to the limited number of observations, more sUAS flights are required to support this hypothesis.

While this initial deployment focused on method validation in accessible urban environments, the primary motivation for developing this UAS platform was to create a system flexible enough to operate in remote environments at multiple altitudes - aloft to study local particle sources and long-range transport, and low above the ocean to enable MP sampling at the air-sea interface in remote Arctic regions where traditional aircraft and balloon sampling methods are logistically challenging, cost-prohibitive, or sometimes unable to access the critical lower atmosphere.

b. Remaining challenges

Uncertainty analysis. The atmospheric MP concentrations reported here should be considered indicative, as particle losses during transfer from the cyclone to the filter were not quantified. The use of a syringe was an experimental technique and was identified to leave some particles within the syringe. Moreover, pressure applied by the syringe embedded the particles within the filter fibers, and generated difficulties for the microscope to focus clearly on the particles. For particles deep below the fibers, Raman spectra were inconclusive. Other transfer methods should be considered such as vacuum filtering. Nevertheless, future work should include an uncertainty analysis on MP number concentration, which could be conducted using an optical particle counter and polystyrene latex (PSL) particles as standards.

Sample processing. An additional processing step is needed to remove mineral components from environmental samples after organic matter digestion. Recent studies have demonstrated the effectiveness of centrifugation for separating MPs from mineral fractions (Hildebrandt et al., 2020), while flotation methods may also be suitable (Schrank et al., 2022). Regarding the residual organic material, an enzymatic digestion protocol was tested previously (Lavoy & Crossman, 2021), originally developed for high-organic wastewater treatment plant sludge. However, it was observed that for water samples, this treatment caused pronounced flocculation and aggregation, with a cream-colored suspension and residue similar to that reported by Lavoy and Crossman (2021). Because this promoted settling and potential loss of the smallest particles and was incompatible with the GF/F filter workflow, we did not adopt this approach in the present study. We also refrained from applying more aggressive digestion procedures (e.g., Rodrigues et al., 2023) in order to preserve the filter matrix. We therefore retained a modified H_2O_2 digestion following Peeken et al. (2018), accepting some residual organic material to avoid additional aggregation, particle loss, and possible damage to the GF/F filters.

Concentration and identification analysis. Due to logistical and funding constraints, this study was limited to particles larger than 3 µm. Although the Raman system is technically capable of detecting particles as small as 1 µm, the ×100 magnification used here restricted reliable identification below 3 µm. Single-particle analysis at this scale is also highly time-consuming and it would be difficult to sustain in samples containing large numbers of nanoscale particles. Bulk analysis techniques may therefore be more practical for atmospheric studies. Nevertheless, nanoscale particles remain critical to address, as new technologies are emerging that enable detection below 1 µm (Morioka et al., 2024; Luo et al., 2024; Bhat & Gaga, 2024).

Characterizing the number size distribution of MPs and NPs is particularly important for aerosol–cloud interaction research (Dusek et al., 2006), and efforts should not be limited to total concentration alone.

Meteorological variability. Meteorological parameters such as temperature, relative humidity, pressure and wind should be recorded along the MP concentration to identify the structure of the boundary layer which could greatly influence the particle concentration aloft. Investigating synoptic patterns could also provide understanding of long-range transport and particle mixing along the vertical axis.

Spectral identification. Weathering processes alter both the morphology and chemical signatures of MPs, which can complicate spectral identification. Although OpenSpecy's community library increasingly incorporates spectra of environmentally weathered plastics to improve recognition of aged particles, many reference libraries are still biased toward pristine materials, so heavily weathered or oxidized MPs may remain under-identified or misclassified despite careful preprocessing and conservative correlation thresholds.

Identification of tire and road wear particles. To probe the behavior of automated spectral classification on traffic-related material, we analyzed particles grated from the surface of an old roadside tire using Raman spectroscopy and OpenSpecy (Fig. S3). The majority of spectra were classified as minerals, consistent with literature showing that tire–road wear particles are hetero-aggregates of rubber and road material rather than pure elastomer (Gillibert et al., 2022). A subset of spectra yielded best matches to engineering-polymer classes (e.g., poly(phenylene ether), epoxy/polyester-like materials). Real tire fragments from environmentally weathered tire and road wear particles indeed differ from pure polymer: they contain rubber blends, fillers, antioxidants, processing oils, and potentially road dust, paints, and other adhered materials (Kole et al., 2017; Wagner et al., 2018; Gilibert et al., 2022). We interpret these assignments as library-based best matches for complex, aged, carbon-black–rich particles containing minor polymer phases and/or co-abraded road coatings and markings, rather than as evidence that tire tread is composed primarily of these polymers. Complex compositions render Raman analysis challenging, as the laser spot may interact with a coating, an oxidized layer, or an adhered contaminant rather than the rubber core. Long-term UV/oxidative aging and deposition of secondary organics significantly alter Raman spectra and can degrade or mask the original elastomer features (Gilibert et al., 2022). Increasingly sophisticated analytical approaches are emerging to differentiate tire and road wear particles from other components such as black carbon and polystyrene particles (Kovochich et al., 2021), and further methodological advances are anticipated in the near future. Accordingly, we treat such labels in our samples as indicative of complex traffic-related material and avoid assigning individual spectra uniquely to tire wear.

c. Potential applications

Vertical profiling for aerosol characterization within and above the atmospheric boundary layer
sUAS platforms provide flexibility to sample across altitudes, enabling us to link source, transport, and in situ studies and facilitate simultaneous measurements (e.g., with multiple airborne platforms at different altitudes). Coupling MNP sampling with conventional aerosol instrumentation, such as optical particle counters (0.1- 3 µm) and scanning mobility particle sizers (8-300 nm), will contribute to quantify the proportion of MNPs in total aerosol concentration, and particle number size distribution. Expanded datasets will also inform regulatory efforts addressing airborne plastics in both remote regions (e.g., the Arctic) and polluted environments.

Ocean-Atmosphere exchange and marine deployments

Laboratory experiments demonstrate that sea-spray aerosols are enriched in MPs, with enrichment factors varying by particle size, polymer density, and seawater characteristics; smaller particles (1–10 µm) and denser polymers (e.g., polyethylene, polystyrene, polypropylene) exhibit higher aerosolization efficiency (Allen et al., 2020; Lambert et al., 2024). Modeling work suggests that ocean-atmosphere MP fluxes may be underestimated by 1–2 orders of magnitude, and that micrometer-range MPs can be transported globally through atmospheric circulation (Bucci et al., 2024). However, direct measurements at the air-sea interface remain absent, as traditional aircraft and tethered balloon platforms cannot effectively sample the lower marine boundary layer where sea-spray aerosols are generated. sUAS are particularly well suited to operate at low altitudes over the ocean surface, providing a platform to quantify the contribution of sea spray to airborne MNP concentrations. More broadly, advancing atmospheric MNP research will require not only technical innovation but also expanded in situ measurements linking ocean–atmosphere exchange and aerosol–cloud interactions. Importantly, the method demonstrated here proved robust (i.e., collection of MPs) despite its current limitations (i.e., count and identification of MPs). Having shown feasibility within the atmospheric boundary layer at 100 m a.g.l., the same approach could readily be applied at the air–sea interface at 5 m a.g.l., offering new opportunities for direct sampling from research vessels and opening monitoring capabilities for remote regions such as the Arctic.

d. Synthesis

Together, these findings demonstrate both the feasibility and the convenience of sUAS-based sampling for atmospheric MP research. The primary motivation for developing this platform was to enable direct measurements within and above the atmospheric boundary layer to study local and long-range particle transport, and at the air-sea interface, e.g., in Arctic regions, environments inaccessible to traditional aircraft and tethered balloon methods. Planned deployments at coastal wave-breaking zones and Arctic marginal ice zones will provide the first in situ observations of sea-spray MP fluxes-data essential for constraining atmospheric MP budgets and validating ocean-atmosphere exchange models.

The proof-of-concept confirms that lightweight instrumentation can collect and characterize MPs aloft, while the identified methodological limitations provide a clear roadmap for refinement, including expanding the sample size, improving counting efficiency, enabling detection of nanoscale particles, enhancing the separation of MPs from minerals, strengthening uncertainty analysis, and incorporating more systematic measurements of meteorological variables. Addressing these challenges could enable reliable quantification of MPs and NPs across a range of environments and altitudes. Ultimately, integrating airborne measurements with established aerosol observation techniques will advance understanding of plastic pollution pathways, their role in cloud microphysics, and their broader impacts on climate and human health.

Data availability

The spectra file processing is available on GitHub R repository:
https://github.com/AlessandraDAngelo/from_Raman_csv_to_siMPle_csv.git

The flow rate data files recorded during the sUAS flights, particle counts, and Raman spectra are available on Zenodo: https://zenodo.org/records/17695949

References

Aeschlimann, M., Li, G., Kanji, Z. A., & Mitrano, D. M. (2022). Potential impacts of atmospheric microplastics and nanoplastics on cloud formation processes. Nature Geoscience, 15(12), 967-975. https://doi.org/10.1038/s41561-022-01051-9

Allen, S., Allen, D., Moss, K., Le Roux, G., Phoenix, V. R., & Sonke, J. E. (2020). Examination of the ocean as a source for atmospheric microplastics. *PloS one*, *15*(5), e0232746. https://doi.org/10.1371/journal.pone.0232746

Allen, S., Allen, D., Baladima, F., Phoenix, V. R., Thomas, J. L., Le Roux, G., & Sonke, J. E. (2021). Evidence of free tropospheric and long-range transport of microplastic at Pic du Midi Observatory. Nature communications, 12(1), 7242. https://doi.org/10.1038/s41467-021-27454-7

Allen, D., Allen, S., Abbasi, S., Baker, A., Bergmann, M., Brahney, J., ... & Wright, S. (2022). Microplastics and nanoplastics in the marine-atmosphere environment. *Nature Reviews Earth & Environment*, *3*(6), 393-405. https://doi.org/10.1038/s43017-022-00292-x

Araujo CF, Nolasco MM, Ribeiro AMP, Ribeiro-Claro PJA. (2018). Identification of microplastics using Raman spectroscopy: Latest developments and future prospects. Water Res.; 142:426–440. https://doi.org/10.1016/j.watres.2018.05.060

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, C.M., van Sebille, E., & Tekman, M.B. (2022) Plastic pollution in the Arctic. *Nat Rev Earth Environ* 3, 323–337. https://doi.org/10.1038/s43017-022-00279-8

BGI (2014). Cyclone calculator spreadsheet available at: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://mesalabs.com/hubfs/inmind/public/cyclone_calculator.xlsx%3Fsrsltid%3DAfmBOopWvKslb_0SA_nq1WGTmJiHvzltPbVwF-t0hNYn-B253KvdlHTf&ved=2ahUKEwjCmeyug_mQAxVE7AIHHahCIsUQFnoECBUQAQ&usg=AOvVaw3B7gLnHS6Rx3RDc8Xsy66N , last access: 17 Nov. 2025

Bhat, M. A., & Gaga, E. O. (2025). Unveiling the invisible: first discovery of micro-and nanoplastic size segregation in indoor commercial markets using a cascade impactor. *Air Quality, Atmosphere & Health* 18, 1-13. https://doi.org/10.1007/s11869-024-01624-0

Bousquet, O., Barruol, G., Cordier, E., Barthe, C., Bielli, S., Calmer, R., ... & Marquestaut, N. (2021). Impact of tropical cyclones on inhabited areas of the SWIO Basin at present and future horizons. part 1: overview and observing component of the research project RENOVRISK-CYCLONE. Atmosphere, 12(5), 544. https://doi.org/10.3390/atmos12050544

Bucci, S., Richon, C. & Bakels, L. (2024). Exploring the Transport Path of Oceanic Microplastics in the Atmosphere. Environmental Science & Technology 2024 58 (32), 14338-14347. https://doi.org/10.1021/acs.est.4c03216

Busse, H. L., Ariyasena, D. D., Orris, J., & Freedman, M. A. (2024). Pristine and aged microplastics can nucleate ice through immersion freezing. ACS ES&T Air, 1(12), 1579-1588. https://doi.org/10.1021/acsestair.4c00146

Cai, H., Carrier-Belleau, C., Guilmette, C., Massicotte, P., Luthi-Maire, A., & Gigault, J. (2026). Nanoplastic concentration and potential transport in the Arctic Ocean. *npj Emerg. Contam*. 2, 4. https://doi.org/10.1038/s44454-025-00024-y

Cassano, J. J., Seefeldt, M. W., Palo, S., Knuth, S. L., Bradley, A. C., Herrman, P. D., ... & Logan, N. J. (2016). Observations of the atmosphere and surface state over Terra Nova Bay, Antarctica, using unmanned aerial systems. *Earth System Science Data*, 8(1), 115-126. https://doi.org/10.5194/essd-8-115-2016

Cauda, E., Sheehan, M., Gussman, R., Kenny, L., & Volkwein, J. (2014). An evaluation of sharp cut cyclones for sampling diesel particulate matter aerosol in the presence of respirable dust. *Annals of occupational hygiene*, 58(8), 995-1005. https://doi.org/10.1093/annhyg/meu045

Cowger W., Gray A., Christiansen S.H., … & Primpke, S. (2020). Critical Review of Processing and Classification Techniques for Images and Spectra in Microplastic Research. *Applied Spectroscopy*. 2020;74(9):989-1010. https://doi.org/10.1177/0003702820929064

Chen, J., Kawamura, K., Li, S. M., Bottenheim, J. W., Zhang, Y., Huang, X., ... & Fu, P. (2024). Dominance of Plastic Emission in the High Arctic Aerosol in Light Spring. *Environmental Science & Technology*, 58(52), 23088-23098. https://doi.org/10.1021/acs.est.4c06090

Dawson, A. L., Santana, M. F. M., Nelis, J. L. D., & Motti, C. A. (2023). Taking control of microplastics data: A comparison of control and blank data correction methods. *Journal of Hazardous Materials*, 443(Part A), 130218. https://doi.org/10.1016/j.jhazmat.2022.130218

Dusek, U., Frank, G. P., Hildebrandt, L., Curtius, J., Schneider, J., Walter, S., ... & Andreae, M. O. (2006). Size matters more than chemistry for cloud-nucleating ability of aerosol particles. *Science*, 312(5778), 1375-1378. https://doi.org/10.1126/science.1125261

Evangeliou, N., Tichý, O., Eckhardt, S., Zwaaftink, C. G., & Brahney, J. (2022). Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: From global emissions to deposition. *Journal of Hazardous Materials*, *432*, 128585. https://doi.org/10.1016/j.jhazmat.2022.128585

Gilibert, R., Magazzù, A., Callegari, A., Bronte-Ciriza, D., Foti, A., Donato, M. G., ... & Gucciardi, P. G. (2022). Raman tweezers for tire and road wear micro-and nanoparticles analysis. *Environmental Science: Nano*, *9*(1), 145-161. https://doi.org/10.1039/d1en00553g

González-Pleiter, M., Edo, C., Aguilera, Á., Viúdez-Moreiras, D., Pulido-Reyes, G., González-Toril, E., ... & Rosal, R. (2021). Occurrence and transport of microplastics sampled within and above the planetary

boundary layer. *Science of the Total Environment*, 761, 143213. https://doi.org/10.1016/j.scitotenv.2020.143213

Habibi, N., Uddin, S., Fowler, S. W., & Behbehani, M. (2022). Microplastics in the atmosphere: A review. *J. Environ. Expo. Assess*, 1(6), 10-20517. https://doi.org/10.20517/jeea.2021.07

Hamilton, J., de Boer, G., Doddi, A., & Lawrence, D. (2022). The DataHawk2 uncrewed aircraft system for atmospheric research. *Atmospheric Measurement Techniques Discussions*, 2022, 1-28. https://doi.org/10.5194/amt-15-6789-2022

Hildebrandt, L., Mitrano, D. M., Zimmermann, T., & Pröfrock, D. (2020). A nanoplastic sampling and enrichment approach by continuous flow centrifugation. *Frontiers in Environmental Science*, 8, 89. https://doi.org/10.3389/fenvs.2020.00089

Hervo, M., Romanens, G., Martucci, G., Weusthoff, T., & Haefele, A. (2023). Evaluation of an Automatic Meteorological Drone Based on a 6-Month Measurement Campaign. *Atmosphere*, 14(9), 1382. https://doi.org/10.3390/atmos14091382

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023). ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://doi.org/10.24381/cds.adbb2d47 (Accessed on 17-11-2025)

Intergovernmental negotiating committee on plastic pollution, available at: https://www.unep.org/inc-plastic-pollution, accessed on 11 August 2025

Jahn, A., Holland, M. M., & Kay, J. E. (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth & Environment*, *5*(3), 164-176. https://doi.org/10.1038/s43017-023-00515-9

Jurkschat, L., Gill, A. J., Milner, R., Holzinger, R., Evangeliou, N., Eckhardt, S., & Materić, D. (2025). Using a citizen science approach to assess nanoplastics pollution in remote high-altitude glaciers. *Scientific Reports*, 15(1), 1864. https://doi.org/10.1038/s41598-024-84210-9

Kenny, L. C., Gussman, R., & Meyer, M. (2000). Development of a sharp-cut cyclone for ambient aerosol monitoring applications. *Aerosol Science & Technology*, 32(4), 338-358. https://doi.org/10.1080/027868200303669

Kole, P. J., Löhr, A. J., Van Belleghem, F. G., & Ragas, A. M. (2017). Wear and tear of tyres: a stealthy source of microplastics in the environment. *International journal of environmental research and public health*, *14*(10), 1265. https://doi.org/10.3390/ijerph14101265

Kovochich, M., Liong, M., Parker, J. A., Oh, S. C., Lee, J. P., Xi, L., ... & Unice, K. M. (2021). Chemical mapping of tire and road wear particles for single particle analysis. *Science of the Total Environment*, *757*, 144085. https://doi.org/10.1016/j.scitotenv.2020.144085

Lambert, S., Vercauteren, M., Catarino, A.I., Li, Y., Van Landuyt, J., Boon, N., Everaert, G., De Rijcke, M., Janssen, C.R., Asselman, J. (2024). Aerosolization of micro- and nanoplastics via sea spray: Investigating the role of polymer type, size, and concentration, and potential implications for human exposure. *Environmental Pollution*, 351, 124105, ISSN 0269-7491, https://doi.org/10.1016/j.envpol.2024.124105.

Lappin, F., de Boer, G., Klein, P., Hamilton, J., Spencer, M., Calmer, R., ... & Pillar-Little, E. (2023). Data collected using small uncrewed aircraft system during the TRacking Aerosol Convection Interactions ExpeRiment (TRACER*). Earth System Science Data Discussions*, 2023, 1-23. https://doi.org/10.5194/essd-16-2525-2024

Lavoy, M., & Crossman, J. (2021). A novel method for organic matter removal from samples containing microplastics. Environmental Pollution, 286, 117357. https://doi.org/10.1016/j.envpol.2021.117357

Luo, D., Chu, X., Wu, Y., Wang, Z., Liao, Z., Ji, X., ... & Shang, X. (2024). Micro-and nano-plastics in the atmosphere: A review of occurrence, properties and human health risks. *Journal of Hazardous Materials*, 465, 133412. https://doi.org/10.1016/j.jhazmat.2023.133412

Nene, A., Sadeghzade, S., Viaroli, S., Yang, W., Uchenna, U. P., Kandwal, A., ... & Galluzzi, M. (2025). Recent advances and future technologies in nano-microplastics detection*. Environmental Sciences Europe*, 37(1), 7. https://doi.org/10.1186/s12302-024-01044-y

MacDonald, A., Evangeliou, N., Eckhardt, S., Castle, D., White, C. J., Phoenix, V. R., & Materić, D. (2025). Polar Particles: Atmospheric Microplastic Pollution in the Arctic Region–an examination of deposited and suspended microplastics in Ny-Ålesund, Svalbard. https://doi.org/10.21203/rs.3.rs-7543661/v1

Mao, C. N., Gohil, K., Rastogi, D., & Asa-Awuku, A. (2024). The hygroscopicity of nano-plastic particles and implications for cloud formation and climate. *Aerosol Science and Technology*, 58(9), 1024-1032. https://doi.org/10.1080/02786826.2024.2361041

Morioka, T., Tanaka, S., Kohama-Inoue, A., & Watanabe, A. (2024). The quantification of the airborne plastic particles of 0.43–11 μm: Procedure development and application to atmospheric environment. *Chemosphere*, 351, 141131. https://doi.org/10.1016/j.chemosphere.2024.141131

Muir, D., Gunnarsdóttir, M. J., Koziol, K., Von Hippel, F. A., Szumińska, D., Ademollo, N., ... & Vorkamp, K. (2025). Local sources versus long-range transport of organic contaminants in the Arctic: future developments related to climate change. *Environmental Science: Advances*, *4*(3), 355-408. https://doi.org/10.1039/D4VA00240G

Nafea, T. H., Chan, F. K. S., Xu, Y., Wang, C., Wang, X., Zhao, W., ... & He, J. (2024). Microplastics Aloft: A comprehensive exploration of sources, transport, variations, interactions and their implications on human health in the atmospheric realm. *Earth-Science Reviews*, 104864. https://doi.org/10.1016/j.earscirev.2024.104864

Peeken, I., Primpke, S., Beyer, B., Gutermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G. (2018). Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nat. Commun*., 9, 1505. https://doi.org/10.1038/s41467-018-03825-5

Pinto, J. O., O'Sullivan, D., Taylor, S., Elston, J., Baker, C. B., Hotz, D., ... & Houston, A. L. (2021). The status and future of small uncrewed aircraft systems (UAS) in operational meteorology. *Bulletin of the American Meteorological Society*, 102(11), E2121-E2136. https://doi.org/10.1175/BAMS-D-20-0138.1

Primpke, S., Cross, R.K., Mintenig, S.M., Simon, M., Vianello, A., Gerdts, G., Vollertsen, J. (2020). Toward the Systematic Identification of Microplastics in the Environment: Evaluation of a New Independent Software Tool (siMPle) for Spectroscopic Analysis. *Appl. Spectrosc*., 74, 1127–1138. https://doi.org/10.1177/0003702820917760

Raincrow, K. L., Al-Mashala, H. H., & Schnitzler, E. G. (2024). Partitioning of secondary organic aerosol onto nanoplastics leading to hygroscopic partially-engulfed particles. *Environmental Science: Atmospheres*, 4(1), 9-17. https://doi.org/10.1039/D3EA00103B

Reuder, J., Jonassen, M. O., & Ólafsson, H. (2012). The Small Unmanned Meteorological Observer SUMO: Recent developments and applications of a micro-UAS for atmospheric boundary layer research. *Acta Geophysica*, 60(5), 1454-1473. https://doi.org/10.2478/s11600-012-0042-8

Revell, L. E., Kuma, P., Le Ru, E. C., Somerville, W. R., & Gaw, S. (2021). Direct radiative effects of airborne microplastics. *Nature*, 598(7881), 462-467. https://doi.org/10.1038/s41586-021-03864-x

Roberts, G. C., Ramana, M. V., Corrigan, C., Kim, D., & Ramanathan, V. (2008). Simultaneous observations of aerosol–cloud–albedo interactions with three stacked unmanned aerial vehicles. *Proceedings of the National Academy of Sciences*, 105(21), 7370-7375. https://doi.org/10.1073/pnas.0710308105

Rodrigues, S. M., Espincho, F., Elliott, M., Almeida, C. M. R., & Ramos, S. (2023). Methodology optimization to quantify microplastic presence in planktonic copepods, chaetognaths and fish larvae. *MethodsX*, 11, 102466. https://doi.org/10.1016/j.mex.2023.102466.

Sanchez, K. J., Roberts, G. C., Calmer, R., Nicoll, K., Hashimshoni, E., Rosenfeld, D., ... & Russell, L. M. (2017). Top-down and bottom-up aerosol–cloud closure: towards understanding sources of uncertainty in deriving cloud shortwave radiative flux. *Atmospheric Chemistry and Physics*, 17(16), 9797-9814. https://doi.org/10.5194/acp-17-9797-2017

Segales, A. R., Greene, B. R., Bell, T. M., Doyle, W., Martin, J. J., Pillar-Little, E. A., & Chilson, P. B. (2020). The CopterSonde: an insight into the development of a smart unmanned aircraft system for atmospheric boundary layer research. *Atmospheric Measurement Techniques*, 13(5), 2833-2848. https://doi.org/10.5194/amt-13-2833-2020

Schrank, I., Möller, J. N., Imhof, H. K., Hauenstein, O., Zielke, F., Agarwal, S., ... & Laforsch, C. (2022). Microplastic sample purification methods-Assessing detrimental effects of purification procedures on

specific plastic types. *Science of the Total Environment*, 833, 154824. https://doi.org/10.1016/j.scitotenv.2022.154824

Su, W. C., Tolchinsky, A. D., Chen, B. T., Sigaev, V. I., & Cheng, Y. S. (2012). Evaluation of physical sampling efficiency for cyclone-based personal bioaerosol samplers in moving air environments. *Journal of Environmental Monitoring*, 14(9), 2430-2437. https://doi.org/10.1039/C2EM30299C

Tatsii, D., Gasparini, B., Evangelou, I., Bucci, S., & Stohl, A. (2025). Do Microplastics Contribute to the Total Number Concentration of Ice Nucleating Particles?. *Journal of Geophysical Research: Atmospheres*, 130(2), e2024JD042827. https://doi.org/10.1029/2024JD042827

Trainic, M., Flores, J. M., Pinkas, I., Pedrotti, M. L., Lombard, F., Bourdin, G., ... & Koren, I. (2020). Airborne microplastic particles detected in the remote marine atmosphere. *Communications Earth & Environment*, 1(1), 64. https://doi.org/10.1038/s43247-020-00061-y

WITec GmbH. (n.d.). WITec Suite FIVE: Data acquisition, evaluation and processing software [Software manual]. WITec. https://www.witec.de

Yang, Q., Kang, S., Yu, H., & Yang, Y. (2023). Impact of the shrinkage of Arctic sea ice on Eurasian snow cover changes in 1979–2021. *Advances in Atmospheric Sciences*, *40*(12), 2183-2194. https://doi.org/10.1007/s00376-023-2272-x

Yang, S., Brasseur, G., Walters, S., Lichtig, P., & Li, C. W. (2025). Global atmospheric distribution of microplastics with evidence of low oceanic emissions. *npj Climate and Atmospheric Science*, *8*(1), 81. https://doi.org/10.1038/s41612-025-00914-3

Wagner, S., Hüffer, T., Klöckner, P., Wehrhahn, M., Hofmann, T., & Reemtsma, T. (2018). Tire wear particles in the aquatic environment-a review on generation, analysis, occurrence, fate and effects. *Water research*, *139*, 83-100. https://doi.org/10.1016/j.watres.2018.03.051

Zhang, X., Chen, X., Orr, A., Overland, J. E., Vihma, T., Wang, M., Yang, G. H., & Zhang, R. (2023). Preface to the special issue on changing Arctic climate and low/mid-latitudes connections. *Advances in Atmospheric Sciences*, *40*(12), 2135-2137. https://doi.org/10.1007/s00376-023-3015-8.

Zheng, K., Wang, P., Lou, X., Zhou, Z., Zhou, L., Hu, Y., ... & Gao, X. (2024). A review of airborne micro-and nano-plastics: Sampling methods, analytical techniques, and exposure risks. *Environmental Pollution*, 363, 125074. https://doi.org/10.1016/j.envpol.2024.125074

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Author contributions

R.C. acquired funding. R.C. and A.D. designed the project and wrote the manuscript. R.C. built the instrumentation. M.R. prepared the sUAS platform and integrated the instrumentation. M.R. and R.C. conducted the sUAS flights. A.D. conducted the microplastic analysis. G.d.B. and D.L. contributed to project planning and oversight, participated in project meetings, and provided feedback and support. All authors contributed to the development of the manuscript and reviewed it.

Declarations

The use of artificial intelligence: Artificial Intelligence (e.g., ChatGPT, Claude) was used through an AI aggregator platform (Mammouth AI), which is based in Europe, following the privacy and security rules of the General Data Protection Regulation (GDPR). AI was used to proofread the manuscript and to improve the readability and language. After using this tool, the authors reviewed and edited the content as needed, and take full responsibility for the manuscript content, claims, and references.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Files

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