



MASTERARBEIT | MASTER'S THESIS

Titel | Title

Microplastic Deposition Flux in Vienna

verfasst von | submitted by

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angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of
Master of Science (MSc)

Wien | Vienna, 2026

Studienkennzahl lt. Studienblatt | Degree
programme code as it appears on the
student record sheet:

UA 066 614

Studienrichtung lt. Studienblatt | Degree
programme as it appears on the student
record sheet:

Masterstudium Meteorology and Climate Science

Betreut von | Supervisor:

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Abstract

Atmospheric microplastic (MP) deposition presents an important pathway for plastic pollution in all ecosystems. Among all environments, cities have been suggested to be hotspots for MP emissions and deposition. Nonetheless, quantitative data on atmospheric deposition fluxes in urban areas remain sparse. More specifically, no such study has been conducted in Vienna yet. This study quantifies atmospheric MP deposition fluxes in Vienna using an observational approach, specifically measured using a wet and dry passive sampler, allowing for separate calculations of both the wet and dry deposition fluxes. Passive samplers offer a time and cost-effective method for quantifying MP deposition, whilst simultaneously facilitating the collection of precipitation. Samples are collected daily over one-week campaigns during winter and spring, to quantify the daily deposition fluxes and evaluate the seasonal variability. These samples are processed via oleoextraction, a recently developed technique of MP extraction. It has been selected for this study as it minimises both particle and polymer loss and yields a cleaner analysis in comparison to traditional approaches. The samples are then analysed via Focal Plane Array (FPA) Fourier Transform Infrared spectroscopy and microscopy for particle identification and classification. Using FPA detector facilitates the detection of particles down to $5\mu\text{m}$, a critical capability when assessing atmospheric MP which typically exhibit a smaller size distribution in comparison to other ecosystems. The FPA based automated analysis also reduces operator bias, along with covering a substantial portion of the total filter ($\sim 40\%$). After analysis, key meteorological data is assessed to consider any correlation between the quantity of deposition and wind speed, direction and rainfall.

The results show, from both the winter and spring sampling campaigns, several days of high deposition fluxes, in both the wet and dry, with fluxes ranging from $375 - 42,807.69 \text{ MP/m}^2/\text{day}$, significantly higher than published literature. This large range illustrates the high daily variability present throughout the campaigns. Alongside this, supported by the high resolution detection limit of FPA, the analysis shows a dominant size range to be between $20-45 \mu\text{m}$. Within these campaigns, polypropylene is found to be the dominant polymer, with other prominent species including polyethylene, polyethylene terephthalate and Polyvinyl Chloride. However, a large seasonal and daily variation in polymer type is observed, providing evidence for the presence of multiple sources and transport pathways, rather than one dominant source. In contrast to previous studies, the analysis shows only 9% of total plastic particles analysed to be microfibers, the remainder are fragments. This is in strong contrast with existing literature which has suggested fibres to be the dominant atmospheric morphology. To investigate these findings further, this study also assesses the impact of local human activity on atmospheric MP deposition, by conducting a dedicated short-term sampling experiment near the sampler, taking advantage of a public visit to the measurement site. The results reveal within a 3-hour window there is a notable increase in deposition reaching a flux of $18,965.5 \text{ MP/m}^2/\text{day}$, showing a particular increase in fibres. This demonstrates even limited human presence can contribute to a large local source of atmospheric MP and highlights the importance of the location of observations, showing a major difference from human influence between ground and rooftop activities. Assessing the meteorological variables reveals wind speed does not impact the variability across seasons, however, it is essential when assessing the daily fluctuations over shorter periods, with higher

wind speeds associated with increased deposition. This suggests, while there are several processes influencing MP deposition, wind speed is the dominant local influence on short timescales. Simultaneously, the results highlight the extremely effective wet scavenging mechanism for the removal of atmospheric MP, finding minimal plastic detection following rainfall events.

The overarching results of these campaigns uncover the oleoextraction method recovers a higher abundance of atmospheric MP than previously reported in literature, despite Vienna not being considerably more polluted than other European cities. These findings highlight the importance of gaining MP deposition fluxes at a high temporal frequency, in order to answer to the need to isolate potential sources, accurately quantify their high episodic variability and precisely characterise polymer and morphology variations.

Kurzfassung

Die atmosphärische Mikroplastikablagerung stellt einen wichtigen Übertragungsweg für die Plastikverschmutzung in allen Ökosystemen dar. Insbesondere Städte gelten als Hotspots für Mikroplastikemissionen und -ablagerungen. Dennoch sind quantitative Daten zu atmosphärischen Ablagerungsflüssen in städtischen Gebieten nach wie vor rar, und in Wien wurde bislang keine entsprechende Studie durchgeführt. Daher quantifiziert diese Arbeit die atmosphärischen Mikroplastikablagerungsflüsse in Wien anhand eines beobachtungsbasierten Ansatzes. Die Messungen sind speziell mit einem passiven Nass- und Trockensammler durchgeführt worden, was eine getrennte Berechnung eben dieser Ablagerungsflüsse ermöglicht. Passive Sammler bieten eine zeit- und kosteneffiziente Methode zur Quantifizierung der Mikroplastikablagerung und dienen gleichzeitig als Niederschlagssammler. Die Proben werden täglich im Rahmen einwöchiger Messkampagnen im Winter und Frühjahr entnommen, um die täglichen Ablagerungsflüsse zu quantifizieren und die saisonale Variabilität zu bewerten. Diese Proben werden mittels Oleoextraktion aufbereitet, einer neu entwickelten und vielversprechenden Technik, die für diese Studie ausgewählt worden ist, da sie sowohl den Partikel- als auch den Polymerverlust minimiert und im Vergleich zu herkömmlichen Ansätzen eine sauberere Analyse ermöglicht. Die Proben werden anschließend mittels Focal-Plane-Array (FPA)-Fourier-Transform-Infrarotspektroskopie und -Mikroskopie zur Identifizierung und Klassifizierung der Partikel analysiert. Der Einsatz eines FPA-Detektors ermöglicht den Nachweis von Partikeln bis zu einer Größe von 5–10 μm . Dies ist entscheidend bei der Untersuchung von Mikroplastik in der Atmosphäre, da es in diesem Kontext verglichen mit anderen Ökosystemen typischerweise eine feinere Größenverteilung aufweist. Die FPA-basierte automatisierte Analyse reduziert zudem den Operatorbias und deckt gleichzeitig einen erheblichen Teil des gesamten Filters ab (~40 %). Anschließend werden mögliche Korrelationen zwischen der Ablagerungsmenge und der Windgeschwindigkeit, Windrichtung sowie Niederschlag untersucht.

Sowohl bei den Probenahmen im Winter als auch denen im Frühjahr weisen mehrere Tage hohe Ablagerungsflüsse auf. Im nassen und im trockenen Zustand liegen diese deutlich über den Literaturwerten und schwanken zwischen 375 und 42.807,69 $\text{MP}/\text{m}^2/\text{Tag}$. Diese große Spanne verdeutlicht die hohe tägliche Variabilität, die während der gesamten Kampagnen zu beobachten war. Darüber hinaus zeigen die Ergebnisse, dass der vorherrschende Größenbereich zwischen 20 und 45 μm liegt, was den operativen Vorteil der FPA-Methode für atmosphärisches Mikroplastik unterstreicht. Im Rahmen der Kampagnen erwies sich Polypropylen als das vorherrschende Polymer, wobei andere bedeutende Arten wie Polyethylen, Polyethylenterephthalat und Polyvinylchlorid ebenfalls vertreten waren. Es sind jedoch große saisonale und tägliche Schwankungen bei den Polymerarten beobachtet worden, was darauf hindeutet, dass es mehrere Quellen und Transportwege gibt anstatt einer dominierenden Quelle. Im Gegensatz zu früheren Studien zeigt die Analyse, dass nur 9 % der insgesamt analysierten Kunststoffpartikel Mikrofasern sind, der Rest sind Fragmente. Dies steht in starkem Widerspruch zur bestehenden Literatur, die darauf hindeutet, dass Fasern die dominierende Morphologie in der Atmosphäre darstellen. Um diese Ergebnisse weiter zu untersuchen, bewertet die vorliegende Arbeit auch den Einfluss lokaler menschlicher Aktivitäten auf die Ablagerung von Mikroplastik aus der Atmosphäre.

Dazu wurde im Rahmen eines öffentlichen Besuchs am Messstandort eine gesonderte kurzzeitige Messung durchgeführt. Die Ergebnisse zeigen, dass innerhalb eines Zeitfensters von drei Stunden ein deutlicher Anstieg der Ablagerung auf 33 Kunststoffpartikel zu verzeichnen ist, wobei insbesondere bei den Fasern ein Anstieg festzustellen ist. Dies belegt, dass bereits eine begrenzte menschliche Präsenz zu einer erheblichen lokalen Quelle für atmosphärisches Mikroplastik beitragen kann. Ebenso unterstreicht dies, wie bedeutend die Wahl des Beobachtungsstandorts ist, da sich der menschliche Einfluss bei Aktivitäten am Boden und auf dem Dach deutlich unterscheidet. Die Auswertung der meteorologischen Variablen zeigt, dass die Windgeschwindigkeit keinen Einfluss auf die saisonalen Schwankungen hat. Sie ist jedoch entscheidend für die Beurteilung der täglichen Schwankungen, wobei höhere Windgeschwindigkeiten mit einer erhöhten Ablagerung einhergehen. Wenngleich mehrere Prozesse die Mikroplastikablagerung beeinflussen, deutet dies darauf hin, dass die Windgeschwindigkeit auf kurzen Zeitskalen den dominierenden lokalen Einfluss darstellt. Gleichzeitig unterstreicht die Studie, dass zur Entfernung von Mikroplastik aus der Atmosphäre das wet scavenging sehr effizient ist, da nach Regenfällen nur minimale Mengen an Plastik nachgewiesen worden sind.

Anders als bisher in der Literatur berichtet, zeigen die übergreifenden Ergebnisse dieser Kampagnen, dass mit der Oleoextraktionsmethode eine höhere Menge an atmosphärischem Mikroplastik gewonnen wird, obwohl Wien nicht wesentlich stärker verschmutzt ist als andere europäische Städte. Diese Erkenntnisse unterstreichen, wie wichtig es ist, Mikroplastikablagerungsflüsse mit hoher zeitlicher Frequenz zu erfassen, um potenzielle Quellen isolieren zu können, ihre hohe episodische Variabilität genau zu quantifizieren und Unterschiede bei Polymeren und Morphologie präzise zu charakterisieren.

Acknowledgments

Firstly I would like to thank my supervisor Silvia Bucci, for not only her passion and motivation for this project, but to also being the most supportive and compassionate supervisor I have ever encountered. From the hours spent assisting in the lab, to troubleshooting the microscopy procedure, to answering all my questions (usually physics related) without any judgement. She has introduced me to an incredibly fascinating topic on which this thesis is based, whilst also supporting my personal and career growth. I highly recommend her both as a supervisor and an individual, you will not find anyone better.

I would like to also like to express my gratitude for those closest in my life. To my parents who, without their constant support and encouragement, I would not be successfully completing this masters, their unwavering confidence in my abilities has carried me through this programme. To my closest friends, both near and far, who have seen me through the duration of these studies and constant reassurance has motivated through all challenging exams and courses. I could not have done it without their love, and support. Finally, to Alex Duțu, who's patience and understanding listening to the endless challenges of this project has been invaluable and is likely the only reason this project was completed with minimal tears.

Finally, I would also like to acknowledge the meteorological ground observation data was obtained from GeoSphere Austria and further want to acknowledge the use of Gemini AI for aid in some of the plotting scripts. Furthermore, I acknowledge the, as always helpful, use of python libraries throughout my scripts.

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1.0 Introduction

1.1 Background and Motivation

Global plastic production has risen substantially, with current estimates indicating an annual output of approximately 400 million tonnes (Mt) (Mohajan, 2025; Plastics Europe, 2021). Within Europe alone, this accounts for 55 Mt per year, corresponding to roughly 110 kg of plastic per individual annually (Mohajan, 2025; Plastics Europe, 2021). Whilst recycling initiatives are prevalent, they remain inefficient: in 2020 only 34.6% of the 29.5 Mt collected was recycled, with the remainder disposed of, or released into the environment (Plastics Europe, 2021). However, instead of fully degrading, plastics fragment into micro- and nano-sized particles which can persist in the environment for up to 500 years (Gasperi et al., 2018; Mohajan, 2025). As suggested by Thompson et al. 2024., the largest source of MP comes from this fragmentation of large pieces of plastic (macroplastics) which degrade into microplastics (MP) (Thompson et al., 2024). Whilst MP sizing is inconsistent, the most common definition lies within the range of $1\mu\text{m}$ - 5 mm, and nanoplastics 1000 nm or less (Allen et al., 2022; Gasperi et al., 2018; Thompson et al., 2004). This large range is peculiar as it presents analytical identification challenges and varied exposure pathways (Din et al., 2024; Rednikin et al., 2024). Due to the wide range of plastic sources, for example, paint, plastic pellets, synthetic textiles, tyres and personal care products, all of which contribute to MP leakage, results in the high variability of morphology, polymer and sizes present within all ecosystems (Rednikin et al., 2024; Thompson et al., 2024). After this release, MP migrate into various ecosystems including, soil (350 – 1604 MP/kg), rivers (3.5×10^{-4} MP/L) and sea ice (38 – 234 MP/m) (Büks & Kaupenjohann, 2020; Horton et al., 2017; Obbard et al., 2014; Thompson et al., 2024). In this context, MP fallout from the atmosphere (2–1007 MP/m²/day) can represent an efficient pathway for widespread contamination (Aeschlimann et al., 2022; Allen et al., 2021; Dris et al., 2016; Wright et al., 2020).

Plastics can be further characterised by their composition, mainly comprising polymers and additives, such as flame retardants, colourants and stabilisers, all of which improve the functional properties of plastics (Gigault et al., 2021; Hahladakis et al., 2018). Studies are now examining the impact of MP on human and ecosystem health, where they can be absorbed via different routes: inhalation, dietary intake and dermal absorption (Cox et al., 2019; Gouin, 2022; Thompson et al., 2024). The research on MP and the human body is relatively novel, however, there have been new findings quantifying MP in various organs e.g. liver (3.2MP/g) hair (3.5 MP/individual/day), saliva (0.33 MP/individual/day) and blood (1.6 ug/ml) (Horvatits et al., 2022; Leslie et al., 2022; Sun & Wang, 2023; Thompson et al., 2024). The presence of associated additives represents an additional health concern, triggering immune and stress responses which can lead to reproductive and developmental toxicity (Blackburn & Green, 2022). Additionally, some plastics absorb organic pollutants, such as, polycyclic aromatic hydrocarbons (PAH), which act as carcinogenic and mutagenic agents (Gasperi et al., 2018; O'Brien et al., 2023; Rubin & Zucker, 2022).

The importance of the atmosphere and its role in MP distribution is significant, it acts not only as a compartment for MP, but also as a critical medium for redistributing particles across the terrestrial, freshwater and, marine environments, as highlighted in Figure 1 (Aeschlimann et

al., 2022; Long et al., 2022). Understanding these atmospheric processes is vital for quantifying the global plastic cycle and identifying sources and sinks, as currently it acts as an unknown conduit (Brahney et al., 2021; Shan et al., 2026a). MP become airborne initially by the MP fragmentation process described earlier, the pieces become smaller until they become entrained into the air (Jahnke et al., 2017). There are several key suspension mechanisms, resuspension from soil, entrainment with desert dust and sea spray (Abbasi et al., 2023; Aeschlimann et al., 2022; Allen et al., 2020; Kallenbach et al., 2022). The MP after entering the atmosphere can remain there for a varied period of time depending on their size, morphology and density, low density polymers include polyethylene (PE) and polypropylene (PP) ($<1\text{ g cm}^3$) and high-density polymers ($>1.2\text{ g cm}^3$) include polyvinyl chloride (PVC) and polyethylene terephthalate (PET) (Abbasi et al., 2023; Brahney et al., 2021; Kallenbach et al., 2022; Long et al., 2022; Reininger et al., 2025). The morphology of plastics also influences their atmospheric residence time, as demonstrated by Tatsii et al 2024., as a larger surface to volume ratio, or very irregular morphology, make the aerodynamic drag significantly higher, creating a higher suspension lifetime (Long et al., 2022; Ravi et al., 2020). Similarly, heavier MP quickly settle from the air and are unlikely to be transported far from their sources (Brahney et al., 2021; Long et al., 2022). A study by Reininger et al 2025., showed morphology having a large impact on settling velocities, showing glitters and fibres can settle slower, up to 74% and 78% respectively, compared to volume equivalent spheres (Reininger et al., 2025). These variations in plastic morphology and sizes have led to the presence of plastics within remote regions, such as: the arctic, glaciers and remote mountains (Bergmann et al., 2019; Rednikin et al., 2024). MP also have the potential to be entrained into clouds where the scavenging effects occur, as illustrated in Figure 1, however, these processes are still not well understood (Aeschlimann et al., 2022). In principle, the MP are hydrophobic, however due to weathering and coating with biological material, they become significantly more hydrophilic, with the then potential for MP to be uplifted into clouds, potentially becoming hygroscopic (Jahnke et al., 2017; Lobelle & Cunliffe, 2011; Mao et al., 2024; Moyal et al., 2023; Xu et al., 2024). This has been highly supported by the fact there are often more MP in precipitation than in dry deposition (DD) (Dris et al., 2016; Kernchen et al., 2024; Shan et al., 2026b).

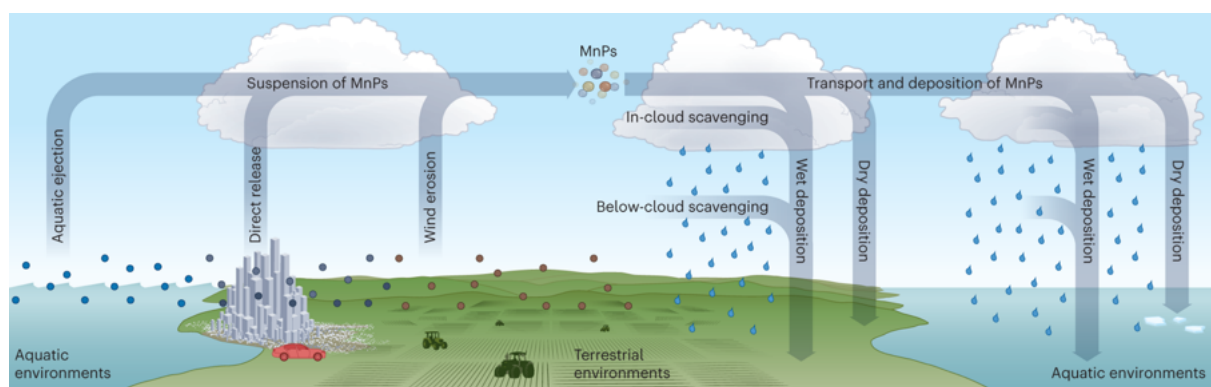


Figure 1: Shows the suspension and transport pathways of atmospheric MP (Aeschlimann et al., 2022).

MP can also be subcategorised by morphology into fibres, fragments, films, foams and beads/pellets (Szewc et al., 2021). The fibres, fragments and films represent the dominant forms within the atmosphere, each morphology exhibiting unique transport and deposition behaviours (O'Brien et al., 2023; Tatsii et al., 2024; Turner & Kyriakoudes, 2022; Zhang et al., 2020). Atmospheric MP lend themselves to be smaller in comparison to other ecosystems, some examples include, Kerchen et al., finding a range of 11 – 130 μm and Gaston et al.,

finding an average size of $104.8 \pm 64.9\mu\text{m}$, however, these values are often limited by analytical techniques (Carriera et al., 2024; Gaston et al., 2020; Kernchen et al., 2024). A notable contribution to the larger size ranges observed in atmospheric MP within the literature are microfibrils, which can reach up to a few millimetres in length, such as in Dris et al 2016., seeing a microfibre distribution of $50 - 3000\mu\text{m}$ and Wright et al., 2020 seeing the most abundant fibre lengths to be between $400 - 500\mu\text{m}$ (Dris et al., 2016; Wright et al., 2020). Despite their large lengths, fibres have a similar diameter to other MP shapes, lending themselves to atmospheric transport (Reininger et al., 2025; Tatsii et al., 2024).

1.2 Previous Studies

There have been several studies calculating the atmospheric MP deposition flux across large European cities, such as London (771 ± 167 particles/ m^2/day), Paris (110 ± 96 particles/ m^2/day), Hamburg (275 particles/ m^2/day) and Barcelona (235.9 particles/ m^2/day) (Dris et al., 2016; Edo et al., 2023; Klein & Fischer, 2019; Wright et al., 2020), however, no such study has been performed for Vienna. There have been only two studies based in Austria: Graz (238 ng/ m^3) and Sonnblick (35 ng/ m^3 PM₁₀ and 21 ng/ m^3 PM₁) both of which focussed on concentration rather than deposition (Kau et al., 2024; Kirchsteiger et al., 2023). In this instance, it is difficult to compare these Austrian values to other European studies, as they have incompatible size ranges comparatively, and are given in concentration rather than deposition, which is typically more prevalent in other cities. This highlights one of the most pressing issues with MP research, which is the mismatch of methods and data sets, making it challenging to accurately compare different studies to gain a relevant pool of data.

The size distribution of MP is not well characterised within the literature, presenting a noticeable gap largely due to analytical limitations, mostly due to the lower limit of detection, reaching $20\mu\text{m}$, common within most analytical methods (Faauma et al., 2026; Maurizi et al., 2023). Nonetheless, it is imperative to have a size distribution which encompasses finer particles, as particle size directly governs the atmospheric residence time, transport distances, deposition velocities and inhalation potential (Long et al., 2022; Ravi et al., 2020). These smaller particles, order of a few microns or less, become critical for transport, cloud and atmospheric processes, making the quantification of these smaller size fractions critical (Brahney et al., 2021; Jahnke et al., 2017; Shan et al., 2026a; Thompson et al., 2024). The size distributions, however, are not well known or characterised and only reported in a limited number of studies, for instance, Wright et al 2020., shown in Figure 2.

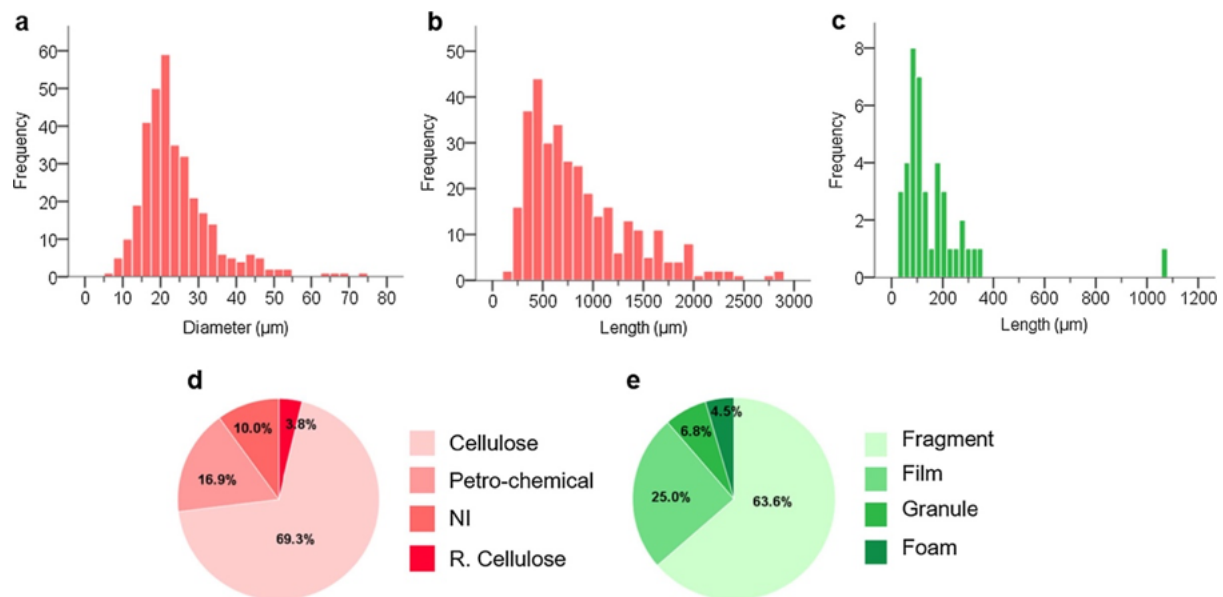


Figure 2: The size and shape data from Wright et al 2020., from all the particles analysed in their atmospheric microplastic deposition study.

Within the literature, there has been specific focus on capturing fibres and observing their prominence within atmospheric deposition, for instance, Dris et al 2016., have found almost all MP collected within their study were fibres and Napper et al 2023., found a large flux of 81.6 fibres/m²/day (Dris et al., 2016; Napper et al., 2023). A study conducted in London by Wright et al 2020., found fibrous MP accounted for 92% of all analysed MP (Wright et al., 2020). Whilst the data on MP is currently limited, a consensus has been drawn on the dominance of fibres within atmospheric deposition, specifically within wet deposition (WD) (Bergmann et al., 2019; Turner & Kyriakoudes, 2022; Welsh et al., 2022). Similarly, while the data on size distributions is limited, some papers have reviewed the common polymers and shapes across several studies. Ahmadi et al 2026., reviews 84 published studies between 2019 and 2025, creating figures comprising common polymer and shapes highlighted in Figure 3 (Ahmadi et al., 2026). Figure 3 introduces an interesting contradiction showing within outdoor samples fragments are the dominant shape rather than fibres, stating an opposite view than what the above papers have mentioned. This highlights the disparity of results seen across literature and the growing need for more concrete data and datasets.

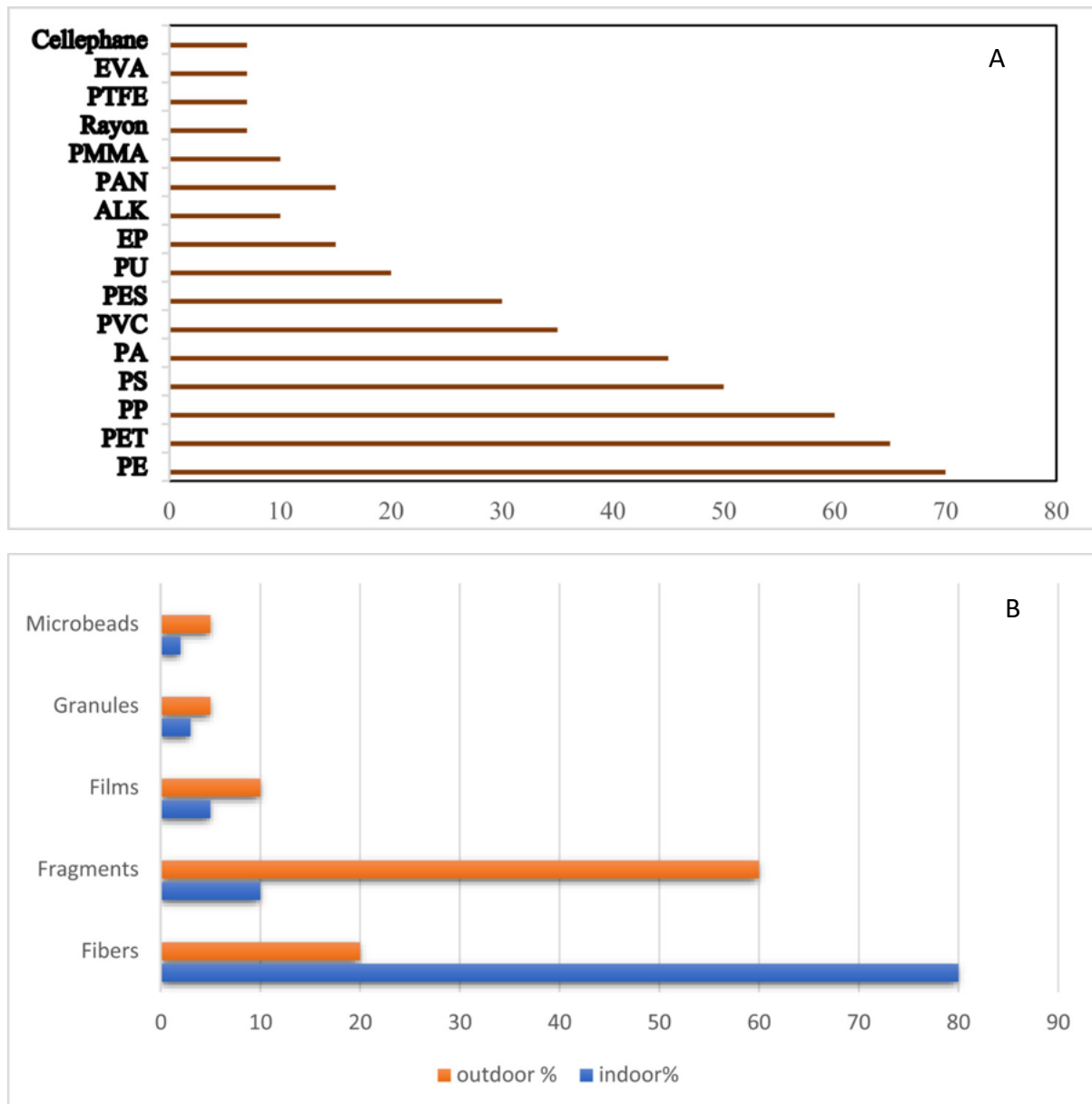


Figure 3: Figures from Ahmadi et al 2026 showing the dominant polymer and shape categorisations across 84 published studies. Plot A) highlights the dominant polymers plotted as a percentage across 84 studies and plot B) showing the different morphologies across all 84 studies (Ahmadi et al., 2026).

An important influence on the quantity of MP observed are specific meteorological variables (Roblin et al., 2020). Most notably researched being the scavenging effects, this can be split into below-cloud, the removal of particles by precipitation, and in-cloud, acting as cloud condensation nuclei or particles captured by cloud water, highlighted in Figure 1 (Zhao et al., 2015). The scavenging effect results in a higher number of MP to be found within the initial hours of rainfall in comparison to the last hours of rainfall, a process known as atmospheric washout (Abbasi et al., 2024). This effect has been observed to clean a polluted atmosphere by the removal of particulates and pollutants (Abbasi, 2021; Zhao et al., 2015). A study by Turner & Kyriakouides 2022., found significant differences between MP captured from WD and DD (Turner & Kyriakouides, 2022). WD showed generally coarser particles, with a higher proportion of fibres, fragments and foams comparatively to the DD (Turner & Kyriakouides, 2022). Results here also showed specific polymers, such as rayon and acrylic are more likely to be scavenged than other polymers, such as PET (Turner & Kyriakouides, 2022). These

morphology and polymer characteristics of MP may be crucial in the transportation and residence times within the atmosphere and their associated deposition fluxes (Roblin et al., 2020; Turner & Kyriakouides, 2022). Wind speed and direction are equally as important when assessing MP abundance, with some studies observing a positive correlation between wind speed and MP quantity and others finding direction to be more relevant (Bergmann et al., 2019; Roblin et al., 2020; Welsh et al., 2022). It is therefore imperative when conducting MP experimental studies, to incorporate relevant meteorological data into the study.

1.3 Novelty of the study

This thesis has been built to address the existing research gaps present within current literature. The deposition studies across Europe are scarce, and Vienna has not yet been covered. Additionally, there are very few studies which have achieved a daily temporal resolution of analysis in both the wet and dry fluxes, and even fewer studies capture particles below 20µm (Faauma et al., 2026; Maurizi et al., 2023). The chosen methodology is meant to achieve these objectives combining a cutting-edge, highly effective extraction method and automatic collection of spectra on a 40% section of the filters, with a high temporal spatial resolution of separated wet and dry. This method also involves cross checking the classified polymer spectra and a rigorous determination of sizes and morphologies, going beyond automatic detection. The study also includes an additional experiment aiming to isolate the impact of human presence on the emissions of MP, conducting a 3-hour campaign during a university open day to test two critical hypotheses: the first, to assess if sampling on the 35m rooftop is isolating the measurements from ground-level contamination. The second, to assess whether human movement and presence in the outdoors can act as an immediate, localised source of atmospheric MP and fibres themselves.

With the chosen analytical and sampling methods, special attention can be placed on the morphology, appearance and sizes of all detected particles. This level of detail is essential for identifying specific polymers and disentangling them from the various emission sources present. This is particularly meaningful when adopted along with short time resolution sampling, as the daily variation of morphology, colour and composition can be concretely assessed. This aids in linking the potential sources and transport processes of these plastic particles. This fine temporal resolution allows for better understanding of the meteorology and its impact on MP deposition. The expectation, due to previous studies, is for MP presence to result from the overlap of the intensity of emissions, source regions, size range and meteorological patterns (wind speed and direction). Repeating the sampling campaign during the winter and spring aims to provide a comprehensive understanding of seasonal dynamics and temporal variability.

1.4 Research Questions

As evidenced above, there are significant gaps in the field of MP research, specifically referring to characterising MP abundance in urban areas, their likely sources and the dominant processes influencing MP transport. The methodological difference used between all MP studies further exacerbates the knowledge gaps already present whilst also reducing the ability for study intercomparisons. For this reason, amongst the major limitations outlined within this section, the lack of detailed polymer and size categorisation at a high temporal

interval could be considered one of the largest gaps. Therefore, having observational based campaigns with robust methodologies is critical to advance and improve the research within this field.

The aim of this thesis is to address some of the major limitations and knowledge gaps, by providing the first detailed study of MP deposition in the densely populated city of Vienna. The study uses a Wet&Dry passive sampler, combined with the progressive oleoextraction method and FPA-micro-FTIR microscopy, allowing for the accurate calculation of both WD and DD fluxes. The study further aims to investigate how meteorological conditions affect MP abundance, linking key meteorological variables to accurate MP values. This piece of work therefore follows the research questions outlined below:

1) What is the atmospheric deposition flux of MP in Vienna?

Due to the current data gap, the primary aim of this study is to provide the first quantitative assessment of atmospheric MP deposition flux in Vienna. The chosen method of daily sampling, along with the chosen sampler, allows for separate wet and dry deposition collection. This will provide a robust baseline dataset for future studies operating within similar regions.

2) What are the morphological and size data of collected MP within Vienna?

As the presence of atmospheric MP is due to a combination of physical factors, this thesis will characterise the analysed particles and categorise them by their species, size and morphology. These attributes, given their lack within the research, will provide valuable data on the potential MP sources along with potential atmospheric transport processes and deposition behaviour. The developed method allows for smaller particles to be assessed as these are often misrepresented in the literature, despite their prominent role in atmospheric transport and human health.

3) How does atmospheric deposition vary under differing meteorological conditions?

Atmospheric MP are heavily influenced by meteorological conditions, from the high removal rate from wet scavenging to the higher resuspension influence associated with higher wind speeds. This thesis aims to assess the relationship between key variables (wind speed, wind direction and precipitation) against the calculated deposition fluxes to assess any systematic patterns. Specifically, the study will assess the role of wet scavenging as a removal process for MP and also investigate, with the daily sampling, the daily variability of meteorological conditions and their associated influence on the daily variability of MP abundance.

4) Can a seasonal variability of MP deposition be observed, including any differences in size, morphology and species?

To ascertain any seasonal differences, two sampling periods are conducted, one within winter and one within spring. Due to the meteorological and transport differences between these periods, an expected difference in the MP quantity, composition and size could be seen due

to the varying emission sources and resuspension processes. This could in turn result in a large variability throughout the year, a behaviour still not well known.

2.0 Methods

The chapter presents the research methodology, which includes three phases: sampling, extraction, and analysis. The methodology is further broken down into the three different campaigns: pilot study, winter campaign and spring campaign.

2.1 State of the Art

2.1.1 MP Methodologies

In order to quantify atmospheric MP deposition, a robust methodology must be developed. This commonly consists of a sampling strategy (active or passive sampling), a procedure to extract MP from the sampler and a method to analyse and quantify the plastics from the sample. Several methodologies exist for MP sampling, extraction and analysis, all with advantages and limitations outlined within this section.

2.1.2 Sampling Methods

The sampling methods for atmospheric MP collection are either achieved via passive or active sampling (Habibi et al., 2022). Active sampling operates by drawing air into a vessel using an integrated vacuum pump, whereas passive sampling relies on deploying equipment to a fixed location for a prolonged period, allowing deposition to fall (Habibi et al., 2022). A study by Habibi et al., 2022 showed out of the 38 outdoor studies, 21 used passive sampling and the others used active sampling, whilst indoor studies showed an even split of six studies using active sampling and five using passive. Active sampling is well established and is very time efficient, taking in large volumes of air quickly. However, they incur higher operating costs than passive samplers, require a consistent power supply and require skill to operate (Habibi et al., 2022). Conversely, passive samplers are more cost effective, require less skill to operate and allow distinct differentiation between WD and DD (Habibi et al., 2022). However, they are time consuming to operate and cannot be effectively used for short periods (Habibi et al., 2022). Due to the cost effectiveness and the necessity to differentiate between WD and DD, passive sampling is chosen for this study.

2.1.3 Extraction Methods

There are several MP extraction methods commonly used, density separation is amongst the most popular. This method involves the addition of a dense solution, typically made dense with salts (e.g. Zinc Chloride, Zinc Bromide, sodium iodide) to the environmental sample, causing MP with lower densities to float (Crutchett & Bornt, 2024; Quinn et al., 2017). This method is highly effective at separating dense MP from solution, even reaching a 95% recovery rate in a study by Crutchett & Bornt, 2024. Within a study by Quinn et al., 2017, they analysed the recovery rate of several plastic polymers across three different brine solutions showing zinc bromide had the highest recovery across all plastic polymers (Quinn et al., 2017). However, this method is subject to limitations, including the associated costs of reagents, potential health impacts, both human and environmental, and the limited efficiency of

recovering certain polymers, especially if characterised by a density higher than salts (Tirkey & Upadhyay, 2021).

Another popular method involves direct filtration, which eliminates preprocessing and instead passes the environmental sample directly through a vacuum pump. This method is highly effective as it minimises MP loss, which may occur in other methods through the transference between different vessels. This lends itself towards a very high MP recovery rate, witnessed by Weber & Kerpen 2023, finding recovery rates ranging from 85-88% using a direct filtration approach (Weber & Kerpen, 2023). However, if no preprocessing is done in conjunction with filtering, all organic material will remain within the sample, which makes analysis more challenging. Therefore, some degree of preprocessing would be more optimal, but could result in higher MP loss and increased costs (Klein & Fischer, 2019). For this study, simple filtration is tested to assess its effectiveness, evidenced in section 2.4.1 Sampling Strategy. For the reasons outlined within section 2.4.1 Sampling Strategy, the study proceeded with a recently developed method known as oleoextraction, which involves the extraction of MP with oil (Corami et al., 2021; Rosso et al., 2023). Oleoextraction exploits the hydrophobic nature of plastic polymers. Due to the fact both plastics and vegetable oils are non-polar, MP particles are attracted into the oil phase rather than remaining within the aqueous phase. This method is highly effective at recovering MP without damaging them, as strong oxidants are avoided. Despite the likelihood of loss during the digestion phase needed to remove organic material, this method shows a higher MP retrieval in comparison to other above-mentioned methods, while simultaneously offering a more cost effective and less hazardous procedure (Corami et al., 2021; Crutchett & Bornt, 2024; Cutroneo et al., 2021; Rosso et al., 2023). After assessing the requirements for this study, the oleoextraction method is considered the most appropriate.

2.1.4 Analytical Methods

The methods of analysis also vary across studies, each exhibiting a unique set of benefits and limitations. The first is Raman spectroscopy, this has a high spatial resolution and can assess smaller particles up to 2 μ m, particularly useful for atmospheric MP (Käppler et al., 2016; Liu et al., 2023; Zada et al., 2018). However, due to the size resolution, the method is very time-consuming comparatively to others (Käppler et al., 2016; Liu et al., 2023; Zada et al., 2018). Furthermore, coloured particles may lead to fluorescence interference, making it particularly challenging to use for environmental MP.

Other techniques include Pyrolysis Gas Chromatography Mass Spectrometry and Thermal Desorption Mass Spectrometry. These methods involve the burning of plastics to assess either, the gas released from the particle, or to be run through spectroscopy (Forbes et al., 2023; Meier & Faix, 1992). These are effective methods as they are unrestricted by mass, a notable limitation to other analytical techniques (Zada et al., 2018). However, the destructive nature of these approaches, prevents reanalysis or validation of findings (Zada et al., 2018). Additionally, no shape or size data can be obtained, which is a particularly useful trait for atmospheric MP (Zada et al., 2018).

Finally, Fourier Transform Infrared Microscopy (Micro-FT-IR) is a commonly used analytical method for MP. This method allows for exact polymer identification through spectral analysis

and spectra libraries, alongside allowing for exact size and shape information, something not possible with other methods (Käppler et al., 2016; Renner et al., 2019). However, this method is time-consuming in comparison to others, it is extremely labour intensive requiring the use of liquid nitrogen to operate and has a size limit of 5-10 μ m (Käppler et al., 2016; Renner et al., 2019). Another notable limitation of this analysis is the ability to assess tire wear spectra. Tire wear is not easily detected by FTIR due to the presence of black carbon, which absorbs the IR beam, resulting in spectra which cannot be analysed via fingerprint peaks (Hossain et al., 2026; Le Picard et al., 2026). Despite these limitations, based upon the needs of this project, FTIR is considered the optimal choice. A highly promising advancement for the FTIR is the use of Focal Plane Array (FPA). FPA operates using a grid of many detector elements allowing for the automatic detection of spectra to be obtained in a short time span (Löder et al., 2015). The FPA improves the accuracy of MP analysis and reduces operator bias (Primpke et al., 2017). For this study, the samples were analysed with a FTIR equipped with a 32 x 32 FPA detector, this refers to the number of pixels collected over the x and y axis of the image, each corresponding to the collection of an infrared spectrum.

2.2 Study Site

The study site is located in Vienna, Austria (N 48.22168°, E 16.355580°) on the rooftop of Boltzmanngasse 5, shown in Figure 4 with a height of 32m above ground level (203 m +/- 4.3 m above sea level). The sampler is placed in an elevated position on the roof, 1m above the platform, resulting in a total height of 33m above ground level. The sampler has a bucket depth of 35cm. This location hosts the observatory laboratory of the University of Vienna Physics Department, already used for aerosol observations and accommodates several sampling and observation devices. The surrounding area of the sampler consists of residential buildings and a construction site less than a kilometre away.

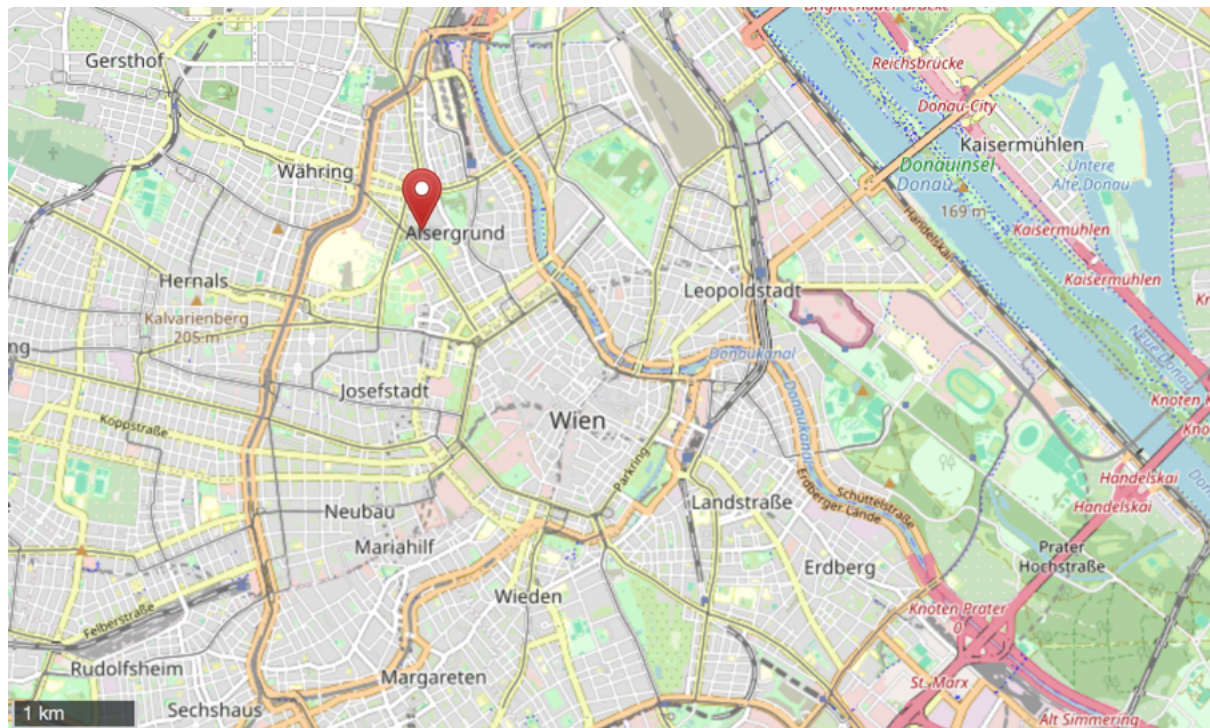


Figure 4: Map showing the location of the study site at Boltzmanngasse 5 on the rooftop of the University of Vienna Physics department and the surrounding area. This image was sourced from OpenStreetMap.org

2.3 Sampling Procedure

The sampling is performed with the Wet&Dry passive sampler used for the collection of the atmospheric depositions, generated from both rainy and snowy precipitations (wet) and from the dust depositions (dry). It is split into DD and WD collection chambers, in accordance with the European Air Quality directive (2004/107/EC). It operates via a rain sensor in the middle, which automatically triggers a plate to move, exposing the wet collection chamber during heavy rainfall events, whilst protecting the dry collector. During dry conditions, the system operates in the opposite configuration. This system allows for a large range of environmental conditions to be captured. An image highlighting the key components of the sampler are shown in Figure 5.

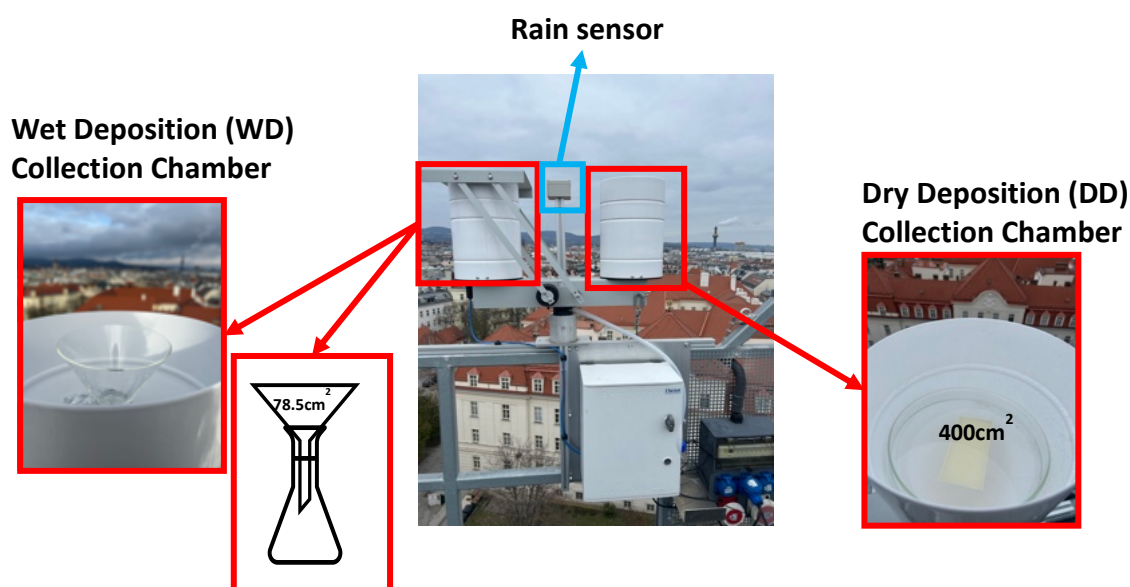


Figure 5: Showing the Wet&Dry passive sampler located at Boltzmannngasse 5. The figure highlights the WD and DD collection chambers with collection vessels, a glass bottle with funnel and a petri dish respectively.

To completely remove plastic from the sampling equipment, relying solely on metal or glass items, the sampling is achieved by placing a glass bottle and funnel (78.5cm^2) in the WD container, removing the standard plastic tube and collection bottle, and using a glass petri dish (400cm^2) in the DD container. Preliminary experiments indicated the sampling period for the deposition flux at this location should not exceed 2 weeks or more. Under these extended sampling durations, the sample becomes obscured by a large number of particles, making analysis ineffective due to particle overlap and overload on the filter, as seen in the example of Figure 6A. After testing, for all campaigns, a daily retrieval period is considered to provide the optimal results, as seen in Figure 6B. Therefore, the campaigns have been performed, using the equipment shown in Figure 5, for a period of 24 hours (from 11:30am – 11:30am CET) before being collected. The DD sample is collected by replacing the lid on the petri dish directly in the collection chamber and covering in foil. The WD is rinsed with 40ml of Milli-Q water, followed by covering the top of the bottle in foil and finally replacing a foil covered plastic cap. All equipment is then exchanged with sterilised glassware for the following 24-hour sampling period. A limitation to this approach, having a very limited amount of material, is the impossibility of performing sampling replicates, resulting in an unknown uncertainty to be calculated, as further explained in the section

2.9 Sources of Uncertainty and Methodological Limitations.

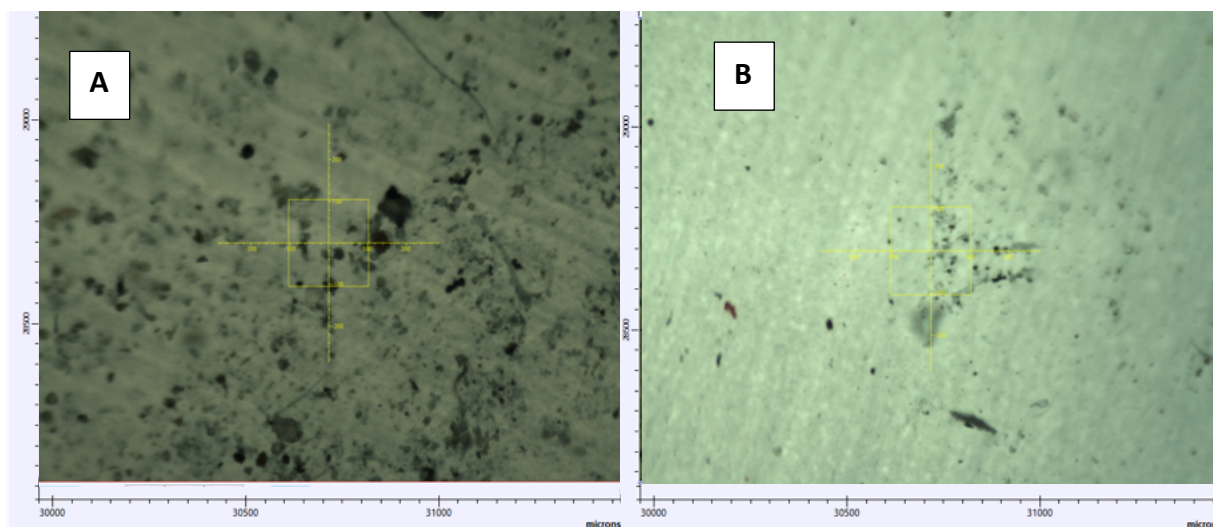


Figure 6: Shows two separate filters A) filter taken from the preliminary studies conducted in October, which has a 2-weekly sampling period and B) from the pilot study done in November.

2.4 Method Selection

2.4.1 Sampling Strategy

As explained in section 2.1.3 Extraction Methods, there are multiple methods of MP extraction. For this study, oleoextraction is chosen over alternative techniques due to its high retrieval rate and lower costs. However, a DD sample is extracted via direct filtration to provide a methodological comparison, as direct filtration would be considered more time and cost effective. The results of this however, as shown in Figure 7, highlight the complexity of analysis. The filter is obscured by a high number of particles and due to the lack of H_2O_2 , the majority of these are found to be organics. Due to the complexity of assessing the polymer, shape and morphology characteristics of particles across the filter, despite the simplicity of the method, it is deemed an inappropriate technique.

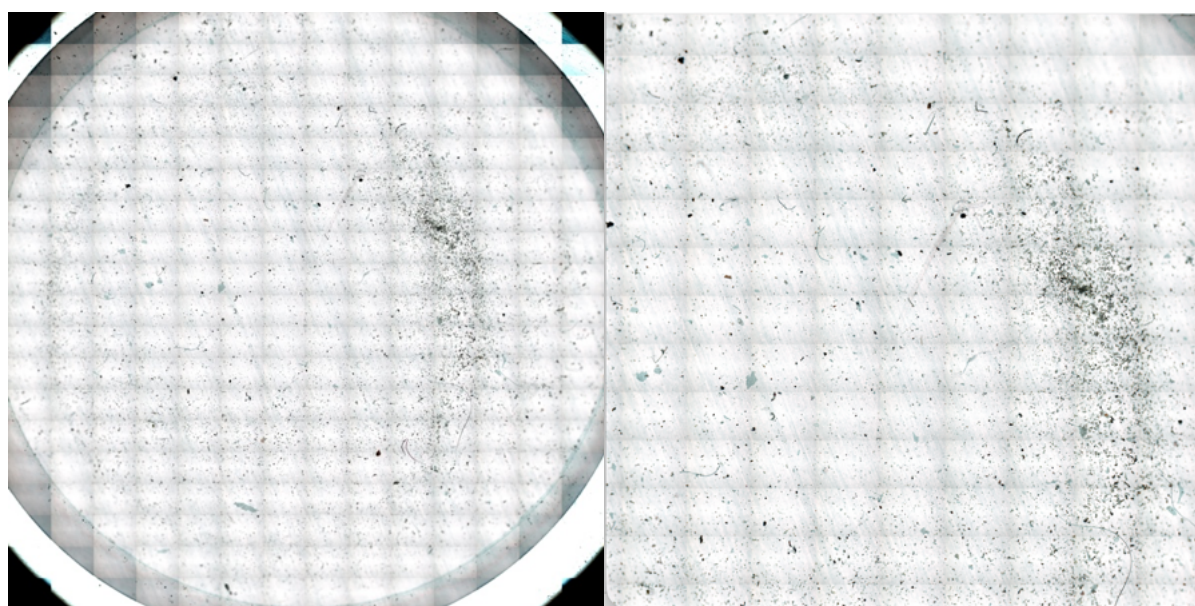


Figure 7: Shows a filter from the 24/03/2026 DD with the different methodology of direct filtration.

2.4.2 Extraction Technique

The oleoextraction method aims to isolate MP for subsequent analysis of polymer type, morphology and size. The laboratory procedure consists of three stages: sample recovery, digestion and oil separation, and filtration. As the lab procedure across campaigns involves minorly varying methodologies, they will be explained individually. Within the procedure, blanks are processed alongside each round of samples to ensure the correct ambient plastic is accounted for, as outlined in section 2.5.2 Procedural and Field blanks.

2.5 Quality Assurance and Quality Control

2.5.1 Contamination Prevention

To reduce contamination across all campaigns, glassware is sterilised with 3 washes of water, isopropanol, distilled water and Milli-Q water. The extraction is conducted within a sterilised fume hood, where all glassware is covered with foil across all phases of the procedure, as seen in Figure 8. To further minimise contamination during sampling and extraction, clothing composed of 100% cotton or wool is worn throughout all procedures, and all lab coats are lint rolled before and during the laboratory procedure. Alongside this, wherever possible when not using solvents, the fume is switched off to reduce particles entering the fume via the air flow.



Figure 8: Image of the fume hood within the Division of Environmental Geosciences (EDGE) laboratories where the extraction is conducted.

2.5.2 Procedural and Field blanks

Within each round of sampling a procedural blank is obtained to assess the ambient contamination present within the laboratory. This is achieved by carrying out the same procedure as outlined in section 2.4.2 Extraction Technique, described in detail within section 2.6 Protocol Development. With the sole difference of replacing the environmental samples with clean Milli-Q water. This allows identification of the plastic particles introduced from the laboratory procedure to further be from the environmental samples allowing for an accurate MP count. The field blanks are assessed in a similar way, simply performing the procedure of collection in absence of any real atmospheric sampling. After these blank values are obtained, they are removed from the sample with the following methodology. A correction function has been developed considering the morphology, species and area of the synthetic particles within the blanks. The function removes particles found within the blank from the environmental samples only when they exhibit matching characteristics within the species, morphology and comparable area (deviation of 20%). If these traits do not match, the blank particles are not removed from the sample. This method ensures only particles comparable to the blank, and therefore most likely to come from laboratory contamination, are removed.

2.5.3 Recovery Experiments

The laboratory procedure included several recovery experiments to assess the degree of loss which could be expected during the processing, allowing for the results to be upscaled against this value. Recoveries are achieved by placing a known amount of plastic at the beginning of the laboratory experiment in a clean Milli-Q water sample. The protocol is then executed as normal and the filter is analysed at the end, to determine the number of plastic particles remaining. This is done with a range of shapes and polymers to assess the effectiveness of the procedure across different plastic characteristics. Varying glitter sizes ranging from 0.1mm – 0.4mm are commonly used for recoveries, specifically chosen to visually determine where loss is occurring throughout the procedure.

2.5.4 Instrument QA

In order to avoid underestimation in the number of particles, a hit threshold of 400 is chosen for the MP classification as explained in section 2.7.2 Spectral Analysis: MPID OPUS and OpenSpeccy. This threshold is chosen to not neglect particles with noisier spectra due to atmospheric weathering and particle degradation. Due to this lower threshold, to maintain robustness in the results, the suspected plastic particle spectra are also processed through Spectragryph to convert the file type from a .0 to a .spc format. The spectra could then be analysed under the OpenSpeccy software, using the suggested preprocessing settings of min-max normalisation, smoothing/derivative and conform wavenumbers, along with the suggested threshold correlation of 0.7. An example of a PP detected spectra is shown in Figure 9, showing the original spectra detected from OPUS in white, and the reference spectra from OpenSpeccy plastic spectra libraries shown in red. The software compares the reference spectra to the environmental spectra and creates a match value based upon the fingerprint peaks. The notable variation between the OPUS and OpenSpeccy results is polyamide (PA) and organic material, as it is common for OPUS to classify a particle as PA and OpenSpeccy to consider the same particle to be organic material. All results should be interpreted with the methodological disparity, understanding PA is likely to be overestimated. Therefore, for specific particles with unknown or noticeably misidentified particles, the spectra were

evaluated manually to determine species, however, this is avoided where possible to minimise operator bias.

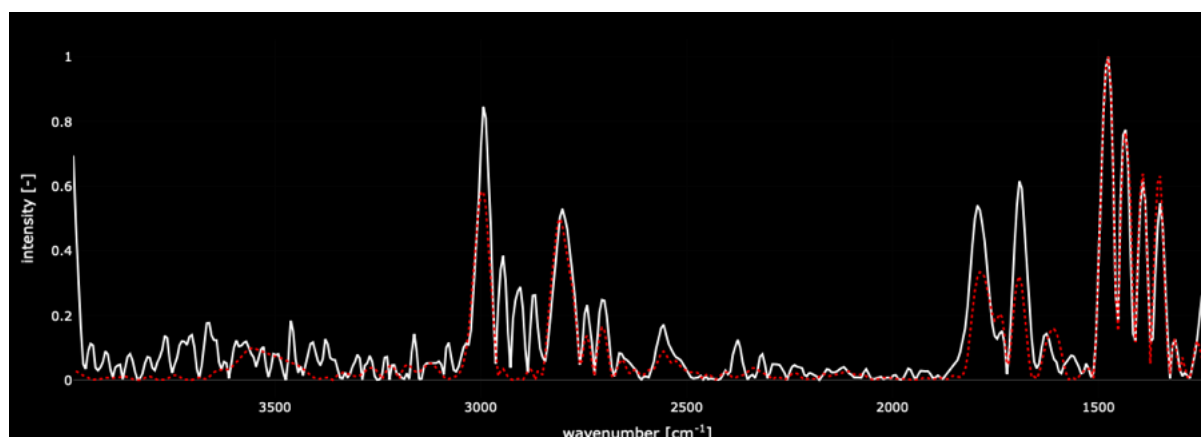


Figure 9: Example PP categorised spectra from the 24/02/2026 WD in OpenSpecy, the original spectra is highlighted in the white line and the reference spectra from a plastic library is in the red line.

2.5.5 Ancillary Data

To include meteorological comparisons within this study, data was obtained from a nearby weather station from Geosphere Austria <https://dataset.api.hub.geosphere.at/app/frontend/station/historical/klima-v2-10min>. All data was checked for completeness and consistency before inserting into the study. The same weather station (Hohe Warte: ID 105) is used for the duration of all campaigns to ensure comparability between campaigns.

2.6 Protocol Development

The oleoextraction protocol utilised for this study is originally taken from a developed procedure by F. Corami and B. Rosso (Corami et al., 2021; Rosso et al., 2023). However, this procedure has been further adapted and developed based upon the scientific considerations present throughout the study. The specific methodology of each campaign is described below

2.6.1 Pilot Study (26/11/2025 – 03/12/2025)

The first stage involves recovering the DD and WD from the petri dish and glass bottle respectively. This is achieved by rinsing the vessels with 500ml of Milli-Q water and transferring into 500ml separating funnels, where 10ml hydrogen peroxide (H_2O_2) is added to digest organic material. Subsequently 5ml of solvent-free, cold pressed sunflower seed oil is added, to separate the MP from the remainder of the solution. A glass stopper is added, and the funnel is shaken several times, ensuring to vent from the valve to release the build-up of pressure from digesting organics. The solution is left for 24 hours to allow for phase separation.

The second stage involves pouring the gathered oil phase from the top of the funnel into a 250ml separating funnel. This process is repeated 5 times, pouring from the top and refilling with Milli-Q water to ensure the majority of oil is incorporated into the 250ml funnel. The funnel is closed with a glass stopper and shaken vigorously several times, again ensuring to

vent from the valve. This stage is left for three hours to ensure phase separation. The water is drained from the bottom of the funnel ensuring to keep all the oil phase. The oil phase is then transferred into a conical flask, with 2 rinses of 10ml of hexane to dissolve the oil, followed by 2 rinses of 15ml methanol-ethanol (1:1 ratio) to clean the funnel. All these rinses are poured from the top of the funnel into the conical flask ensuring all oil, and by proxy MP, are removed from the funnel and added to the conical flask.

The final stage is filtration, where the sample is passed through a 0.2 μm pore-size Anodisc filter attached to a vacuum pump to accelerate flow. In the preliminary studies a 0.02 μm pore-sized filter is used, however, this was determined to be excessively fine, resulting in significantly reduced filtration rates, rendering the process impractically slow. The filtering involves sequential adding of Milli-Q water, sample and solvents to maximise particle recovery and remove oil from the filter. The sequence is as follows: Milli-Q water followed by ethanol, add in roughly 5-10ml of sample, followed by hexane, methanol-ethanol and finally ethanol. The sequence is repeated starting with the sample and ending with ethanol until all the sample is filtered, the conical flask is rinsed twice with methanol-ethanol and then twice with ethanol. Once all the solvents are filtered, the anodisc is removed and placed in a sterilised petri dish, left covered to dry completely, allowing solvent residues to evaporate.

While this procedure is largely effective, analysis reveals significant oil residue which interfered with the analysis, an example can be seen in Figure 10. Several large fibres can also be seen throughout the filters, including the blanks, suggesting they are contamination from either the fume hood or laboratory clothing. Therefore, the methodology needs to be adapted for the following campaigns to improve the quality of the analysis.

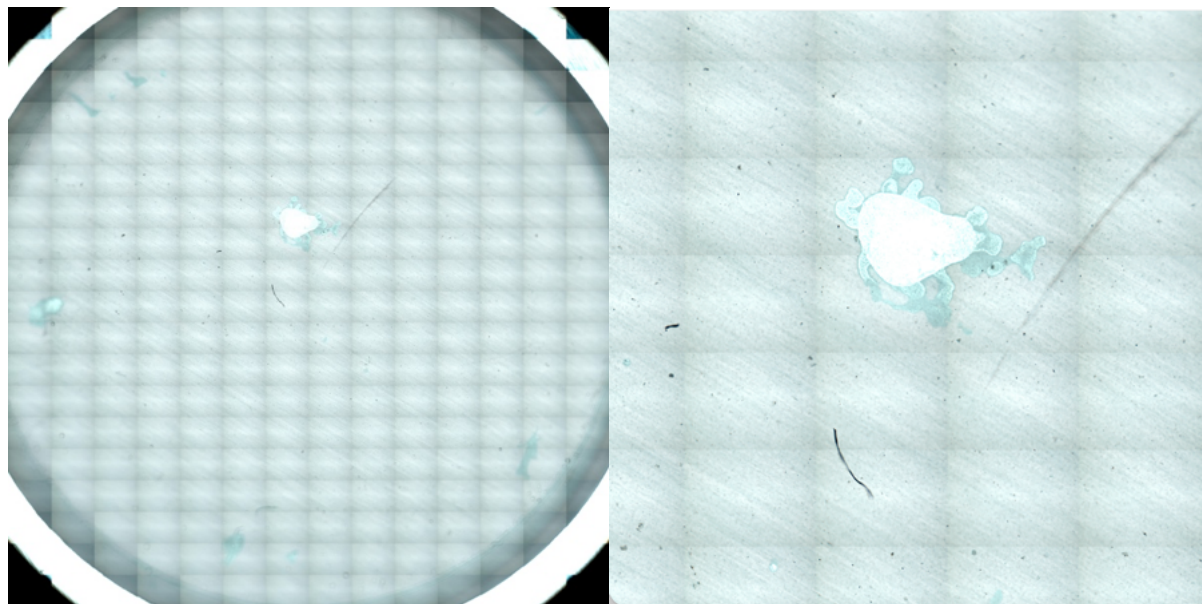


Figure 10: Showing a filter from the 03/12/2025 DD with large oil residue marks across the filter.

2.6.2 Winter Campaign (23/02/2026 – 02/03/2026)

For the winter campaign, the laboratory protocol follows the previously outlined procedural stages and steps. However, to minimise oil residue on the filter, the volume of hexane used during the second phase is increased from 20ml to 30ml, while the amount of methanol-ethanol is increased from 30ml to 40ml. While no set volumes are used during the filtration

sequence, the amount of solvents are generally increased here. The increase of solvents is successful at removing oil residue from the filter as seen in Figure 11, allowing for a successful analysis. Furthermore, the reduced filtering time significantly minimises the accumulation of contamination fibres, resulting in cleaner filters for both the procedural blanks and samples.

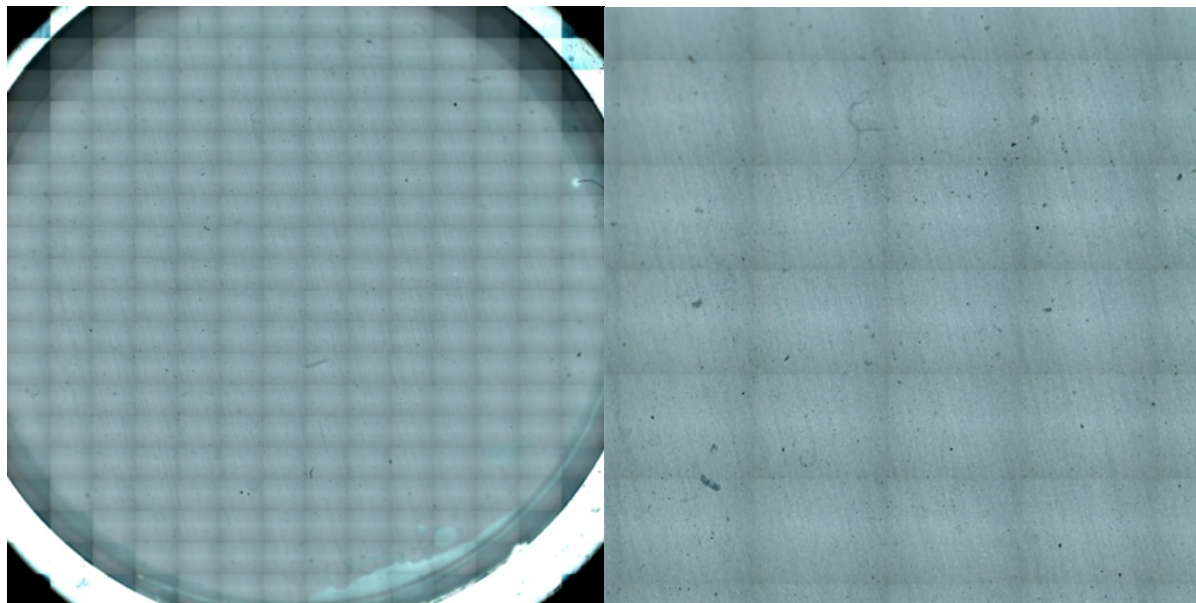


Figure 11: Shows an example filter from the 24/02/2026 DD from the winter campaign.

Alongside this campaign, 3 spikes are done to assess the effectiveness of the laboratory procedure. These spikes include a funnel with 0.4mm glitter, 0.2mm glitter and fibres from a PET jacket. The results show a 52%, 50% and 48% recovery respectively, with a large amount of the loss seen by the 0.4/0.2mm glitters during the funnel phases. The plastics become trapped in the valve of the large 500ml funnels during phase one, and become subsequently trapped again in the 250ml funnels during phase two, with this resulting in the largest loss. Therefore, for the final campaign the procedure is modified to further maximise recovery.

2.6.3 Spring Campaign (20/03/2026 – 30/03/2026)

The spring campaign follows the same protocol as the above two campaigns with some adjustments. Within phase 2, to stop glitter and hence MP, from becoming trapped in the valve of the funnel, oil is added first, followed by the sample and H_2O_2 . An additional modification involves adding several drops of ethanol to the sample. This step neutralises the surface charge on plastic particles, thereby reducing their tendency to adhere to the glassware. Furthermore, the application of ethanol facilitates enhanced separation between the oil and aqueous phases. At this stage, the funnel is shaken twice separately, once with 250ml of water and again with 500ml of water. This approach reduces the number of particles adhering to the glassware.

Within phase 2, the method deviates between the two halves of the campaign (20-26/04/2026 and 27 – 30/04/2026) for the second half of phase 2. The volume of solvents used is the same, however, the number of rinses increases to three for both hexane and methanol-ethanol to maximise recovery. In addition to this, at the end of rinsing the funnels, the valve is opened, ensuring all residual contents are collected in the conical flask, this significantly

reduces the number of trapped particles. Within the first half of the campaign the oil phase is initially poured from the top to maximise particle recovery and reducing particles adhering to the glassware. However, when taking these samples to filtration, the water phase decreases the filtration rate significantly, therefore, the samples are returned to a separating funnel for the aqueous phase to be removed, keeping only the hexane oil layer. For the second half of the campaign, no pouring from the top is introduced minimising the amount of water in the conical flask. A spike is done alongside this method, and an 87% recovery is achieved.

2.6.4 Concluding Remarks

The evolution of the methodology from the original protocol to the final optimal procedure is driven by several key changes. The main alteration being the volume of solvents used, increasing these removes the majority of oil residue from the filters, allowing for a clean analysis. Another critical alteration is the minimisation of the volume of water included at the top of the sample. If a coarse pore filter is used, this is an unnecessary adjustment as the water introduced from the pouring from the top action highlighted in section 2.6.3 Spring Campaign (20/03/2026 – 30/03/2026) increases the recovery rate. However, if a fine pore filter is used, the water causes a significantly reduced filtration rate. In the absence of a clean room, contamination can be well mitigated with the introduction of the thorough sterilisation outlined in section 2.5.1 Contamination Prevention, along with turning off the fume and lint rolling all clothes, especially when uncovering the samples during all stages of the procedure. These preventative measures allow for a relatively clean blank and a high recovery. This protocol can therefore be used for similar campaigns at similar resolutions when only fume hoods are available.

2.7 Analysis

2.7.1 Particle Recognition: Micro-FT-IR

Following the lab procedure, the anodiscs are analysed with a Bruker LUMOS II FT-IR microscope in transmission mode, placed on the BaF₂ glass lenses, allowing a high-resolution overview image of each filter in both transmission and reflection to be obtained. A grid of 1 cm² (covering 40%) of the filter is taken at the centre of the filter, as seen in Figure 12, measuring at 63 x 63-point grid. A spectral background is also required, chosen by selecting an area with no particles, aiming to capture only the filter, shown in Figure 12A. The automatic analysis uses the FPA detector (32 x 32 pixels, every 5 μm with 2 scans per grid point) is averaged over the spectral range 4000–1200 cm⁻¹. This results in an effective spatial resolution of ~5 μm per pixel, consistent with the 5 μm laser spot size of the instrument, which when combined with a spectral library, determines the exact polymer. This, therefore, allows for an analysis of particles down to 5 μm, significantly lower than previous research usually limited at 20 μm.

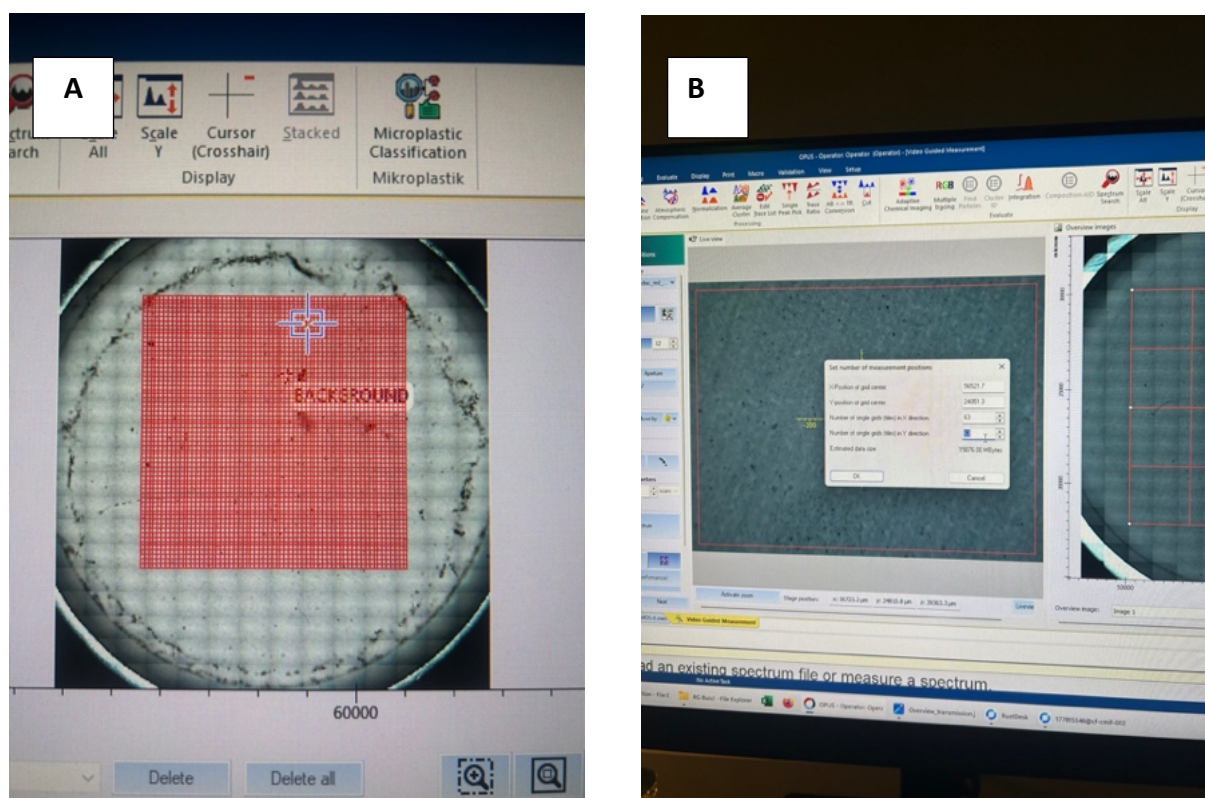


Figure 12: A and B) images of the analysis grid being added to the filter prior to analysis.

One notable limitation of this analytical method is the analysis area. During the filtration process, particles gravitate towards the edge of the filter, along the rim of the filtration glassware, as seen in Figure 13. However, due to the grid placement within the centre of the filter, these particles are not included within the analysis. Consequently, this may result in an underestimation of the particle count per filter. Another limitation as highlighted in the introduction is the inability for the FTIR to detect tire wear particles.

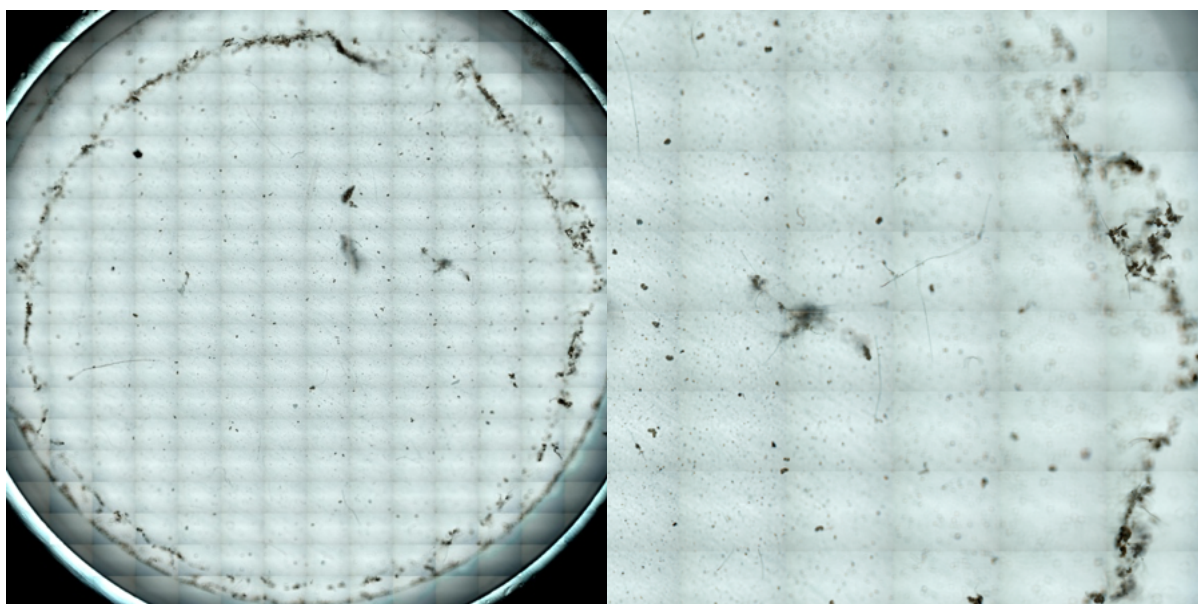


Figure 13: Overview image in transmission of the filter form 27/04/2026 DD showing particles gravitating towards the outside of the filter rather than the middle where the analysis occurs. It is worth noting all particles are not all MP but organic particles, such as pollen. This filter has been chosen as an example because it clearly illustrates the accumulation along the rim.

2.7.2 Spectral Analysis: MPID OPUS and OpenSpecCy

Upon completion of the initial data processing, the resulting file is subjected to analysis using the OPUS MP identification (MPID) classification machine learning algorithm. This algorithm systematically evaluates each spectrum generated from the analytical grid, matching them against a reference library containing multiple plastic polymer species. The algorithm determines the degree of correlation (hit rate) between each sample spectrum and the reference spectra, assigning specific hit rates to indicate the confidence of identification for each plastic type. A minimum spectral match score of > 40% (400 hit rate) is applied for each sample. In comparison to other studies, where the threshold is set to 65-85%, 40% represents a low threshold. However, an assessment of the type of plastic observed needs to be considered: most studies utilising FTIR assess much larger plastics >500µm, which lend themselves to have less noisy, high confidence spectra (Clough et al., 2024; Geraldino, 2025). The environmental samples measured here are significantly smaller, oxidised and highly weathered, therefore, are likely to have noisier spectra comparatively. Whilst, this lower threshold may increase the likelihood of false positives, it allows at the same time to be able to capture more environmental plastics, after attentive second examination. After the analysis is complete, each particle would be annotated by their ID number, so individual images of each particle can be taken for size classification. An example of the output table produced by this process is provided in the supplementary material.

The MPID has one notable bug, where one large particle can be detected as hundreds of small ones. Under these conditions, gaining an accurate particle count with the provided table is challenging, an example is presented in Figure 14. This is apparent within two samples, however, only one sample (29/04/2026) posed a major issue, having a predicated total particle count of 1,317. To mitigate against this issue, a python script was generated which took the top 7 largest particles and removed any particles from inside these, along with removing a 20µm area around the large particles. The buffer period is added to ensure the majority of the large particle is captured, whilst also ensuring surrounding small particles are retained. This is highly effective, reducing the total particle count to 333. Whilst this is not completely effective, some of the large particle remained classified as several small particles, this approach removed the majority, allowing an accurate particle to be obtained.

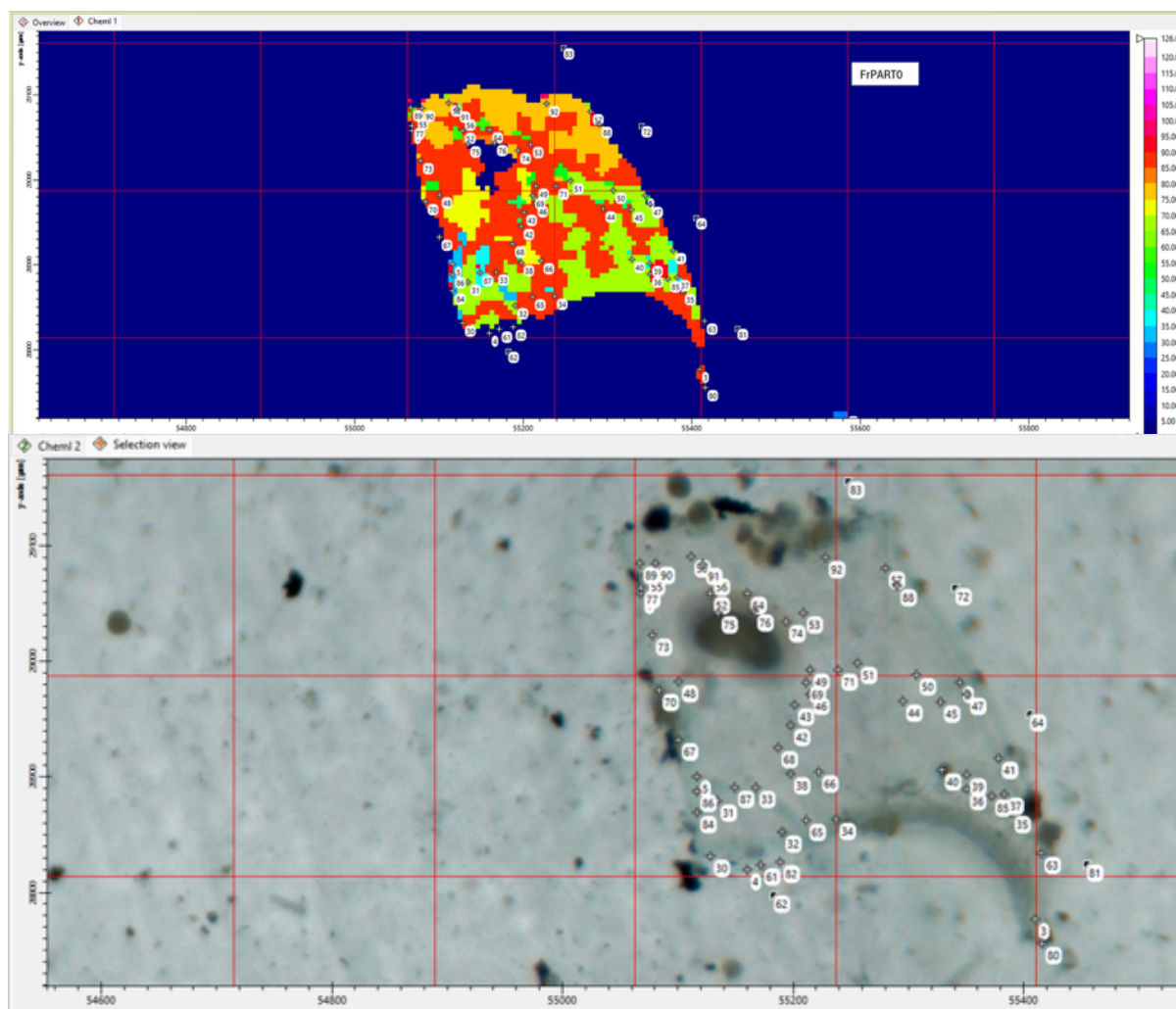


Figure 14: An example of the software bug presented in the MPID from the sample 28/04/2026 DD. The different colours which appear on the top image, highlight different polymers which were detected by the software.

2.7.3 Size Analysis: FIJI

After the table of plastic particles is obtained via OPUS, individual images are taken of each particle ensuring to include the scale, as shown in Figure 15. As the automatic size information gained from OPUS appears inaccurate (particle sizes are, at times, over or underestimated), the individual images are exported into the software FIJI where the scale of the image is set (turning pixels into microns). From here the particle can be outlined with the drawing tool and the Feret measurements are gained. A limitation of the size classification is the focus of the initial overview image taken. Due to the method of filtration and filters drying, particles do not lay flat during analysis making it difficult to get an optimal focus across the whole analysis area. Therefore, some particles towards the edge of the analysis area are out of focus and become challenging to measure.

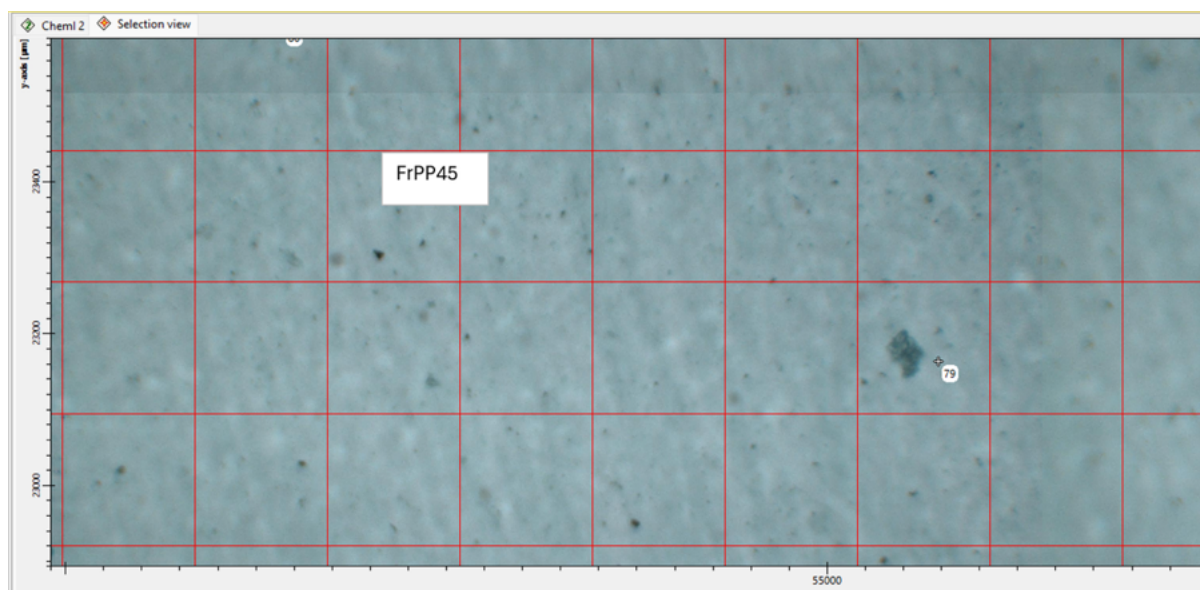


Figure 15: Shows an example PP, named FrPP45 with the ID number 79, particle from the 24/02/2026 DD.

2.7.4 Particle Selection

After the sample files are obtained, the method of selecting particles can be decided. Having collected the results of the spectra analysis from both OPUS and OpenSpeccy, a function was developed which favours OpenSpeccy over the OPUS spectra. The function operates by searching if the particle has an OpenSpeccy result and, if so, the resulting polymer is chosen. If the particle detection falls within a case in which multiple particles are detected for a large single one, see section 2.7.2 Spectral Analysis: MPID OPUS and OpenSpeccy, the hit rate of each collected spectra is analysed and the resulting polymer with the highest hit rate is chosen. If the particle returned an OpenSpeccy result of 'unknown', the OPUS result is taken, again using the logic of the highest hit rate. This method is more conservative in preserving particle count, however, this is still considered the optimal method to gain an accurate MP count. The blanks are then subsequently removed by the process previously outlined in section 2.5.2 Procedural and Field blanks.

2.8 Flux Calculations

2.8.1 DD Flux

After the table with the number of particles is gained, the deposition flux for both the WD and DD can be calculated and plotted. The number of particles (No.particles) are scaled up based on the recovery rate (RR) of the specific procedure, the area of the petri dish (A_{petri}) and of the covered area of the filter (F_{cov}), see in Figure 12. The calculation seen in the below equation can be used to calculate the flux, over a period of sampling (t) one day.

$$DD_{\text{flux}} = \frac{\text{No. Particles}(DD)}{RR \times F_{\text{cov}} \times A_{\text{petri}} \times t}$$

2.8.2 WD Flux

As done for the DD flux the No. particles are upscaled based on the RR and F_{cov} . From here there are several ways to calculate the WD flux, the equation below shows the calculation for the flux in MP/mL/day with the volume of water inside the collection bottle (V):

$$WD_{flux} = \frac{No. Particles (WD)}{RR \times F_{cov} \times V \times t}$$

The WD flux can also be converted into the units MP/m²/day, so the bulk deposition can be calculated by summing it to the DD flux. This is achieved by incorporating the area of the funnel (A_{Funnel}) used in the WD container:

$$WD_{flux} = \frac{No. Particles (WD)}{RR \times F_{cov} \times A_{Funnel} \times t}$$

2.9 Sources of Uncertainty and Methodological Limitations

Due to the large amount of processing required within this methodology, there are several places for uncertainty. This section aims to characterise and account for all the uncertainty throughout the protocol of this work, split into the systematic and random errors.

2.9.1 Systematic Error

As previously mentioned, one area of uncertainty is the assumption of uniformity, where particles are expected to fall within the centre of the filter evenly. However, as previously shown in Figure 13, particles gravitate towards the outer edges of the filter, rather than the centre. This leads to a systematic underestimation of particles across all samples, however, it has not been possible to quantify this uncertainty and is therefore left as a limitation of the study.

Finally, the lack of replicates is another uncertainty present within this study. Due to the fact daily sampling is chosen, to allow characterising the temporal variability of the MP transport, it has not been possible to produce replicate samples to be assessed for variation between themselves.

2.9.2 Random Error

Another area of uncertainty is the variation of the laboratory blanks seen during the laboratory work, the variation between the blanks shows a high degree of background noise present within the laboratory. This uncertainty is the background contamination variability and can be accounted for by taking the standard deviation of each blank, to be incorporated into the combined standard uncertainty (u_{blanks}). The mean of the blanks is 6 particles, resulting in the squared deviation to be 2.5 particles, this is then divided by the total number of particles for each sample resulting in an uncertainty of 34.3%.

Another uncertainty present within the study is the confidence interval given by the FTIR and the variation of results. As repeat analysis at varying thresholds is not feasible for this study, a conservative uncertainty value of 15% ($u_{algorithm}$) is adopted based on other similar studies (Ashta et al., 2026). This accounts for potential misclassifications and the variability in spectral quality common in environmental samples.

The final uncertainty consideration is the variation of the recoveries. Seen within the winter campaign there is a variation across the recoveries from 48-52%, resulting in a standard deviation of 2%. Following this same variation, an uncertainty can be added to the combined standard uncertainty ($u_{recovery}$).

The random uncertainty is then combined using the root-sum-squared method calculates as seen below:

$$u_{combined} = \sqrt{u_{recovery}^2 + u_{blanks}^2 + u_{algorithm}^2}$$

$$u_{combined} = \sqrt{2^2 + 34.3^2 + 15^2}$$

Calculating this an uncertainty of 37.49% of total particle count is seen and is therefore considered within the remaining sections.

2.9.3 Sizing Uncertainties

Another observed error is the operator bias, specifically when characterising the size of the particles. As each particle is manually outlined, there is an inherent risk of repeatability error present. To quantify the uncertainty associated with manual particle delineation, a sample is measured twice on two occasions several days apart to assess the variability in the two measurements, gaining an uncertainty of 12.8%.

3.0 Results

3.1 Campaign Timeline and Results

This chapter outlines the results of both campaigns conducted in the winter and spring, outlined separately, to present the specific details of each season. This is then followed by a section dedicated to combining the campaigns to gain an overall summary. Each section first discusses the results of the blanks and contamination control, followed by a description of the abundance of particles, meteorological conditions present within the campaigns and particle polymers, sizes and morphologies. Finally, there is a chapter dedicated to the close-human influence experiment. Shown below is Table 1 which presents the summarised campaigns, highlighting the dates and purpose of all observations and campaigns.

Campaign	Period	Purpose
Pilot	26/11 – 03/12/ 2025	Protocol Development
Winter	23/02 – 02/03/2026	Daily Sampling
Spring I	27/03 – 30/03/2026	Capture wet scavenging events for a thorough analysis
Spring II	24/04 – 30/04/2026	Daily sampling
Lange Nacht der Forschung	24/04/2026 18:30 – 20:00	Investigate the direct emissions for people

Table 1: Shows the different sampling campaigns, the period in which they occurred and the purpose of the campaign.

3.2 Winter Campaign

Daily sampling for the winter campaign is conducted with daily sampling at 11:30am (CET) from the 23/02 – 02/03/2026. The campaign included a total of 2 wet days, with the remainder being dry. The wind speed ranged from 0.4 – 20.1 m/s, temperatures ranged from 0.4 – 14.8°C and the relative humidity ranged from 45 – 96%. The winter campaign proceeded with a RR of 48-52% and an F_{cov} of 40% and all cellulose, organic material, mineral and calcium carbonate particles are removed from these results focussing solely on synthetic particles.

3.2.1 Blank Analysis

As discussed within the methodology, each batch of samples contains a blank sample to monitor contamination. Before assessing the bulk of the data, a brief analysis of the blank samples is shown in the Figure 16.

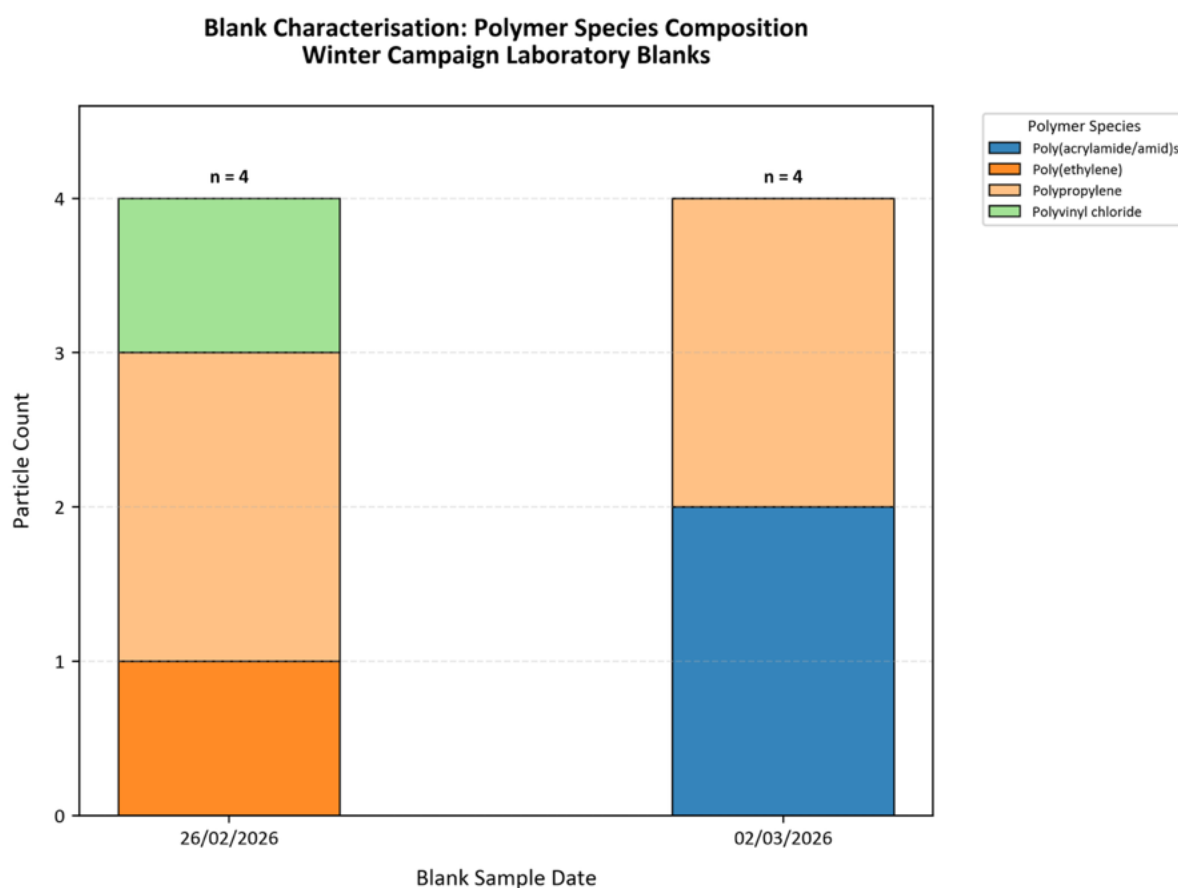


Figure 16: Showing the two procedural blanks conducted during the extraction process for the winter campaign.

Figure 16 highlights the presence of plastic particles within both procedural blanks, however, showing a low quantity, with only 4 plastic particles observed, exhibiting minimal contamination from the laboratory procedure. In the following sections the blanks are subtracted from their respective samples, following the technique outlined in section 2.5.2 Procedural and Field blanks, ensuring all samples are solely environmental findings.

3.2.2 MP Total Particles

Figure 17 shows the total number of particles found across the whole campaign, separated by sample day and further separated by DD, WD and species. This is overlayed with the key meteorological data, including wind speed and direction, precipitation volume from the Hohe Warte MET station and the total volume of rain collected from the collection bottle. These results have intentionally not been scaled up to the RR or F_{cov} to illustrate the raw particle count observed on each filter after analysis.

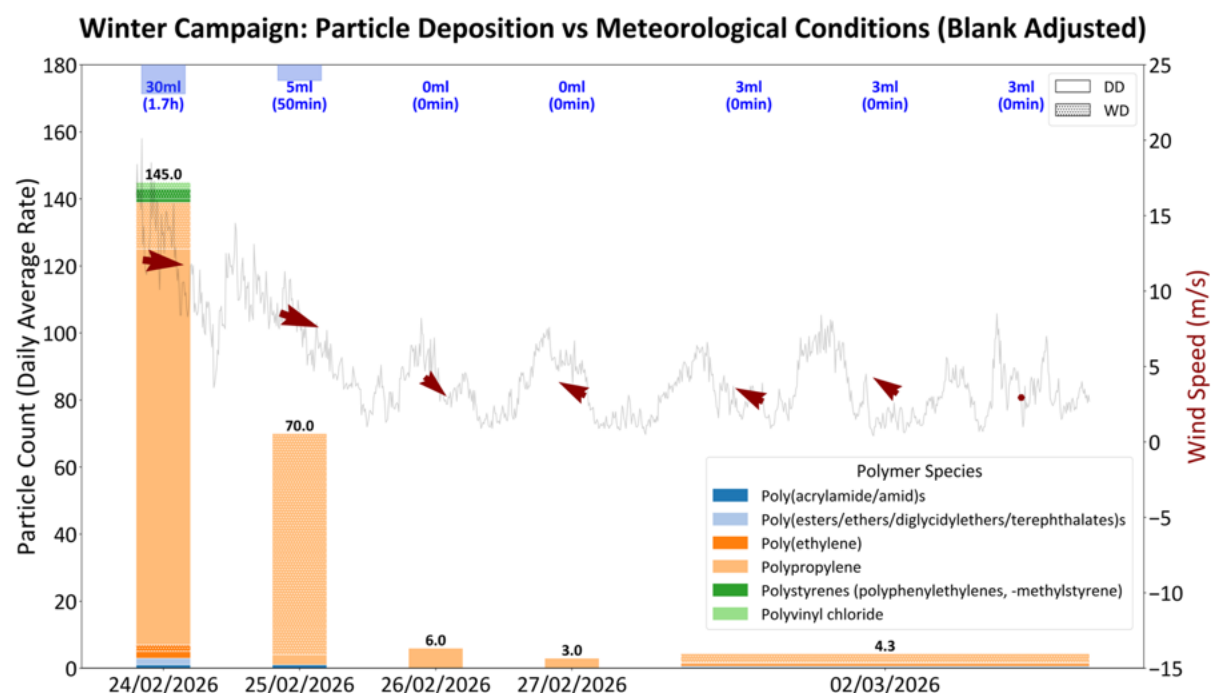


Figure 17: Showing the results of the winter campaign (23/02/2026 – 02/03/2026). The figure shows the total particle count (blank adjusted) of each collected sample split into DD and WD, the polymers are coloured based on the legend shown. The MET data consists of wind speed (grey line), average wind speed (arrow size) and direction (arrow angle), total recorded rainfall by the nearby MET station in the blue bars and total volume of rainfall (ml) collected by the sampler. Finally, the total duration of rainfall recorded at the nearby MET station in blue text.

The results show a large range of 3 – 141 total particles found per day. A large number of particles are observed at the beginning of the campaign (24 – 25/02/2026), showing significantly less towards the end, where only 3 particles were observed on the 27/02/2026. The results also highlight the dominant species observed to be PP, with other less common species including PA, PET, Polyethylene (PE), Polyacrylonitriles (PAN) and Polystyrene (PS). A notable missing species is tire wear, commonly recorded in other studies, however, as mentioned in section 2.1.4 Analytical Methods, this is due to the invisibility of tire wear spectra from FTIR.

3.2.3 MET data

The variation in the MET data could explain the large variation in the number of particles observed. As seen on the first two days, there were significantly higher wind speeds comparatively to the remainder of the week. Alongside this, the prevailing wind direction switches from Northwest to Southeast halfway through the campaign. Both factors may contribute to the variation in the MP quantity during the observation period. WD is prominent within the first 2 days of the campaign seeing a total of 35ml of rain, and none observed throughout the remainder of the campaign. This could be the result of the discussed scavenging effect, washing out the atmospheric MP present in the nearby atmosphere. Due to these effects, it is also relevant to look at the MET data for the previous week of the campaign which is shown in Figure 18.

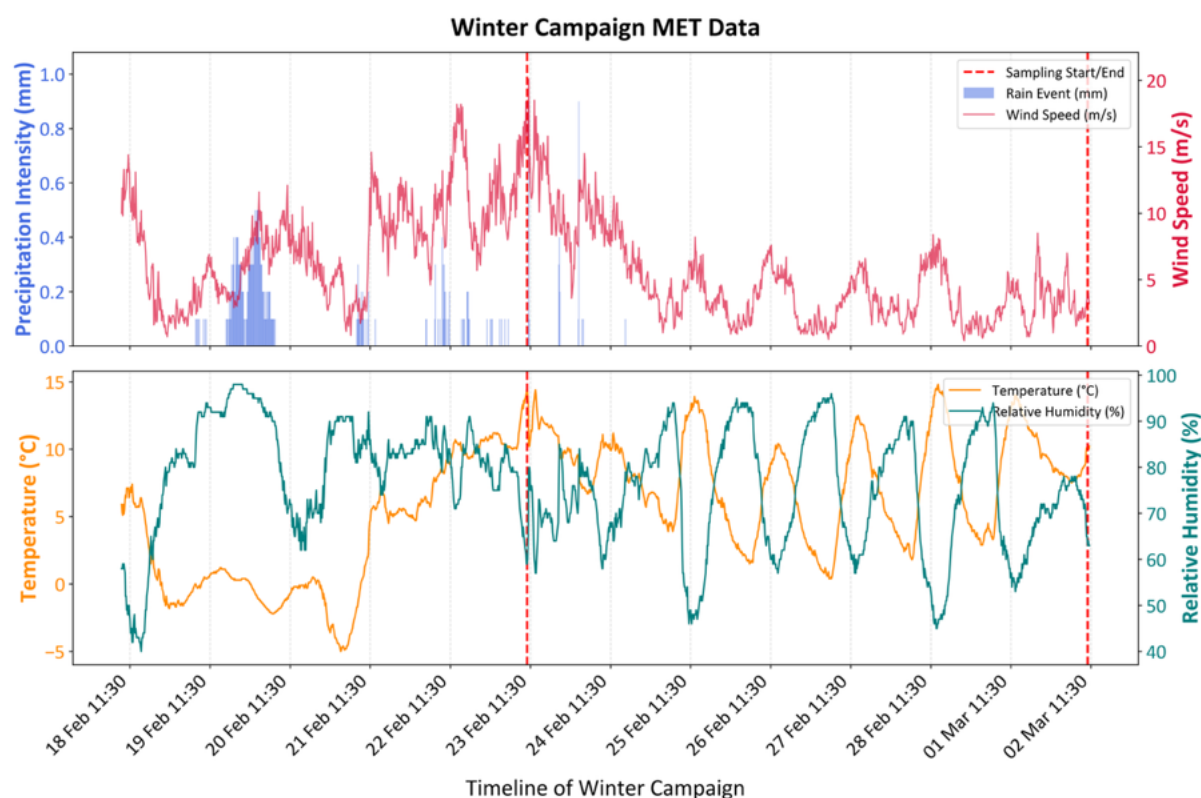


Figure 18: Showing the relevant meteorological data (Precipitation volume and duration, wind speed and direction, humidity and temperature profiles) from Hohe Warte station 105. The dotted red lines shows the date and time at which the sampling started and ended, the grey lines highlight the daily resolution corresponding to the sampling. All data was collected from geosphere.

Figure 18 highlights the MET data during the campaign, showing the low wind speeds, however, more critically for interpretation includes the week prior to the campaign. The data shows a large rain event, both in duration and volume, on the 19/02/2026, which is followed by a period of small showers prior to the campaign. Most notably, the wind speed gradually increases from the 20 – 23/02/2026 which could explain the significantly higher DD seen in the 24/03/2026 sample. This could be a result from increased resuspension from higher wind speeds leading to higher quantities of atmospheric MP.

From the 3-day accumulated sample (02/03/2026) an observed WD of 3ml did not coincide with the data from the MET station. This could be due to a localised small shower, even though or a more likely hypothesis is the presence of morning dew. The rain sensor is triggered by any type of precipitation, therefore, morning dew could result in a triggering of the sampler, acquiring a small catchment of precipitation and DD from the open container.

3.2.4 Deposition Flux

For the deposition flux assessment, the results have been split into DD, WD and bulk deposition flux. Each flux value has been upscaled accounting for the RR and F_{cov} of the respective extraction and analysis procedure.

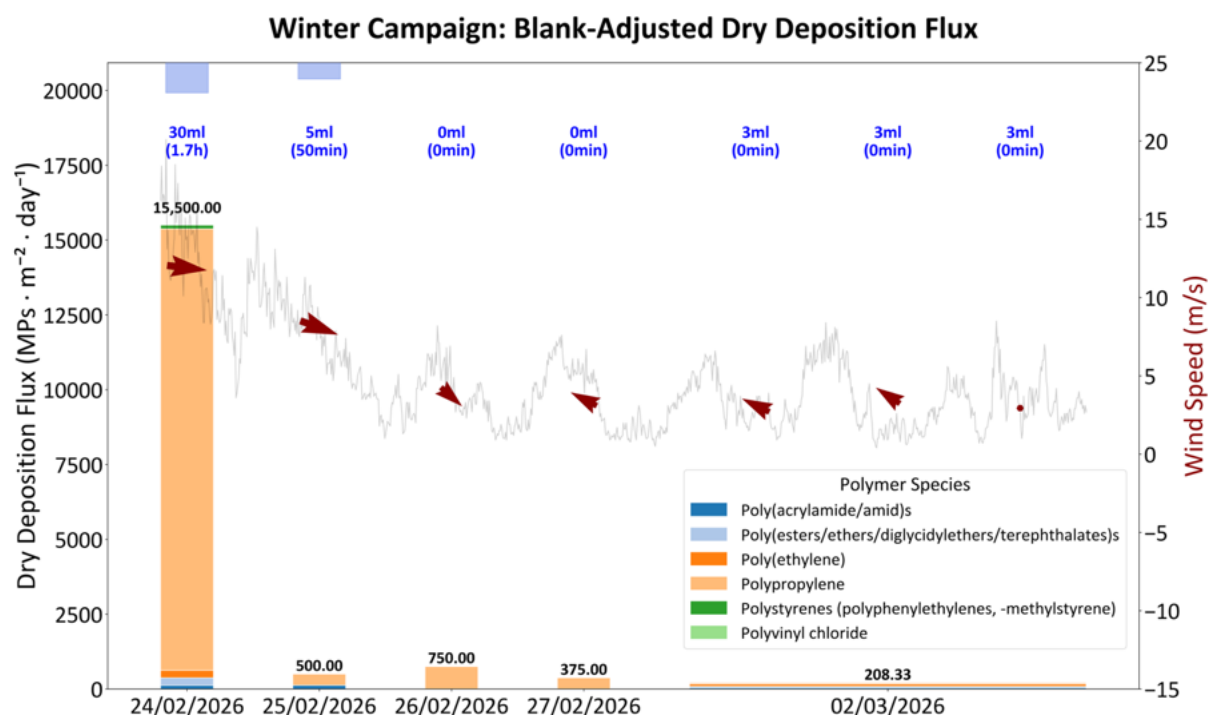


Figure 19: Shows the DD flux, adjusted for blanks, per sampling day across the winter campaign in MP/m²/day.

The results of Figure 19 show a wide variety of the DD calculated flux. Between the 25/02 – 02/03/2026, the flux is close to the average when comparing to other studies conducted in urban locations. However, the 24/02/2026 sample is significantly larger than any published study. Due to the fact all the samples are processed at the same time, this is unlikely to be a result of contamination and more likely to be a result of previously discussed MET data (wind speed and direction), or from a local source, such as, construction. Within the sampling area there is one large construction project, which was ongoing throughout the campaign and could, therefore, result in the significantly high quantity observed during this period. It is worth noting in this sampling period, the sampler had a fault where the DD container remained ajar once the sensor is triggered, as shown in Figure 20. Whilst there is a small risk of some extra particles contributing to the DD sample, the fault is not significant enough to have rationalised the large number of particles seen within the 24/03/2026 sample.



Figure 20: An image taken on the 23/02/2026 showing the gap present within the sampler likely to have persisted for the duration of the sampling for the sample 24/02/2026.

Figure 21 shows the WD flux in the units MP/mL/day and highlights the relatively low flux on the first day, despite the large volume collected and the duration of rainfall seen. As seen in Figure 18 there is a large amount of rainfall seen prior to the campaign which could have resulted in a less polluted atmosphere leading to less MP within the WD. The 25/02/2026 shows a very high WD flux despite the low amount of rainfall collected, this is likely due to the large amount of MP deposition present in the air, as seen in the DD on the 24/02/2026, and the small rain event here removes a large portion of the particles.

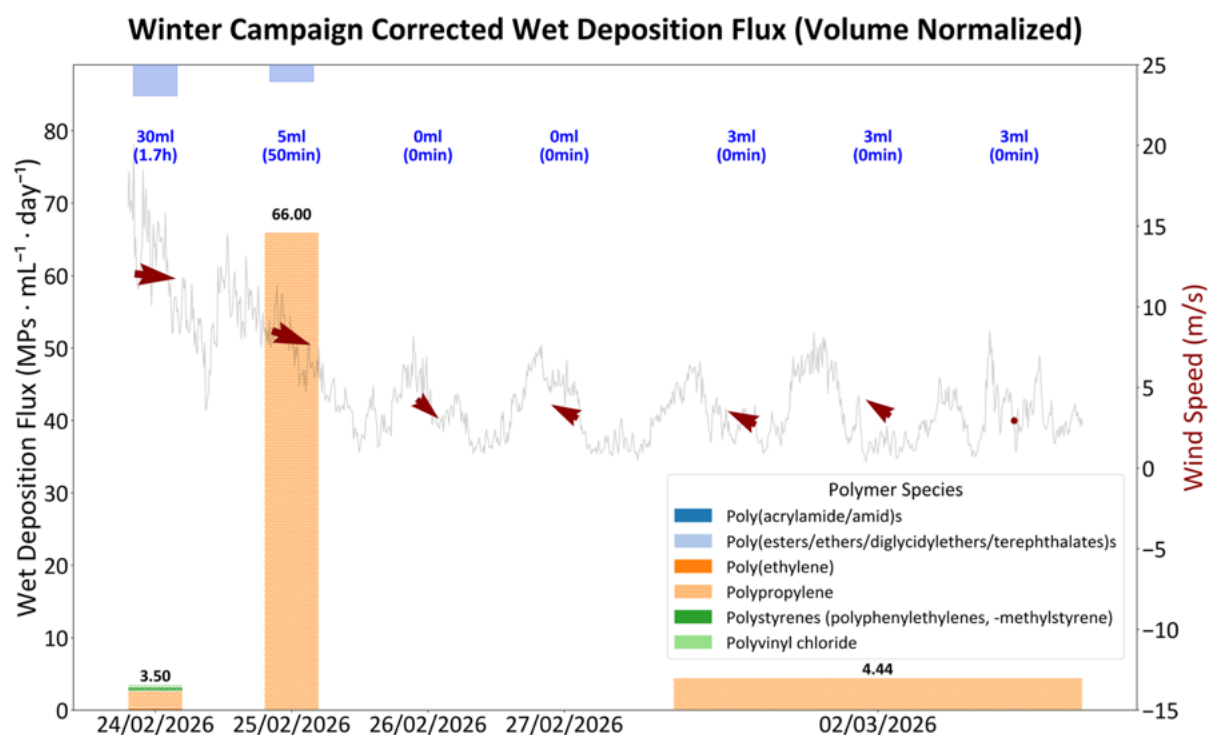


Figure 21: Shows the WD flux adjusted for blanks, per sampling day across the winter campaign in MP/mL/day.

Finally, Figure 22 shows the total bulk deposition flux calculated as explained in the methodology, given in the units MP/m²/day. The 24/02/2026 reaches a combined flux of 28,961.54 MP/m²/day, which is significantly higher than any other study across urban areas. The 25/03/2026 has a larger flux of 42,807.69 MP/m²/day contributed predominantly by the WD. Despite the volume of collected rainfall the scavenging effect is the likely cause of the high calculated flux, particularly when considering the high DD seen in the day prior. The remaining days show smaller fluxes where the 26/02/2026 has a flux of 750 MP/m²/day, 27/02/2026 has a flux of 375 MP/m²/day and the 02/03/2026 has a flux of 1,917.74 MP/m²/day.

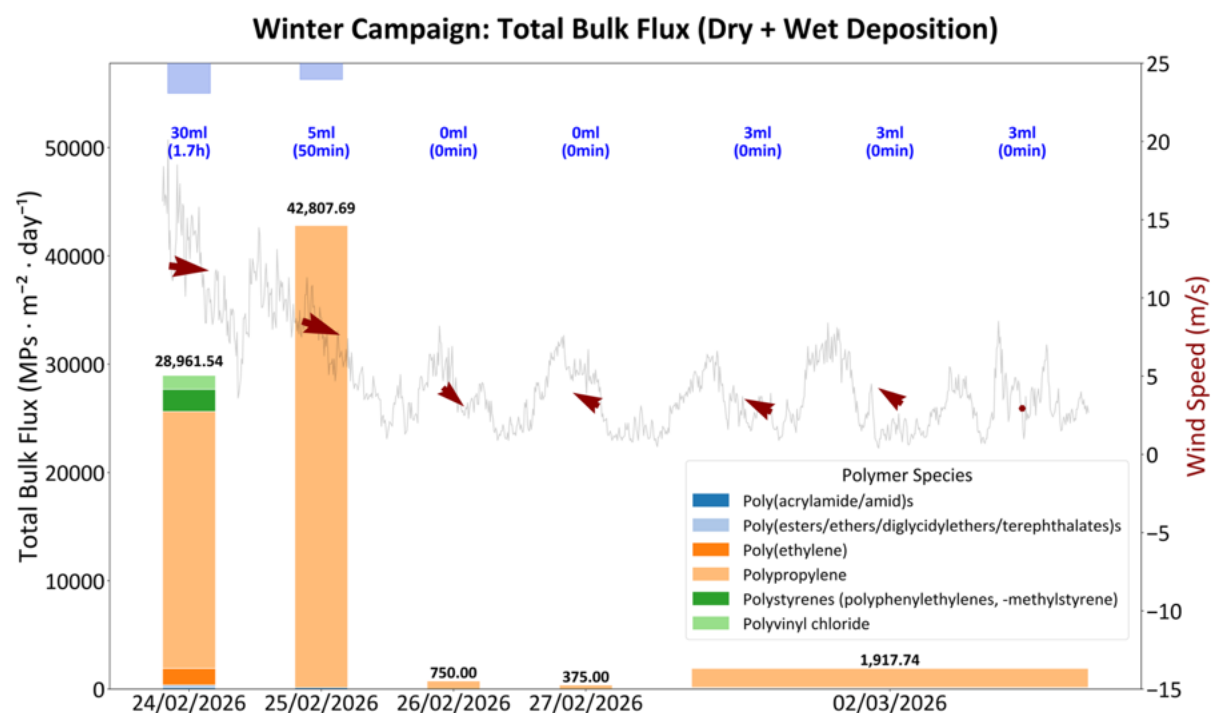


Figure 22: Shows the total bulk deposition flux across the winter campaign in MP/m²/day.

3.2.5 Size and Classification

All the particles were then sized using the techniques outlined in section 2.7.3 Size Analysis: FIJI, allowing the size distribution of all particles to be examined.

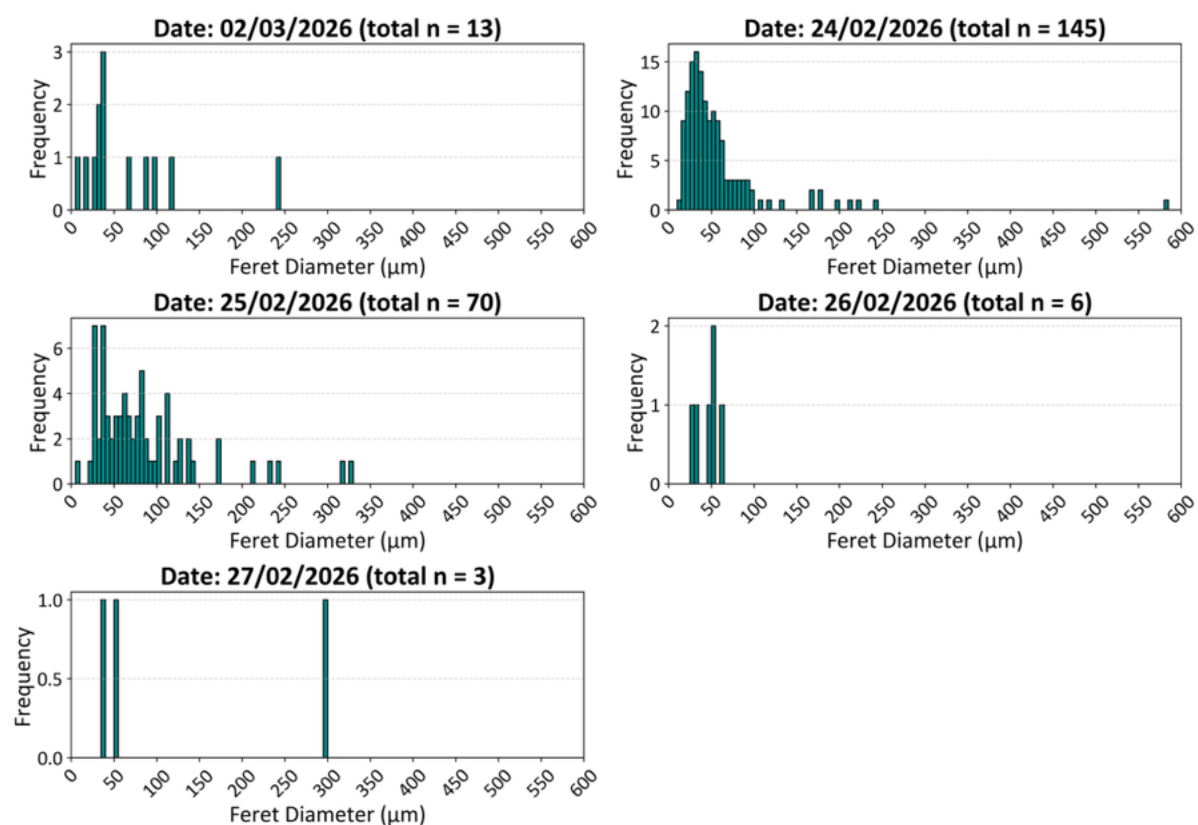
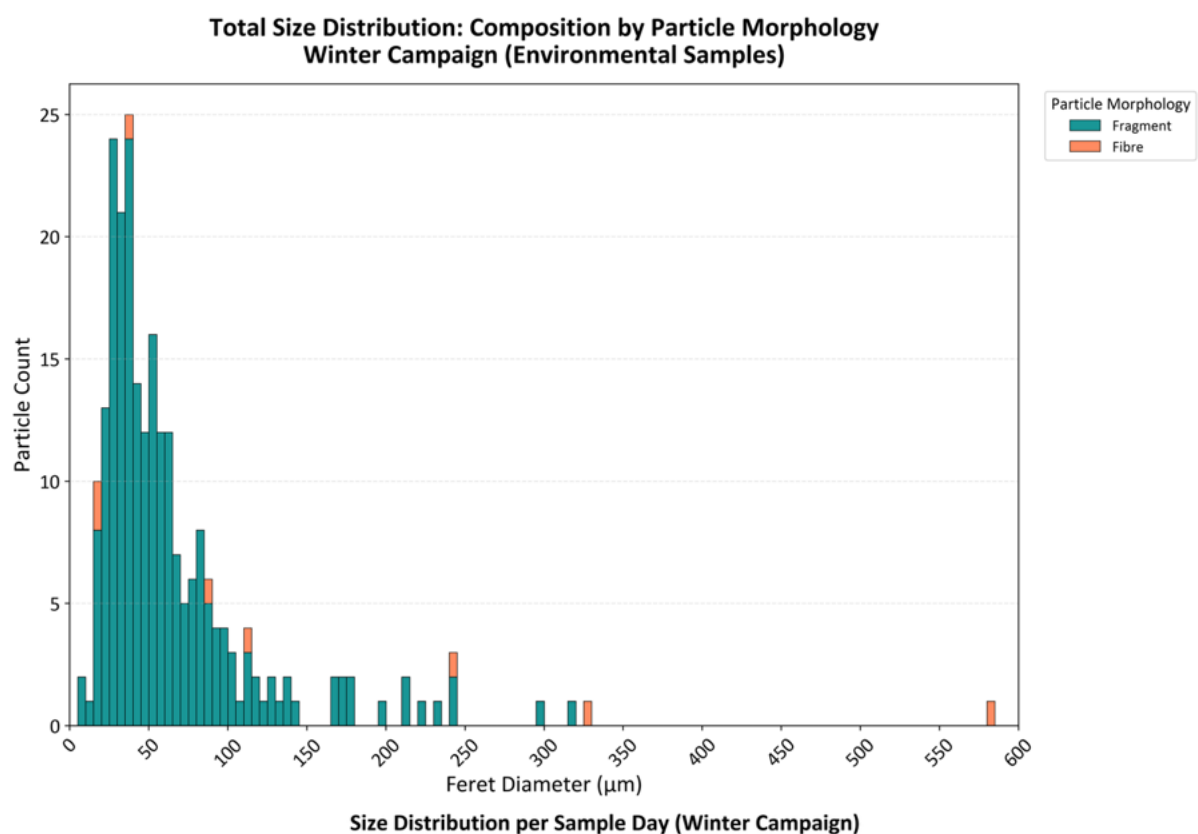


Figure 23: Shows the morphology of each particle along with the size of particle. This is further characterised by sample day showing the size of each particle per each day of the winter campaign.

The size classification shown in Figure 23 highlights the range of sizes seen across the campaign ranging from 5 – 580µm in feret diameter. The dominant size range falls between 25 – 40µm. Figure 23 also segregates the particles by morphology, showing the dominant shape seen across both WD and DD samples is fragments, with only 8 synthetic fibres being observed across the winter campaign. This is controversial to the literature which shows a large portion of particles observed to be fibres, particularly within WD. This campaign has a relatively low amount of rainfall and is, therefore, not highly representative for wet days and more WD needs to be evaluated before speculating further.

Figure 24 shows the dominant species across the winter campaign to be PP, reaching 92.4% of the total particle count. Other species include PE, PS, PET and PVC all ranging with low percentages from 0.8% - 2.5%.

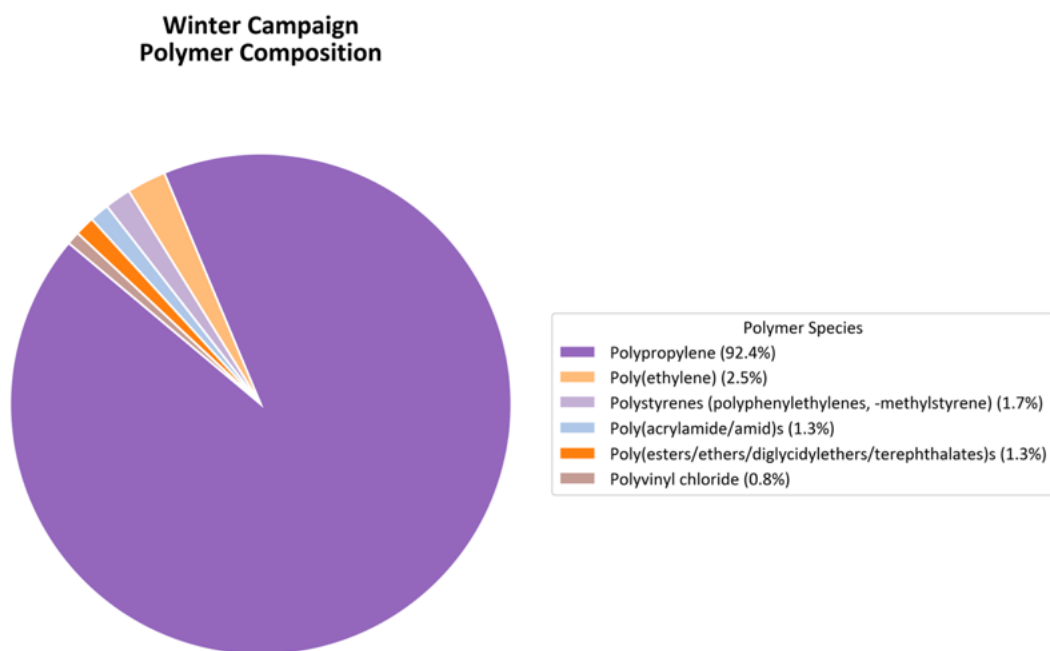


Figure 24: A pie chart highlighting the percentage of each species of all particles in the winter campaign.

Finally, Figure 25 showing the particle sizes separated by polymer species shows the majority of particles lie between 5 – 120µm. The outlier in the sample is a PET fibre at 580µm. Due to the fact the dominant species found in this campaign is PP, the size distribution is heavily driven by with PP particles ranging from 5 – 340µm.

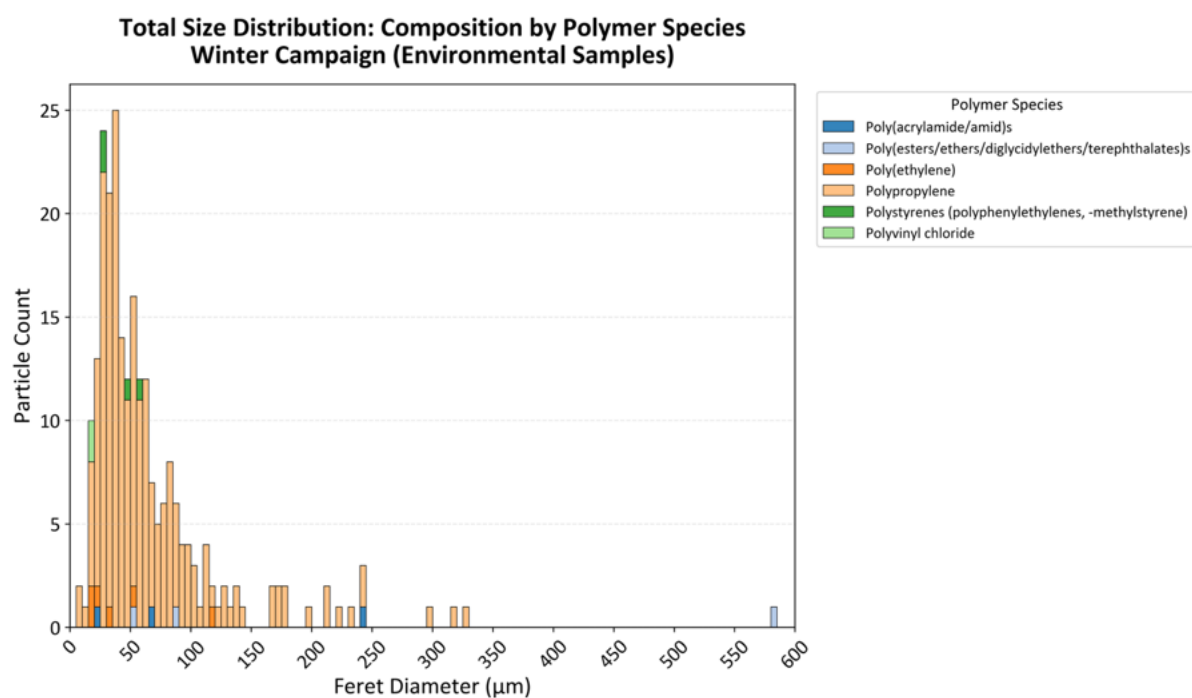


Figure 25: Shows the size of all the particles throughout the winter campaign separated by polymer species and colour coded as shown in the legend.

To capture the wide variety of observed MP, a small gallery of microscopy pictures is given to show some of the features of the particles from the winter campaign and can be seen in Figure 26.

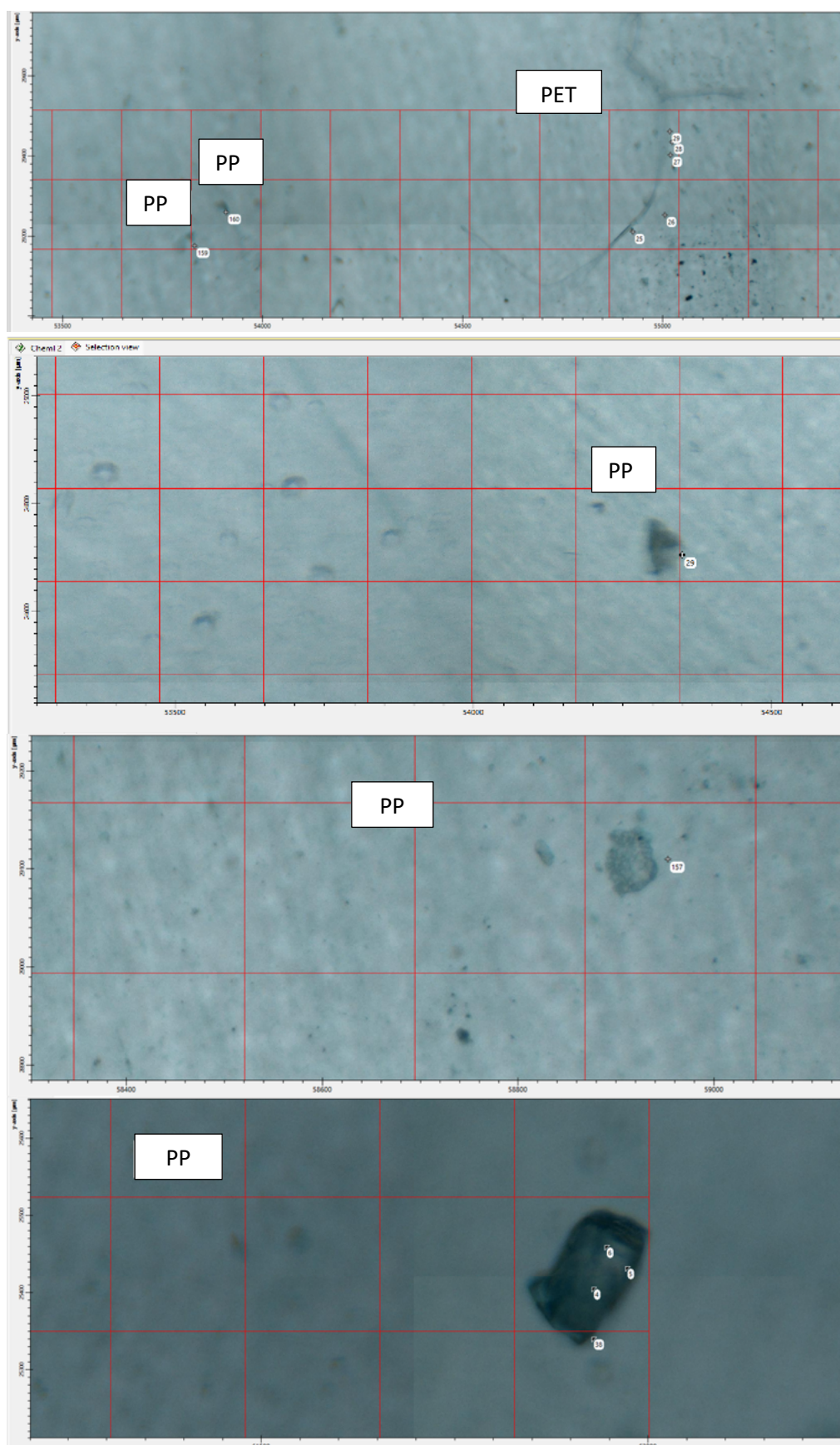


Figure 26: A selection of microscopy images from both WD and DD samples within the winter campaign, showing the presence of long PET fibres and several PP fragments of various sizes and shapes. The names given are based upon the classification system as outlined in the methods.

3.2.6 Concluding Remarks

The winter campaign showed, two high deposition events at the beginning of the campaign, followed by significantly lower fluxes within the following days of the sampling period. Across this campaign it is observed PP is the dominant species, along with fragments being the dominant shape, largely exceeding fibres. The majority of these particles fell within the 20 – 40µm range. Finally, it is observed WD is linked heavily to precipitation events, as expected, whereas DD shows a greater relationship to higher wind speeds.

3.3 Spring Campaign

Sampling for the spring campaign is also conducted with daily sampling at 11:30am (CET) with two sampling periods from the 27/03 – 30/03/2026 (spring I) to capture heavy precipitation events, and from the 24/04 – 30/04/2026 (spring II). The whole campaign included a total of 3 wet days and 3 dry days. For spring I, the wind speed ranged from 2.9 – 19.2 m/s, temperature ranged from 2.1 – 9.5°C and the relative humidity ranged from 45 – 94%. For spring II, the wind speed ranged from 0.4 – 16.3 m/s, temperature ranged from 3.7 – 24.4°C and the relative humidity ranged from 21 – 72%. All the spring campaign proceeded with a methodology of an RR of 87% and an F_{cov} of 40% and all cellulose, organic material, calcium carbonates and minerals are removed from these results focussing solely on synthetic particles.

3.3.1 Blank Analysis

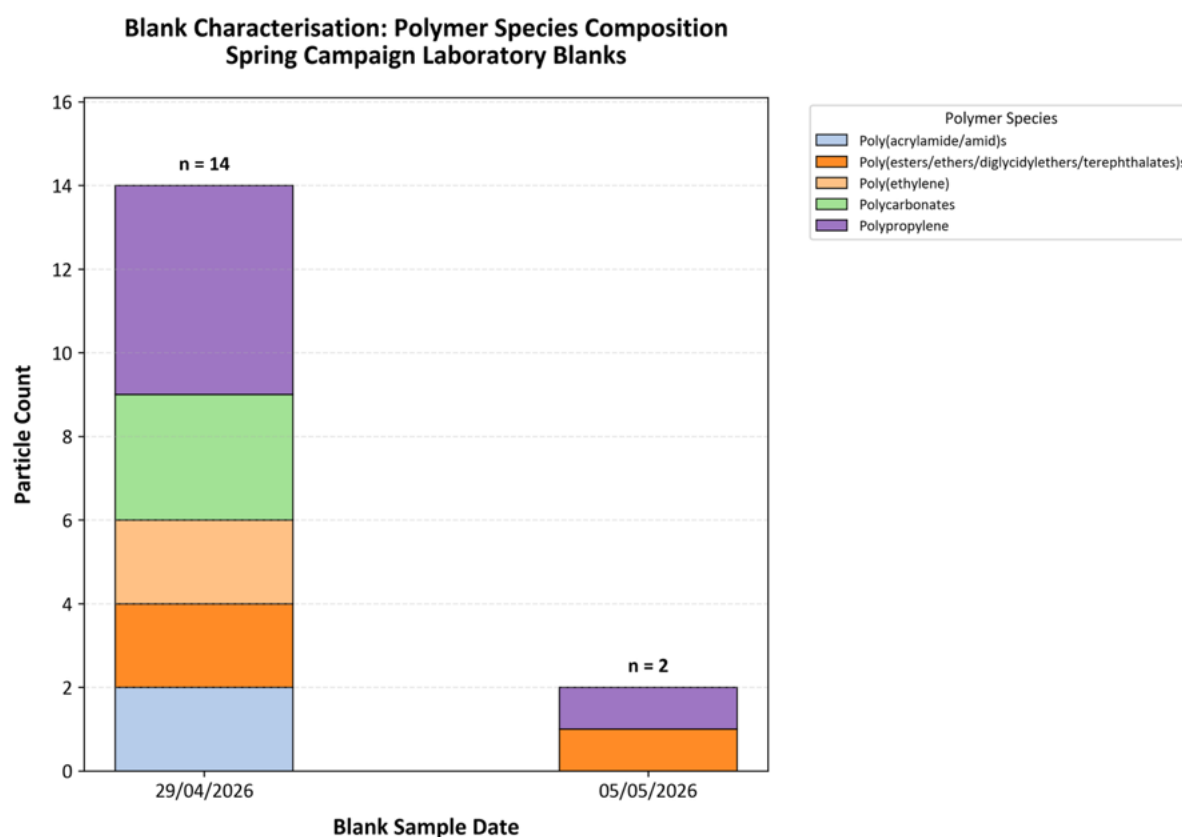


Figure 27: Showing the two procedural blanks conducted during the extraction process for the spring campaign.

Figure 27 highlights the plastic particles within both procedural blanks used across both campaigns. The blank conducted on the 05/05/2026 has a very low amount of only 2 plastic particles, meaning contamination during this period is minimal. The 29/04/2026 however, has a significantly higher amount reaching 14, showing a large amount of contamination present in the laboratory. No instances with this procedural blank were documented during the work. The only notable difference is due to the particle selection method chosen outlined in section 2.7.4 Particle Selection, some of the particles detected come from OPUS. As previously explained, due to misclassification errors particularly with PA, the real particle count can be lower. However, in the interest of consistency across the research, this blank will be accounted for as it is presented. In the following sections the blanks are subtracted from their respective samples ensuring all samples are solely environmental findings.

3.3.2 MP Total Particles

Figure 28 shows the total number of particles found across the whole campaign, separated by sample day and further separated by DD, WD and polymer species. This is overlaid with the key meteorological data, including wind speed and direction, precipitation volume from the Hohe Warte MET station, along with the total volume of rain collected from the collection bottle. These results are not yet scaled up to the RR or F_{cov} to simply illustrate the raw particle count observed on each filter after analysis.

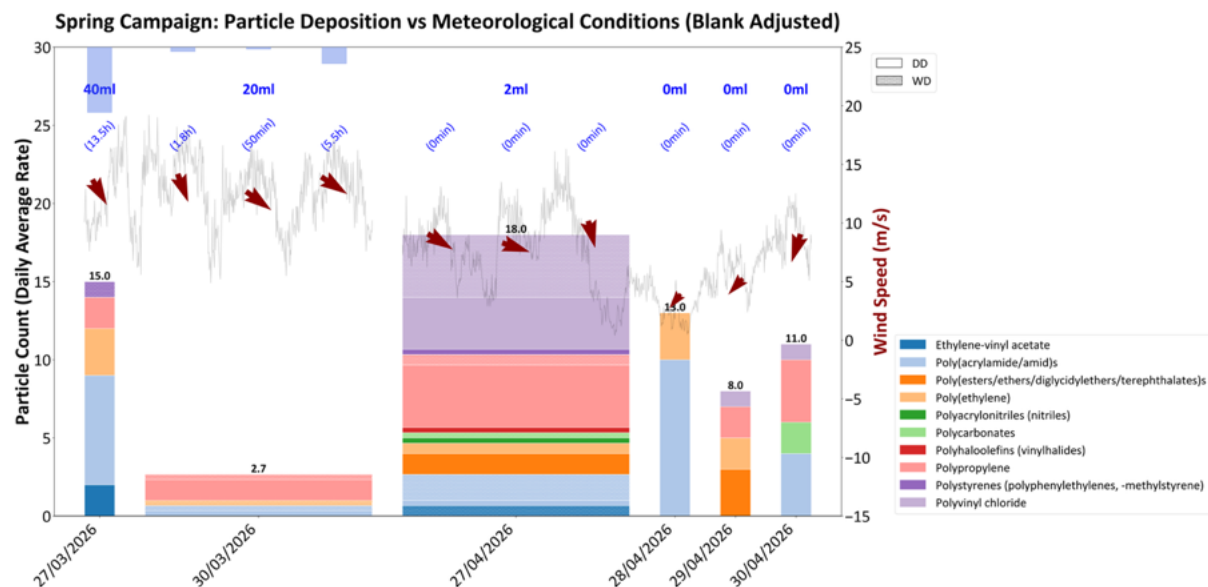


Figure 28: Showing the results of the spring campaign which was completed in two campaigns (27/03 – 30/03/2026 and 24/04 – 30/04/2026). The figure shows the total particle count (blank adjusted) of each collected sample split into DD and WD, the polymers are coloured based on the legend shown. The MET data consists of wind speed (grey line), average wind speed (arrow size) and direction (arrow angle), total recorded rainfall by the nearby MET station in the blue bars and total volume of rainfall (ml) collected by the sampler and the total duration of rainfall recorded at the nearby MET station in blue text.

Figure 28 comprising of two sampling periods, shows the results of the WD and DD across all sampling days ranging from a total of 2.7 – 18 particles found per day. On the 27/03/2026, 15 particles are observed, predominantly seen in the DD despite the large amount of rainfall and long rainfall duration. From the 28 – 30/03/2026 (the 3-day accumulated sample named 30/03/3036) there is a significantly lower number of particles of only 2.7. These results are likely heavily influenced by the meteorological conditions as seen in the corresponding MET

data from the week prior to sampling. In the second sampling period, the 3- day accumulated sample (from the 24 – 27/04/2026) has 18 total particles, with a large portion observed in the WD, despite the low volume of collected WD. The following days consisted of solely DD, with the 28/04/2026 having 13 particles, the 29/04/2026 having 8 particles and the 30/04/2026 having 11 particles. The sample on the 29/04/2026 has a software classification issue, explained in the following section 3.3.3 29/04/2026 Classification. This error significantly reduces the number of particles present on the 29/04/2026.

A wide variety of polymers is observed across this whole campaign, with the dominant observation being PA. However, due to the misclassification issues particularly with PA, this is suspected to be too high. These samples also saw a high portion of pollen across the filters, where these were commonly misclassified as PVC. The classification method outlined in section 2.7.4 Particle Selection minimises the impact of these effects, however, it should be noted this polymer may be subject to overestimation.

3.3.3 29/04/2026 Classification

The sample 29/04/2026 showed a high amount of abnormally large particles comparatively to the other samples. Due to the limitation of identifying large particles within the OPUS MPID, this sample is processed differently as outlined in section 2.7.2 Spectral Analysis: MPID OPUS and OpenSpeccy. Several spectra across these large particles were saved and examined individually through OpenSpeccy, these multiple spectra were further averaged together, and these averaged spectra were passed through OpenSpeccy. The results of these spectra, however, were seen to be predominantly organic material whilst OPUS classified them as polymers. For understanding, Table 2 shows the particle name with the OPUS polymer classification, individual spectra classification from OpenSpeccy and the average spectra classifications. The dominant polymer in the OPUS classification is determined based upon the highest hit rate.

Particle Name	OPUS Classification	OpenSpeccy spectra	all OpenSpeccy average spectra
FrPE0	PP	Organic matter, 1xPE	Organic Matter
FrPE4	PP	Organic matter, 1xPET	Organic Matter
FrPE3	PE	All Organic matter	Organic Matter
FrPE5	PP	All Organic matter	Organic Matter
FrPE1	PP	Organic matter, 1xPE	Organic Matter
FrPP2	PP	Organic matter, 1xPS	Organic Matter
FrABS2	PP	Organic matter, 3 PET, 1 PP,	Organic Matter
FrABS0	PE	All organic matter	Organic Matter
FrABS1	PP	Organic matter, 1xPP, 1xPS	Organic Matter

Table 2: Shows the particle name of the uncertain large particles. The table includes the OPUS polymer classification, individual spectra classification from OpenSpeccy and the average spectra classifications.

Table 2 highlights the large discrepancies in the classifications between OPUS and OpenSpecCy. In this instance, considering the appearance of the particles, an example shown in Figure 29, shows they are unlikely to be considered organic. Due to the classification method outlined in section 2.7.4 Particle Selection, some of these larger particles are not accounted for as MP due to the favouring of the OpenSpecCy spectra results. Figure 29 also illustrates the effect of particles clustering around larger ones and even illustrates, due to their transparency, particles trapped underneath. Despite the mitigation strategies implemented in section 2.7.4 Particle Selection, a residual margin of particle loss is expected. Therefore, for the following results, a slight underestimation of the flux for this day can be assumed.

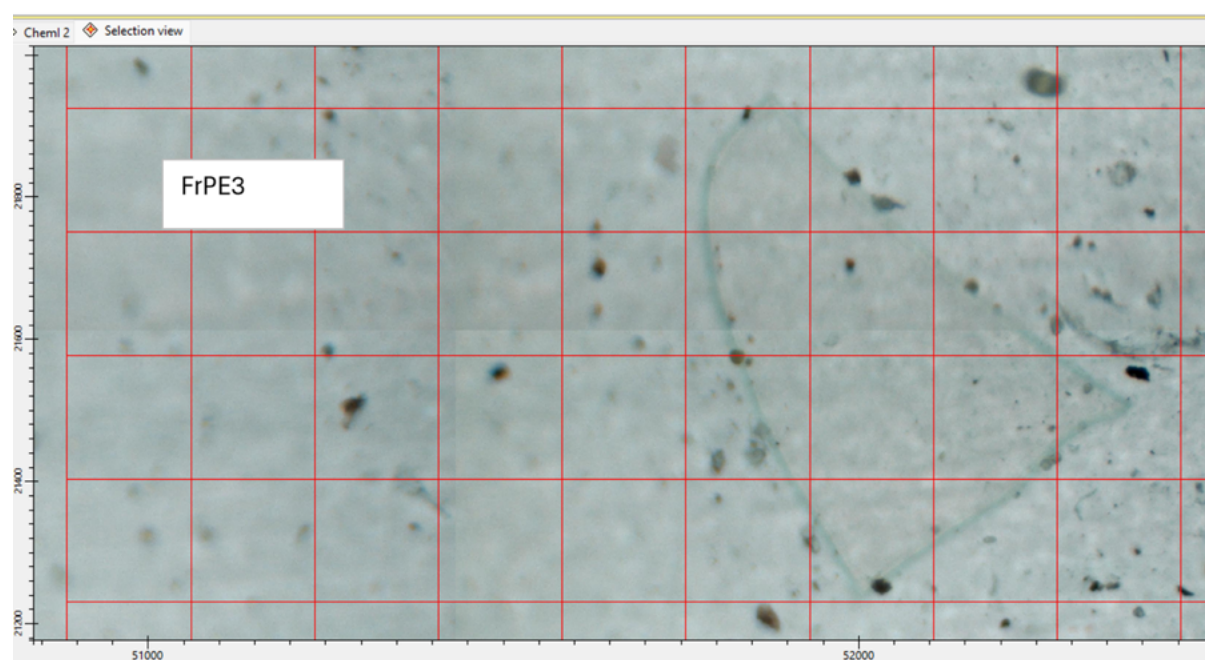


Figure 29: Image from the 29/04/2026 DD sample showing particle FrPE3, one of the outlier large particles found within the sample.

3.3.4 MET Data

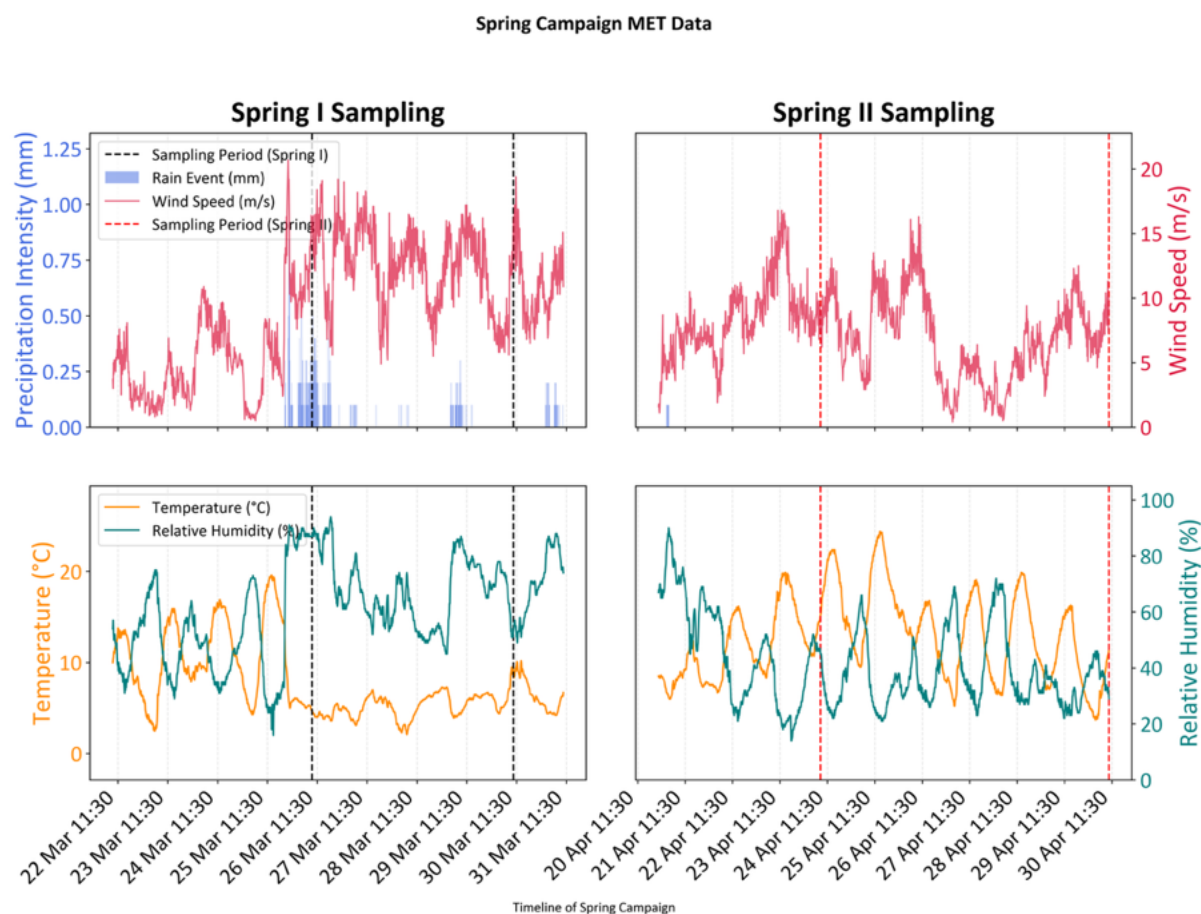


Figure 30: Showing the relevant meteorological data (precipitation volume and duration, wind speed and direction, humidity and temperature profiles) from Hohe Warte station 105. The dotted red and black lines show the respective start and end date and times of both sampling periods. The grey lines highlight the daily resolution corresponding to the sampling. All data was collected from geosphere.

Focussing on the first sampling period, the discrepancies of the WD can be rationalised by the volume of rainfall seen prior to the beginning of the campaign. There is a large volume of rainfall in the hours leading up to the sampling, therefore, once the first sample was placed, the initial rainfall had not been collected. When assessing the scavenging effect, the initial rain event is considered the primary driver, accounting for the majority of MP removal. Therefore, in this instance, the WD lacks particles as the initial rainfall is not captured. The high DD seen on the same day can be rationalised by the high wind speeds observed, similarly to the winter campaign. The 3-day accumulated sample during this period is significantly lower, however, this is as expected due to the atmospheric washout effect.

The second sampling period begins with the 3-day accumulated sample showing a predominant amount of the deposition to be from WD. This is unexpected due to the lack of rainfall accounted for during and prior to the campaign. However, as previously discussed, this may be attributed to the hypothesised influence of morning dew, suggesting either the dew, or the length of time the container is exposed for, results in an increase in the amount of MP. In the subsequent days (28/04/2026 and 30/04/2026) high DD is observed, despite the absence of significant wind speeds. This, therefore, could be influenced by the North-west prevailing wind direction, which has not been observed in previous samples, suggesting an association with distinct or previously unobserved sources.

3.3.5 Deposition Flux

For the deposition flux assessment, the results are split into DD, WD and bulk deposition flux. Each flux value is upscaled accounting for the RR and F_{cov} of the respective extraction and analysis procedure. The DD deposition flux plot observed in Figure 31 shows the flux with the units $MP/m^2/day$ as calculated in the methodology.

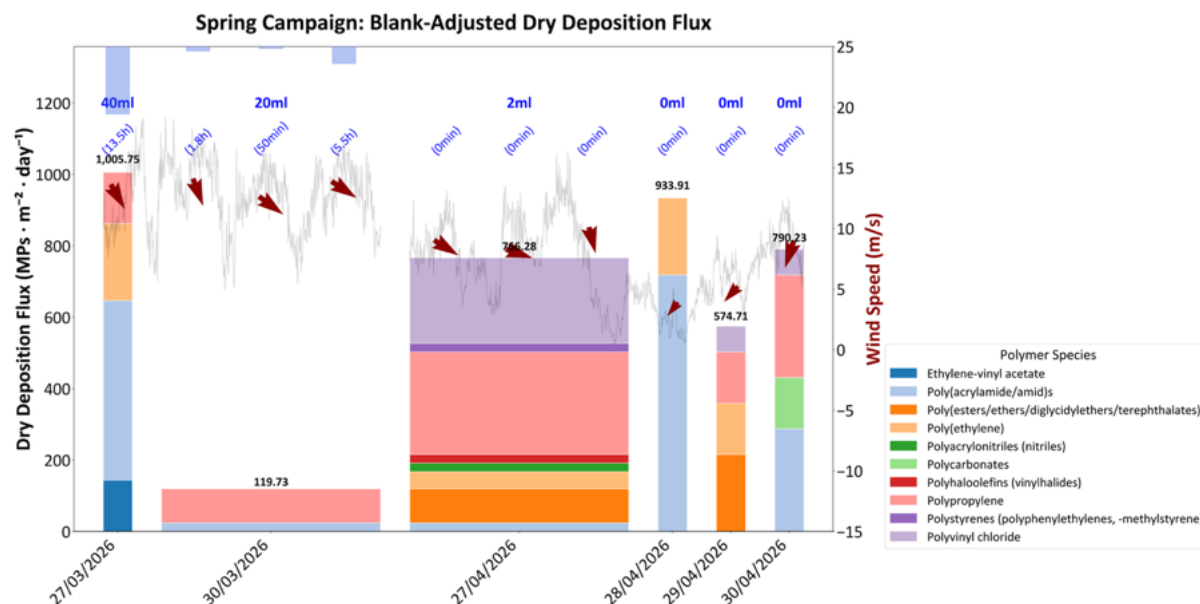


Figure 31: Shows the DD flux across the spring campaign including both sampling periods calculated in $MP/m^2/day$.

The results of Figure 31 show a wide variety of the calculated DD flux ranging from 119.73 – 1005.75 $MP/m^2/day$. All these fluxes are considered average when comparing to other studies conducted in urban locations, however, the majority of samples still maintain a flux larger than average. The variation across this campaign can be rationalised by the MET data, baring the previously discussed 29/04/2026 sample.

Figure 32 shows the variation of the WD across the spring campaign. Unsurprisingly, the deposition flux is low for the first sampling period having fluxes of 0.07 and 0.14 $MP/mL/day$, however, the 27/04/2026 sample is much larger at 10.54 $MP/mL/day$. This has already been rationalised by the likelihood of dew during this period and the washout effect observed within the first sampling period.

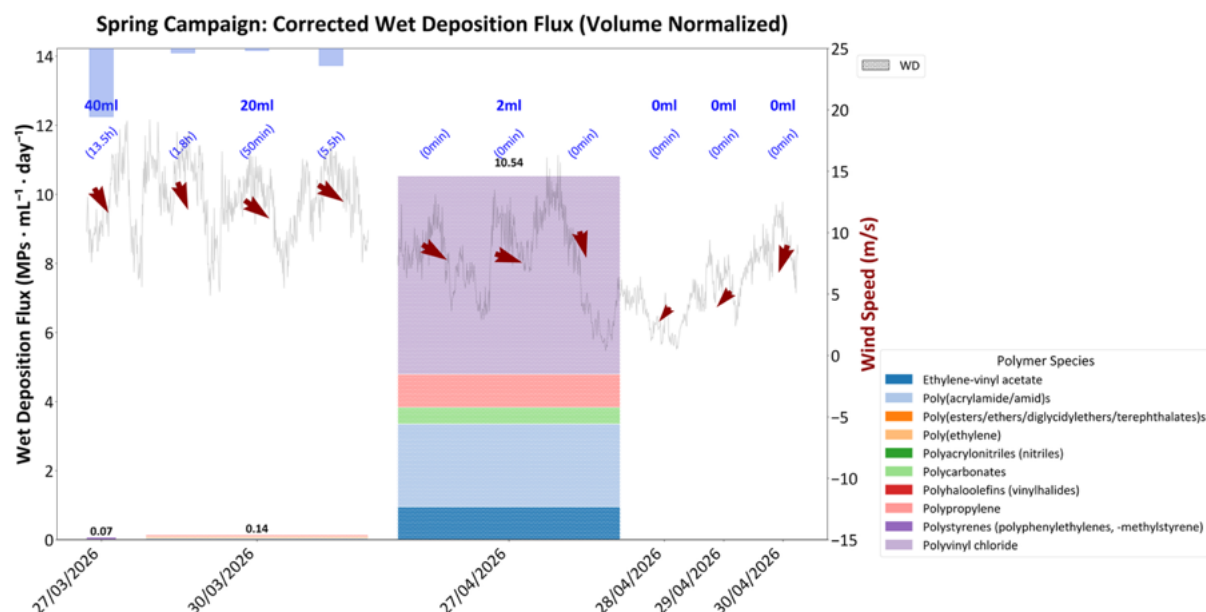


Figure 32: Shows the WD flux across the spring campaign including both sampling periods calculated in MP/mL/day.

After reviewing the WD and the DD individually, the combined bulk flux results are as expected shown in Figure 33. 27/03/2026 has a flux of 1,374.15 MP/m²/day, whilst these values exceed expected averages, they remain within a plausible range of deviation. The 30/03/2026 has a smaller flux of 488.14 MP/m²/day. For the second half of the sampling campaign show similar fluxes the 28/04/2026 has a flux of 933.91 MP/m²/day, the 29/04/2026 has a flux of 574.71 MP/m²/day and the 30/04/2026 has a flux of 790.23 MP/m²/day. The 27/04/2026 has a higher flux value of 3,467.92, predominantly attributed to the WD. These values alone emphasise the daily variation seen in the fluxes, which are currently unrepresented in other studies.

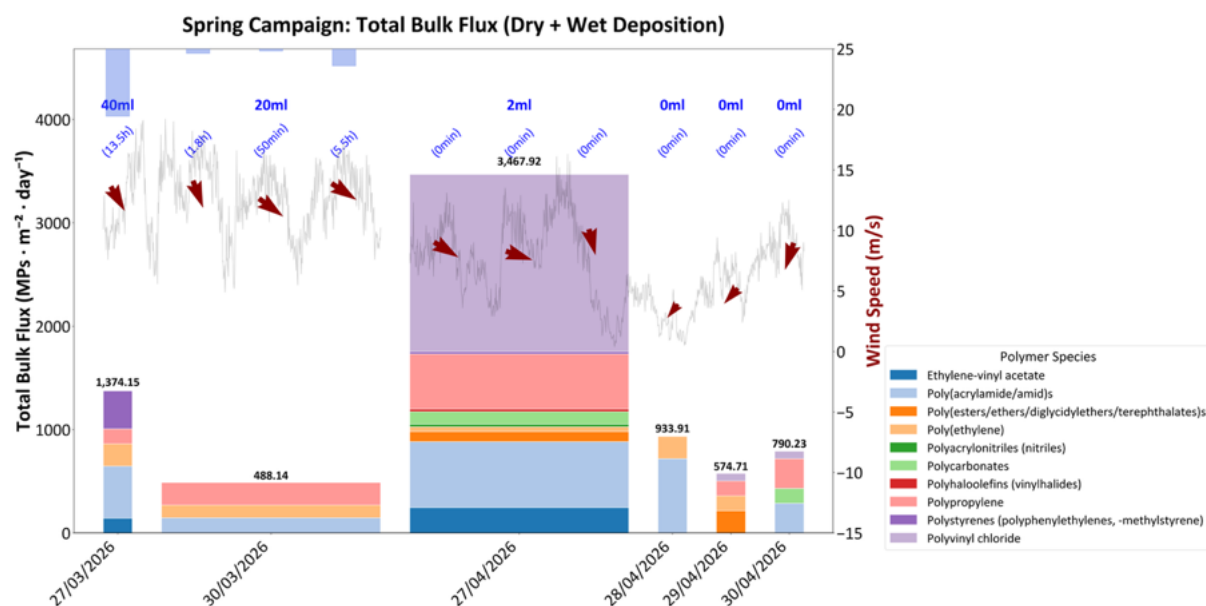


Figure 33: Shows the combined WD and DD flux across the spring campaign including both sampling periods in MP/m²/day.

3.3.6 Influence of Local Human Presence on Atmospheric MP Deposition

During the spring campaign the Lange Nacht der Forschung event was conducted at the aerosol physics observatory on the 24/04/2026. Due to the high volume of people which

would be in close proximity to the sampler, a separate experiment is conducted to assess the impact of the increased amount people near the sampler. To facilitate this measurement, a petri dish is placed for the duration of the tours (3 hours) and is subsequently retrieved at the end of the event. Table 3 summarises the key data, including attendance times, duration of visit and the total number of participants present within each tour.

Time	Duration of stay(mins)	No. People
17:40 – 17:50	10	11
18:30 – 18:40	10	3
19:15 – 19:30	15	3
19:40 – 20:00	20	14
21:40 – 21:50	10	14

Table 3: Shows the time, duration of stay near the sampler and the number of people present at each tour throughout the whole event.

Particle Count and calculated DD flux

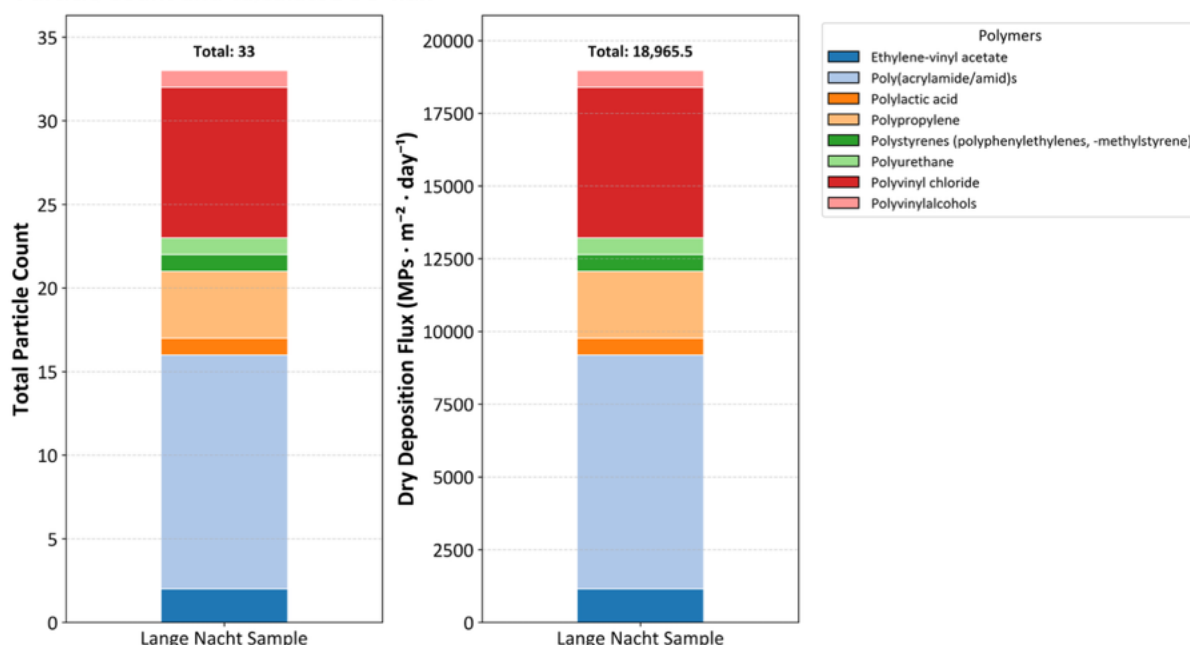


Figure 34: Showing the raw particle count and calculated dry deposition flux ($\text{MP}/\text{m}^2/\text{day}$) of the Lange Nacht Forschung sample conducted on the 24/04/2026 for 3 hours.

The results of the Lange Nacht sample, seen in Figure 34, have significant implications when calculating deposition fluxes. The results show a total of 33 particles observed within this 3-hour period, equating to a deposition flux of $18,965.5 \text{ MP}/\text{m}^2/\text{day}$. Despite considering the previously discussed overclassification of PA, likely to be organic, and PVC, most often corresponding to pollen, a significant number of MP remain for such a brief sampling duration. Notably, this sample contains a higher number of synthetic fibres, 3 prior to blank adjustment, than the other environmental samples. Alongside the synthetic fibres, there is a high number of pigmented fibres observed, which remained unclassified by OPUS MPID, as seen in Figure 35.

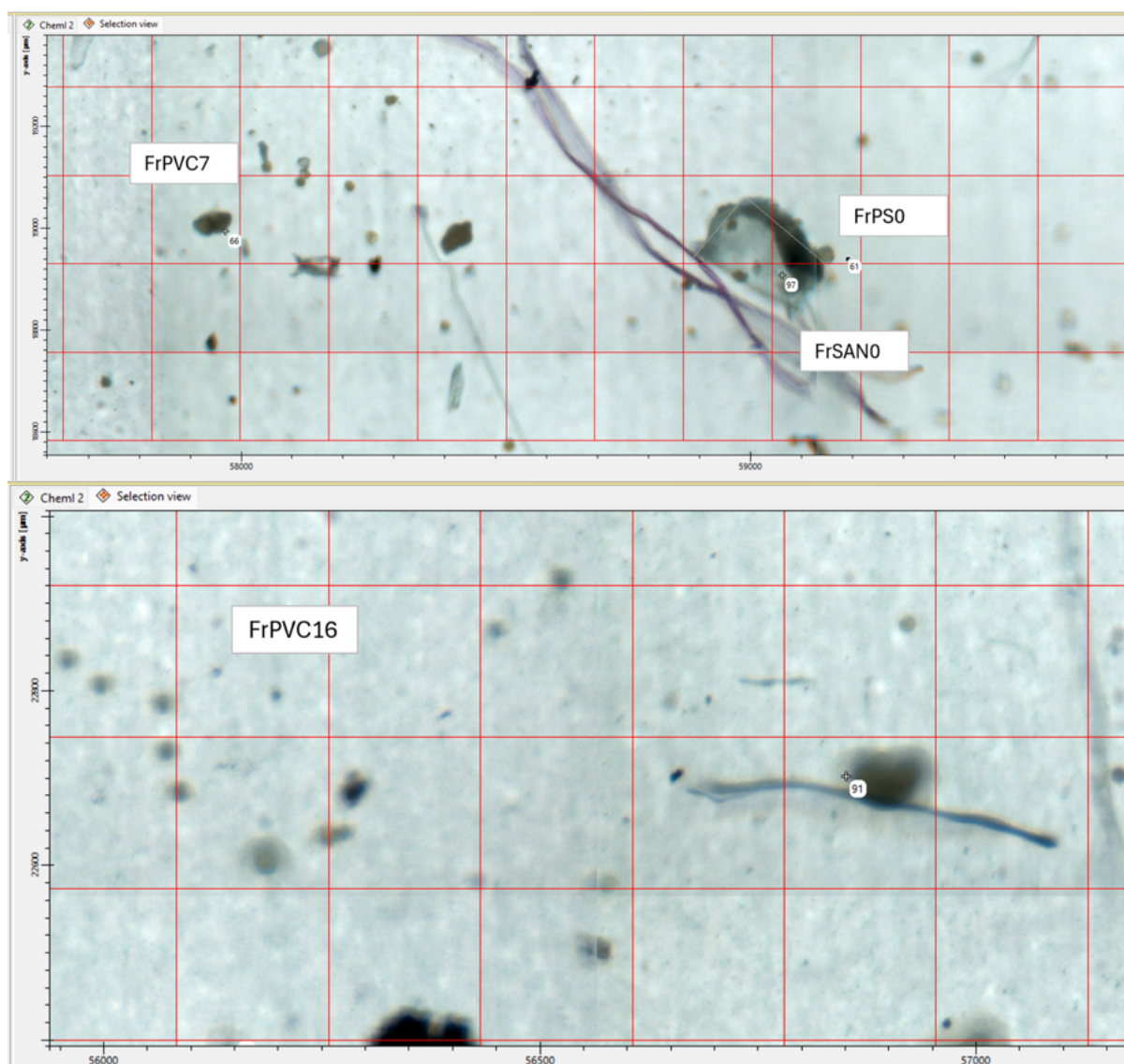


Figure 35: Showing microscopy images taken on the LUMOS II microscope of the fibres observed visually, however, were not detected by the MPID.

Figure 36 shows the dominant polymer found within the 3-hour human influence experiment to be PA at 42.4%. However, as explained, OPUS has a high misclassification rate for PA and this is therefore likely to be overestimated. Although PVC represents a significant portion of the sample reaching 27.3%, this value is likely inflated due to the OPUS MPID misclassification of PVC from pollen. However, despite the short sampling period, the sample shows a high amount of plastic particles, seeing 12.1% to be PP. Other species found are Ethyl-vinyl acetate (EVAc), Polylactic Acid (PLA), PS, Polyvinyl alcohols (PVAs) and Polyurethane (PU) ranging from 3 – 6.1% of the sample.

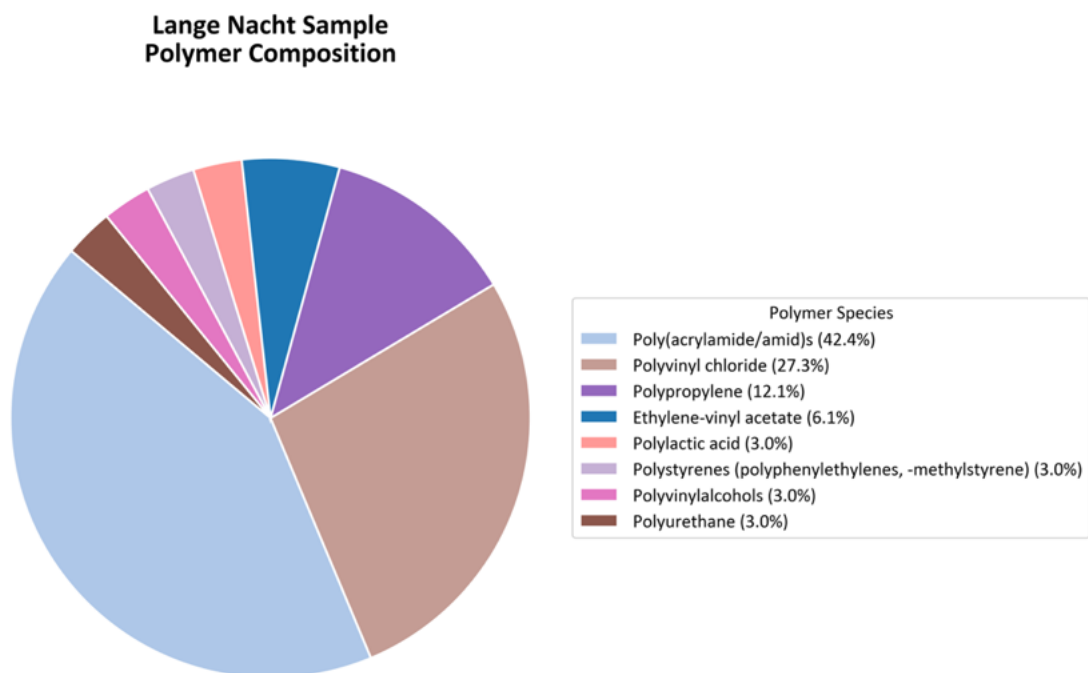


Figure 36: Pie chart highlighting the percentage of each species of all particles in the human influence experiment (Lange Nacht).

3.3.7 Size Classification

All the particles were then sized using the methods previously discussed allowing the size distribution of all particles to be examined.

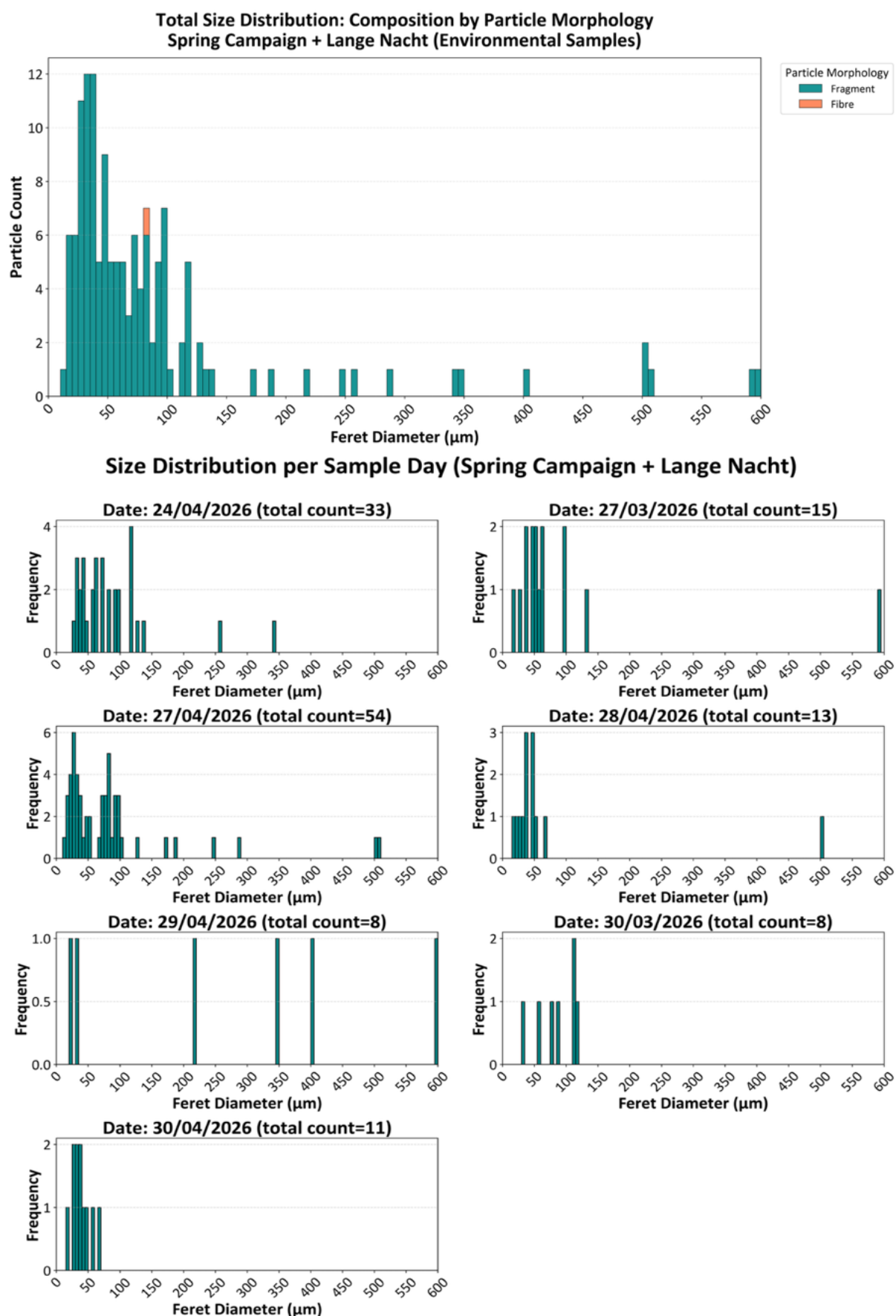


Figure 37: Showing the morphology of each particle along with the size of each particle. This is further characterised by sample day, highlighting the size of each particle per each day of the spring campaign. The Lange Nacht sample was conducted on the 24/04/2026.

The size classification shown in Figure 37 highlights the range of sizes seen across the campaign ranging from 5 – 340µm in Feret diameter. The dominant size range falls between 25 – 40µm. Figure 37 also segregates the particles by morphology, displaying the dominant shape observed, across both WD and DD samples, are fragments, with only 1 synthetic fibre being observed across the spring campaign.

The results from Figure 38 show the dominant species within the spring campaign to be PA reaching 26.6% of the total particle count. However, due to OPUS MPID misclassifications, this polymer is likely overestimated. Therefore, it can be interpreted, PP is the dominant polymer reaching 24.8% of the total particles. PVC is also a relatively dominant species at 22%, however, as previously discussed this is also often misclassified. PE accounts for 10.1% of the particle count and PET accounts for 6.4%. Other species include EVAc, Polycarbonate (PC), PS, PAN and Polyhalo-olefins ranging from 0.9 – 2.8%.

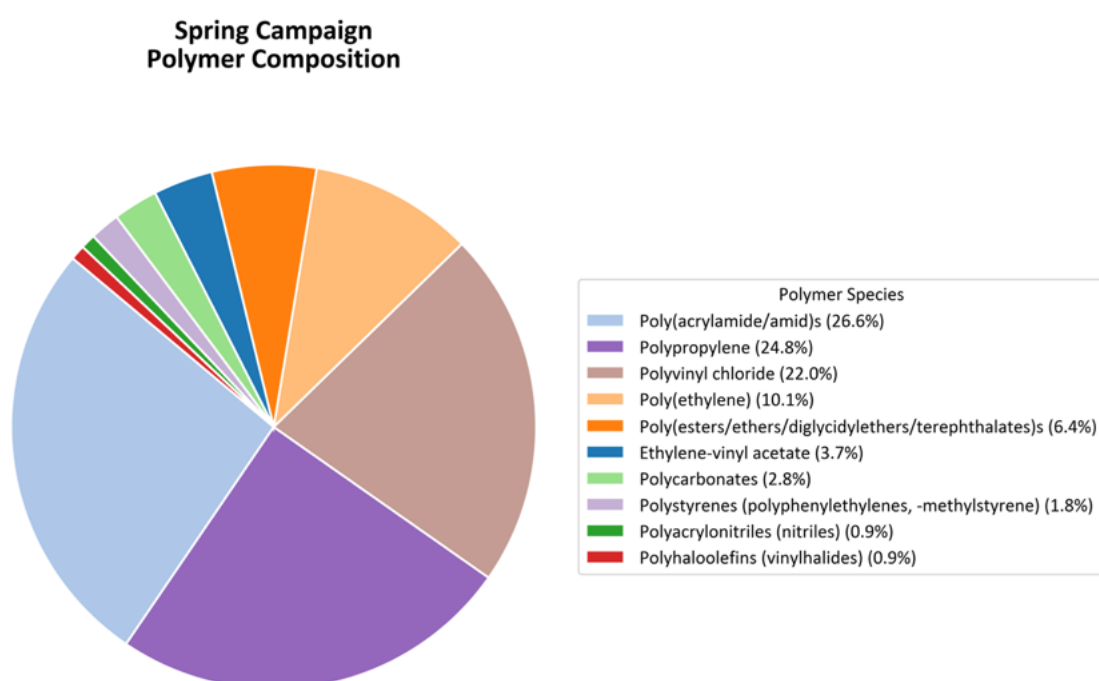


Figure 38: A pie chart highlighting the percentage of each species of all particles in the spring campaign.

Figure 39 shows the particles sizes separated by polymer species. The outlier in the samples falling out of the dominant ranges of 10 – 140µm are some PVC particles, one of which is considered a fibre.

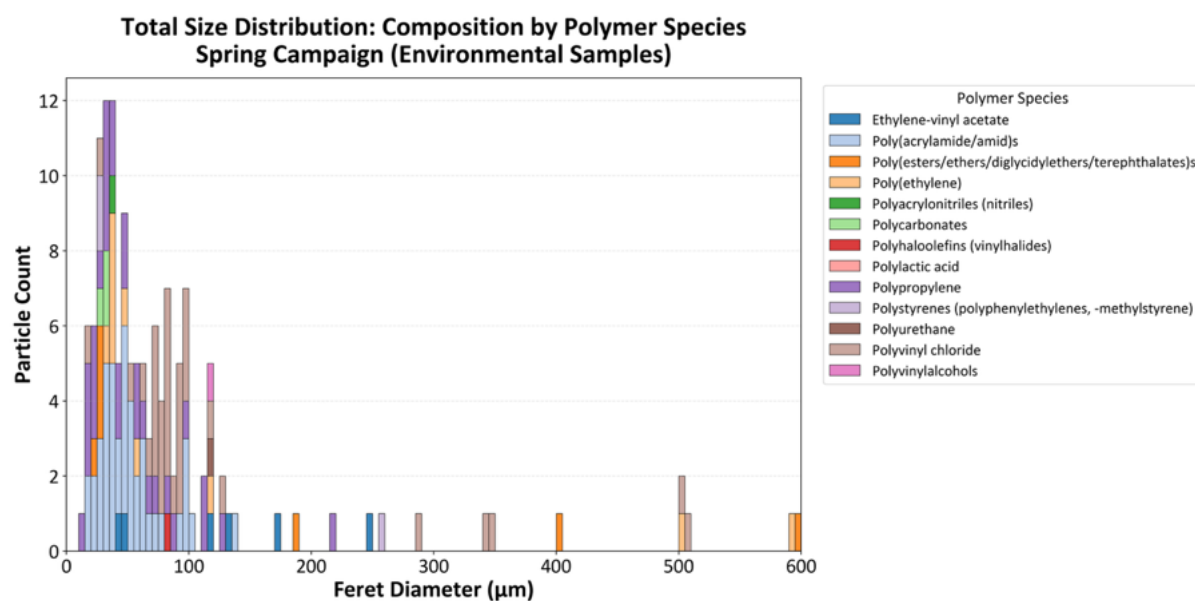


Figure 39: Shows the size of all the particles throughout the Spring campaign separated by polymer species and colour coded as shown in the legend.

To capture the wide variety of observed MP, a small gallery is included to highlight some of the unique particles from the spring campaign and can be seen in Figure 40.

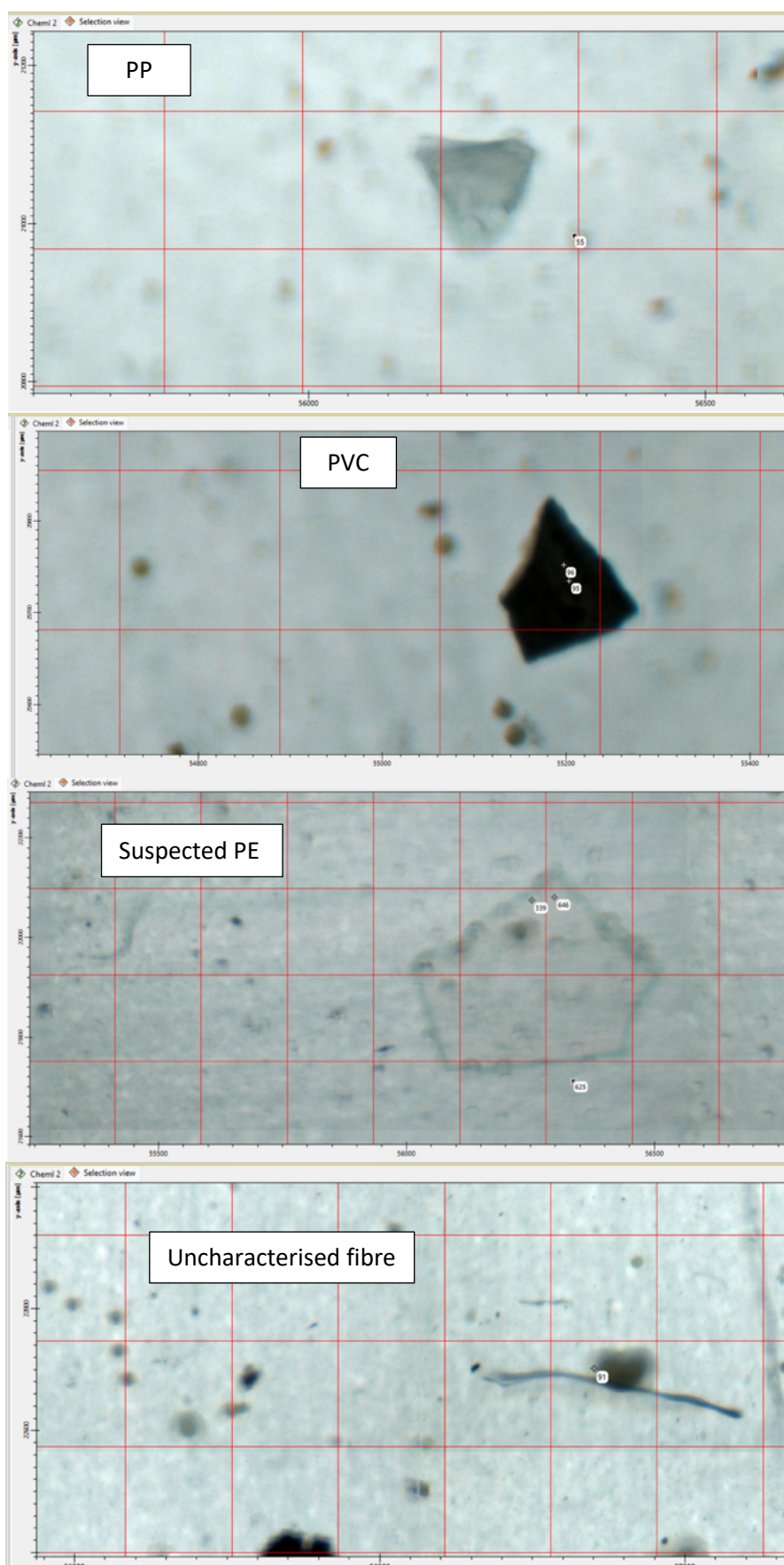


Figure 40: A selection of microscopy images from both WD and DD samples within the winter campaign. The names given are based upon the classification system as outlined in the methods.

3.3.8 Concluding Remarks

The spring campaign shows relatively consistent fluxes across both sampling periods. This campaign shows a large range of species observed including: PP, PS, PE and PVC. Fragments are the dominant shape, largely exceeding fibres with the majority of these particles falling within the 20 – 50 μ m range. It is observed WD is linked heavily to precipitation events, whereas DD shows some relationship to higher wind speeds, however this is minimal. The scavenging effect is well illustrated in these samples, showing a significantly lower MP count following rainfall events. Within this campaign, the experiment investigating human influence reveals a significantly higher MP deposition flux when individuals are in close proximity to the sampler.

3.4 Totals

3.4.1 MP Total Particles

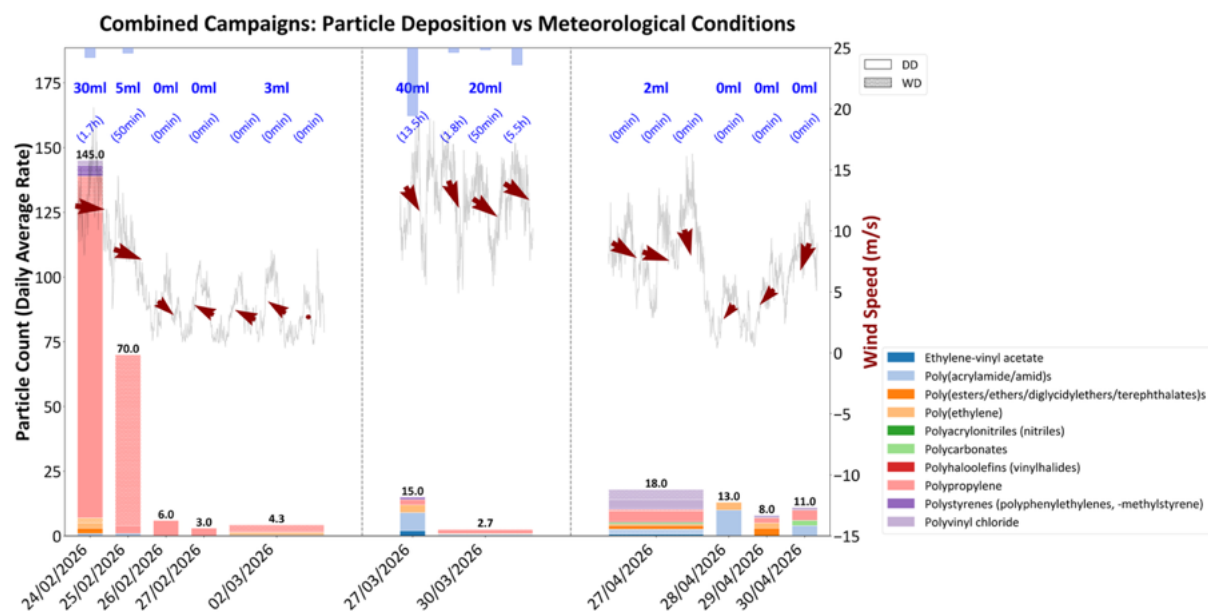


Figure 41: Showing the results of the both the winter and spring campaign (23/02/2026 – 02/03/2026, 26/03/2026 – 30/03/2026, 24/04/2026 – 30/04/2026). The figure shows the total particle count (blank adjusted) of each collected sample split into DD and WD, the polymers are coloured based on the legend shown. The MET data consists of wind speed (grey line), average wind speed (arrow size) and direction (arrow angle), total recorded rainfall by the nearby MET station in the blue bars and total volume of rainfall (ml) collected by the sampler and the total duration of rainfall recorded at the nearby MET station in blue text.

The comparison of all sampling periods shown in Figure 41, reveals a notable high abundance of particles observed in the initial days of the winter campaign. The remaining days of both campaigns exhibit comparable values, ranging from 2.7 – 18 particles. Therefore, these first few days where 145 and 70 particles are observed for the 24 and 25/02/2026 can now be considered outliers comparatively.

3.4.2 Deposition Flux

This section includes the total bulk flux of the WD and DD across both campaigns, the individual plots of the combined WD and DD fluxes across both campaigns can be found in the supplementary material.

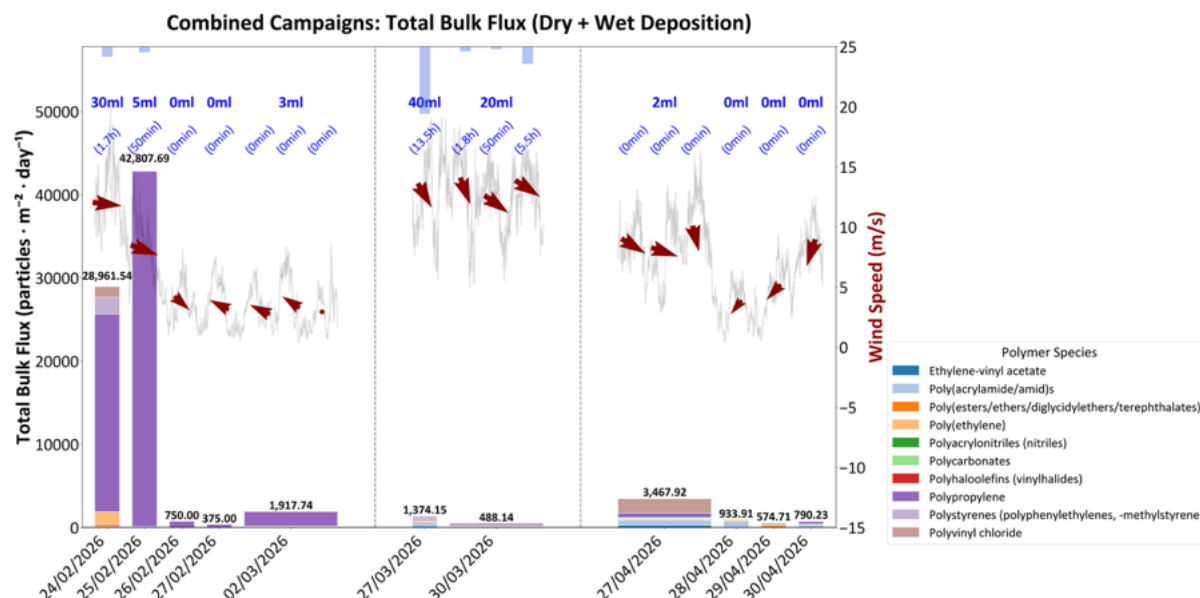


Figure 42: Shows the bulk flux in MP/m²/day, across both the winter and spring campaigns, including the key MET data.

Figure 42 shows the bulk flux of both campaigns, for a simple comparison to be drawn. The bulk flux ranges from 375 – 3,467.92 MP/m²/day, with the previously discussed outliers reaching 28,961.54 and 42,807.69 MP/m²/day. The range of fluxes observed shows the prevalence of the daily variation in MP flux. While the data suggests the total flux values remain independent of the seasons, there is a variation in the polymers observed. The winter campaign sees a dominant amount of PP with very minimal amounts of other polymers. Conversely, the spring campaign shows a significantly larger range of polymers including PP, PE, PET and PS found within several of the samples but are notably absent within the majority of the winter campaign. These seasonal differences highlight the potential variability in composition which may be present over the course of a year. The largest factor in influencing deposition fluxes is the relevant meteorological variables. From these results it appears higher wind speeds are loosely correlated with a larger flux. While wind direction appears to influence the flux, this correlation is not consistent to draw concrete conclusions on the precise localisation of the sources. For this scope, longer time series of observations would be necessary to strongly constrain the relationship with wind direction.

3.4.3 Size Classification

The size classification of all the particles across the campaigns are gathered to obtain an average size distribution. The distribution of all particles separated by day is presented in the supplementary material.

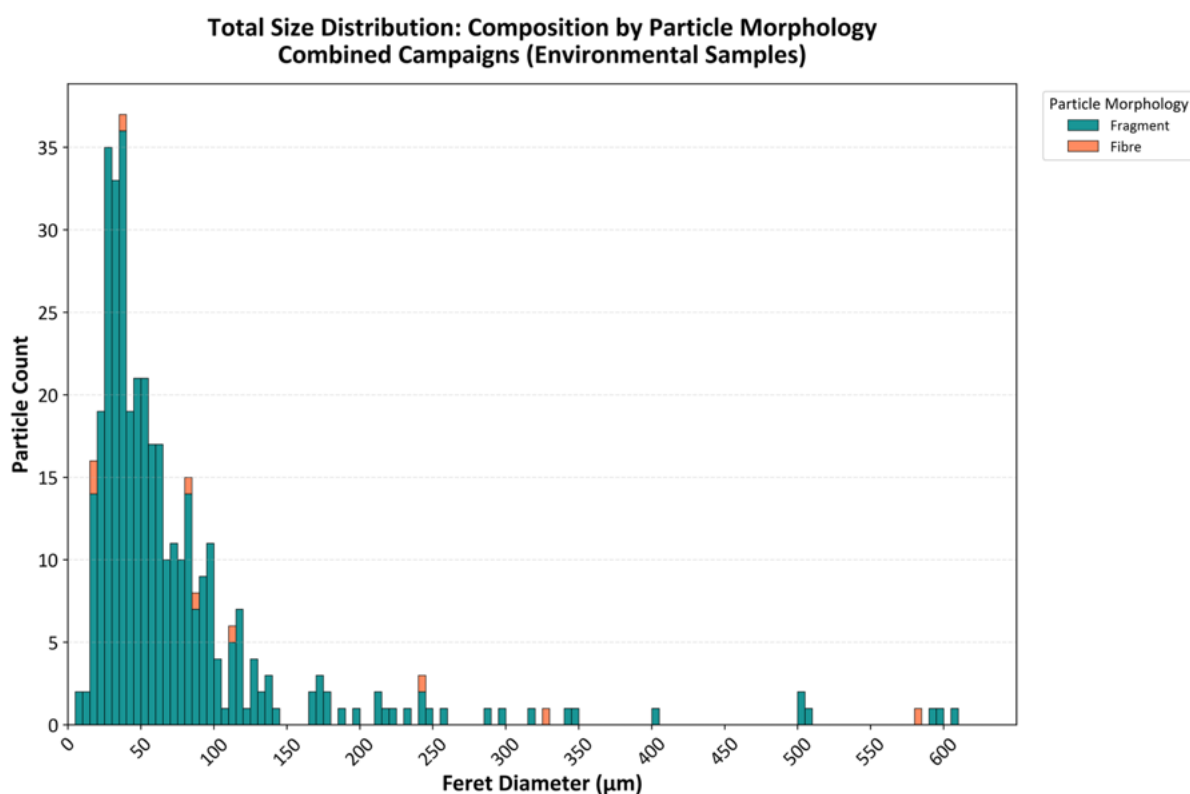


Figure 43: Shows the morphology of each particle along with the size of each particle across both sampling campaigns.

The results of the size classification seen in Figure 43, again highlight the dominant size range between 25 – 40μm. This distribution appears to be a log normal model, consistent with established expectations of atmospheric MP aerosols. The figure also illustrates the prominence of particles falling below 100μm. These values are in line with the atmospheric MP deposition literature, where smaller particle sizes are more prevalent. However, the morphology remains inconsistent with the literature, where the dominant morphology within this study continues to be fragments, observing only 9 fibres across both campaigns. Whilst these campaigns did not capture a large portion of WD, where fibres are suspected to be dominant, this data still shows a disproportionately low amount, disproving previous claims.

Combined Total (Winter + Spring) Polymer Composition

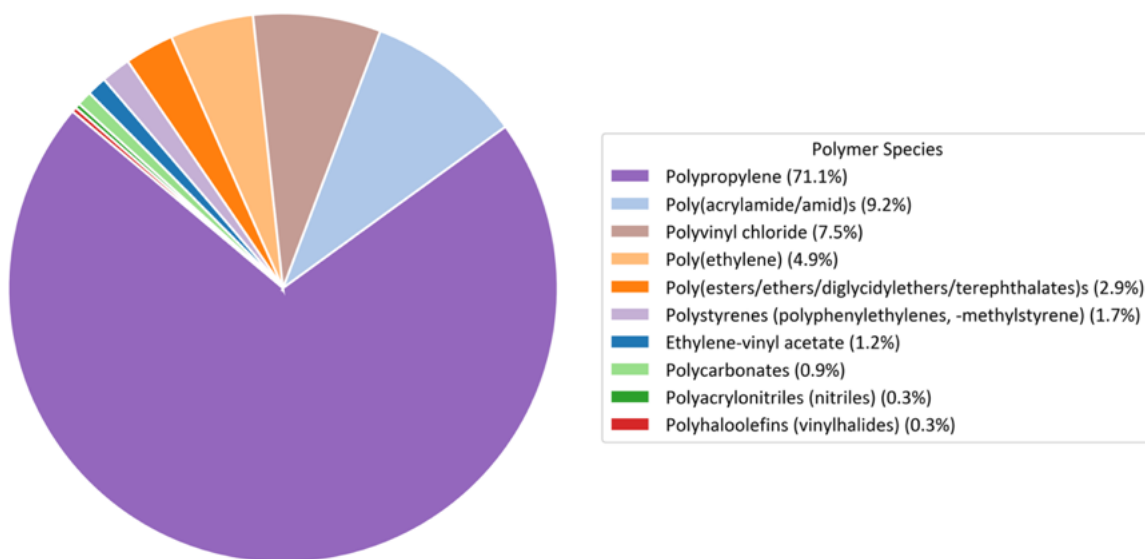


Figure 44: A pie chart highlighting the percentage of each species of the combined campaigns.

The results of the combined campaigns highlighted in Figure 44 shows the dominant species to be PP reaching 71.1% of all samples. This value is disproportionality influenced by the dominance seen in the winter campaign, however, PP persists across all sampling periods. Other common species included PS, PVC, PE, PET and EVAc ranging from 1.2 – 9.2%. Fewer common polymers included PC, PAN and PHV raging from 0.3-0.9%.

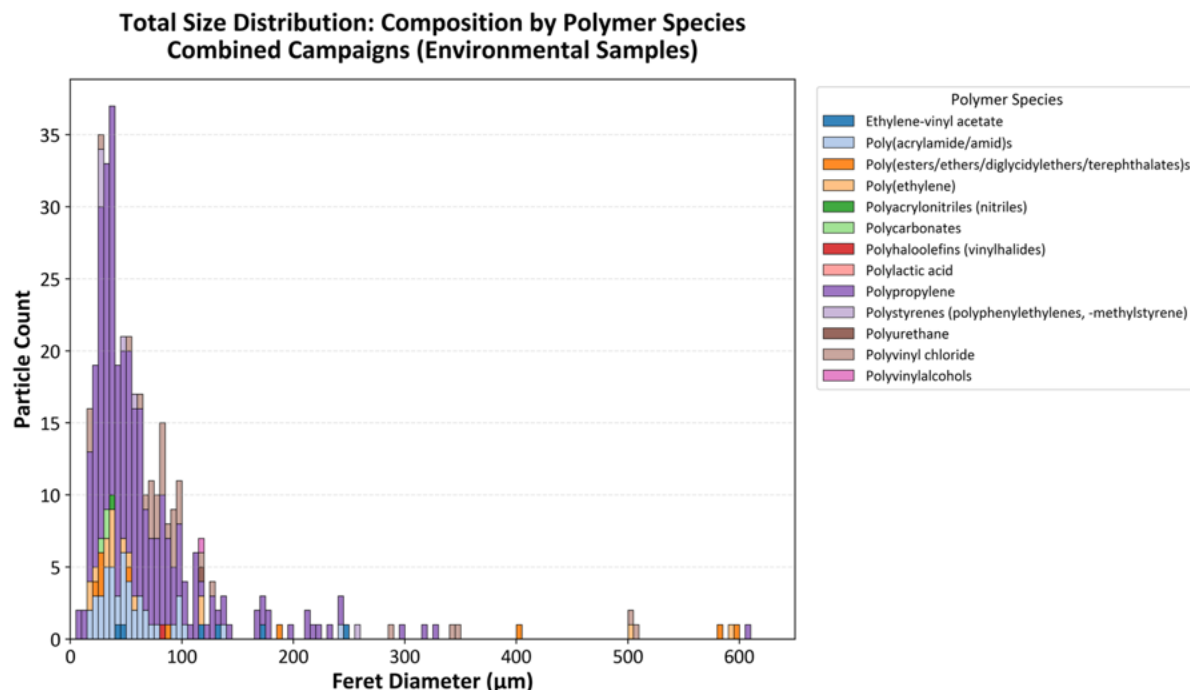


Figure 45: Shows the size of all the particles throughout both campaigns separated by polymer species and colour coded as shown in the legend.

Figure 45 highlights PP as the dominant species seen throughout both campaigns, however, whilst PP is found within the spring campaign, this prominence is due to the large number of particles observed on the 24 – 25/02/2026. Other more commonly observed species include PE and PET.

3.4.4 Total Values

An overview of the various campaigns, summarising the main results is documented in the table below.

Variable	Winter	Spring	Human Influence	Total (spring + winter)
Number of Samples	5	6	1	11
Mean DD	3,466.66	698.44	18,965.5	1,956.72
Mean WD	24.65	3.79	N/A	14.12
Mean bulk Deposition	15,161.39	1,271.51	18,965.5	7,494.64
Dominant Polymer	PP	PA/PP	PP	PP
Dominant Morphology	Fragments	Fragments	Fragments	Fragments
Mean Particle Size	66.83µm	149.22µm	107.58 µm	92.79µm

Table 4: Shows the key values collected across the campaigns. It outlines the mean WD, DD and bulk flux along with the dominant polymer, morphology and mean particle size.

4.0 Discussion

The results presented previously have opened several questions which aim to be resolved within this section. This will be split into relevant topics and questions, aiming to resolve the research questions posed and the uncertainties presented within the results.

4.1 MP Deposition in Vienna

4.1.1 Daily Variability of Atmospheric MP Deposition and Comparison within the Literature

The research has confidently ascertained the MP deposition flux within Vienna across several days, both within the winter and spring. However, the results highlighted the large daily variation seen across samples is significant, in comparison to other published research. Other published studies of urban MP deposition found fluxes ranging from 110 – 771 MP/m²/day (Dris et al., 2016; Edo et al., 2023; Klein & Fischer, 2019; Wright et al., 2020). Whilst in certain days there are values in line with the literature, e.g. the 30/03/2026 at 488.18 MP/m²/day, some of the daily fluctuations surpass average values by several orders of magnitude. As in 25/02/2026, which showed a bulk flux of 42,807.69 MP/m²/day. This variability is larger on the daily scale than across the seasons, suggesting any episodic event can dominate observed values, usually masked by other studies with sampling durations between 1-2 weeks. If the winter campaign bulk flux values were totalled and averaged over a 7-day period, the flux value would be 10,687.42 MP/m²/day. If the same process is conducted for the spring campaign, a bulk flux of 1,089.87 MP/m²/day would be calculated. Whilst these values are higher than given literature, they are significantly closer, evidencing the fact a coarser temporal variability may be smoothing out extremes. This variability is seen not only in abundance of MP, but also in species and sizes, highlighting the importance of daily sampling and the need to develop the chosen methodology further to decrease uncertainties.

The observations presented indicate previous studies are likely systematically underestimating atmospheric deposition due to the methodological limitations present within the majority of MP studies. In this instance, with the results of these campaigns, the logical conclusion for these particularly large samples is a combination of the benefits of daily sampling and the likelihood of local resuspension from a specific local source.

4.1.2 Meteorological Influence and Deposition Processes

Along with the MP collection, the meteorological analysis done within the results allows for conclusions to be drawn on the role of atmospheric conditions and MP abundance. Despite some individual deposition days coinciding with higher wind speeds, varying directions or rainfall events, no single meteorological variable consistently explained the observed variability throughout the campaign. From this, it could be inferred atmospheric MP are influenced by several processes rather than one. From the results, a hypothesis on the likelihood of resuspension from stronger winds, resulting in an increase of previously deposited particles from varying locations could be assumed. Alongside resuspension, the transport of particles from regions further away could be occurring simultaneously. Changes in the wind direction may also expose samples to different sources, resulting in not only a change in the deposition flux, but also in the polymers, size and morphologies likely to be

present. The observed variation in polymer type and abundance seen within the daily sampling supports the idea of varied emissions sources and various transport pathways.

This large daily variability also supports the idea of short atmospheric residence times for MP, making local meteorological conditions and nearby sources particularly important at an urban level. This hypothesis of a local source is supported by the occasional presence of very large particles (e.g. within the 29/04/2026 sample). The daily resolution opted for this study allows for the discrete discrimination of the transport of these particles to be localised to a specific time. One such particle is present on the 28/04/2026, followed by several on the 29/04/2026, with finally none being observed on the 30/04/2026. This information supports the statement it is a real atmospheric emission, rather than a local contamination. This is maintained by the fact no human presence has been reported close to the measuring site within that period. If accumulation over one week had been chosen, these particles may not have been disentangled from the surrounding days and could have even been considered contamination. The absence within the campaigns of strong variations in the meteorological conditions, alongside the strong variations in MP, supports the hypothesis for local influence rather than long range transport. However, this would be better evaluated with longer campaigns.

The results further highlight precipitation as the primary removal mechanism for atmospheric MP particles. Periods with rainfall usually saw lower DD within the following days, evidencing the effect of precipitation as an atmospheric cleaning mechanism. This is consistent with other studies describing the atmospheric washout effect (Abbasi et al., 2024). However, not all samples show a strong relationship between rainfall and deposited MP. It appears the initial rainfall event has a higher influence on the presence of MPs. During the spring sampling period, explicitly aimed at capturing more WD, the initial rainfall event was missed, showing a low amount of MP obtained within the samples collected. Factors such as this, indicates the efficiency of the initial rainfall from precipitation events. These aspects are therefore deemed more influential on the total MP deposition rather than the total rainfall volume.

4.2 Particle Characteristics and Potential Sources, Size, Morphology, Polymers, Considerations about the Sources

For all days of both campaigns, both the size and morphologies of all synthetic particles are determined. This polymer composition provides some insight into the atmospheric MP deposition in Vienna. Despite the fact polymer type cannot identify emission sources alone, the combination of collecting morphology, size and meteorological conditions in addition, allows for plausible sources to be considered.

Throughout the study PP is determined to be the dominant polymer across all campaigns, reaching 71.7% of the total accounted for particles. This is unsurprising as PP is one of the most widely, globally produced plastics, used in packing materials, food containers, household products and construction materials (*Global Plastics Outlook*, 2022). Therefore, due to its dominance, the high quantities observed here suggest fragmentation of macroplastics, followed by resuspension into the atmosphere, to be a likely source. These large episodic events of high quantities of PP suggest local activities, for instance, construction, waste handling and surface resuspension could contribute significantly to

general atmospheric deposition. Alongside PP, PE and PET were also present, 4.9% and 2.9% respectively, within several samples. PE is often used for plastic films bags and packaging materials, whereas PET is used for synthetic textiles and plastic bottles (*Global Plastics Outlook*, 2022). These polymer types are contrusive with the hypothesis of emissions originating for human activities.

Further evidence of fragmentation being the dominant emission source is the dominance of fragments over fibres within the campaigns. This finding is specifically relevant when considering the measurement site. Alongside the hypothesis rooftop emissions capture primarily background emissions, while ground level experiments result in more fibres, suggests fragmentation is likely the largest contributor to long range atmospheric transport.

The size distribution of the given data corresponds with literature, showing the size range of atmospheric MP are smaller than within other ecosystems (Thompson et al., 2024). However, within this study, due to the resolution of the LUMOS II FPA-FTIR, a slightly lower size range was captured comparatively to other FTIR microscopes, usually capped at a resolution of 5 – 20µm (Käppler et al., 2016; Renner et al., 2019). This allowed for particle sizes from 5 up to 605µm to be observed. In existing research there are usually peaks around 20µm due to this detection limit (Faauma et al., 2026; Maurizi et al., 2023). However, within this study, despite having rigorous sizing for each particle and a lower detection limit, a peak still forms around 20 – 40µm. This suggests the peak previously observed from detection limits may indeed be the dominant size of atmospheric MP. This dominant size range further supports the idea of local influences versus long range transport, as large particles are expected to rarely be transported beyond regional scales. An interesting observation is the dominant morphology characterisation, finding a significantly higher number of fragments over fibres. This is controversial to the published literature highlighting instead fibres as the dominant species (Bergmann et al., 2019; Turner & Kyriakoudes, 2022; Welsh et al., 2022).

4.3 Influence of Local Human Activity

4.3.1 Considerations of the Influence of Nearby People on Detected Atmospheric Deposition

A unique aspect of this study is the dedicated experiment sought out to assess the influence of human activity on atmospheric MP deposition when within close proximity to the sampler. During the 3 hours of the Lange Nacht der Forschung event, a substantially higher quantity of MP deposition is observed in comparison to background observations. A likely explanation for this increase is in the number of pedestrians (45 people) near the sampler, acting as an emission source. During the visit, people did not perform any unusual activities, mostly walking close by, listening for a 10-minute talk and then leaving. It is not novel information human activities release synthetic particles through the abrasion of footwear and textiles (De Falco et al., 2020). However, these results highlight the importance of pedestrians as a key driver for local sources of airborne MP, especially within dense urban areas. However, this is mostly limited to the lower layers of the atmosphere, within a few meters from the ground. This experiment also highlighted the rate deposition can increase after human influence, for 33 particles to be observed within a 3-hour window is staggeringly high, evidencing the pronounced influence on short temporal scales.

4.3.2 Considerations on Fibres

Alongside the increase of the total number of particles, the total number of fibres also increased. Within this sample a larger number of fibres were found comparatively to other samples, where no human presence is recorded near the sampler. This is specifically contradictory to other studies finding fibres are dominant over other morphologies (Bergmann et al., 2019; Turner & Kyriakouides, 2022; Welsh et al., 2022). These results introduce an interesting theory on the difference between measurement sites. Samplers located at ground level may capture freshly emitted synthetic fibres, whereas rooftops may represent the background emissions of the urban area more generally. This combined information suggests a change in the previously assumed behaviour of fibres, now insinuating fibres are not uplifted as high as previously expected. This hypothesis is further supported by the small number of fibres found within the campaign data, despite the high calculated fluxes. This theory holds even within the WD samples, where a higher number of fibres are usually reported (Bergmann et al., 2019; Turner & Kyriakouides, 2022; Welsh et al., 2022). It is worth noting this conclusion remains even if the spectra analysis detected only 3 synthetic particles, as this behaviour is mostly dictated by the morphology of these particles rather than their composition. Wearing synthetic clothes, or a high synthetic composition ratio, would therefore, imply a large environmental contamination in the form of plastic fibres.

4.3.3 Methodological Implications

From this experiment come some interesting and critical methodological implications which must be addressed within future studies. The location of the sampler should be selected to minimise the influence of local sources if the objective of the study is to characterise background urban emissions or the influence of long-range transport. Inversely, studies aiming to characterise the influence of humans on MP emissions need to place the sampler in a location with high pedestrian activity. Differing in this way may provide valuable information for interpreting deposition measurements in the future. Another, interesting finding is while more fibres were found within the sample, not all were detected by the FTIR MPID, as shown in Figure 35. This means there could be an even higher number of synthetic fibres seen within this period. To rectify this issue within the automatic FPA 32x32 scan, it is suggested the ATR crystal analysis could be used in parallel, specifically for fibres, to gain confident polymer identification results. This is a methodology which could be implemented into future studies, in samples where a higher number of fibres is expected.

4.4 Seasonal Variability

Conducting both the winter and spring campaign allowed for seasonal comparisons to be drawn. The WD, DD and bulk fluxes across both campaigns remained relatively consistent, barring the two large fluxes at the beginning of the winter campaign (24 – 25/02/2026). However, due to the short length of these campaigns, a consistent difference may not be observed, which could instead be revealed in a longer time frame. A notable difference however between the two campaigns, is the identified polymers. The winter campaign saw a very large amount of PP and very few other polymers, however, the spring campaign found less PP, showing a wider variety of polymers including, PS, PE and PC. Due to the fact the wind direction and speed do not vary significantly between the campaigns, one can conclude the

different species identified are therefore influenced by seasonality. The morphology of the particles also did not vary significantly across the campaigns, where fragments prevail and fibres are less common. On the 28 and 29/04/2026, new large particles were found, seen to be transparent and followed a morphology closer to films. These particles were deemed to be environmental as they were not observed in the blanks and no maintenance occurred on the roof during that period. Therefore, these particles likely came from a source located near to the sampler due to their size, making it unlikely they were transported from afar.

4.5 Limitations

While this study has been designed to maximise the amount of information deducible, it still holds limitations. The uncertainty of lab-based work remains intrinsically high and creating more occasions to reduce this uncertainty, via replicates and reducing human influence which introduces human error, would be desirable. The classification methods developed for this study are also not without fault. The OPUS MPID has many benefits and was chosen for this work to reduce bias when selecting particles. However, the software contains many flaws, misclassifying organic material as PA or pollen as PVC is common, and influences the MP quantities seen within the results. Despite confirmation tests with OpenSpecpy, this has not created a foolproof system and offers an area for improvement.

4.6 Conclusions

This study provides the first quantitative assessment of atmospheric MP deposition in Vienna using daily passive sampling to calculate both WD and DD fluxes. The results presented show atmospheric MP are present within both the WD and DD, showing a substantial quantity over short time scales. Overall, the behaviour of atmospheric MP transport is evidenced to be more complex than limiting to a set number of variables. The fluxes were largely controlled by a combination of short term meteorological conditions and episodic emission events rather than specific seasonal differences, where higher wind speeds are linked to higher DD fluxes. Assessing the polymer type, size and morphology of collected particles, however, showed the complexity of interactions acting together to influence deposition.

The deposition fluxes reflect both the combined effects of local emissions, key meteorological conditions and various removal processes. The observations also suggest the atmospheric MP flux is dominated with intermittent localised events, operating within a low background flux. The work here supports the need for longer observational records at high temporal variability to accurately capture short, infrequent emission events, coupled with the importance of meteorological conditions versus seasonal differences. The study, with the use of daily sampling, reveals a substantial amount of variability, likely to be unnoticed using a coarser temporal resolution sampling period.

Key results linked to the research questions:

RQ1: The atmospheric MP deposition was successfully quantified for Vienna. The average values appear slightly higher than published literature from similar cities, but more importantly show significant episodic peaks of deposition, both in the wet and dry.

RQ2: Particle size, morphology and polymer composition were characterised, with fragments being the dominant morphology, PP being the dominant polymer and the dominant size range extending from 20 – 40µm.

RQ3: Meteorological conditions influenced deposition, however, no one variable consistently explained the observed variability. This showcases the likely multiple drivers influencing MP deposition.

RQ4: The observed seasonal differences were less pronounced than the day-to-day variability. However, there were notable shifts in polymer composition suggesting seasonal shifts in source contributions.

Overall, this work emphasises the importance of choosing sampling locations, sampling periods, extraction and analysis methods. All of which heavily influence the outcome of MP studies and should be chosen optimally depending on the varying needs of the study. Particular care should be taken when assessing the role of human influence as a MP emission source. The results highlighted high frequency observations can provide valuable information on the dynamics of atmospheric MP allowing to see specific short term emission events. The combination of oleoextraction and micro-FPA-FTIR provides an excellent framework for recovering, characterising and assessing MP composition, a combination desirable for future monitoring campaigns.

4.7 Future work

Whilst this research has provided a valuable amount of research, there are some improvements which could be made to enhance and form the basis of future studies. The absence of fibres found has created an interesting gap in the research regarding fibre transport and the height to which they reach. Interesting work could be conducted here on ground level vs roof level MP deposition fluxes to evaluate the differences. Future research specifically regarding analysis could be done on developing more advanced machine learning or automated spectra analysis tools designed specifically for MP to reduce the amount of misclassifications seen within the literature. Longer sampling periods would also be beneficial in order to gain more robust data on seasonal differences. Alongside this, coupling these observational studies with atmospheric transport modelling and air mass trajectory analyses, would further aid in assessing the importance of each process and improve our understanding of the global plastic cycle and atmospheric MP.

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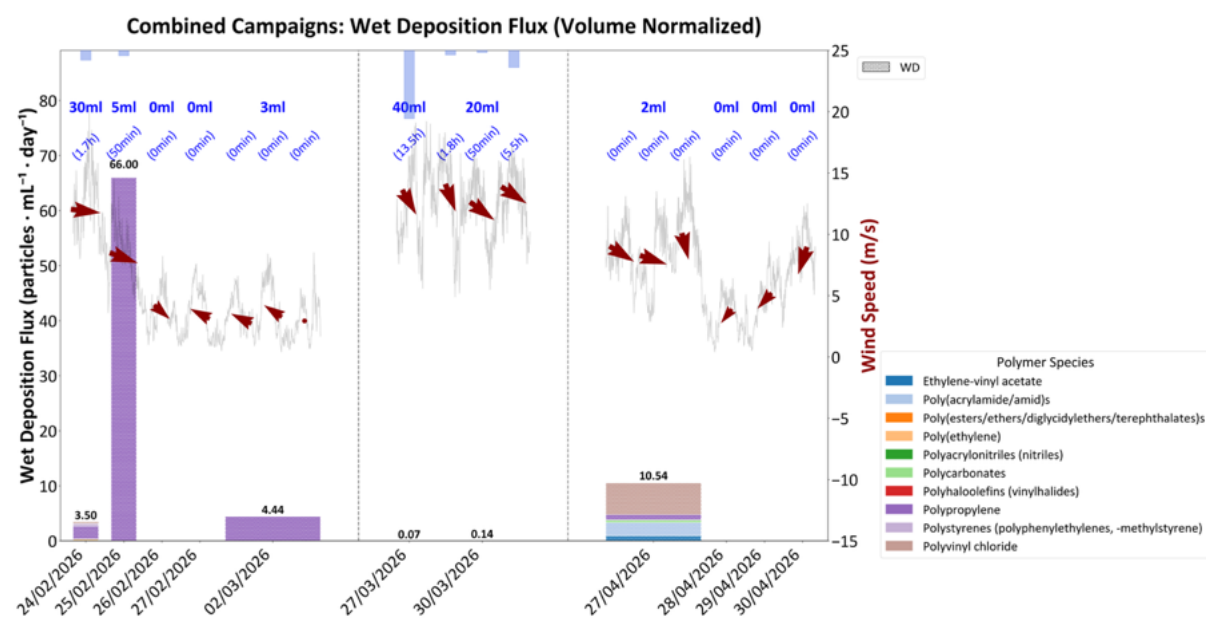
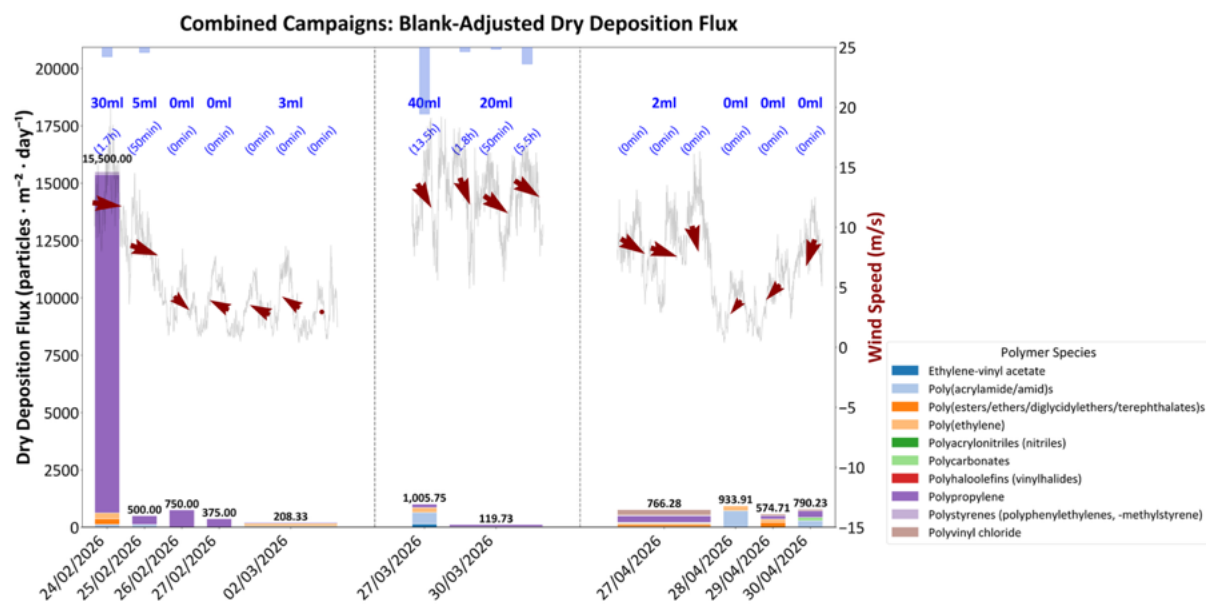
Supplementary Material

Example output table from OPUS 25/02/2026 WD:

ID	Area	Width	Height	OnBoundary	Substance	Quality	IsFibre	FiberSize
1	117.83	21.68	16.31	FALSE	PA	880	FALSE	12.25
2	913.22	43.36	38.05	FALSE	PA	924	FALSE	27.14
3	29.46	10.86	5.42	FALSE	PA	865	FALSE	6.12
4	29.46	17.55	7.86	FALSE	PA	763	FALSE	6.12
5	29.46	10.84	5.44	FALSE	PA	728	FALSE	6.12
6	88.38	20.79	13.09	FALSE	PA	864	FALSE	10.61
7	29.46	5.42	5.44	FALSE	PA	686	FALSE	6.12
8	58.92	16.3	16.27	FALSE	PA	849	FALSE	8.66
9	44.19	16.3	10.85	FALSE	PA	846	FALSE	7.5
10	29.46	13.11	9.26	FALSE	PA	794	FALSE	6.12
11	29.46	5.42	5.44	FALSE	PA	683	FALSE	6.12
12	2474.53	136.7	49.05	TRUE	PP	855	TRUE	32.71
13	397.69	27.16	27.11	FALSE	PP	799	FALSE	17.89
14	29.46	5.42	5.44	FALSE	PP	575	FALSE	6.12
15	29.46	10.84	5.44	FALSE	PP	694	FALSE	6.12
16	294.59	28.47	20.77	FALSE	PP	790	FALSE	15.08
17	618.63	38.03	32.54	FALSE	PP	898	FALSE	22.23
18	147.29	21.68	16.31	FALSE	PP	713	FALSE	13.69
19	1443.48	68.57	39.68	FALSE	PP	890	FALSE	31.99
20	1649.69	59.76	43.38	FALSE	PP	898	FALSE	45.94
21	29.46	5.42	5.44	FALSE	PP	735	FALSE	6.12
22	88.38	27.26	12.72	FALSE	PP	686	FALSE	10.61
23	117.83	27.26	15.14	FALSE	PP	710	FALSE	12.25
24	1649.69	71.2	46.26	FALSE	PP	874	FALSE	33.98
25	1148.89	81.49	32.54	FALSE	PP	820	TRUE	22.22
26	29.46	5.42	5.44	FALSE	PP	660	FALSE	6.12
27	29.46	5.42	5.44	FALSE	PP	685	FALSE	6.12
28	88.38	26	14.02	FALSE	PP	758	FALSE	10.61
29	162.02	28.47	16.93	FALSE	PP	750	FALSE	11.75
30	29.46	5.42	5.44	FALSE	PP	640	FALSE	6.12
31	2076.84	64.05	64.22	FALSE	PP	887	FALSE	42.54
32	2592.37	76.05	59.65	FALSE	PP	917	FALSE	45.99
33	5390.93	102.97	76.1	FALSE	PP	927	FALSE	66.78
34	29.46	5.42	5.44	FALSE	PP	638	FALSE	6.12
35	515.53	38.03	32.54	FALSE	PP	796	FALSE	19.42
36	29.46	5.42	5.44	FALSE	PP	556	FALSE	6.12

37	44.19	16.3	10.85	FALSE	PP	806	FALSE	7.5
38	250.4	51.03	23.88	FALSE	PP	697	TRUE	12.39
39	309.32	32.52	21.74	FALSE	PP	819	FALSE	15.01
40	486.07	32.52	27.18	FALSE	PP	792	FALSE	20.32
41	88.38	27.16	10.85	FALSE	PP	717	FALSE	10.61
42	1060.52	86.69	41.33	FALSE	PP	799	TRUE	22.48
43	1531.85	65.19	48.8	FALSE	PP	797	FALSE	27.22
44	353.5	43.84	20.77	FALSE	PP	727	TRUE	14.19
45	1885.35	59.61	54.36	FALSE	PP	805	FALSE	35.13
46	957.41	48.78	38.05	FALSE	PP	787	FALSE	27.97
47	235.67	35.83	22.79	FALSE	PP	660	FALSE	12.2
48	544.98	49.08	31.35	FALSE	PP	708	TRUE	16.17
49	29.46	13.11	9.26	FALSE	PP	664	FALSE	6.12
50	29.46	13.08	5.44	FALSE	PP	592	FALSE	6.12
51	1001.59	43.36	38.05	FALSE	PP	932	FALSE	29.51
52	147.29	32.59	16.27	FALSE	PP	582	FALSE	11.3
53	147.29	21.73	16.27	FALSE	PP	631	FALSE	13.69
54	88.38	21.68	16.31	FALSE	PP	684	FALSE	10.61
55	29.46	5.42	5.44	FALSE	PP	630	FALSE	6.12
56	427.15	32.59	27.11	FALSE	PP	662	FALSE	17.89
57	147.29	32.52	19.56	FALSE	PP	764	FALSE	11.75
58	44.19	16.3	16.27	FALSE	PP	726	FALSE	7.5
59	736.47	58.88	25.1	FALSE	PP	795	FALSE	21.71
60	103.11	22.45	15.12	FALSE	PP	712	FALSE	11.46
61	88.38	21.73	10.85	FALSE	PP	714	FALSE	10.61
62	279.86	31.03	21.98	FALSE	PP	739	FALSE	13.74
63	58.92	21.68	10.87	FALSE	PP	612	FALSE	8.66
64	29.46	5.42	5.44	FALSE	PP	565	FALSE	6.12
65	530.26	76.05	16.27	FALSE	PP	822	FALSE	26.19
66	29.46	10.86	10.85	FALSE	PP	632	FALSE	6.12
67	1178.35	54.32	37.96	FALSE	PP	810	FALSE	39.88
68	279.86	49.09	17.47	FALSE	PP	685	TRUE	12.2
69	29.46	5.42	5.44	FALSE	PP	530	FALSE	6.12
70	29.46	5.42	5.44	FALSE	PP	553	FALSE	6.12
71	2710.21	90.71	60.02	FALSE	PP	807	FALSE	39.43
72	29.46	5.42	5.44	FALSE	PP	587	FALSE	6.12
73	29.46	10.86	5.42	FALSE	PP	735	FALSE	6.12
74	2179.94	76.05	43.38	FALSE	PP	798	FALSE	37.64
75	73.65	21.68	10.87	FALSE	PP	788	FALSE	9.68
76	206.21	33.05	21.24	FALSE	PP	684	FALSE	11.75
77	88.38	27.97	12.97	FALSE	PP	728	FALSE	10.61
78	29.46	5.42	5.44	FALSE	PP	522	FALSE	6.12

79	29.46	5.42	5.44	FALSE	PP	622	FALSE	6.12
80	633.36	55.36	28.44	FALSE	PP	804	FALSE	18.79
81	162.02	33.66	18.45	FALSE	PP	682	FALSE	11.75
82	29.46	20.79	9.26	FALSE	PP	603	FALSE	6.12
83	1384.56	63.65	41.86	FALSE	PP	793	FALSE	29.15
84	250.4	24.63	20.77	FALSE	PP	688	FALSE	13.74
85	5258.39	113.84	71.65	FALSE	PP	810	FALSE	60.71
86	382.96	28.47	28.44	FALSE	PP	717	FALSE	16.62
87	795.38	57.24	35.73	FALSE	PP	805	FALSE	20.95
88	1266.72	82.15	45.49	FALSE	PP	805	TRUE	22.99
89	692.28	40	36.11	FALSE	PP	769	FALSE	23.95
90	6863.89	176.46	86.09	FALSE	PP	807	TRUE	51.7
91	795.38	61.7	31.27	FALSE	PP	718	FALSE	20.57
92	633.36	46.08	34.02	FALSE	PP	767	FALSE	21.59
93	29.46	10.84	5.44	FALSE	PP	613	FALSE	6.12
94	88.38	16.3	16.27	FALSE	PP	691	FALSE	10.61
95	1045.78	56.86	38.08	FALSE	PP	768	FALSE	28.42
96	29.46	13.08	5.44	FALSE	PP	715	FALSE	6.12
97	73.65	16.95	13.09	FALSE	PP	691	FALSE	9.68
98	18367.47	247.75	155.14	FALSE	PP	821	FALSE	86.27
99	220.94	44.73	19.69	FALSE	PP	672	TRUE	11.75
100	162.02	34.6	15.12	FALSE	CELLULOSE	795	TRUE	11.3
101	3225.73	123.53	45.94	FALSE	CELLULOSE	930	TRUE	39.46
102	44.19	16.26	10.87	FALSE	CELLULOSE	662	FALSE	7.5
103	147.29	32.86	15.74	FALSE	CELLULOSE	633	FALSE	11.3
104	456.61	63.04	20.77	FALSE	CELLULOSE	864	TRUE	15.27
105	191.48	27.16	16.27	FALSE	CELLULOSE	932	FALSE	12.84
106	147.29	21.73	16.27	FALSE	CELLULOSE	486	FALSE	13.69
107	2533.44	175.66	29.59	FALSE	CELLULOSE	744	TRUE	22.99
108	103.11	39.63	13.33	FALSE	CELLULOSE	516	TRUE	10.86
109	3137.35	133.48	54.51	FALSE	CELLULOSE	724	TRUE	34.58



Size Distribution per Sample Day (Winter + Spring Campaign)

