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Airborne Microplastics: Mechanisms for Microplastics Aerosolization and their Effects on Atmospheric Processes

Introduction

Microplastics (MPs) are small, synthetic polymer particles, typically 1 μm to 5 mm in size, produced from the breakdown of larger plastics or manufactured for industrial use. Although they have emerged as pervasive pollutants over the past few decades, research on MP transport and effects on the environment is lacking, with most papers focusing on their presence and transport only in aquatic ecosystems. Only recently has there been a shift to researching the transport of MPs in the atmosphere and the discovery of the atmosphere as an active participant in the plastic cycle. With implications for climate and public health, microplastic prevalence must be thoroughly understood.

Microplastics have been recently discovered on every continent and found inside of both marine and land animals. With the increasing discovery of microplastics in remote areas, there has been a paradigm shift in research to increase sampling and identification of MPs in a wide range of environments. Through this process, MPs have generally been studied from a primary emission or a secondary emission standpoint. Primary emissions include plastics intentionally manufactured at microscopic size for a particular application such as personal care products, cleaning products, pellets, and (Xu et al., 2022). Secondary emissions include those that originate from the degradation of larger plastic items that were not originally intended to exist in a microplastic state on their own such as synthetic textiles and fabrics that fall off (Xu et al., 2022). Secondary emissions also include any re-suspended plastics that historically existed in the environment. Waste mismanagement from landfills and recycling can also lead to secondary emissions.

Although the field is growing, research into atmospheric microplastics remains fragmented. The majority of studies are concentrated in the northern hemisphere with most in North America and south-east Asia. Most of these studies focus on specific urban or remote sites for a short time period rather than multi-seasonal campaigns, limiting the availability of comprehensive temporal and spatial data available. Methodological variability also remains a challenge, with different studies employing a wide spectrum of sampling equipment, identification and characterization protocols, and definitions for counting or classifying microplastics by size, shape, or polymer type. These limitations have led to major data gaps, undermining efforts to model MPs as aerosols or the atmosphere as a major part of the plastic cycle.

Many MPs possess physicochemical properties that allow them to participate in fundamental atmospheric processes. Weathering and photochemical oxidation of MPs modify their surface roughness, hydrophilicity, and chemical functionality, enabling them to act as cloud condensation nuclei (CCN) or ice nucleating particles (INP). This introduces the prospect that MPs, even at relatively low concentrations, could influence cloud lifetime, albedo, and precipitation regimes, particularly in remote regions where natural INPs are rare.

Robust research on atmospheric microplastics is not only important for understanding their environmental and climate impacts, but also for addressing their serious implications for human health. Inhalation and ingestion of airborne microplastics may contribute to inflammation, respiratory diseases, and cardiovascular diseases (Thomspon et. al 2025). Additionally, these particles can serve as vectors for toxic chemicals, heavy metals, and pathogens (Thomspon et. al 2025). As the prevalence of microplastics in the atmosphere rises, advancing our knowledge of their health effects is critical for protecting the public.

This paper aims to provide a meta-analysis and gap assessment of research on atmospheric microplastics, with a particular emphasis on studies addressing their occurrence, transport, properties, and environmental effects. Specifically, this paper synthesizes current knowledge and identifies gaps in knowledge on how microplastics are aerosolized, transported, and affect atmospheric processes.

Methods

To synthesize the current understanding of MPs, multiple meta-analyses were conducted to provide a comparison of recent literature. Conducting the literature review revealed that many articles written on microplastics in the atmosphere were published recently. On the ScienceDirect website between 2000 and 2025 there are 7,969 results for the combination of “microplastic(s)” and “atmosphere” in article titles. 7,562 of those results are just between 2019 and 2025 alone, where 2019 is a key date when Hartmann et al. did one of the first large scale in depth analyses on the definition and categorization of plastic litter. These recent publications display the growth of the field and the necessity for more consensus on methodologies and characterization. However, due to the amount of recent published work still being peer-reviewed, a truly comprehensive literature review would be impossible. Instead, this paper primarily focuses on largely known and cited articles that involved key words such as “microplastics,” “atmospheric microplastics,” “deposition,” “aerosol,” “dry deposition,” “wet deposition,” etc. Key parameters extracted included data sources, model characteristics, geographic scope, major findings, validation methods, and limitations. For comparability, these factors were organized in summary tables to illustrate common methodologies and distinctions across studies.

Microplastic Transport & Deposition

The reviewed literature encompassed a range of methodologies for atmospheric MP sampling and analysis. Passive samplers, such as bulk deposition collectors (NILU samplers), were commonly used to quantify total atmospheric deposition (both wet and dry), while active air samplers (high-volume air pumps with filter membranes) provided data on suspended microplastics in air masses. Analytical techniques included micro-Raman spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and pyrolysis-gas chromatography-mass spectrometry (py-GC/MS) for polymer identification and quantification. Several studies also employed atmospheric transport models, such as the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, to estimate particle residence times and potential source regions.

Data extraction focused on reported deposition rates (particles m^{-2} day^{-1}), particle size and morphology, polymer composition, and modeled or assumed sources. Studies reporting both dry and wet deposition rates were compared to assessing the mechanics of each pathway. The meta-analysis also considered the standardization of sampling and analytical protocols, the spatial and temporal coverage of studies, and the extent to which studies addressed the fate and transport of MPs.

Geographical and Extrapolation Implications

This meta-analysis was conducted to MP modeling efforts based on extrapolations from established data. Key information was extracted and synthesized focusing on critical parameters such as primary datasets or empirical measurement inputs, the types of atmospheric transport and deposition models used, the geographic scope of each paper, key findings regarding MP sources and fluxes, methods used for model validation, and the limitations in each approach. This comparative synthesis is summarized in a comprehensive table, which allows insights into data manipulation in this area of research.

Microplastic Atmospheric Implications

Studies were selected that applied laboratory simulations of mechanical abrasion, UV-induced photochemical weathering, chemical analyses of functional group modifications, and in situ atmospheric sampling of MPs across diverse geographic contexts. Particular attention was given to investigations that quantified the ability of both pristine and environmentally transformed MPs to act as ice nucleating particles (INPs) and cloud condensation nuclei (CCN), as well as those that modeled or measured their influence on radiative transfer and cloud microphysics. The review also includes research that characterizes the progression of MP physical and chemical properties as a function of atmospheric aging, aggregation, and interaction with environmental pollutants. Articles were evaluated for their methodological rigor, the comparability of their experimental setup to real environmental settings, and the range of MP types and conditions tested.

Results

Microplastic Transport & Deposition

Both dry and wet deposition pathways contribute to the transfer of atmospheric MPs from the atmosphere to terrestrial and aquatic surfaces. Reported deposition rates vary widely, with studies in urban areas such as Paris and Shanghai documenting rates from hundreds to thousands of particles m^{-2} day^{-1}, while remote sites such as the Pyrenees and the Arctic report lower but still significant values (Allen et al., 2019; Bergmann et al., 2019).

The reviewed studies consistently found that fibers and fragments are the dominant shapes of atmospheric MPs, with fibers often comprising the majority in urban and indoor environments, and fragments more comprising the majority in remote or outdoor samples (Klein & Fischer, 2019; Dris et al., 2017). Polymer composition varies by region and source, but polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) are most frequently reported, reflecting global plastic production and usage patterns (Xu et al., 2022; Brahney et al., 2021). Significantly, the density and size of detected particles influence their atmospheric residence times and transport distances, with smaller and less dense particles remaining airborne longer and traveling further (Brahney et al., 2021).

Modeling studies indicate that the majority of atmospheric microplastic depositions to land surfaces is derived from secondary re-emission sources, including roads, oceans, and agricultural dust, with the ocean increasingly recognized as a major global source (Brahney et al., 2021). The atmospheric residence times of MPs are highly variable with some MPs deposited long-range to remote regions (Allen et al., 2019). Wet deposition from precipitation events like rain and snow is an efficient scavenging mechanism, with some studies reporting higher microplastic concentrations in snow than in rain, and both exceeding those in dry deposition under certain conditions (Bergmann et al., 2019; Zhang et al., 2020).

A systematic analysis of the literature reveals persistent methodological and conceptual gaps that constrain study comparability. Major gaps identified in the studies reviewed are summarized in Table 1 below, categorizing the deficiencies for both dry and wet deposition mechanisms.

Table 1. Knowledge Gaps in Microplastic Deposition Mechanisms

Parameter	Dry Deposition Gaps	Wet Deposition Gaps	Impact on Understanding
Sampling & Measurement	•Lack of standardized for collection protocols •Difficulty measuring re-suspension rates •Challenges quantifying terminal velocities of irregularly shaped particle •Limited size fraction detection capabilities	•No standardized protocols for precipitation collection •Difficulty separating wet from dry deposition •Unknown scavenging coefficients •Limited understanding of snow crystal/MP interactions	Affects data comparability and reliability across studies
Modeling & Prediction	•Overestimation of deposition for asymmetric particles •Poor understanding of fiber aerodynamics •Limited particle size distribution data •Inadequate models for impact of surface roughness	•Incomplete understanding of in-cloud vs below-cloud scavenging •Limited data on MPs as cloud condensation nuclei •Poor prediction of removal rates during different precipitation types	Limits ability to predict transport and fate
Environmental Factors	•Limited data from remote locations •Poor understanding of seasonal variations •Insufficient long-term monitoring •Unknown effects of regiona meteorology	•Limited understanding of precipitation intensity effects •Poor geographical coverage •Unknown impact of different storm types •Limited data on post-deposition fate	Affects understanding of global distribution
Physical Properties	•Complex behavior of irregularly shaped particles •Unknown impact of particle aging •Limited understanding of density effects •Poor knowledge of size dependency behavior	•Unknown particle/droplet interactions •Limited understanding of snow scavenging efficiency •Poor knowledge of MPs in different precipitation types	Affects accuracy of transport models
Temporal Aspects	•Limited understanding of diurnal patterns •Poor knowledge of re-suspension timing •Unknown particle residence times	•Unknown seasonal variation effects •Poor understanding of storm intensity impacts •Limited data on precipitation duration effects	Impacts temporal distribution predictions

These knowledge gaps illustrate persistent barriers to study comparison efforts to accurately model microplastic transport and deposition at multiple scales. For example, the widespread lack of standardized protocols for both collection and analysis leads to inconsistent deposition metrics and detection of different particle sizes or shapes, which in turn affects comparability of global data. This is particularly evident in the difficulty of separating wet and dry deposition mechanisms in most field studies and in the technical limitations of current methods to capture MPs <5 mm effectively. Addressing these concerns is crucial as they might critically influence modeling results and therefore our interpretation of downstream ecological and health impacts.

Geographical and Extrapolation Implications

A literature review reveals that the investigation of airborne microplastic (MP) occurrence, sources, and fate has relied on a combination of direct environmental measurements and atmospheric modeling approaches. Reported deposition rates vary widely, influenced by site type (urban, roadside, remote), local sources, meteorological conditions, and differences in sampling methodologies. These field observations attempt to quantify local and regional atmospheric MPs and test the modeling capabilities MP transport and deposition.

Table 2 summarizes foundational data sources, modeling systems, geographic applications, key findings, validation approaches, and remaining uncertainties from investigations. These

modeling efforts, ranging from regional to global scales and using systems such as CAM/CESM, FLEXPART, and UKESM1, consistently suggest that marine sources, particularly via sea spray, dominate the global budget of airborne MPs. For example, global estimates were made by extrapolating using a combination of Western US measurement data and Community Atmospheric Model (CAM) simulations. These estimates indicate that over 99% of oceanic plastic emissions ultimately return to the sea via atmospheric processes, with only about 7% depositing on distant land. Meanwhile, studies utilizing FLEXPART consistently find that urban roads, traffic, and agriculture as major terrestrial contributors depending on the region. All three of these sources were identified to re-suspend historic particles through movement or create particles through abrasive processes.

Table 2. Summary of Key Model Based Meta Analysis of Atmospheric Microplastics

Base Data Used	Model Type / Approach	Geographic Scope	Key Findings / Extrapolations	Validation Method	Key Uncertainties / Limitations	Reference
Western US (11 sites, 14 months), Size 4-250 µm	CAM/CESM 1.2.2, Optimal estimation	Global, Western US focus	Ocean sources dominant (99% to oceans), roads 84% in Western US, Ag dust 5%, global atmospheric source 8.6 [0-22] Tg y^{-1}	Field/lab blanks, Model-data comparison	Limited global validation, uncertain ocean source, aerodynamic assumptions	Brahney et al., 2021
Road, tire, brake wear emissions, PM2.5, PM10	FLEXPART v10.4, Ensemble, trajectory modeling	Global, Arctic, marine	High transport of microplastics to remote regions, 34% of coarse TWP, 30% of BWP deposited in World Ocean	Ensemble modeling vs. observed patterns	Limited marine measurement coverage, modeling/scavenging assumptions	Evangeliou et al., 2020
Pyrenees field samples, wet/dry deposition	Trajectory and statistical modeling	Remote European mountains	Microplastics deposited at remote locations via long-range atmospheric transport, wet deposition significant	Field data and back-trajectory analysis	High variability due to meteorology, size detection limit	Allen et al., 2019
Field (Alps, Arctic, European snow)	Quantitative field analysis, atmospheric transport	Arctic, remote continental	Wet (snow) deposition major pathway even at remote locations, high MPs in snow	Lab analysis, field comparison, meteorological analysis	Wet vs dry deposition separation, sample contamination	Bergmann et al., 2019
Synthesis (field & model data)	Global data review, field-model integration	Global	Summarizes atmospheric MP data, methods, and models, identifies global trends and gaps	Literature and data synthesis	Heterogeneous data, lack of standardization, underrepresentation of some regions	Zhang et al., 2020
Method and data review (field/model)	Review/meta-analysis	Global, China-centric	Comparison of atmospheric MP methods, sources, health implications, highlights modeling vs field mismatches	Comparative literature review	Data biases, lack of long-term monitoring	Xu et al., 2022
North Atlantic marine/air field samples	Field sampling, micro-Raman, trajectory modeling	Remote marine (N. Atlantic)	Sea spray emission pathway for marine-to-atmosphere MPs, direct detection in remote air	Field & back-trajectory/size-resolved particle IDs	Detection limit >5 µm, underestimation of smaller particle prevalence	Trainic et al., 2020
Western US atmospheric, North America	Field, trajectory modeling	US, North America	Large area MP deposition via wind/precipitation, mostly secondary emissions	Field and statistical model	Limited global extrapolation	Brahney et al., 2020
Urban London air samples, PM10 MPs	Chemometric, Raman imaging, modeling	Urban (London)	High local concentrations, fine spatial resolution, indoor vs outdoor contrasts	Field sampling, lab analysis	Size and type detection limit, single metro region	Levermore et al., 2020

Many models remain constrained by the limited scope of global observational networks, with continents such as Africa and South America and regions such as the open oceans and polar

environment are comparatively understudied. Determining how to attribute sources based on models is still highly debated, even locally, as source attribution is sensitive to modeling assumptions and the chosen spatial and temporal parameters for input data. Uncertainties in microplastic size distributions, aging/weathering effects, and the efficiency of wet deposition (precipitation scavenging) further complicate global extrapolations due to the fact that most measurements still cannot consistently detect particles within the MP range. Finally, integrating potential atmospheric and climatic impacts of MPs, such as direct radiative effects as studied with UKESM1, has been constrained by incomplete empirical knowledge about the optical and physicochemical properties of complex MPs.

Microplastic Atmospheric Implications

The literature consistently demonstrates that microplastics undergo significant physical and chemical transformations in the atmosphere due to processes such as mechanical abrasion and photochemical weathering. These alterations increase the complexity and reactivity of MP surfaces, as revealed by both field observations and laboratory studies (Brahney et al., 2021). Many studies report that these transformations lead to higher concentrations of functional groups containing oxygen and a general decrease in hydrophobicity, which has been linked to an enhanced ability of MPs to serve as INPs and CCN compared to their pristine counterparts (Brahney et al., 2021). Ice nucleation studies using weathered MPs reveal that these altered particles can initiate freezing at temperatures much warmer than those required for untreated plastics. This finding underscores the influence of atmospheric aging on the relevant climate properties of MPs (Brahney et al., 2021). This trend is further supported in research showing MPs, after coating with salts or organic matter, become more efficient at condensing and freezing water vapor, potentially impacting cloud development and characteristics (Brahney et al., 2021).

A synthesis of these observed environmental transformations and their impacts on atmospheric processes is summarized in Table 3 below. The table illustrates the sequence from initial atmospheric entry of MPs to mechanical and photochemical aging, to the application of surface coatings. Additionally, Table 3 includes their effects on ice nucleation, cloud physics, and atmospheric radiative transfer. As summarized, each transformation stage not only alters the physical and chemical characteristics of MPs but also has downstream effects on their role as atmospheric aerosols. These changes can accelerate MP participation in cloud formation and therefore modifications in precipitation trends. Similarly, the optical properties of aged MPs, combined with changes in concentration and distribution, shape their influence on radiative cooling or warming in the atmosphere.

Table 3. Environmental and Atmospheric Effects of Microplastics

Process & Stage	MP Transformation & Condition	Effect on Particle Properties	Effect on Atmospheric Processes	References
Release & Initial Entry	Pristine MPs (from abrasion, litter, sea spray, etc.)	Hydrophobic, smooth, polymer-specific surface	Pristine MPs are poor cloud condensation nuclei (CCN) and inefficient ice nucleating particles (INP), low atmospheric reactivity.	4, 5, 10, 12
Mechanical Abrasion & Resuspension	Wind, wave, dust re-entrainment during atmospheric transport	Creation of microfractures, new pores leading to increased surface area	Enhanced likelihood of particles acting as INPs due to more active sites for ice formation and possible increase in atmospheric residence time and transport to altitudes where clouds form.	4, 5, 11, 12
Photochemical & UV Weathering	Sunlight exposure (UV), atmospheric oxidation	Introduction of functional groups with oxygen, increased surface roughness, decreased hydrophobicity	Increased particle affinity for water vapor transforming into more effective INP. Earlier onset of condensation and freezing processes in the atmosphere.	1, 4, 5, 11
Sorption of Macromolecules & Chemical Coatings	Contact with atmospheric organics, sea salts, pollutants	Formation of eco-coronas, salt coatings, organic films	Coatings can further lower contact angles, making particles more hydrophilic and boosting water uptake. This can enhance CCN/INP efficiency and modify radiative properties of MPs.	5, 10, 12
Size Reduction & Fragmentation into Nanoplastics	Continued mechanical/chemical degradation	Decreased particle size, increased surface to volume ratio	Smaller particles reach higher altitudes and longer transport distances, making them more likely to interact with clouds and radiative transfer. This could cause potentially higher number concentration.	5 11 12
Cloud Nucleation & Atmospheric Feedbacks	Aged, coated MPs in cloud-relevant size range	Active INP/CCN with diverse composition	MPs can modify cloud microphysics (droplet/ice concentration), precipitation patterns, albedo, and possibly cloud lifetime. This is nonlinear and regionally variable.	4, 5, 6, 11
Direct Radiative Effects	All atmospheric stages	Scattering (UV/visible) and absorption (IR) properties	MPs scatter sunlight (mostly cooling effect) but also absorb infrared, especially in the atmospheric window, which can lead to both cooling and warming.	1, 5, 8
Potential Long-term & Butterfly Effects	Ongoing environmental change, rising concentrations	Accumulated transformations	As properties shift, so do impacts, so local and global effects may amplify over time.	1, 4, 5, 11, 8

Research into the optical and radiative properties of MPs, particularly after modification, suggests that these particles can scatter and absorb solar and infrared radiation, yielding both cooling and warming effects on the atmosphere that vary with particle abundance, size distribution, and chemical composition (Zhang et al., 2020). Some modeling studies have attempted to quantify the potential effective radiative forcing of MPs, generally finding the current global impacts are still small but likely to become more relevant as plastic pollution increases (Zhang et al., 2020). Another consistent finding is that the capacity of MPs to remain airborne for extended increases their spatial and temporal overlap with cloud-forming regions (Brahney et al., 2021). This capacity increases with the MPs decrease in size and density.

Despite these advances, considerable methodological variability and uncertainties are noted across the literature. Studies differ in the range of MP types tested, the extent of their artificial weathering protocols, and their approaches to quantifying MP/cloud interactions and radiative effects. Few studies have systematically integrated in situ atmospheric measurements with controlled laboratory investigations and atmospheric modeling.

Discussion

Microplastic Transport & Deposition

Current literature indicates that both dry and wet deposition serve as critical pathways for MP redistribution across the environment. The relative contributions of dry versus wet deposition remain undetermined. Wet deposition is generally considered more efficient at removing airborne microplastics, especially during intense precipitation, but dry deposition can dominate in arid regions (Zhang et al., 2020; Brahney et al., 2021). Additionally, most are unable to detect particles below 5–10 μm, yet modeling suggests that these smaller particles have greater potential for long-range transport and biological uptake (Bergmann et al., 2019; Brahney et al., 2021). The aerodynamic properties, atmospheric lifetimes, and deposition mechanisms of these smaller particles remain largely uncharacterized. In terms of source origins, studies highlight the importance of integrating physical characterization (size, shape, polymer type) with atmospheric transport modeling to distinguish between local, regional, and long-range sources (Allen et al., 2019; Brahney et al., 2021).

Geographical and Extrapolation Implications

Major advances have come through the integration of direct measurement data with advanced atmospheric transport models, which collectively suggest that MPs are ubiquitous in the lower atmosphere and subject to efficient long-range transport. Still, accuracy in global MP fluxes is constrained by uneven observational coverage, especially across remote marine, rural, and high-latitude or altitude regions. The comparison of modeling approaches further illustrates that results are sensitive to assumptions around particle size distributions, shape, and density—parameters. Methodological variability is further hindered by divergent analytical methods for MP identification, including FTIR, Raman spectroscopy, and TGA-GCMS, which differ in their size detection limits and effectiveness across polymer types.

Source attribution remains uncertain beyond primary sources and quantification of secondary and tertiary emission processes, such as urban resuspension or agricultural activities, is still uncertain. There is also little information on the vertical distribution and lifetime of MPs in the troposphere, factors that are critical for determining where and in what quantities MPs ultimately deposit. Additionally, many of these models use a backward trajectory analysis, which can overestimate trajectories due to ineffectiveness in complex terrain and inability to get exact emission timing since it only indicates maximum residence times.

Geographical and Extrapolation Implications

While many laboratory based studies successfully demonstrate the enhanced ice-nucleating potential activity of aged MPs, there remains a lack of standardized methods for simulating realistic atmospheric weathering. Additionally, insufficient data exists on the abundance and chemical composition of MPs in different atmospheric contexts (Brahney et al., 2021; Zhang et al., 2020). A key gap identified is the limited availability of comprehensive field measurements that directly link atmospheric MP concentrations and properties with observed cloud modifications or regional climate effects. Moreover, the influence of complex coatings (eco-coronas or salt films) and the aggregation of MPs with other aerosol types is often mentioned but rarely quantified in detail. The complexity of MP shape, sizes, and coating and the lack of formal characterization on these parameters further hinders modeling efforts.

Another area in need of deeper exploration is the quantification of the direct and indirect radiative impacts of MPs, particularly under various atmospheric loading scenarios and across different climatic regions. Current estimates are hindered by uncertainties in MP emission inventories, size distributions, and refractive index data, especially after atmospheric transformation (Brahney et al., 2021). There is also a notable deficit in research on nanoplastics due to analytical limitations. However, microplastics will degrade into nanoplastics and are therefore necessary to study alongside with MPs.

Conclusion

Significant progress has been made in detecting and modeling atmospheric microplastics over the past six years, but the field remains hindered by inconsistent methods, limited standardization, and narrow geographic coverage. Extrapolations from local data to increase geographical studies have proven to be unreliable and modeling efforts to identify transport ranges use limited temporal data. The gaps in literature must be addressed through inter-disciplinary work to combine atmospheric transport knowledge with emerging knowledge of MP characterization. Without coordinated global efforts the scale of atmospheric plastic pollution remains uncertain, which limits our ability to understand the full scope of microplastics in the environment and to design effective interventions.

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