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A Preliminary Moss-Based Assessment of Atmospheric Microplastic Deposition at Selected Locations in North Macedonia

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Abstract

Atmospheric microplastics have emerged as an important environmental contaminant due to their widespread occurrence, persistence, and potential ecological and human health implications. However, information regarding atmospheric microplastic deposition in southeastern Europe remains extremely limited. The present study provides a preliminary moss-based assessment of atmospheric microplastic deposition at selected locations in North Macedonia. Moss samples were collected from sites representing different degrees of anthropogenic influence and analyzed following sample preparation procedures consistent with previous national-scale surveys. Microplastic particles were identified using micro-Fourier Transform Infrared (μ-FTIR) spectroscopy. Microplastics were detected in all investigated moss samples, confirming their widespread atmospheric deposition across the country. The highest concentration was recorded at Vodno–Skopje (16.72 MP g^{-1} dry weight), followed by Majdan (7.10 MP g^{-1}) and Bojančište (3.29 MP g^{-1}). Pronounced differences in polymer composition were observed among the sampling locations: Vodno–Skopje exhibited the greatest polymer diversity, with polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polylactic acid (PLA), and cellulose acetate (CA) all detected above their respective limits of detection, whereas Majdan was characterized almost exclusively by polyethylene terephthalate (PET) and Bojančište primarily by cellulose acetate (CA) and PLA. The detected microplastic concentrations were within the range of values reported in some European studies, although direct comparisons should be interpreted with caution because of the differences in sampling and analytical methodologies. The findings demonstrate the potential of moss-based biomonitoring as a complementary approach for assessing atmospheric microplastic deposition. However, studies covering a larger number of sampling locations and different temporal periods are required to further evaluate and validate this approach.

Keywords: atmospheric deposition; microplastics; moss biomonitoring; μ-FTIR; North Macedonia; airborne pollution

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1. Introduction

Plastic production has increased dramatically over recent decades, exceeding 400 million tonnes annually worldwide, making plastic pollution one of the most pressing environmental challenges of the twenty-first century (UNEP, 2023) [1]. Through physical, chemical, and biological weathering processes, larger plastic debris progressively fragments into microplastics (MPs), commonly defined as plastic particles smaller than 5 mm. Owing to their persistence, mobility, and potential ecological impacts, microplastics have become ubiquitous contaminants detected in marine, freshwater, terrestrial, and atmospheric environments (GESAMP, 2019) [2].

Although early microplastic research primarily focused on aquatic ecosystems, increasing evidence indicates that the atmosphere represents an important pathway for the transport, redistribution, and deposition of microplastics [3–9]. Atmospheric microplastics originate from numerous sources, including fragmentation of plastic waste, synthetic textile fibres, tyre wear, construction materials, agricultural activities, and industrial emissions. Once emitted, these particles may remain suspended in the atmosphere for prolonged periods and be transported over hundreds of kilometres before being deposited through dry or wet deposition. Consequently, atmospheric microplastics have been detected not only in densely populated urban areas but also in remote mountain regions, protected ecosystems, and polar environments [3,10].

The environmental significance of atmospheric microplastics extends beyond their widespread occurrence. Airborne microplastic particles may also contain or release chemical additives associated with plastic materials, including plasticizers, flame retardants, stabilizers, and pigments, while their surfaces may additionally adsorb and transport other environmental contaminants [10–13]. Recent studies have demonstrated that atmospheric microplastics can be inhaled and deposited within the human respiratory tract, emphasizing the need for a better understanding of their sources, atmospheric transport, and deposition patterns [4,10].

The increasing recognition of atmospheric transport has stimulated the development of monitoring approaches capable of assessing atmospheric microplastic deposition over large geographical areas. Conventional atmospheric sampling methods generally require specialized instrumentation, continuous operation, and considerable financial resources. Consequently, growing attention has been directed towards the use of biological indicators as passive samplers of atmospheric contamination.

Mosses have long been recognized as effective biomonitors of atmospheric pollutants because they lack a developed root system, possess a high surface-to-volume ratio, and obtain nutrients almost exclusively from atmospheric deposition. These characteristics enable efficient accumulation of airborne particles over extended periods, providing an integrated measure of atmospheric contamination. For several decades, moss biomonitoring has been successfully applied within the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) to assess atmospheric deposition of heavy metals, nitrogen, and persistent organic pollutants across Europe. More recently, mosses have also been proposed as suitable biomonitors for atmospheric microplastics, providing a cost-effective and standardized approach for large-scale environmental monitoring [14].

Recent studies have demonstrated the suitability of mosses for assessing atmospheric microplastic deposition under different environmental conditions. Roblin et al. (2020) [15] reported the widespread occurrence of anthropogenic microfibres in moss samples collected throughout Ireland, including remote areas with limited local emission sources. Capozzi et al. (2023) [16] demonstrated significant urban–rural differences in microplastic accumulation using *Hypnum cupressiforme* in southern Italy, while Cross et al. (2026) [17]

reported widespread atmospheric microplastic deposition across the United Kingdom using moss biomonitoring. However, direct quantitative comparison among these studies requires caution because of the differences in experimental design and analytical methodology. Variations in moss species and morphology, sampling strategy, environmental exposure, sample preparation and digestion procedures, particle size ranges considered, criteria used for particle classification, and analytical techniques for polymer identification can substantially influence the abundance and characteristics of the particles reported. Differences in the units and approaches used to express microplastic abundance may further complicate direct comparison among studies. Therefore, rather than providing directly comparable estimates of atmospheric microplastic deposition, these studies collectively demonstrate the potential of moss-based biomonitoring for identifying the occurrence and spatial variability of airborne microplastic deposition. The observed spatial patterns have been associated with factors such as local emission sources, land use, population density, atmospheric transport, and meteorological conditions [18]. Further methodological harmonization is required before quantitative results obtained from different moss biomonitoring studies can be directly compared.

North Macedonia has participated in the ICP Vegetation programme since 2002 and has extensive experience in moss biomonitoring of atmospheric pollution. During the past two decades, national moss surveys have successfully assessed the atmospheric deposition of potentially toxic elements, nitrogen, and other airborne contaminants, providing one of the longest continuous biomonitoring datasets in southeastern Europe [19–22]. Building upon this experience, moss biomonitoring was applied in the present study to investigate atmospheric microplastic deposition using harmonized sampling and analytical procedures. This approach enables direct comparison with previously published studies while maintaining methodological consistency with established European biomonitoring protocols.

Despite the increasing number of atmospheric microplastic studies conducted in Western and Northern Europe, information from southeastern Europe remains extremely limited. To the best of our knowledge, no previous study has investigated atmospheric microplastic deposition in North Macedonia using moss biomonitoring. This represents an important geographical knowledge gap considering the region's complex topography, diverse land-use patterns, and location along major atmospheric transport pathways connecting Central Europe with the Mediterranean region.

Therefore, the aim of the present study was to assess atmospheric microplastic deposition in North Macedonia using moss biomonitoring. The specific objectives were to (i) determine the abundance of atmospheric microplastics, (ii) identify polymer composition using imaging micro-Fourier transform infrared (μ-FTIR) spectroscopy and (iii) establish the first dataset for atmospheric microplastic deposition in North Macedonia, providing a scientific foundation for future monitoring programmes and regional comparisons with previously published European studies.

2. Materials and Methods

2.1. Moss Sampling

Moss sampling was conducted across North Macedonia (Figure 1) during August 2022 under the UNECE ICP Vegetation framework. Three carpet-forming pleurocarpous moss species were collected according to their availability at each sampling site: *Hypnum cupressiforme* Hedw. at Vodno–Skopje, *Pseudoscleropodium purum* at Bojančište, and *Homalothecium lutescens* at Majdan. *Hypnum cupressiforme*, the standard biomonitor recommended by the UNECE ICP Vegetation programme, was used whenever available. Where this species was absent or insufficiently developed for sampling, *Pseudoscleropodium purum*

and *Homalothecium lutescens* were collected as substitute biomonitors. Although the use of alternative moss species is consistent with the ICP Vegetation sampling framework, species-specific differences in morphology, surface characteristics, and particle interception and retention may influence microplastic accumulation. Differences between accumulation of microplastics in species of moss and lichen have been largely attributed to differences in structural characteristics and habitat differences [23], which is of less concern for the three mosses sampled as part of the current survey. However, as the relative retention efficiencies of these moss species for atmospheric microplastics have not yet been systematically established, comparisons of microplastic concentrations among the three sampling sites should therefore be interpreted with caution.

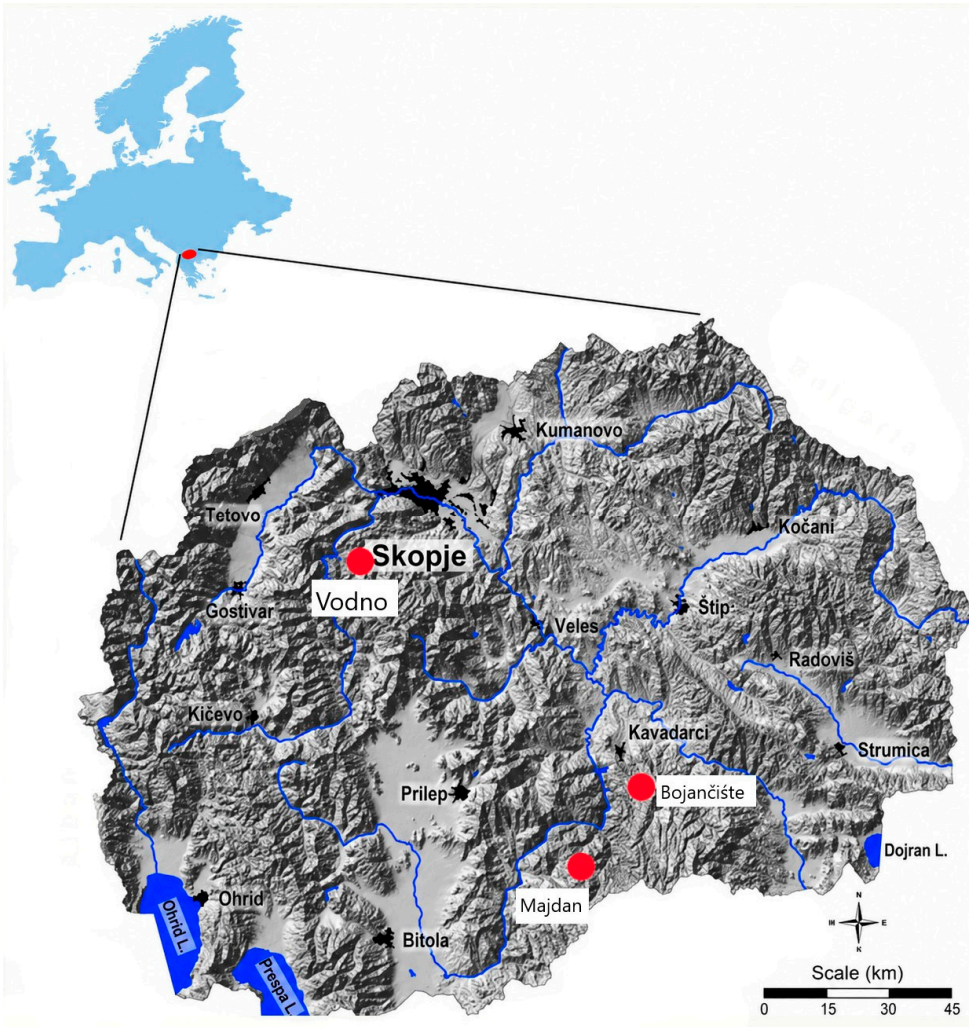

Figure 1. Location of North Macedonia in Europe and the sampling sites (red dots).

2.1.1. Contamination Control Protocols During Sampling

Due to the ubiquitous nature of microplastics (MPs) and the extreme risk of sample cross-contamination during field operations, a rigorous anti-contamination protocol was strictly enforced:

Personnel attire: Field researchers wore exclusively 100% cotton clothing and jackets. Synthetic garments such as polyester, fleece, or nylon were strictly prohibited. Field tools: Non-powdered nitrile gloves were donned at each site and changed between locations. Samples were extracted using pre-cleaned stainless-steel scissors and tweezers; no plastic tools or equipment were permitted on site.

Packaging: Collected biomass was immediately wrapped in heavy-duty aluminum foil (or placed in clean paper bags) and labelled externally using a permanent marker on masking tape, ensuring no ink or adhesive came into direct contact with the moss.

2.1.2. Collection Procedure and Sample Processing

At each of the three selected sampling sites (Table 1), a representative composite sample was collected within a 50 × 50 m plot. In accordance with the ICP Vegetation sampling protocol, all sites were located at least 300 m from major roads and at least 100 m from any minor road or isolated house to minimize the influence of local emission sources. Only the top green and green-brown segments of the moss shoots, corresponding approximately to the last 2–3 years of active growth, were retained. The dead, decaying lower brown parts and soil crusts were carefully separated and discarded on site. Obvious large forest debris (e.g., pine needles, leaves, small twigs) was removed using stainless-steel forceps. The composite samples, weighing approximately (20–30) grams of fresh biomass each, were sealed, stored in a portable cooler, and transported to the laboratory. Geographic coordinates and elevations were recorded at the centre of each plot using a handheld GPS receiver (Table 1).

Table 1. Description of sampling locations and moss species collected in North Macedonia.

Site Name	Date Sampled	Latitude (Deg N)	Longitude (Deg E)	Elevation (m)	Moss Species	Number of Subsamples
Vodno–Skopje	29 August 2022	41.99694444	21.35583333	299	*Hypnum cupressiforme*	15
Bojančište	19 August 2022	41.25111111	22.04972222	933	*Pseudoscleropodium purum*	15
Majdan	20 August 2022	41.15583333	21.94527778	768	*Homalothecium lutescens*	15

2.2. Sample Preparation for Identification

Several previously reported digestion-based approaches for moss or lichen samples have used relatively small sample masses, including 1 g [24], 0.25 g [25], and less than 0.02 g [26]. In comparison, the present method uses a larger moss sample mass, which provides a greater amount of material for microplastic extraction and analysis. To facilitate the processing of this larger sample mass, a specialized high-flow water rinsing chamber developed as part of previous work (Figure 2) was employed, enabling the processing of 3 g of moss per sample [17].

As part of the QA/QC, representative fluorescently labelled PVC (90–150 µm in size, produced through cryomilling in-house) were spiked to each sample, within the moss material as it was laid into the flush unit. The final recovery of these particles (mean = 56 +/− 4%) represents recovery of microplastics along the entire sample preparation workflow. This represents consistent recovery, indicating good repeatability of the method and comparability of the data. Blanks were also run alongside batches of samples. The present data forms part of a wider dataset, for which 19 blanks were run. These blanks are used to correct for the baseline contamination on a polymer-by-polymer basis using the mean of the blanks. The corrected values are then compared to the limits of detection of each polymer (3.3 × standard deviation in the blanks), before reporting on the basis of a concentration per gramme of moss. This approach is consistent with that followed in the previous nationwide survey of the UK [17] and means that the data in the present study are directly comparable with that survey.

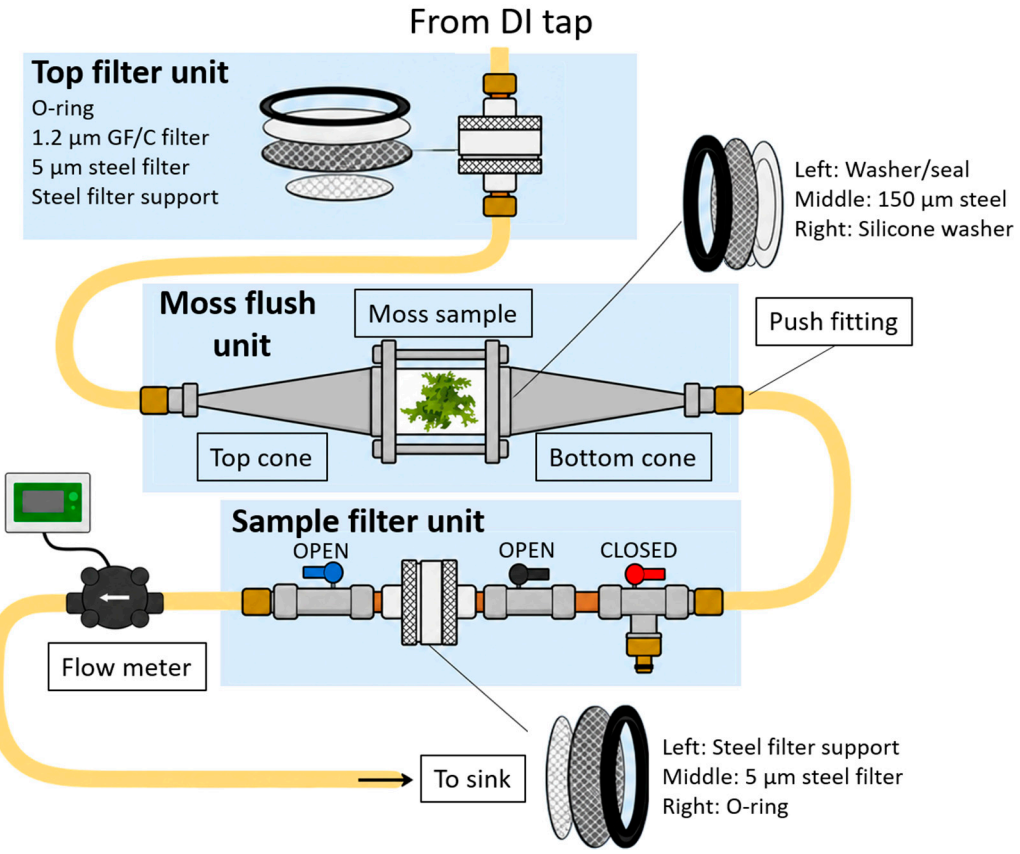

Figure 2. High-flow water rinsing chamber used for the processing of individual moss samples. This approach enabled the efficient separation and filtration of microplastic particles for subsequent characterization and analysis (figure reproduced with modifications from [17], under licence CC by 4.0).

Microplastic particles retained during the rinsing process were subsequently collected by filtration, and clean-up was performed using a Fenton's reaction to reduce interfering organic matter and a density separation step, where plastics are separated from minerals and other dense particulates through suspension in $ZnCl_2$ at 1.7 g cm^{-3}. Fenton's reactions were performed with hydrogen peroxide (H_2O_2, 30%, ACS reagent grade, SLS, Nottingham, UK) and iron(II) sulphate heptahydrate ($FeSO_4 \cdot 7H_2O$, SLS, Nottingham, UK). Acidification used 2% hydrochloric acid (HCl) and 5% sulphuric acid (H_2SO_4). Zinc chloride ($ZnCl_2$, Fisher Scientific, Loughborough, UK) was used to perform the density separation at 1.7 g cm^{-3}. The extracted particles are then analyzed for polymer identification using imaging micro-Fourier transform infrared (µ-FTIR) spectroscopy. The extraction and analysis protocol followed was identical to that published in UK survey [17], with the exception that the mass of moss extracted was fixed at a constant 3 g +/− 0.02 g. This means the data generated as part of the present study is directly comparable with the UK nationwide survey reported in [17].

2.3. Sample Analysis and Polymer Identification

Following extraction and purification, the entirety of each sample was deposited onto one or more 25 mm silver membrane filters (3 µm pore size; Sterlitech, Auburn, WA, USA) to avoid overloading, and allowed to dry under clean laboratory conditions covered in a biological safety cabinet under HEPA-filtered air. As the entire sample is deposited and analyzed, and we know the starting mass of moss introduced to the flow rinsing chamber for extraction, this allows the final results to be expressed as the number of microplastic

particles per gram of dry moss (MP g^{-1} dry weight). Analyzing the whole sample avoids any issues with representative sub-sampling. Chemical identification and quantification of microplastics were performed at the Microplastics Analysis Facility of the UK Centre for Ecology & Hydrology (UKCEH, Wallingford, UK).

Microplastic particles were identified using an imaging micro-Fourier Transform Infrared (μ-FTIR) spectrometer (PerkinElmer Spotlight 400, PerkinElmer Inc., Waltham, MA, USA) operated in reflectance mode over the spectral range of 4000–700 cm^{-1}. Prior to analysis, a background spectrum of the silver membrane filter was collected and automatically subtracted from each measurement. Spectral acquisition was performed at a spectral resolution of 8 cm^{-1} with two scans per pixel, an interferometer speed of 2.2 cm/s and a spatial resolution of 25 μm per pixel, corresponding to the minimum particle size that could be reliably resolved.

Automated particle detection and polymer classification were carried out using Purency Microplastics Finder software (Figure 3), which applies machine-learning algorithms to identify individual particles and compare their infrared spectra with a validated polymer reference library. The analytical workflow minimizes operator bias associated with manual particle selection while simultaneously providing information on particle abundance, dimensions, and polymer composition.

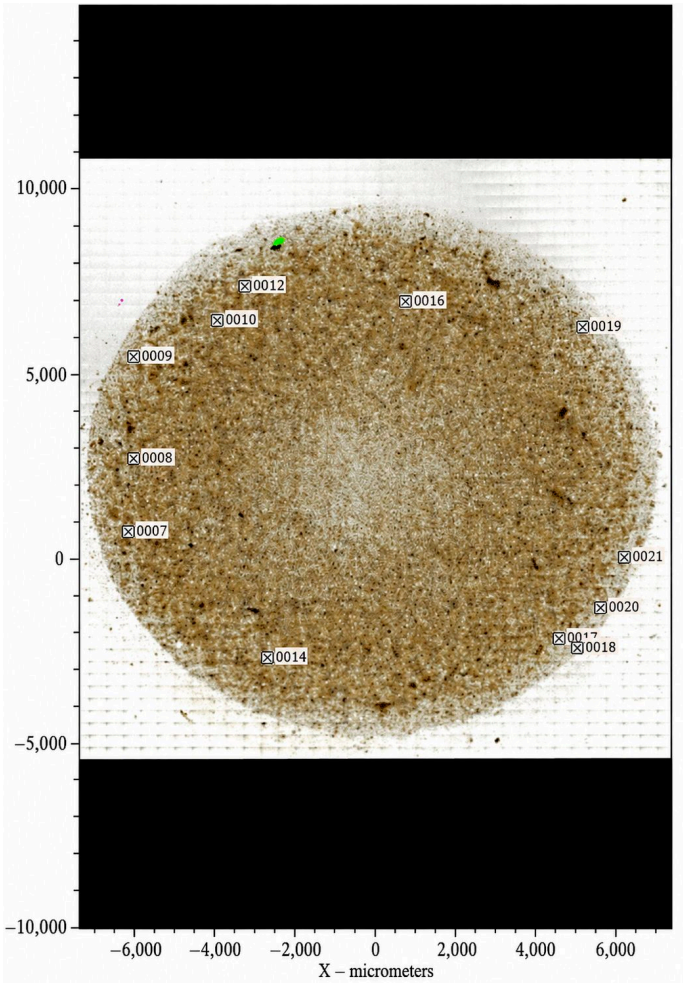

Figure 3. Analysis of infrared μ-FTIR scan of the Majdan site, using Purency Microplastics Finder v1.3.13. Labelled particles with numbers represent positive control internal tracer particles to calculate the recovery in the samples of a representative microplastic.

The reference library comprised twenty-one commonly occurring synthetic and semi-synthetic polymers, including polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalate (PET), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyamide (PA), polycarbonate (PC), polymethyl methacrylate (PMMA), polyoxymethylene (POM), cellulose acetate (CA), ethylene-vinyl acetate (EVAc), ethylene-vinyl alcohol (EVOH), polyacrylonitrile (PAN), polybutylene terephthalate (PBT), polyether ether ketone (PEEK), polyphenylsulfone (PPSU), polysulfone (PSU), silicone, and polylactic acid (PLA). Particles were assigned to polymer classes only when the acquired spectra satisfied the criteria for similarity and relevance established in the UK survey [17].

2.4. Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control procedures were implemented throughout sample preparation, extraction, and instrumental analysis to minimize the risk of contamination and ensure data reliability. Sample preparation was performed using pre-cleaned glassware and stainless-steel equipment whenever possible, while plastic laboratory consumables were avoided throughout the analytical workflow. All aqueous reagents were prepared using reverse-osmosis deionized water and filtered prior to use to reduce potential background contamination.

Samples were processed under clean laboratory conditions, only ever open to the air inside biological safety cabinets circulated with HEPA-filtered air while wearing cotton laboratory coats and powder-free nitrile gloves to minimize airborne fibre contamination. Procedural blanks accompanied the analytical workflow and were subjected to the same extraction and analytical procedures as environmental samples in order to assess potential laboratory contamination. Blank measurements were evaluated during data interpretation and confirmed that background contamination remained below the established analytical limits.

Chemical identification of suspected microplastic particles relied exclusively on infrared spectroscopic confirmation rather than visual classification, thereby minimizing false-positive identification of non-plastic materials. Polymer assignments were accepted only when the spectral matching fulfilled the criteria for similarity and relevance established in [17].

As described elsewhere both positive (spike recovery) and negative controls (blank assessment and establishment of LODs) were performed and demonstrated that the method produced consistent, repeatable results and that the contamination was controlled sufficiently in the lab to establish limits of detection sufficiently low to allow for detection of microplastics in the moss samples.

3. Results

3.1. Atmospheric Microplastic Occurrence in North Macedonia

Atmospheric microplastics were detected in all investigated moss samples, confirming their presence at all sampling locations in North Macedonia (Figure 4). Microplastic abundance differed among the three sampled locations, with concentrations ranging from 3.29 to 16.72 MP g^{-1} dry weight, indicating marked spatial variability in atmospheric deposition. The highest concentration was recorded at Vodno–Skopje (16.72 MP g^{-1}), followed by Majdan (7.10 MP g^{-1}) and Bojančište (3.29 MP g^{-1}).

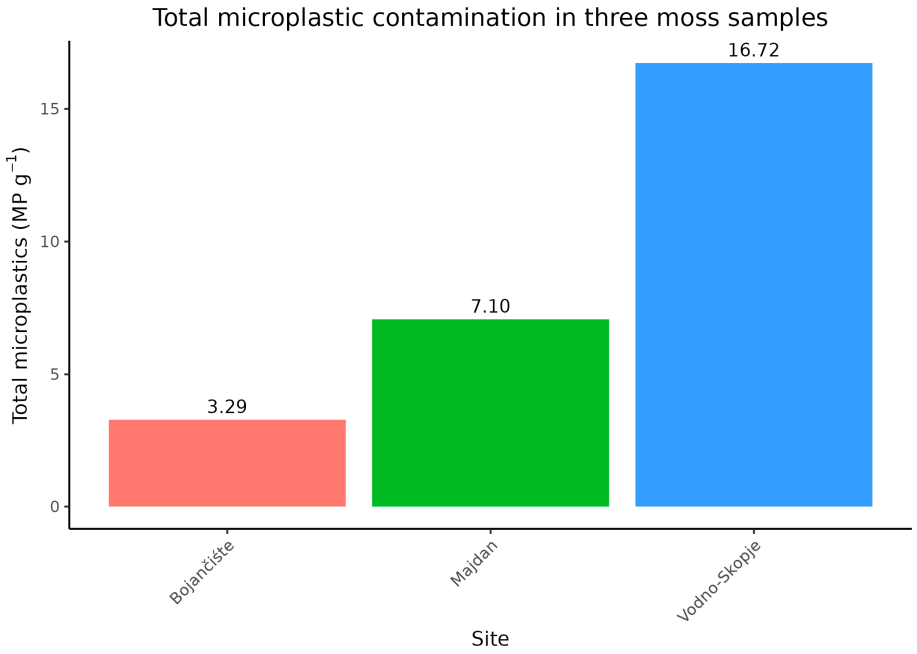

Figure 4. Total microplastic contamination in three moss samples collected across North Macedonia.

3.2. Polymer Composition

The polymer composition of atmospheric microplastics identified in the moss samples is presented in Figure 5. Several polymer types were identified across the investigated samples, demonstrating the heterogeneous nature of atmospheric microplastic deposition. Differences in both polymer diversity and relative abundance were observed among the three analyzed samples, indicating site-specific differences in the composition of the detected atmospheric microplastics.

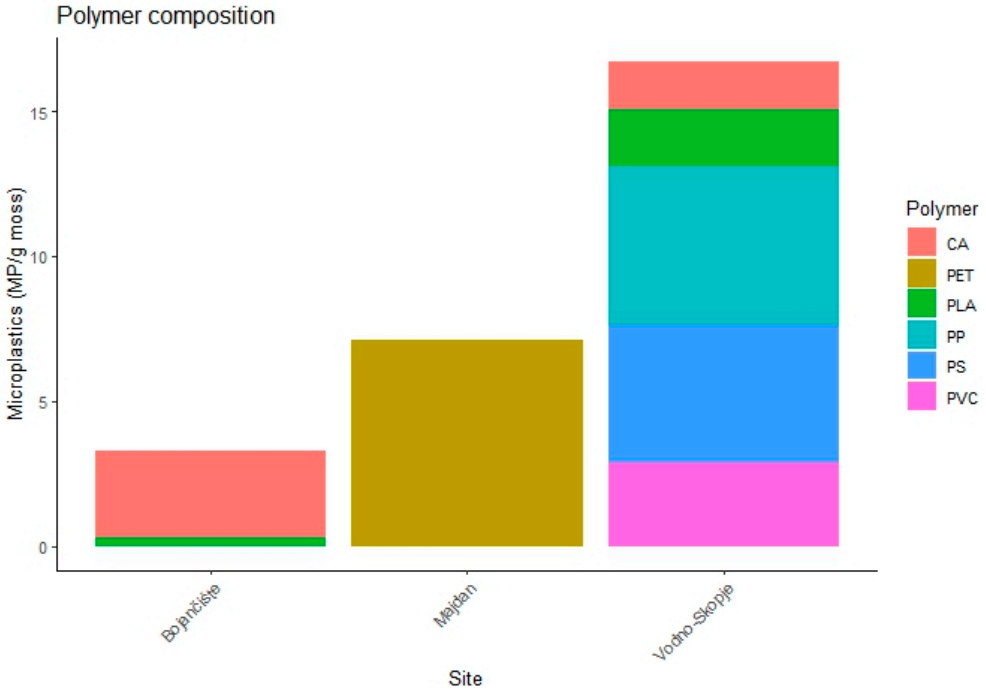

Figure 5. Polymer composition of microplastics in moss samples from three sampling sites (Bojančište, Majdan, and Vodno–Skopje), expressed as MP g^{-1} dry weight.

Vodno–Skopje exhibited the greatest polymer diversity, with polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polylactic acid (PLA), and cellulose acetate (CA) all detected above their respective limits of detection (LODs). This is to be expected, as this location had the highest overall concentration of microplastics, increasing the likelihood of multiple polymers exceeding their LODs. In contrast, both Majdan and Bojančište showed a much simpler polymer profile: PET was the only polymer detected above its LOD at Majdan, whereas CA and PLA were detected above their respective LODs at Bojančište.

These differences in polymer profiles should be interpreted with caution, as several polymer-specific concentrations were close to or below their respective LODs. Concentrations below the polymer-specific LODs cannot be interpreted as evidence of polymer absence, nor used reliably for quantitative comparisons among sites. Therefore, the present results provide a descriptive indication of the polymer profiles in the analyzed moss samples, while the limited number of samples and polymer-specific detection limits preclude robust conclusions regarding site-level differences in polymer composition. Notably, PET was the only polymer quantified above its LOD at Majdan, whereas at Vodno–Skopje and Bojančište PET concentrations remained below the respective site-specific LODs.

To place the obtained results into a broader context, the measured concentrations were compared with previously published European moss biomonitoring studies (Table 2). The concentrations determined in North Macedonia (3.29–16.72 MP g^{-1}) fall within the range reported for the United Kingdom (0.33–24.92 MP g^{-1}), a survey with which the present study shares a high degree of methodological consistency. Nevertheless, quantitative comparisons should be interpreted with caution because of differences in geographic coverage, survey design, and moss species. Comparisons with studies from Ireland and Italy should be regarded primarily as contextual because of greater differences in sampling design, environmental conditions, and analytical methodologies [23,27].

Table 2. Comparison of atmospheric microplastic deposition reported in European moss biomonitoring studies.

Region/Country	Moss Species	Microplastic Concentration (MP g^{-1})	Dominant Polymers/Particle Types	Main Findings	Reference
Ireland	*Pleurocarpous* mosses	~24	Predominantly microfibres	Demonstrated atmospheric deposition even in remote rural areas	[15]
Italy	*Hypnum cupressiforme*	53–87	Synthetic fibres dominant	Biomonitoring of Airborne Microplastic Deposition in Semi-Natural and Rural Sites Using the Moss *Hypnum cupressiforme*	[16]
UK	Mixed moss species	0.33–24.92	PU, CA, PVC, EVAc	MPs detected in >95% of samples; large-scale national assessment	[17]
North Macedonia	*Hypnum cupressiforme*	3.29–16.72	PP, PVC, PS, CA, PET, PLA	Preliminary moss-based assessment of atmospheric microplastics in the Balkans	This study

4. Discussion

The present study provides a preliminary assessment of atmospheric microplastic deposition at selected locations in North Macedonia using moss biomonitoring and establishes an initial dataset for this emerging environmental contaminant. Microplastics were detected in all investigated moss samples, demonstrating that atmospheric deposition occurs across both urban and rural environments. These findings are consistent with the growing body of evidence indicating that airborne microplastics are ubiquitous environmental pollutants and can be detected even in areas with limited direct anthropogenic influence [3,12,24].

The concentrations measured in North Macedonia (3.29–16.72 MP g^{-1}) fall within the range reported in previously published European moss biomonitoring studies, although direct comparisons should be interpreted with caution given differences in methodology among studies. Roblin et al. (2020) [15] demonstrated that atmospheric microplastics accumulate in mosses even in remote regions of Ireland, highlighting the importance of long-range atmospheric transport. Similarly, Cross et al. (2026) [17] reported concentrations ranging from 0.33 to 24.92 MP g^{-1} across the United Kingdom, indicating some spatial variability which is as yet not fully explained, though it experienced some influence of urban proximity and latitude. The concentrations observed in the present study fall broadly within this published range, although geographical and climatic differences, as well as methodological differences among studies, warrant caution when making direct comparisons [12]. These observations support the growing evidence that atmospheric transport plays a major role in the redistribution of microplastics across regional and continental scales [3,4].

Differences in microplastic abundance were observed among the three sampling locations. Vodno–Skopje exhibited the highest microplastic abundance and the greatest polymer diversity, whereas Majdan and Bojančište showed considerably lower concentrations and simpler polymer assemblages, at least reportable above limits of detection. This spatial pattern is consistent with observations reported by Capozzi et al. (2023) [16], who identified significantly greater atmospheric microplastic deposition at sites affected by urban activities compared with semi-natural and rural locations. The elevated microplastic contamination observed at Vodno–Skopje is consistent with its proximity to Skopje, the largest urban area in North Macedonia, where approximately one-third of the country's population resides. The greater polymer diversity at this site is also consistent with its higher overall microplastic abundance, which increased the likelihood of detecting multiple polymer types above the analytical limits of detection.

Although lower concentrations were measured at Majdan and Bojančište, the detection of microplastics at both sites demonstrates that atmospheric contamination is not restricted to densely populated environments. Airborne microplastics can remain suspended for extended periods and may be transported over hundreds of kilometres before deposition, allowing even relatively remote ecosystems to receive continuous atmospheric inputs [3,4]. Consequently, the presence of microplastics in rural locations should not necessarily be interpreted as evidence of local emission sources alone but rather as the combined result of local emissions and regional atmospheric transport processes.

The polymer composition further characterized the atmospheric microplastics accumulated by the moss samples. In the Vodno–Skopje samples, polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) were the most abundant polymers identified. PP is widely used in packaging materials, textiles, household products, and automotive components, whereas PS is commonly employed in disposable food containers, packaging materials, insulation products, and other consumer goods. PVC is extensively used in piping systems, cables, flooring, window frames, and other construction materials. These

polymers are among the most widely produced and used plastics worldwide; however, polymer composition alone does not permit definitive source apportionment.

Majdan exhibited a comparatively simple polymer composition, with polyethylene terephthalate (PET) representing the only polymer reported above limits of detection. In contrast, Bojančište was characterized primarily by cellulose acetate (CA) together with PLA. Cellulose acetate is commonly associated with cigarette filters and cellulose-based consumer products and has also been identified quite frequently in the comparable atmospheric deposition study in the UK. Although polymer composition alone cannot provide definitive source apportionment, the distinct polymer profiles observed among the investigated sites may reflect differences in local land use and anthropogenic activities; however, these potential influences cannot be evaluated or confirmed with the present dataset.

Previous European studies, despite methodological differences among investigations, consistently demonstrate that microplastics can be detected in moss samples, supporting the potential application of mosses for atmospheric microplastic biomonitoring. Studies by Roblin et al. (2020) [15], Roblin and Aharne (2020) [28] and Capozzi et al. (2023) [16] support further investigation of mosses as a practical approach for atmospheric microplastic biomonitoring. The results obtained in the present study are consistent with these findings and suggest that the methodology can be applied under Balkan environmental conditions, although further studies across a larger number of sites are needed to confirm this.

An additional strength of this study is the application of μ-FTIR spectroscopy for polymer identification. Spectroscopic confirmation reduces the likelihood of false-positive identification compared with purely visual particle classification and increases confidence in polymer assignments. The implementation of strict quality assurance and quality control procedures further enhances the robustness and reproducibility of the reported data. The sample collection, preparation and analysis methodology followed the previous UK survey, and sample preparation and analysis were performed at the same laboratory, providing a strong methodological basis for comparison between the present samples and this more extensive nationwide survey. Nevertheless, differences in survey design, geographic coverage, and moss species should be considered when interpreting quantitative similarities or differences between the datasets.

An additional source of uncertainty is the use of different moss species among the sampling sites. Although *H. cupressiforme*, *P. purum*, and *H. lutescens* are pleurocarpous mosses commonly used or considered suitable for atmospheric biomonitoring, species-specific morphological characteristics may affect the interception and retention of airborne particles. Differences in leaf size and orientation, branching architecture, surface roughness, and water-holding capacity could potentially influence the accumulation of microplastic fibres and fragments. Nevertheless, the three species considered here share a broadly similar overall growth form: all are prostrate, mat-forming pleurocarpous mosses within the Hypnales/Brachytheciaceae, characterized by regularly to sub-regularly pinnate branching and small, overlapping (imbricate) leaves that together form a continuous, densely interwoven canopy surface. This shared architecture suggests that gross differences in particle-interception surface among the three species are likely modest compared with, for example, the contrast between pleurocarpous and acrocarpous (upright, cushion-forming) mosses. Some finer-scale differences do exist—*P. purum*, in particular, is characterized by a more tightly overlapping leaf arrangement and swollen shoot appearance associated with enhanced water retention compared with *H. cupressiforme*—and these cannot be excluded as a source of variability, as no study has yet directly compared microplastic retention efficiency among *H. cupressiforme*, *P. purum*, and *H. lutescens* specifically. Consequently, the observed differences in microplastic abundance among the three sites cannot be attributed

exclusively to differences in atmospheric deposition without further systematic investigation, as a species-related effect cannot be excluded. However, it is well recognized that it is often impossible to sample the same moss species across a large survey area. For trace element deposition in carpet-forming moss species, concentrations of various metals were found to correlate well between species [29]. Indeed, there is early evidence that the same holds true for microplastics, with variance in concentrations across the UK of microplastics measured in *Hylocomium splendens* and *Pleurozium schreberi* found to be similar [17].

Nevertheless, several limitations should be acknowledged. The present investigation represents a pilot study based on only three sampling locations and therefore cannot fully characterize the spatial variability of atmospheric microplastic deposition across North Macedonia. Although differences in microplastic abundance were observed among the three sampling locations, the limited spatial coverage and absence of independent site replication preclude statistical evaluation of spatial variability. The observed differences should therefore be considered site-specific and exploratory. Furthermore, only a polymer composition was evaluated, whereas particle morphology, particle size distribution, and atmospheric transport modelling were beyond the scope of the present investigation. Future research should expand the national monitoring network, include seasonal sampling campaigns, investigate additional biomonitor species, integrate atmospheric transport models to improve source apportionment and better understand the mechanisms controlling airborne microplastic deposition. The selection of μ-FTIR provides a balance between increased resolution and chemical specificity to smaller microplastics down to a limit of $\leq$25 μm in size, increasing the analytical range from an assessment of larger microplastic fibres which has been the main focus of previous light microscopy-based assessments. However, we know that there is a fraction of microplastics smaller than this approximate lower size limit achievable with infrared-based vibrational spectroscopy. For example, an assessment using Raman found that ~80% of the identified microplastics were <10 μm in size. It should be noted, that from a mass perspective, these particles < 10 μm only contributed 3.2% of the total mass of microplastics, meaning the size range targeted by μ-FTIR is good at representing the majority of the mass of microplastic particles in moss. This makes it complementary to mass-based thermoanalytical analyses. There is no single analytical method that can analyse and quantify microplastics across their entire diversity of particle size, shapes and polymers, particularly in the sub-micrometre range [30]. The selection of μ-FTIR analysis therefore represents a pragmatic choice, extending the analytical range to describe microplastics not possible with visible light microscopy techniques alone, whilst still being somewhat scalable to allow for analysis of samples from a wide geographical distribution.

Overall, this study fills an important geographical gap in European atmospheric microplastic research by providing the first evidence of atmospheric microplastic deposition in North Macedonia using moss biomonitoring. The observed contamination levels fall within the range reported in previously published European studies, consistent with the view that atmospheric microplastic pollution represents a widespread environmental issue throughout Europe. The results establish a valuable dataset that will support future monitoring programmes and provide a scientific basis for evaluating long-term trends in atmospheric microplastic deposition.

5. Conclusions

This study presents a preliminary assessment of atmospheric microplastic deposition at selected locations in North Macedonia using moss biomonitoring and provides an initial dataset for this emerging environmental contaminant. Microplastics were detected in all

investigated moss samples, indicating that atmospheric microplastic deposition occurs across both urban and less populated environments.

Differences in microplastic abundance and polymer composition were observed among the three sampling locations. The highest concentration and greatest polymer diversity were recorded at Vodno–Skopje; however, the present dataset does not allow these differences to be attributed to urban activities or to any specific emission source. Microplastics were also detected at the less populated Majdan and Bojančište sites, indicating that atmospheric microplastic deposition is not restricted to densely populated environments.

The polymer composition provides complementary information to microplastic abundance, as different polymers may differ in their properties, uses, and environmental behaviour. Incorporating polymer composition alongside particle abundance may therefore improve the environmental interpretation of atmospheric microplastic assessments.

The occurrence of microplastics in moss samples from North Macedonia is consistent with findings reported in previous European studies, although substantial methodological differences currently limit direct quantitative comparison among studies. The present findings support further investigation of mosses as passive biomonitors for atmospheric microplastic deposition, while the performance, reproducibility, and broader applicability of this approach require further validation.

The present investigation represents a pilot study based on only three sampling locations and the absence of independent site replication, and therefore cannot fully characterize spatial patterns of atmospheric microplastic deposition across North Macedonia. Further research should expand the monitoring network, include spatial and temporal replication, use consistent moss species where possible or systematically investigate interspecies effects, improve extraction and recovery procedures, and apply harmonized analytical and reporting protocols. Integration with meteorological information, atmospheric transport analysis, and source-characterization approaches will be important for improving the interpretation of microplastic accumulation patterns and for assessing long-term trends in atmospheric microplastic deposition.

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