A Review of Atmospheric Micro/Nanoplastics: Insights into Source and Fate for Modelling Studies

Fei Jiang[1], Chengze Gao[2], Arthur W. H. Chan[3], David O. Topping[1], Hongliang Zhang[4], Weijun Li[5], Hugh Coe[1,6], Xiaohong Liu[7], Joseph Ching[8], Zhonghua Zheng[1*]

[1*]Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK.
[2]Department of Chemistry, Imperial College London, London, SW7 2AZ, UK.
[3]Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, M5S 3E5, Canada.
[4]Department of Environmental Science and Engineering, Fudan University, Shanghai, China.
[5]School of Earth Sciences, Zhejiang University, Hangzhou, China.
[6]National Centre for Atmospheric Science, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK.
[7]Department of Atmospheric Sciences, Texas A&M University, College Station, US.
[8]Department of Science and Environmental Studies, The Education University of Hong Kong, Hong Kong SAR, China.

*Corresponding author(s). E-mail(s):
zhonghua.zheng@manchester.ac.uk;
Contributing authors: fei.jiang-4@postgrad.manchester.ac.uk.com;
gaochengze17@gmail.com; arthurwh.chan@utoronto.ca;
david.topping@manchester.ac.uk; zhanghl@fudan.edu.cn;
liweijun@zju.edu.cn; hugh.coe@manchester.ac.uk;
xiaohong.liu@tamu.edu; ppching@eduhk.hk;

Abstract

Micro/nanoplastics (MNPs), as emerging pollutants, have attracted increasing attention due to their potential adverse effects on human health, ecosystems, and climate. The rapid, turbulent, and large-scale nature of atmospheric transport facilitates both horizontal and vertical movement of MNPs over long distances within a short time, largely independent of topographical constraints, thereby accelerating their global cycle and exacerbating their impacts. Research on the atmospheric life cycle of MNPs primarily relies on a combination of observations and numerical modelling, yet emission estimates remain the major source of uncertainty, posing substantial challenges for lifecycle assessment. This review synthesises findings from atmospheric observations and numerical modelling studies conducted over the past five years to examine the sources and long-range transport dynamics of MNPs, as well as the key factors influencing their transport, while also quantifying uncertainties in emission flux estimates. Two major uncertainties persist: the wide variability in marine emission estimates, which span four orders of magnitude, and the unresolved question of whether terrestrial or marine sources are the dominant contributors to atmospheric micro/nanoplastic emissions. Furthermore, this review highlights critical factors driving these uncertainties, including limited data availability, inconsistencies in observational methodologies, oversimplified simulations, and gaps in understanding atmospheric cycling mechanisms. Additionally, variations in the particle size ranges targeted by different observational and modelling studies hinder cross-comparisons and model evaluations, representing another important source of uncertainty. To address these issues, we call for establishing a global network of standardised observations, improving sampling and simulation practices, and incorporating artificial intelligence. These strategies will enhance our understanding of the complete atmospheric cycle of MNPs, paving the way for more effective environmental management and better-informed policy decisions.

Keywords: microplastics, nanoplastics, emission, atmospheric transport and lifecycle, modelling

Statement

This manuscript is a preprint submitted to *EarthArXiv* and will be shortly submitted for publication in a scientific journal. As a function of the peer-reviewing process that this manuscript will undergo, its structure and content may change.

If accepted, the final version of this manuscript will be available via the 'Peer-reviewed Publication DOI' link on the right-hand side of this webpage. Please feel free to contact any of the authors. we welcome feedback

1 Introduction

Global plastic production grew from 2 million tons in 1950 to 400.4 million tons in 2022, with plastic waste accumulating to 35–50 billion tons by 2019, and both are increasing at an accelerating rate [1–5]. Over time, plastic waste degrades into micro/nanoplastics

(MNPs) through physical, chemical, and biological processes, including UV radiation, weathering, oxidation, and biodegradation. [6–8]. In addition to degradation-related pathways, MNPs can be released directly from anthropogenic activities, including industrial processes such as manufacturing and plastic heating [9–11], abrasion during transportation and use, such as tire wear [12], and daily activities like textile washing and wearing [13]. According to ISO [14], environmental microplastics (MPs) are defined as particles ranging from 1 μm to 5 mm, whereas nanoplastics (NPs) are classified as particles smaller than 1 μm.

Characterised by their small size, low density, and inert nature, MNPs have become ubiquitous in global ecosystems due to their uncontrolled dispersion and the limited removal efficiency [15–18]. This widespread occurrence contributes to a "plastic cycle" that extends from the equator to the poles and from surface waters to deep-sea sediments [15]. MNPs have been detected in various environmental compartments—terrestrial systems (agricultural, urban, and industrial soil) [19–22], aquatic environments (rivers, lakes, groundwater, and marine) [19, 20, 23–28], atmosphere (urban air, remote regions, and marine air) [29–33], and human exposure pathways (food products and indoor spaces) [34–41]—with atmospheric transport serving as the main route of their global spread. Unlike hydrological pathways (e.g. ocean currents and water runoff), which are constrained by topography, atmospheric micro/nanoplastics (AMNPs) can be transported in multiple directions over long distances within days to weeks, often crossing continents and oceans. [42–44]. Moreover, the presence of MNPs in high-altitude regions without local MNP pollution [45], as well as in cloud water [46, 47] and stratospheric samples [48], provide strong evidence of their vertical transport. This capacity allows MNPs to cross geographical barriers and be entrained into global atmospheric circulation systems, leading to their long-range transport and ultimately settling in remote ecosystems such as protected areas [49], mountains [45, 50], deserts [51, 52] and polar ice caps [53, 54].

The ubiquity of AMNPs underscores their capacity to infiltrate both natural and anthropogenic systems via atmospheric transport, posing multifaceted risks to ecosystems [55, 56], climate [57–59], and human health [34, 60–65]. For example, inhalation is considered a primary exposure pathway for AMNPs, particularly in densely populated and industrialised regions [60–62]. Once inhaled, AMNPs can penetrate cell membranes, cross biological barriers, and distribute to various organs via the circulatory system [62, 66, 67]. The potential for bioaccumulation, coupled with toxicological effects, has serious concerns for public health[60, 68]. Beyond human health, AMNPs deposited from the atmosphere impact terrestrial and aquatic ecosystems. They can alter soil microbial diversity and physicochemical properties [55, 69, 70], affect pollinator activity [56, 71–73], and interfere with plant functions such as nitrogen cycling and chlorophyll synthesis [69, 74–76], ultimately disrupting ecological balance and increasing the risk of trophic transfer. Moreover, preliminary studies suggest that AMNPs may possess physicochemical properties enabling them to influence direct radiative forcing [57] and serve as cloud condensation nuclei (CCN) [47, 58, 77] or ice nucleating particles (INP) [58, 59, 78, 79]. However, current evidence remains limited regarding their atmospheric abundance, activation efficiency, and whether they exert a measurable influence on cloud processes or the climate system, highlighting the need for

further investigation. Altogether, AMNPs threaten both environmental integrity and the stability of socioeconomic systems, hindering the achievement of more than 80% of the United Nations Sustainable Development Goals (SDGs) [80].

Research on AMNPs emerged relatively late, with initial recognition originating from detecting AMNPs by Dris et al. (2015) in Greater Paris samples [23]. Early studies remained largely limited to local observations and no research on the large-scale transport of AMNPs. This gap was primarily due to limitations in observation techniques and the delay in recognising atmospheric pathways as a major transport route for these particles [30, 81, 82]. It was not until Allen et al. (2019) combined back-trajectory modelling with observational data that the first insights into long-range transport of AMNPs were provided [30]. Currently, atmospheric research employs specialized modelling approaches, including Lagrangian Particle Dispersion Models (LPDMs) such as the FLEXible PARTicle (FLEXPART) model [83–85] and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [86, 87], as well as numerical atmospheric models like Community Earth System Model (CESM) [88] and GEOS-Chem [89]. These models are widely used for source identifications, large-scale transport simulations, and deposition assessments of AMNPs [30, 90–93]. However, the accuracy of AMNP simulations remains limited, primarily due to the substantial uncertainty in emission estimates. For example, estimates of AMNP emissions from oceanic sources vary by up to four orders of magnitude across different studies [90, 91, 94]. These uncertainties in emission estimation primarily stem from model simplifications, limitations in representing the physical and chemical properties of AMNPs, knowledge gaps in emission and transport mechanisms, and observational constraints such as data heterogeneity and uneven spatial distribution.

Despite notable progress in AMNP research over the past five years, with more than 50 review articles summarising advancements in AMNP collection and analysis techniques, sources, physical characteristics (shape, colour, and size) [40, 82, 95–115], atmospheric transport mechanisms [44, 116–119], and their impacts on the environment and human health [64, 67, 68, 81, 120–135], a systematic analysis of uncertainties in AMNP simulations remains largely lacking. In particular, emission flux estimation, a critical component of AMNP simulations, has not been thoroughly examined in terms of its sources of uncertainty and potential mitigation strategies. This gap not only affects the accuracy of global AMNP transport models but also limits the quantitative assessment of their environmental fate, human health risks, and climate impacts.

To bridge this research gap, this review synthesises studies on AMNPs from 2019 to 2025, covering the known and unknown aspects of their lifecycle. It places particular emphasis on existing assessments of emission fluxes. Additionally, this review discusses key uncertainties, identifies major challenges in AMNP simulations, and proposes potential solutions. The structure of this paper is as follows: Section 2 reviews the lifecycle of AMNPs, discussing their occurrence, abundance, sources, major mechanisms of long-range transport, and influencing factors. Section 3 summarises current knowledge on AMNP emission fluxes, highlighting uncertainties and their underlying causes. Section 4 not only delves into strategies for addressing model uncertainties but also takes a broader perspective on the future development of AMNP research. By

integrating insights from observational data, numerical modelling, and artificial intelligence (AI) applications, this section highlights emerging opportunities and potential advancements in AMNP studies.

2 Atmospheric Lifecycle of MNPs

MNPs from marine and terrestrial sources can be released into the atmosphere and transported over long distances by wind and turbulence [102, 104, 117] (Figure 1). Once airborne, these particles are removed through dry deposition, gravitational settling, and wet deposition via precipitation [108, 136, 137]. Despite growing research interest, substantial knowledge gaps remain in understanding the emission source contributions to AMNPs, particularly regarding the mechanisms and magnitudes of emissions from different sources. Additionally, the influences of MNP properties, ageing processes, and atmospheric transport mechanisms on their distributions are still poorly characterised. These knowledge gaps introduce uncertainties in global AMNP cycle modelling, particularly in estimating their total atmospheric budget, the rates of emission and deposition fluxes, and long-range transport potential across regions. This section examines the current understanding and key unresolved questions related to the occurrence, sources, transport mechanisms, and major factors shaping the atmospheric lifecycle of MNPs.

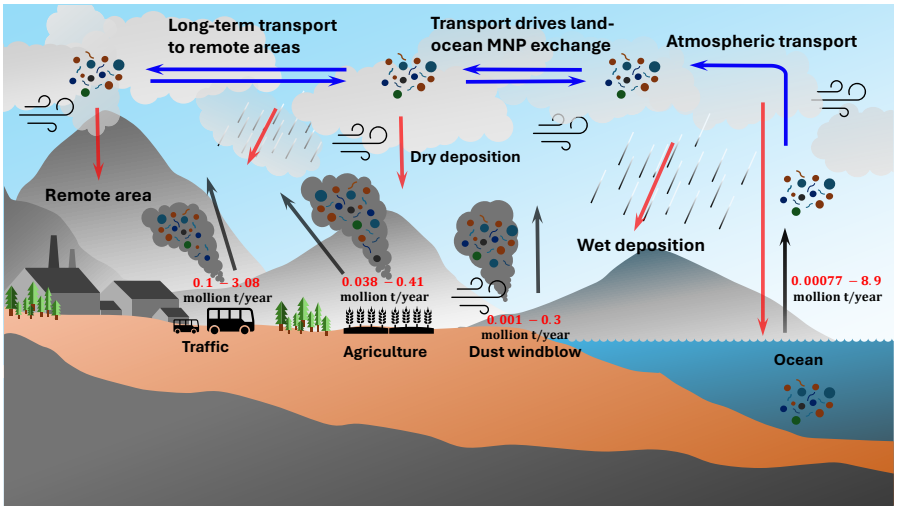

Fig. 1 Schematic of AMNPs lifecycle. The black arrows indicate the emission of MNPs into the atmosphere, primarily from terrestrial sources and marine sources [90–92, 94, 138–142]. The blue arrows illustrate the atmospheric transport process, where AMNPs are rapidly carried over long distances by airflows, unaffected by terrain, facilitating the exchange of MNPs between land and ocean and dispersing them to remote areas far from the emission sources. The red arrows represent the deposition process, which deposits AMNPs onto the ground, leading to their long-term accumulation in various ecosystems.

2.1 Occurrence and Abundance of AMNPs

Over the past five years, nearly 100 observational studies have been conducted on AMNPs across diverse regions worldwide (Supplementary data), including remote areas (e.g. the French Pyrenees [45], U.S. protected areas [49], the Antarctic continent [143], the Lut and Kavir Deserts [51], the Tibetan Plateau [50], the Arctic [53, 144], and the Forni Glacier [145]), urban and rural areas (e.g. China [146–152], France [38, 153], USA [154, 155], New Zealand [156–158], Thailand [159], UK [160–162], Canada [163], and Germany [164–166]), and the marine atmosphere (e.g. the North Atlantic Ocean [167], the Pacific Ocean [150, 168, 169], the Northeastern South China Sea [170]). Quantitative measurements of AMNPs primarily include passive, active, and surface sampling techniques [119, 171]. Passive sampling, such as wet and dry sediment collection, measures MNP deposition rates (unit: MP/day/m^2, where "MP" means the number of MNPs detected) [43, 45, 48, 146, 147, 172]. Active sampling uses pumps to concentrate airborne particles, measuring MNP abundance in air (unit: MP/m^3) [164, 165, 173–175]. Surface sampling, involving the collection of dust or snow, indicates AMNP deposition (unit: MP/g or MP/L) [53, 176–178]. Reviews discussing these techniques and their applications can be found in [96, 110, 119, 171, 179].

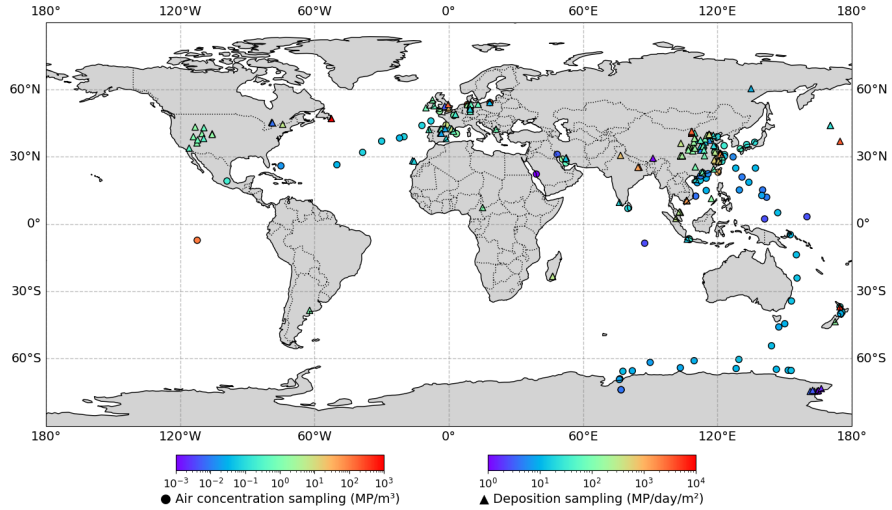

Fig. 2 AMNP sampling sites and measured values. Circles represent MNP abundance (MP/m^3) from air concentration sampling, while triangles indicate MNP deposition (MP/day/m^2). Data are based on 86 observational studies published from 2019 to 2025 (details provided in the supporting information).

Figure 2 indicates that AMNP concentrations across terrestrial regions vary widely, spanning several orders of magnitude. For example, reported concentrations range from as low as 0.00537 MP/m^3 in Ahvaz, Iran [31], and 0.09 MP/m^3 in Sri Lanka [39] to 0.9 MP/m^3 in Paris, France [38], 1.77 MP/m^3 in Plymouth, England [180], 20.2 MP/m^3 in Shannan, China [32], 161 MP/m^3 in Gdansk Harbor, Poland [181], and as high as 5700 MP/m^3 in Beijing, China [148]. These variations are primarily

driven by differences in land use, human activities, and environmental conditions. In general, urban areas exhibit higher MNP concentrations than rural and remote regions (e.g. forests, mountains, and deserts) due to intensive human activities such as traffic, industry, plastic waste disposal, construction, and household emissions [32, 182–184].

2.1.1 Urban Areas

In urban areas, AMNP concentrations are primarily influenced by the intensity and patterns of plastic usage. Higher concentrations and deposition fluxes are typically observed in commercial and residential areas, as well as in proximity to recycling centres and incineration facilities, compared to parks and industrial zones [184–186]. This difference is mainly attributed to higher population densities, more frequent human activities, and larger amounts of plastic waste in these areas. Liu et al. (2024) found that in northern Chinese cities, MNP deposition fluxes positively correlated with population density and Gross Domestic Product (GDP), with commercial districts contributing more to MNP pollution than industrial and agricultural areas [187]. Similarly, Liu et al. (2022) reported that during the COVID-19 lockdown, MNP abundance in Lanzhou, China, declined from 487.38 MP/m^3 to 222.25 MP/m^3 [185]. In Paris, MNP deposition rates dropped from 110 MP/day/m^2 before the COVID-19 pandemic to 14.3 MP/day/m^2 in 2020 and then increased to 34.4 MP/day/m^2 in 2021 as human activities resumed [38, 153]. These patterns not only highlight the influence of human activities on urban AMNP levels, but also offer insights into dominant source types. Notably, the sharp decline in AMNP concentrations during lockdowns, despite the persistence of indoor activities such as laundry, suggests that outdoor emission sources related to public mobility, commercial operations, and waste handling may play a more critical role in shaping AMNP pollution.

Moreover, urban vegetation plays a crucial role in capturing AMNPs. Leaf characteristics such as hydrophobicity, stomatal density, and surface roughness influence the retention of MNP, introducing uncertainties in the assessment of urban MNP pollution [188–194]. Recent studies have explored the potential of biomonitors such as foliage samples, mangrove plants, lichens, moss bags, and pine needles, for evaluating MNP pollution in urban environments [192, 195–198]. However, MNPs tend to be uniformly deposited on vegetation leaves within the same urban area, regardless of land use type [199]. Consequently, MNP concentrations on leaves can provide a general estimate of AMNP exposure but may not accurately reflect variations across different regions within a city [199]. Furthermore, MNP accumulation on leaves varies with their height above the ground, emphasising the importance of leaf position in MNP capture [199].

2.1.2 Remote Regions

AMNPs in remote regions primarily derive from long-range atmospheric transport, exhibiting an inverse correlation between deposition rates and proximity to major pollution sources (e.g. urban areas) [32, 48, 52]. Deposition measurements illustrate this gradient: remote sites near urban areas, such as Bernadouze, France (365 MP/day/m^2) [200] and Guangxi, China (98.85 MP/day/m^2) [115], exhibit fluxes roughly two orders of magnitude higher than those at more isolated locations like Larsen Glacier (3.44 MP/day/m^2) [143] and Inexpressible Island (2.13 MP/day/m^2), Antarctica [143].

Moreover, localized human activities can enhance MNP deposition in remote regions. For instance, in the Badain Jaran Desert of China, the deposition rate in tourist areas (6 MP/kg) is about five times that in non-tourist areas (1.1 MP/kg) [52]. Similarly, at ET Teide on Tenerife, accessible and climbing areas accumulate 167 to 188 MP/L, compared to 51 MP/L in pristine areas [201]. High-altitude remote environments also show evident signs of MNP contamination. Cloud water collected at Mount Fuji in Japan (1252–1300 m above sea level (a.s.l.)) and Mount Tai in China (1545 m a.s.l.) contains MPs with 13.9 MP/L [46] and 463 MP/L [47], respectively. Air samples from the Pic du Midi Observatory (2877 m a.s.l.) reveal deposition rates of 0.23 MP/m^3 [45], while snow samples from the Sonnblick Observatory in Austria (3106 m a.s.l.) contain NPs at an average concentration of 46 ng/mL [202]. Soils from the Qinghai-Tibet Plateau (average altitude 4500 m a.s.l.) exhibit MNP levels ranging from 53.2 to 64.8 MP/kg [50]. These findings collectively indicate that MNPs are present in the free troposphere, thereby providing a potential pathway for their atmospheric long-range transport.

2.1.3 Regions over the Ocean

Marine air samples generally exhibit lower AMNP concentrations than terrestrial environments [44]. Reported concentrations range from 0.004 MP/m^3 to 1.37 MP/m^3 across various regions, including the Atlantic Ocean, Indian Ocean, Pacific Ocean, South China Sea, Bohai Sea, Yellow Sea, and East China Sea (Figure 2) [150, 167, 169, 170, 203–205]. The variation in MNP concentrations over marine regions is influenced by oceanic and atmospheric processes, as well as proximity to pollution sources. Remote ocean areas, such as the open Atlantic and Pacific Oceans, tend to have lower concentrations, ranging from 0.004 to 0.079 MP/m^3 [167, 169, 203]. In contrast, coastal regions and areas near shipping routes, such as the South China Sea, Bohai Sea, and East China Sea, show elevated concentrations, reaching up to 0.2 MP/m^3 [204]. Moreover, AMNPs in marine environments tend to be smaller than those in terrestrial regions, with most particles measuring less than 2 mm and primarily appearing as fibres [150, 168, 170, 204]. This size distribution may enhance long-range transport, as smaller particles and fibre-like morphologies are more susceptible to atmospheric dispersion over extended distances.

2.2 Sources of AMNPs

The sources of AMNPs are inferred primarily based on their observed shapes and materials, which are influenced by their origins, transport, degradation processes, and atmospheric residence time [114, 206]. For example, fibrous MNPs are typically derived from textile industries, carpets, and laundry activities [38, 151, 207–209]; fragments result from the weathering and breaking of large plastic items [30, 210]; films are produced from the degradation of plastic bags, packaging materials, and agricultural films [211–213]; and spherical MNPs originate from products containing MNPs, such as facial scrubs and toothpaste [214, 215]. Freshly emitted MNPs typically feature sharply defined edges, but with prolonged atmospheric exposure, these edges gradually become smoother [216].

Since Allen et al. (2019) employed back-trajectory modelling for tracing the sources of MNPs, LPDMs have become the commonly used tools for identifying the origins of AMNPs [30, 45, 186, 217–219]. Among these, the FLEXPART model [83–85] and the HYSPLIT model [86, 87] are notable for studies on AMNPs [63, 103, 169, 203]. These models simulate pollutant dispersion by calculating the trajectories of virtual particles influenced by meteorological factors (such as turbulent diffusion and precipitation) and physical processes (such as gravitational settling and chemical losses) [84]. LPDMs operate in two main modes: in forward mode, particles are emitted from specific sources, and their concentration distributions are calculated over a latitude-longitude-altitude grid [84]. This approach is commonly used to study aerosol dispersion following events such as volcanic eruptions or wildfires [220–222]; In contrast, backward simulations use the Source-Receptor Relationship (SRR) to trace the pathways of pollutants from their observation or reception point ("receptor") back to their emission source ("source") [223, 224]. Receptors can represent the average concentration of an atmospheric substance in a grid cell over a specific time interval, a deposition value, or specific observations at measurement stations [224]. Sources can be defined as point, area, or volume emissions during a given time. More detailed principles can be found in Seibert and Frank (2004) [224].

In the atmospheric lifecycle of MNPs, the generation and emission of AMNPs originate from terrestrial and marine environments. LPDMs have highlighted critical interactions between the ocean and the atmosphere: the ocean acts as a persistent source of atmospheric MPs, while atmospheric transport conveys terrestrial MPs to marine environments [167, 203, 205]. Field and laboratory studies have further illuminated the dynamics of the ocean-to-atmosphere exchange of MNPs [43, 167, 181, 225–227]. Similar to sea salt aerosols, MNPs are emitted into the atmosphere through processes such as the erosion and entrainment of beach sand, wave action, and the bursting of sea spray bubbles [43, 44, 181, 225]. Precipitation also contributes to the air-sea exchange of MNPs: wet deposition carries AMNPs into the ocean, while raindrops impacting the ocean surface generate spray [225].

Terrestrial environments are the main sources of AMNP emissions, with contributions from road traffic, soil, and various human activities. Soil functions as both a transport medium and a temporary reservoir in the MNP cycle, accumulating MNPs through atmospheric deposition, rainfall-runoff, plastic waste burial, and agricultural activities such as composting, irrigation, and the use of plastic-based greenhouse materials [8, 33, 118, 228, 229]. Estimates indicate that MNP concentrations in soils are 4–23 times higher than those in the ocean [22, 42]. MNP content in soils varies with land use and management practices, with agricultural soils treated with plastic mulch or compost exhibiting higher concentrations than control soils without plastic exposure [230]. In wind-transported sediments, MNP concentrations are higher than in the original soil, suggesting that MNPs, due to their small size and low density, are more easily carried by wind than heavier soil particles like sand [29, 33]. The influence of MNP content variation in soil and properties, such as shape, on resuspension and wind transport is not fully understood. While MNP emissions from agricultural soils have been roughly estimated at 0.08–1.48 mg/m^2/min [44] or 6.91–20.27 mg/kg [42] of

wind-eroded soil, understanding the mechanisms and achieving accurate quantification remains challenging.

Road traffic contributes to MNP emissions, primarily from tire and road wear. Emission levels are affected by various factors including engine power, vehicle weight, load, tire material, position, age, road conditions, and weather [12, 231, 232]. Global per capita emissions are estimated to be 0.2–0.55 kg per year [95], while in the United States, the figure reaches about 4.6 kg per year, with the emitted particles mainly consisting of rubber and polymers [231]. In Austria, per capita emissions are around 2.4 kg per year, with 6% of particles falling within the 0.1–10 μm size range [232]. Among total particulate emissions, non-exhaust sources, such as tire, brake, and road wear, contribute approximately 9% [232]. Due to analytical limitations, tire and brake wear particles are often measured separately and excluded from AMNP analyses (e.g. MP/m^3 or MP/m^2/day). This exclusion may lead to an underestimation of the total MNP burden and limit a comprehensive understanding of traffic-related emissions [44, 233].

Urban and metropolitan areas are primary sources of AMNPs due to various anthropogenic activities, including household emissions (e.g., fibres from clothing and textiles), industrial processes (e.g., plastic manufacturing), construction activities (e.g., use of paints and plastic materials), and waste management practices [24, 115, 234–236]. Wright et al., (2020) used the HYSPLIT model to trace MP deposition in central London, identifying local emissions as the dominant source [161]. Furthermore, several studies indicate that MNP deposition in urban areas shows weaker correlations with meteorological variables (wind speed, wind direction, relative humidity, and precipitation) compared to remote regions, reinforcing the conclusion that cities are major contributors to AMNPs [30, 146, 161, 203]. Despite the increasing availability of observational data on urban AMNPs, these data often do not distinguish between contributions from local emissions, long-range transport, and atmospheric loss from urban areas [44, 152, 159, 237, 238]. These uncertainties, along with the limited understanding of MNP fate and emission mechanisms, make it challenging to accurately estimate MNP emission rates in urban atmospheres.

2.3 Long Range Transport of AMNPs and the Governing Factors

Upon entering the atmosphere, MNPs undergo complex transport and ageing processes. Their small size allows them to stay suspended for days or weeks, enabling regional and long-range transport driven by local wind fields and atmospheric circulation [42–44]. Atmospheric transport plays a key role in redistributing MNPs across different regions, including remote areas where no direct MNP sources exist [8, 42, 45, 49, 51, 145, 178]. In addition, atmospheric transport facilitates the bidirectional exchange of MNPs between terrestrial and marine environments [42–44, 205]. Through atmospheric transport, MNPs are carried from urban, industrial, and agricultural sources to ocean surfaces. Conversely, marine-derived MNPs enter the atmosphere via sea spray, wave action, and evaporation, undergoing further atmospheric transport to inland regions [43, 63, 150, 168, 203].

During atmospheric residence, AMNPs undergo chemical and physical ageing processes, such as photooxidation, thermal degradation, and mechanical abrasion, which alter their properties and interactions with environmental factors [6–8]. They are eventually removed from the atmosphere through various deposition mechanisms, including dry deposition, wet deposition, and gravitational settling [166, 186, 239]. Dry deposition occurs in the absence of precipitation, driven by turbulence and particle diffusion, with deposition rates influenced by surface roughness and meteorological conditions [240, 241]. Wet deposition involves scavenging by raindrops, snow, or fog, efficiently removing AMNPs from the atmosphere and depositing them on terrestrial or marine surfaces [241]. AMNPs with hygroscopic properties or partially soluble components may activate into cloud droplets under humid conditions and be removed via in-cloud scavenging [58]. However, their behaviour in cloud microphysical processes remains poorly understood and requires further investigation. Additionally, gravitational settling contributes to the removal of larger MNPs, with its efficiency influenced by particle morphology, size, and related physical characteristics. Overall, the fate and lifetime of AMNPs are governed by a combination of physicochemical properties, such as size, shape, and surface composition, and meteorological factors, including wind speed, humidity, and precipitation. These factors collectively determine their transport, transformation, and removal pathways in the atmosphere.

2.3.1 Effects of Particle Properties on Atmospheric Transport

MNP shape influences the transport and deposition behaviour. Unlike spherical particles, non-spherical particles, such as fibres, fragments, and films, exhibit distinct aerodynamic properties, including differences in inertia and rotational dynamics [242–246]. These variations affect their settling velocity, atmospheric residence time, and transport distance [247–250]. For instance, fall column experiments by Presto et al. (2023) demonstrate that fibres have the slowest settling velocity, followed by films and fragments, while spheres, owing to their symmetrical shape and higher drag efficiency, settle the fastest [249]. Field observations further support the long-range transport capability of fibrous MNPs. Fibres have been predominantly detected in remote and high-altitude regions with minimal or no local emission sources, such as the French Pyrenees [45], the Ecuadorian Andes [178], and the Southern Alps of New Zealand [218], the Tibetan Plateau [251], the Italian Alps [145], protected area of USA [49], and Antarctic snow [252]. These observations indicate that fibrous MNPs can remain suspended for extended periods under turbulent atmospheric conditions and resist gravitational settling to travel thousands of kilometres. Numerical simulations further support these findings. Xiao et al. (2023) demonstrated that fibres travel farther than spheres with the same equivalent spherical diameter (D_{eq}), with flat fibres travelling even farther [247]. Tatsil et al. (2023) incorporated shape-dependent drag coefficients into the FLEXPART model, showing that fibres travel farther than spheres, with smaller fibers being more likely to reach the stratosphere [248]. Using HYSPLIT, Ward et al. (2024) confirmed that fibres settle the slowest, followed by films, cylinders, and spheres, with spheres settling the fastest [250].

In addition to shape, the size and density of MNPs also influence their long-range transport behaviour. Smaller and lower-density particles experience weaker gravitational forces, making them more responsive to turbulence and uplift [200, 210, 253]. Their lower settling velocities allow them to remain suspended for longer durations, facilitating long-distance transport through atmospheric circulation. NPs, due to their colloidal properties, are affected by Brownian motion and turbulent diffusion, further extending their atmospheric residence time and transport range [200, 202, 254]. As a result, NPs exhibit a greater potential for long-range transport compared to MPs. Additionally, Ward et al. (2024) [250] reported that for particles with an D_{eq} smaller than 6 μm, the effect of shape on settling velocity becomes negligible. These interdependent characteristics contribute to the complexity of the MNP transport behaviour, highlighting the need for further studies to better understand their atmospheric dynamics.

2.3.2 Meteorological Influences on Atmospheric Transport

Meteorological conditions influence the transport and distribution of MNPs in the atmosphere. Wind is the primary driver of MNP movement, determining transport distances, suspension durations, and spatial distribution patterns [29]. Strong winds can mobilise particles from terrestrial or marine sources, shaping their distribution. Coastal winds, for example, can carry marine-derived MNPs inland, while high-altitude airflows facilitate long-range or even global transport [45, 219, 255]. The relationship between wind speed and MNP deposition remains controversial. Some studies suggest higher wind speeds enhance dry deposition by increasing particle flux to surfaces [30, 137, 203, 256, 257]. Others argue that strong winds dilute AMNP concentrations and intensify turbulence, leading to particle resuspension and reducing deposition efficiency [136, 258]. Atmospheric stability also influences deposition dynamics. Under stable conditions, weaker turbulence allows particles to accumulate near the surface, increasing dry deposition flux [257, 259]. Similarly, the impact of wind direction is inconsistent across environments. Studies in offshore and open-sea regions have found no clear correlation between MP deposition flux and wind direction [169, 203]. However, in urban areas, AMNP abundance has been shown to strongly correlate with wind direction, indicating localised environmental influences [146, 165, 258].

Precipitation plays a crucial role in wet deposition, serving as a major pathway for the removal of AMNPs. As precipitation occurs, MNPs are scavenged by raindrops and snowflakes, ultimately settling onto the surface [30, 58, 59, 78, 253, 260]. Larger MNPs tend to settle early in a rainfall event due to direct impaction [239, 261], while smaller AMNPs may undergo aggregation or hygroscopic growth before being scavenged [58, 262]. Observational data suggest that the frequency and intensity of rainfall events are more critical in determining MNP deposition than the total precipitation volume [30, 38, 137, 152, 239, 253, 256, 263–265]. Rainfall following prolonged dry periods effectively reduces MP concentrations in the atmosphere [265, 266]. During consecutive rainfall events, the washout effect and suppression of MP resuspension maintain low MP levels over the following days [239, 265, 266]. However, when AMNP concentrations are low, precipitation has a limited influence on deposition rates, as fewer particles are available for wet scavenging [30, 38, 137, 152]. In addition, the presence of AMNPs

detected in cloud water samples suggests their potential to serve as CCN [46, 47]. These MPs are predominantly composed of particles bearing hydrophilic functional groups such as carboxyl and/or hydroxyl groups [46]. Mao et al. conducted experiments using a condensation particle counter combined with in situ aerosol techniques to measure the hygroscopicity of three types of NPs (PET, PVC, and LDPE), with the derived single-parameter hygroscopicity κ ranging from 0.17 to 0.26 [267].

Temperature and humidity regulate MNP deposition by influencing hygroscopicity, surface interactions, and settling velocity [257, 268, 269]. Under high humidity conditions, MNPs may absorb moisture and grow in size, which accelerates their deposition [256, 270, 271]. At higher altitudes, high humidity may trigger CCN activation, facilitating the removal of MNPs [58]. Besides, high humidity may promote the formation of water films on surfaces such as soil, vegetation, and urban structures, which enhances particle capture efficiency while suppressing resuspension [184, 272]. Temperature, on the other hand, is the key factor in the activation of INPs, as lower temperatures generally enhance ice nucleation efficiency. While CCN activation is primarily governed by particle hygroscopicity and ambient supersaturation, temperature may influence it indirectly by modifying saturation vapour pressure and aerosol phase state. AMNPs have the potential to act as CCN and INPs, with temperature variations potentially modulating this activation potential [58, 59, 78, 79].

Climate change is likely to exacerbate the transport and deposition of MNPs, influencing the global flux and concentrations of plastic pollution [133, 273]. For example, Arctic sea ice serves as a major sink for MPs (38–234 MP/m^3), but with global warming accelerating ice melt, these plastics are being released into the marine environment [274, 275]. Additionally, climate change has led to an increase in extreme weather events [276], such as typhoons, hurricanes, and dust storms, which can enhance the long-range transport of MNPs and alter their deposition patterns in various environments [219, 255]. During Typhoon Sinlaku (2020), the MNP deposition rate in the South China Sea peaked at 2014 MP/m^2/d [255]. Similarly, Hurricane Larry over Newfoundland, Canada, extended the transport range of MNPs and increased local deposition by 500% [219]. In addition, post-typhoon events have been observed to elevate MP concentrations in seawater and sediments, with a 40% increase reported in Sanggou Bay, China [277]. Furthermore, dust storms also play a crucial role in enhancing long-range MNP transport. In Shiraz, Iran, MNPs during dust storms exhibited clear weathering characteristics, indicating that dust storms not only act as transport mechanisms but may also alter the surface properties and environmental behaviour of MNPs [278].

2.3.3 AMNPs Ageing Processes

MNPs undergo various ageing processes before and after entering the atmosphere, including hydrolysis, photooxidation, photodegradation, biodegradation, and mechanical stress [279–282]. UV radiation plays a key role in ageing by breaking polymer chains, reducing mechanical strength, roughening surfaces, and creating microcracks [279, 283]. It can also produce small organic molecules or release additives like plasticisers [284–286]. Combined with oxygen, UV radiation introduces oxygen-containing functional groups (e.g., carbonyl, hydroxyl) on plastic surfaces, altering

their hydrophilicity, polarity, and reactivity [281, 286–291]. Larger particles exhibit more pronounced ageing effects, though further experimental studies are needed [292]. Temperature fluctuations in the atmosphere, such as diurnal or seasonal variations, accelerate thermal ageing, causing surface brittleness and fragmentation [6, 7, 293]. Furthermore, wind abrasion and particle collisions in high-wind environments increase surface area, enhancing exposure to environmental factors [278].

The biodegradation of MNPs is inefficient and primarily relevant in marine and terrestrial environments, where plastic lifespans extend from decades to centuries. These timescales far exceed the atmospheric residence time of MNPs, making biodegradation less relevant in the atmospheric context. Research on biodegradation in atmospheric conditions remains limited and has yet to attract substantial attention [294, 295]. However, the mechanisms and processes of MNP biodegradation have been well-documented in previous reviews [280, 296–300].

3 Emission Flux of AMNPs

Quantifying MNP emissions into the environment is essential for assessing their environmental impact and developing effective mitigation strategies. Regionally, Wang et al., (2019) [234] developed an MP emissions inventory for mainland China by integrating human activity data with emission factors across different provinces. Van Sebille et al., (2015) compiled a global inventory of small floating plastic debris [301], while Boucher and Friot (2017) estimated plastic inputs into the oceans through multiple pathways, including wind transport, wastewater discharge, and road runoff, by calculating plastic usage, MP loss rates, and transfer ratios to marine environments [302]. Kaandorp et al. (2023) quantified global ocean plastic concentrations, ranging from 0.1 to 1600 mm, and examined their vertical distributions at depths below and above 5 m [303]. More recently, Cottom et al. (2024) [304] applied machine learning techniques (quantile regression random forests), in combination with material flow analysis (MFA) and global/local activity data, to estimate MP pollution emissions across 50,702 regions, producing a global inventory of plastic pollution. These studies have improved our understanding of plastic pollution via aquatic and terrestrial pathways. However, global emissions of MNPs through the atmospheric pathway remain poorly quantified due to sparse spatiotemporal observations and the limited understanding of relevant emission processes.

3.1 Methods

The estimation of AMNP emission fluxes relies on quantifying emission sources based on characteristic data and assumed emission factors. The emission flux E for a specific source can be simply expressed as:

$$E = k \times X, \tag{1}$$

where k is the emission factor, representing the fraction of MNPs released into the atmosphere from a given source, and X denotes one or multiple activity-related parameters associated with the emission sources, which may be combined depending on the source characteristics. Details of X are summarised in Table 1.

Table 1 AMNP Emission Calculation Basis and References for Various Source Categories

Source Category	Emission Calculation Basis	Reference
Marine	• Microplastic concentration in the upper ocean	[90, 92, 93, 138–141]
	• Sea spray aerosols	[91, 94]
Agricultural Soil	• Dust generation by agricultural soil	[90]
	• Global farmland and pasture dataset (developed by combining agricultural inventory data with satellite-based land cover data)	[91]
	• Agricultural land cover data	[92]
Traffic road	• Tire (braking) wear particle (TWP and BWP) emission	[90, 305]
	• NO emissions from traffic sources	[92]
	• Dust emissions from traffic sources	[91]
Human activities	• Population density dataset	[90–92]
Micro and nanoplastic resuspended/Dust	• Dust emission	[90, 91, 142]
Mismanage micro and nanoplastic waste (MMPW)	• Total MMPW production globally	[92, 306]

The emission factor k could be determined through modelling, observations, and experiments. A common approach is forward modelling, where models simulate MNP emissions and atmospheric transport based on an initial estimate of k [90, 92]. The simulated MNP deposition and concentrations are then compared with observational data, and k is iteratively altered until the model output aligns with observations. An alternative approach is inverse modelling, which uses observational data to constrain MNP emissions. This method first employs FLEXPART in backward mode to establish source-receptor relationships, identifying potential emission sources based on observed MNP deposition and concentrations [91]. Then, the variational Bayesian methodology is applied to estimate the posterior distribution of emissions by minimising the Kullback-Leibler divergence between the approximated and true posterior, incorporating prior knowledge and regularisation to ensure physical consistency while reducing uncertainties [91]. Experimental parameterisation involves direct measurements of MNP emissions in laboratory or field settings, quantifying emissions from specific sources such as ocean spray or soil dust [138, 139, 142].

3.2 MNP Emission Flux Estimates

The estimation of AMNP emission fluxes, particularly from the atmosphere-ocean interface and terrestrial sources, involves considerable uncertainties. These uncertainties mainly arise from various in-model assumptions, limited observational data, and an incomplete understanding of emission mechanisms.

Table 2 Ocean Emission Flux Estimates for MNPs. This table summarises annual ocean emission fluxes (in tons) obtained from various approaches, including forward and inverse modelling (e.g., FLEXPART, GEOS-Chem, WRF-MP) and experimental parameterisations, across different spatial scales and particle size ranges. Each estimate is supported by the corresponding reference.

Method	Scale	Size	Ocean Emission Flux	Reference
FLEXPART (Forward Modelling)[1]	Global	0.3–70 μm	8.6 million tons annually	[90]
WRF-MP[1]	Asia, the Pacific, and adjacent areas of the Indian Ocean	10–5000 μm	0.06 million tons annually	[93]
FLEXPART (Inverse Modelling)[2]	Global	5–250 μm	8.9 million tons annually	[91]
GEOS-Chem (Forward Modelling)[1]	Global	0.3–70 μm	0.17 million tons annually	[92]
FLEXPART[1]	Global	1–60 μm	1231 tons annually	[141]
MOZART-4	Global	0–70 μm	800 tons annually	[307]
Experimental Parameterization[2]	Global	0.3–70 μm	773 tons annually	[94]
Experimental Parameterization[1]	Global	10–280 μm	0.02–0.74 million tons annually	[138]
Experimental Parameterization[1]	Global	<10 μm	0.72–4.13 tons annually	[139]
Experimental Parameterization[1]	Global	<100 μm	<100 μm MNPs: 1 million tons annually; <10 nm NPs: 0.3 tons annually	[140]

[1]Calculation basic: MNP concentration in the upper ocean

[2]Calculation basic: Emission inventory of sea spray aerosol

3.2.1 Atmosphere-Ocean Inferfacial MNP Emission Flux

There is ongoing debate regarding the estimation of atmosphere-ocean MNP emission fluxes, with reported values spanning several orders of magnitude (Table 2). Some studies report extremely high fluxes. For instance, Evangelou et al., (2022) estimated an annual atmosphere-ocean emission flux of 8.9 Mt for MNPs in the 5–250 μm range [91]. Similarly, Brahney et al. (2021) used the CESM model to estimate that the air-marine MNP flux for particles smaller than 70 μm is around 8.6 Mt/year [90]. In contrast, Fu et al. (2023) applied the NJU-MP model and reported a significantly lower annual flux of 0.17 Mt for the same size range [92], while Yang et al. (2025) employed the MOZART-4 model and estimated an even lower flux of only 800 t/year [307]. For comparable size ranges, Bucci et al. (2024) estimated a global air-marine MNP emission flux of only 1231 t/year using the FLEXPART model [141], which is lower than the regional estimate for Asia by Long et al. (2022), who reported an annual emission flux of 60,000 t [93].

The experimental parameterisation of atmosphere-ocean MNP exchange is primarily based on the enrichment factor (EF) of MNPs in sea spray aerosols (SSA), measured in laboratory studies [140]. Yang et al. (2022) applied EF values associated with varying MP concentrations and sizes across different ocean surfaces to estimate a global

air-marine flux of 773 t/year for MNPs smaller than 70 μm [94]. Shaw et al. (2023) considered the relationships between EF, bubble rise height, and bubble radius, estimating a global air-marine flux of 20,000 to 740,000 t/year for MNPs in the 10–280 μm size range [138]. Harb et al. incorporated foam (whitecap) area into EF calculations and estimated that the global flux of MNPs smaller than 10 μm ranges from 0.72 to 4.13 t/year [139]. Yang et al. (2024) applied a well-established particulate transfer model at the air-marine interface, providing an upper bound estimate for global MNP emissions [140]. They suggested that for MNPs smaller than 100 μm, the upper bound could be as high as 1 million tonnes per year, while for those smaller than 10 nm, the estimated upper limit is only 0.3 t/year [140].

3.2.2 Air-Terrestrial MNP Emission Flux

Estimating terrestrial MNP emissions is more challenging than atmosphere-marine emissions due to the complexity of sources, including roadways, agricultural soils, resuspended particles, and human activities. The diversity of these sources prevents the use of a single factor for accurate estimation.

Studies have refined estimates of specific terrestrial sources. Evangelou et al. (2020) estimated that tire wear particles (TWP) contribute 2.907 Mt/year of MNP emissions annually, while brake wear particles (BWP) contribute 175,000 t/year [305]. Brahney et al. (2021) estimated global road-based emissions at 100,000 t/year [90], while Evangelou et al. (2022) reported a higher estimate of around 280,000 t/year (around 40% of total terrestrial MNP emission) [91]. Fu et al. (2023) further increased this estimate to 1.15 million tonnes per year using NOx emissions as a proxy for transportation-related NMP emissions (around 70% of total terrestrial MNP emission) [92].

For soil-based emissions, Yang et al. (2024) estimated an annual flux of 48,000 t for sub-100 μm NMPs [142], which aligns with Fu et al. (2023), who reported 38,000 t/year (around 70% of total terrestrial MNP emission) [92]. Brahney et al. (2021) provided a higher estimate of 70,000 t/year based on the CESM model (around 41% of total terrestrial MNP emission) [90], while Evangelou et al. (2022) estimated soil-based NMP emissions at 280,000 t/year using observational data (around 45% of total terrestrial MNP emission) [91].

MNP emissions from resuspension are relatively minor. Evangelou et al. (2022) estimated that resuspension accounts for approximately 100,000 t/year globally, representing only 1.4% of total terrestrial MNP emissions [91]. Yang et al. estimated the total flux of AMNP emissions from soil to the atmosphere as 48,000 t/year for particles within the 0–250 μm size range, which is relatively lower; for particles within the 0–70 μm range, the estimated flux was 22,000 t/year. In contrast, Fu et al. (2023) based on the same 0–70 μm size range, reported a significantly lower global resuspension emission of only 110 t/year, accounting for less than 1% of the total [92].

The dominance of terrestrial versus marine MNP emissions remains a topic of debate. Brahney et al. (2021) estimated marine emissions to be much higher (8.6 Mt/year) compared to terrestrial emissions (0.17 Mt/year) [90]. Similarly, Evangelou et al. (2022) used the FLEXPART model and concluded that marine sources contribute 93% (8.9 Mt/year) of total MNP emissions, while terrestrial sources account for only 7% (0.07 Mt/year) [91]. In contrast, Fu et al. (2023) suggested that marine

and terrestrial emissions are comparable [92]. Their GEOS-Chem model estimated annual marine emissions at 170,000 t/year (52.6%) and terrestrial emissions at 154,000 t/year (47.4%) [92]. Furthermore, Long et al. (2022) estimated that terrestrial emissions (310,000 t/year) to be substantially higher than marine emissions (60,000 t/year) in the Asia-Pacific and Indian Ocean regions [93].

3.3 Uncertainty Analysis of AMNP Emission Flux Estimates

Quantifying atmospheric plastic fluxes remains highly uncertain, particularly for atmosphere-marine MNP fluxes, which range from 773 tons to 8.9 Mt annually [91, 94]. This variability primarily stems from differences in observations, emission source data, and assumptions in model simulations and parameterisations.

3.3.1 Uncertainties in Observational Data

Reliable constraint of AMNP emission estimates requires observational data with adequate spatiotemporal coverage and representative sampling. For example, Brahney et al. (2021) and Evangeliou et al. (2022) used CESM and FLEXPART, respectively, to estimate global oceanic MNP emissions based on data from remote sites in the western U.S., yielding high values of 8–9 Mt/year, with ocean sources accounting for over 90% of total emissions [90, 91]. However, these estimates rely heavily on observational data from areas with minimal local terrestrial emissions. Without sufficient constraint from urban, coastal, or industrial source regions, the models tend to attribute long-range transported particles to marine or background sources, potentially overestimating oceanic contributions while underestimating distant land-based sources.

In contrast, when broader and more representative observation networks are used, estimates of ocean-sourced AMNP and MNP emissions are substantially lower. Fu et al. (2023), using GEOS-Chem constrained by global datasets compiled by Allen et al., estimated oceanic sources to account for 53% of total emissions, with an annual flux of 0.17 Mt [44, 92]. Yang et al. (2025) further modelled an ocean-minimal scenario, finding it better reproduced global MNP patterns, with ocean contributions below 0.01% of total emissions [307].

In recent years, observations of AMNPs have increased across different regions worldwide. However, the lack of standardised sampling and analytical methods complicates cross-study comparisons. Although various sampling techniques are assumed to accurately represent environmental or medium-specific conditions, their efficiency and associated uncertainties remain largely unquantified [44, 81, 103]. These uncertainties primarily stem from differences in particle size classifications, particle characteristics (e.g., shape, polymer type, ageing), sampling protocols (e.g., methods, heights, durations, and site conditions), and detection and quantification limits (LOD/LOQ). [44, 48, 137, 146, 148, 169, 170, 173, 217]. For instance, passive samplers, such as funnel-equipped bottles [160, 164, 165, 170, 173], standard glass collection jars [308], rain gauges [137, 161], NILU bulk collectors [30, 175], "Brahney Buckets" [49, 309], stainless steel buckets [152, 238], glass Petri dishes [155], and Savitzky-Golay filters [310], exhibit variability in capture efficiency, sample retention, and differ in susceptibility to resuspension or sample loss. Furthermore, none of these variability and susceptibility

have been adequately quantified. Likewise, active samplers are affected by collector size, pump power, and operating conditions, leading to inconsistent efficiencies which challenges intercomparison among studies [32, 39, 179, 311]. Sampling duration further influences results, as shorter durations tend to capture transient MNP events, yielding inflated particle counts [218]. Analytical methods contribute additional uncertainty. While μRaman spectroscopy and Nile red fluorescence microscopy produce comparable MNP counts, their error ranges remain unquantified, limiting the cross-study reliability [44]. A detailed discussion of variations in both sampling strategies and analytical methodologies can be found in several recent reviews [96, 110, 119, 171, 179].

3.3.2 Limitations of Emission Source Data

The accuracy and completeness of foundational data used for AMNP emission estimates remain problematic. Atmosphere-ocean MNP emission estimates often rely on surface ocean MNP concentration data [90, 92, 93, 138–141]. However, due to limited observational coverage, datasets rely on simulations or parameterisation methods to fill gaps, resulting in high heterogeneity across studies [90, 92, 93, 138–141]. Although global databases such as the National Centers for Environmental Information (NCEI) (https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476) (last accessed: 2024/12/28) compile observational data on marine MP concentrations, limited spatial coverage and inconsistent sampling protocols across studies hinder data comparability. This discrepancy introduces biases, resulting in large uncertainties in global atmosphere-ocean MNP emission flux estimates. Additionally, complex ocean-atmosphere interactions, including wind-wave dynamics, further increase the complexity of emission estimates at regional and global scales [43, 44, 181, 225].

For terrestrial MNP emissions, such as those from tire and brake wear, spectroscopic analysis faces challenges due to wavelength absorption and weak vibrational signals from black particles [95, 233]. Tire and brake wear emissions are often quantified separately, and their contributions are frequently overlooked in general AMNP observations [44]. Notably, Saladin et al. (2024) pointed out that many secondary sources report PM_{10} emission factors for tire wear (mean: 6.5 mg/vkm) that are significantly higher than those provided in the original primary literature (mean 1.12.7 mg/vkm) [312]. This discrepancy likely stems from misinterpretation or incorrect citation of the original data, leading not only to systematic overestimation of tire wear emissions but also contributing to greater uncertainty in the overall flux estimates of this category of terrestrial MNP emissions. Furthermore, estimating human activity-related MNP emissions solely based on population density is insufficient. Factors such as economic development, waste management policies, recycling efficiency, and industrial emissions play crucial roles in determining MNP emission intensity [124, 187, 313, 314]. Regions with advanced waste management systems and high recycling rates may have lower MNP emissions despite similar population densities [315], whereas high-production or high-consumption areas face elevated emission risks [187]. These uncertainties highlight the need for more spatiotemporally comprehensive datasets to improve terrestrial MNP emission estimates.

Both experimental and modelling approaches have inherent uncertainties. Experimental studies rely on EF values measured in laboratory settings, which may not

fully capture the complexity of real-world oceanic conditions or global-scale variations. Meanwhile, numerical models are highly sensitive to assumptions, parameterisation choices, and the quality of input data. The experimental parameterisation of atmosphere-ocean MNP exchange is primarily based on the EF of MNPs in SSA, measured in laboratory studies

3.3.3 Uncertainties in Emission Mechanisms and Modelling Assumptions

Current methods for estimating atmospheric MNP fluxes have notable limitations. Many experimental studies have parameterised soil and marine MNP emissions using the EF of MNPs in dust and SSA, but these approaches may not fully capture the complexity of real-world conditions or global-scale variations [94, 138, 139, 142]. Numerical modelling approaches primarily depend on selecting characteristic data for emission sources and the quality of observational data used for validation. As discussed in Section 3.3.1 and Section 3.3.2, the limited representativeness of characteristic data, along with the comparability issues and spatiotemporal gaps in observational datasets, introduce substantial uncertainties in model results.

In addition, structural differences among transport models also contribute to variability in flux estimates. LPDMs (e.g., FLEXPART and HYSPLIT) trace particle-level trajectories and are well-suited for source-receptor analysis, but are sensitive to initial emission parameters. Eulerian models (e.g., GEOS-Chem, CESM-CAM5) compute grid-based, volume-averaged concentrations and fluxes, making them better suited for large-scale mass balance assessments. Nonetheless, their accuracy depends heavily on the parameterisation of key processes such as deposition, resuspension, and on spatiotemporal resolution. Consequently, even when using identical emission inventories, these models may yield substantially different estimates of total flux and spatial distribution.

Research on MNP emission mechanisms is still developing, with knowledge gaps regarding both marine and terrestrial sources. Marine MNP emissions are driven by processes such as bubble bursting and wave action, which involve complex dynamics, including bubble formation, ascent, rupture, and aerosolisation [44, 181, 225]. However, existing models struggle to accurately capture the intricate interactions between multiple factors, such as wind speed, wave activity and temperature, all of which influence the efficiency and variability of MNP emissions.

Regarding terrestrial MNP emissions, different soil media influence MNP release rates. For instance, deserts and roads generally exhibit higher MNP emission rates compared to farmlands and vegetated areas [142]. This difference may be attributed to the stabilising effect of vegetation, which reduces wind erosion and particle suspension. The shape of MNP also plays a critical role in their susceptibility to wind entrainment. Fiber-shaped particles, with their larger surface area and aerodynamic properties, are more easily transported by wind than spherical particles [33]. Soil moisture is another key factor affecting MNP emissions. Under low soil moisture (1–5%), the hydrophobic nature of MNPs increases their likelihood of wind transport compared to aggregated soil particles [142]. However, these influencing factors, including soil type, particle shape, and moisture conditions, are rarely systematically considered in current

research. As a result, large uncertainties remain in the quantitative characterisation of soil-driven MNP emissions.

Beyond emissions, knowledge gaps remain in understanding the transport and ageing processes of MNPs in the atmosphere. The mechanisms of MNP wet deposition and its experimental validation remain incomplete. In atmospheric flux simulations, wet deposition is often modelled using fixed scavenging rates, such as high (0.5), medium (0.05), and low (0.001) rates [305]. While MNPs are generally considered hydrophobic, their surface properties may change due to environmental exposure, including corona effects, photodegradation, weathering, or plasticiser leaching [58, 79, 281, 286–291]. These transformations could enable MNPs to act as CCN or INP [58, 59, 77, 79]. Studies have already detected MNPs in cloud water samples [46, 47], but further research is needed to clarify the atmospheric ageing processes of MNPs and their specific impacts on atmospheric dynamics and cloud microphysics.

Additionally, current models often assume spherical particles and do not fully account for the distinct properties of MNPs, such as their surface charge, high heterogeneity, and potential colloidal behaviour [90, 92, 93, 142, 305, 306]. These properties may influence MNP behaviour in the atmosphere, including transport, re-entrainment, and deposition processes. To improve the accuracy of MNP emission, transport, and deposition simulations, systematic laboratory studies and field observations are necessary to refine parameterisations and reduce model uncertainties.

4 Future Strategies and Outlook

Understanding the environmental behaviour of MNPs requires an integrated approach combining observations, modelling, and data-driven analysis. This section discusses key future strategies to advance AMNP research, focusing on three critical areas: (1) improving observation and sampling campaigns through standardized protocols and global monitoring networks, (2) enhancing numerical modelling to refine MNP transport, deposition, and ageing processes, and (3) leveraging AI to improve the efficiency and accuracy of MNP research, including automated observation, data integration, source attribution, trajectory modelling, and multimodal data-driven predictive modelling. These efforts will provide a more detailed understanding of MNP sources, transport pathways, and environmental impacts, ultimately supporting environmental policies and pollution mitigation strategies.

4.1 Observation and Sampling Campaigns

4.1.1 Standardisation of AMNP Sampling and Data Reporting

Atmospheric MNP observations are crucial for understanding their distribution, deposition processes, emission mechanisms, and transport dynamics. However, the standardisation of sampling and analytical methods for AMNPs remains insufficient [111]. While existing studies have proposed sampling and detection protocols for MNPs in seafood, marine and aquatic environments, these protocols have yet to be systematically adapted or applied for AMNP research [316–324].

Variability in sampling methodologies, analytical workflows and field conditions across studies presents one of the major obstacles to standardising AMNP sampling and analysis. Furthermore, MNP concentrations in the atmosphere are low that even trace contamination—from sampling equipment, laboratory air, reagents or handling—can obscure the true signal, distort results and undermine data comparability and reliability. Although comprehensive standardisation remains challenging, standardising key elements can improve data comparability and reliability. First, research reports should follow a uniform structure, including clear LOD/LOQ, detailed sampling and analytical procedures, sample preparation methods, quality assurance and control (QA/QC) measures, contamination control records, and blank control correction procedures [105, 324–329]. Standardising these elements will help ensure consistency across studies, enabling more reliable comparisons and facilitating integrative analyses of AMNP data.

Second, standardised QA/QC protocols are essential for ensuring data reliability. Measures such as characterisation and assessment of laboratory and field blanks, performing matrix spiked recovery tests, and the use of positive and negative controls can help identify contamination sources and experimental errors, improving the overall robustness of results [111, 210, 326, 328]. Similarly, sample preparation processes, including cleaning, digestion, preconcentration, and separation, should adhere to uniform guidelines to minimise human error and optimise consistency [82]. For example, the type and concentration of separation liquids, as well as the specific reagents and digestion durations, should be explicitly defined [82, 325, 326, 330]. Additionally, analytical techniques for MNP detection and quantification should adopt standardised parameters. Techniques such as Raman spectroscopy, FTIR spectroscopy, and other high-resolution methods should have clearly defined measurement conditions, such as laser wavelength, spectral resolution, and data processing protocols, to improve the accuracy of the results and ensure comparability across studies [319, 325, 331, 332]. These standardisation efforts not only improve data quality but also provide support for advanced analysis using machine learning and other computational tools.

Third, the choice of monitoring metrics directly influences the interpretation and comparability of AMNP data. Currently, most active and passive sampling studies primarily report particle number concentrations (Shown as Support Information). However, relying solely on particle counts fails to capture the high variability in particle size, shape, and polymer component. For instance, at the same mass, the number concentration of NPs can differ by several orders of magnitude from that of MPs. In addition, particle fragmentation or aggregation during sampling and processing further destabilises number-based measurements, undermining cross-study comparability. In contrast, mass concentration is an inherently conserved parameter that allows direct summation across different size fractions, sampling batches, and analytical procedures, minimising the risk of loss or double-counting. Mass-based metrics also seamlessly link with deposition flux estimations, environmental fate modelling, and exposure risk assessments, serving as a unified "currency" across different research domains. Therefore, we recommend adopting mass concentration (e.g., $\mu g/m^3$) as the primary reporting metric for AMNPs, supplemented by particle size, polymer composition, and morphological information.

Regarding particle size characterisation, a balance must be struck between measurement simplicity, data accuracy, and scientific representativeness. We recommend consistently reporting the maximum Feret's diameter [333] as a default size descriptor, given its ease of measurement, broad applicability, and ability to capture the maximum spatial extent of particles. However, a single size metric cannot fully represent the complexity of microplastic morphology. Thus, we advocate for the simultaneous collection and reporting of multiple size descriptors, such as area-equivalent diameter [334], Martin's diameter [335], and geodesic lines [336], with data shared in an open-access format to enhance utility and comparability. For particle morphology, key characteristics can be described by adapting the four classical dimensions used in sediment research–irregularity, roundness, sphericity, and form–supplemented by elongation, to better reflect the physical properties and environmental behaviour of AMNPs [336, 337]. Importantly, the choice of size and shape descriptors should remain flexible according to specific research objectives. For example, maximum size is critical for atmospheric deposition studies, elongation is more relevant in exposure risk assessments involving fibrous particles, and irregularity and sphericity are particularly informative for pollution source attribution. Thus, while promoting standardisation, researchers should be encouraged to adapt and extend descriptor selections based on the scientific questions addressed, ensuring both data comparability and problem-specific relevance.

4.1.2 Expanding AMNP Monitoring Networks

Although AMNP observations have increased in recent years, existing datasets remain geographically concentrated and temporally sparse (Figure 2). Most studies have been conducted in Asia, North America, and Europe, while economically less developed regions, polar areas, and deep-sea environments remain underrepresented (Figure 2). This spatial unevenness hampers the development of a comprehensive understanding of AMNP distribution, transport dynamics, and environmental impacts. Expanding spatial coverage is therefore essential. Establishing new observation sites in currently under-monitored regions, particularly in the Global South, polar areas, and remote marine environments, would help fill critical data gaps. At the same time, building large-scale, standardised data platforms is crucial for organising, sharing, and harmonising AMNP datasets. Existing resources, such as the NCEI marine microplastic database https://experience.arcgis.com/experience/b296879cc1984fda833a8acc93e31476 (last accessed: 2024/12/28) and the Aeronet aerosol optical data platform https://aeronet.gsfc.nasa.gov/ (last accessed: 2024/12/28), provide valuable reference models. A centralised database for AMNPs would facilitate broader access to data, enhance collaborative research between observation and modelling of MNP, and promote the application of big data analytics (e.g. machine learning) in MNP research.

In addition to spatial expansion, enhancing the temporal continuity of AMNP monitoring is equally important. Establishing a global, long-term observation network would allow researchers to track temporal trends, seasonal variations, and long-range transport patterns of AMNPs. This network should integrate fixed stations with mobile platforms, such as ships, drones, and floats, to ensure adequate spatial coverage. Observations at fixed stations require standardised sampling and detection protocols

to maintain data reliability and comparability. Notably, at least two stations within the Global Atmospheric Watch (GAW) program have initiated MNP monitoring, suggesting the feasibility of incorporating MNP observations into existing networks [44].

In regions without long-term observational coverage, periodic supplementary studies can help address the data gaps. For example, ships and floats can conduct regional and open-ocean sampling campaigns, while drones and aircraft can collect vertical profile data critical for understanding AMNP concentration gradients and atmospheric transport mechanisms. Drones, due to their flexibility and lower operational costs, are particularly suitable for short-term, high-frequency monitoring in the lower atmosphere [338, 339]. Aircraft, in contrast, can facilitate observations at higher altitudes and across broader spatial scales. In regions where establishing fixed stations is impractical, such as polar or mountainous areas, intermittent targeted studies can help compensate for observational gaps. In economically constrained areas, deploying mobile sampling vehicles and launching regional research projects can improve local monitoring efforts, contributing to a more comprehensive understanding of MNP distribution and behaviour [340].

4.2 Model Simulations

Numerical models are widely used to simultaneously simulate emissions, deposition fluxes, and MNP transport, enabling source attribution. For example, Lagrangian trajectory models are often employed to trace potential sources of MNPs, quantify their contributions, and estimate deposition fluxes[91]. Similarly, the CESM model has been used to evaluate the impact of different sources, including roads, oceans, dust, and human activities, on the concentration and deposition of AMNPs [90]. However, these models inherently involve simplifications, leading to uncertainties in estimating MNP emission, concentration, and deposition. Future research should focus on addressing these uncertainties by improving the following aspects.

First, optimising model input data is crucial. In current simulations, MNPs are typically assumed to be insoluble spherical particles with a fixed density. However, the defined size ranges and distributions vary significantly across studies. Reported aerodynamic diameter ranges include 0.3—70 μm [90, 94], 10—3000 μm [91], 40—900 μm [93], and 1—60 μm [141]. Future studies should define size ranges and distributions based on specific source characteristics (e.g., marine versus terrestrial sources). Marine-sourced MNPs tend to be smaller due to processes such as bubble bursting at the ocean surface. In addition, particle shape, which influences aerodynamic behaviour, should be incorporated into models [247, 248, 250]. Larger particles (e.g., ¿100 μm) are typically fibrous due to their formation processes [150, 170, 203], whereas smaller particles are often fragmented [45, 149]. For particles smaller than 6 μm, Ward et al. (2024) found that shape has a negligible impact on atmospheric transport [250]. Kooi et al. (2019) proposed a continuous probability distribution combining size, shape, and density, which serves as a useful reference for optimizing model inputs [341]. However, this method should be extended to account for smaller particles (nanometer range) and better represent variations across sources and morphological characteristics.

Regarding the chemical composition/solubility of MNPs, the impact of atmospheric ageing on the transport and wet deposition is not fully understood [90]. Approaches to modelling wet deposition vary across studies. Some assume that precipitation completely removes MNPs [90], while others use a first-order loss process based on rainfall parameters [93] or apply wet deposition mechanisms similar to those used for black carbon [92]. The potential removal of MNPs through cloud and ice formation is either omitted [90] or represented by simplified linear scavenging rates categorised as high (0.5), medium (0.05), and low (0.001) [305]. While these simplifications improve computational efficiency, they often overlook the impacts of MNP ageing and its physical and chemical properties on removal processes. Future research should focus on the interplay between the degree of MNP ageing and wet deposition efficiency, as well as the broader impact on the lifecycle of MNPs in the atmosphere, to improve the accuracy and physical representation of these processes in models.

Furthermore, vertical transport mechanisms require refinement. Observations indicate that MNPs are not only present in the boundary layer but also detected in cloud water and even the stratosphere, highlighting their potential for vertical transport [45–47, 50, 202]. However, current MNP simulations primarily focus on emissions, surface deposition, and concentration, with limited modelling of their distribution at different atmospheric heights. Bucci et al. (2024) simulated the atmospheric transport of marine-source MPs smaller than 60 μm on a global scale [141]. Using ERA5 reanalysis data, their results suggest that MPs can be transported into the free troposphere [141]. Similarly, Wang et al. (2023) collected cloud water samples at altitudes ranging from 1300 to 3776 m near Mount Fuji and detected MNPs with sizes between 7 and 94 μm, with concentrations ranging from 0.67×10^5 to 1.39×10^5 MP/m^3 [46]. HYSPLIT4 backward trajectory analysis indicated that these MNPs primarily originated from the ocean [46]. At the same time and location, Bucci et al. (2024)'s simulation yielded an average MNP concentration of 2.6×10^5 MP/m^3 for particles smaller than 60 μm [141]. While these values are of the same order of magnitude, the discrepancy of up to fourfold suggests potential shortcomings in the current representation of vertical transport processes in models. More detailed models are required to adequately simulate and fully capture these processes.

Finally, aerosol dynamic models offer powerful tools for studying the atmospheric ageing processes of MNPs. Particle-resolved aerosol models [342], for instance, can simulate single-particle-level physical ageing processes, including condensation, evaporation, and surface property changes. These transformations may alter the aerodynamic behaviour and deposition pathways of MNPs. As research progresses, such models can also be extended to simulate chemical ageing processes, such as oxidation, degradation, and surface functionalisation, providing insights into how MNPs evolve in the atmosphere and interact with radiation and other pollutants. By integrating both physical and chemical ageing mechanisms into atmospheric models, future models can improve the accuracy of MNP lifecycle and deposition simulations, contributing to a better understanding of their environmental and climate impacts.

4.3 AI-enabled Research

The rapid development of AI has introduced new tools and perspectives for AMNP research. One of the primary advantages of AI in this field is its ability to improve the comparability of MNP observations and expand spatiotemporal coverage. Traditional MNP quantification and characterisation are labour-intensive and time-consuming, particularly when MNPs exist in complex environmental media or as mixtures of various types [343–345]. In recent years, machine learning (ML), natural language processing (NLP), and computer vision (CV) have been widely applied to spectral enhancement, automatic identification, classification, quantification, and spectral library expansion of MNPs [346–353]. Compared to traditional detection methods, ML can process large-scale data more efficiently [347]. ML models, trained and optimised on large datasets, can identify patterns and make objective predictions, reducing potential errors introduced by human interpretation [346]. Additionally, automated data analysis can extract deeper insights from datasets, revealing new features that might not be immediately apparent to human observers [346]. Despite these advantages, ML applications in this field still face challenges. The accuracy and reliability of models heavily depend on the quality and representativeness of the training data. Limited or unbalanced datasets can result in unpredictable, erroneous, or biased outputs. To enhance model robustness and generalization, future research should focus on expanding training datasets to encompass a wider range of MNP characteristics, including size, polymer type, colour, weathering extent, and interactions with biological substances.

In terms of observation techniques, autonomous drones and robots provide an effective means to expand the spatiotemporal coverage of MNP monitoring. These technologies enable large-scale and efficient MNP sampling, even in challenging environments such as deep oceans, high altitudes, mountainous regions, and deserts [354]. Currently, drones and unmanned surface vehicles have been applied to collect MP samples in terrestrial, marine, and surface water environments [355–358]. However, AMNP sampling remains relatively underexplored. Integrating ML with automated sampling systems in the future could enhance MNP observation coverage and data quality.

ML can integrate multi-source datasets to construct a reasonable MNP emission inventory and global distribution map. Similar studies have achieved success in the fields of air pollution and plastic pollution inventories. For example, ML has been successfully used to generate a long-term illumination dataset (1 km resolution) for walking aerial drones globally [359]. Furthermore, researchers such as Cottom et al. (2024) combined ML with MFA technology to establish a macro-scale plastic pollution inventory from local to global scales [304]. These approaches help improve the quality and coverage of initial datasets, thereby providing a reliable foundation for studying the atmospheric cycling of MNPs.

ML has also demonstrated potential in capturing the complex spatiotemporal dynamics of AMNPs. For source apportionment, methods such as principal component analysis (PCA) and clustering algorithms (e.g., k-means) have been used to infer potential sources based on the chemical composition and physical properties of MNPs [354, 360–362]. However, these methods primarily capture statistical variance, lacking interpretability and failing to incorporate real-world physical processes such as

long-range transport and the atmospheric removal mechanisms of MPs [354]. Moreover, ML has been applied to capture lagrangian trajectories in various environments including flame systems [363], turbulent flow [364–366], sediment transport in natural rivers [367], and granular gas [368]. In atmospheric research, ML applications have expanded, with some studies integrating it with LDPMs to improve model accuracy. For example, Brecht et al. (2023) replaced the interpolation method used in FLEXPART for enhancing input resolution with ML, reducing trajectory prediction errors by 49.5% [369]. Lucas et al. (2017) used ML to quantify the impact of WRF inputs on FLEXPART outputs and identified model parameters that best matched tracer observations [370]. Some studies have further explored using ML as a replacement for LDPMs in trajectory simulations. For instance, Liao et al. (2023) trained an ML model based on HYSPLIT simulations combined with topographic data to predict air quality [371]. Gunawardena et al. (2021) applied ML to FLEXPART data for pollutant deposition predictions [372], while Fillola et al. (2023) trained an emulator on NAME model simulations to track greenhouse gas (GHG) transport [373]. Compared to traditional Lagrangian particle tracking models, ML offers advantages in computational efficiency and resource consumption [372, 373]. It enables faster simulations with lower computational costs. Additionally, ML models can integrate multimodal datasets, such as satellite remote sensing and topographic information, providing more rapid and accurate predictions [371].

When studying the fate and transport of AMNPs, valuable insights can be drawn from research on aquatic environments. For instance, Qian et al. (2024) used an XGBoost model to predict the settling velocities of various MNPs based on their physical properties [374]. Li et al. (2024) employed artificial neural networks (ANNs) to simulate the aggregation and suspension of NPs in water and identified key influencing factors [375]. Mehmood et al. (2022) applied partial least squares (PLS) regression to predict changes in hydroxyl and carboxyl indices during the ageing of microplastics [376]. Those ML methods not only help in understanding the environmental behaviour of AMNPs but also provide data support for more precise numerical simulations.

Compared to traditional numerical methods, ML models can efficiently extract data features, capture nonlinear relationships, and reduce computational costs. Integrating ML with numerical models can effectively address the limitations of traditional approaches. For example, Shen et al. (2024) incorporated ML into the CESM model to optimise representations of black carbon (BC) mixing state and cloud condensation nuclei (CCN) activatio [377]. Behrens et al. (2024) improved the simulation of convective processes (particularly in the planetary boundary layer) in CESM2 using ML and quantified uncertainties [378]. These studies demonstrate that AI techniques can enhance the accuracy of traditional climate and atmospheric models while improving their ability to simulate complex environmental processes.

For MNP atmospheric modelling, future research can further expand the applications of ML. For instance, graph neural networks (GNNs) could be employed to develop trajectory models for MNP transport, providing a more precise representation of their evolution under varying meteorological conditions. Furthermore, ML models can be designed to evaluate the impact of particle size, shape, and ageing processes on MNP transport pathways and to explore their deposition and resuspension behaviour

across different land surface types (e.g. urban areas, forests, oceans). Besides that, with the development of foundation models in aerosol research [379], satellite remote sensing [380–382], and meteorology and climate science (such as ClimateX [383], FengWu [384], PanGu [385], FuXi [386], GraphCast [387], FourCastNet [388], W-MAE [389], and CliMedBert [390]), their potential applications in AMNP research warrant further exploration. These foundation models can integrate multi-source data, including satellite remote sensing and meteorological observations, thereby enhancing the modelling of MNP transport and fate. In the future, leveraging such models could help overcome the limitations of traditional numerical simulations, enabling more efficient and accurate predictions, and providing scientific support for environmental policies and pollution control.

5 Conclusions

Examining the lifecycle of AMNPs is important in assessing their environmental risks, informing management strategies, and advancing research. This review article outlines the established knowledge and the gaps concerning AMNPs, with particular focus on the uncertainties involved in simulating their behaviour. Moreover, it explores the roles and future prospects of observational, modelling, and data-driven approaches in bridging the knowledge gap surrounding the atmospheric lifecycle of MNPs.

Overall, our analysis reveals that while progress has been made in understanding the sources, transport mechanisms, and deposition processes of AMNPs, substantial uncertainties remain in accurately quantifying the AMNP emission fluxes. Notably, the estimated global emissions from ocean sources range widely, from as little as 773 tons [94] to as much as 890 million tons annually [91]—and it remains unclear whether oceanic or terrestrial sources dominate. These uncertainties primarily arise from limited observational data, variability and inconsistency in sampling methodologies, and the oversimplification of AMNP lifecycle mechanisms in existing simulations.

To address these challenges, it is essential to establish a globally unified, standardised observation network, improve sampling protocols that ensure data comparability, and develop numerical models that accurately reflect MNP properties and advanced transport dynamics. In addition, integrating AI into the data analysis process will provide a broader perspective of the atmospheric cycle of MNPs. These strategies are interdependent, creating a synergy: First, high-quality and abundant observational data can help us uncover the behavioural characteristics of AMNPs, such as their spatiotemporal distribution and evolution, thereby providing a solid foundation for training AI models and validating the parameterisation of numerical simulations. Second, numerical models can simulate the dynamic behaviour of MNPs under various environmental conditions, compensating for the spatiotemporal gaps in observational data and offering robust support for AI model training. Third, AI technology not only enhances the efficiency of processing and analysing observational data but also improves data quality and simulation accuracy through data mining and pattern recognition; moreover, AI can integrate multi-source information, such as land use types, meteorological conditions, and particle ageing (including photochemical and biological ageing as well as physical fragmentation and abrasion), to further optimise numerical

model parameterisations. By adopting this integrated framework, we will not only gain deeper insights into the complex lifecycle dynamics of AMNPs and build a solid foundation for predicting future environmental risks but also drive the formulation and implementation of effective environmental policies and management strategies. Ultimately, this approach holds the promise of significantly reducing MNP pollution on a global scale, thereby improving public health and ecological quality and providing robust support for sustainable development goals.

Acknowledgement

This work was funded by the Manchester–Melbourne–Toronto (MMT) Research Fund. Z.Z. appreciates the support provided by the academic start-up funds from the Department of Earth and Environmental Sciences at The University of Manchester. The authors declare no conflict of interest.

References

[1] Geyer, R., Jambeck, J.R., Law, K.L.: Production, use, and fate of all plastics ever made **3**(7), 1700782 https://doi.org/10.1126/sciadv.1700782 . Accessed 2024-11-01

[2] Geyer, R.: Production, use, and fate of synthetic polymers. In: Plastic Waste and Recycling, pp. 13–32. Elsevier. https://doi.org/10.1016/B978-0-12-817880-5.00002-5 . https://linkinghub.elsevier.com/retrieve/pii/B9780128178805000025 Accessed 2024-11-01

[3] EUROPE, P.: Plastics - the Fast Facts 2023. file:///C:/Users/1/Downloads/Plasticsthefastfacts2023-1.pdf

[4] OECD: Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. OECD. https://doi.org/10.1787/de747aef-en . https://www.oecd-ilibrary.org/environment/global-plastics-outlook_de747aef-en Accessed 2024-11-01

[5] Hannah, R., Veronika, S., Max, R.: Plastic pollution

[6] Andrady, A.L.: Microplastics in the marine environment **62**(8), 1596–1605 https://doi.org/10.1016/j.marpolbul.2011.05.030 . Accessed 2024-04-22

[7] Andrady, A.L.: The plastic in microplastics: A review **119**(1), 12–22 https://doi.org/10.1016/j.marpolbul.2017.01.082 . Accessed 2024-04-22

[8] An, L., Liu, Q., Deng, Y., Wu, W., Gao, Y., Ling, W.: Sources of microplastic in the environment. In: He, D., Luo, Y. (eds.) Microplastics in Terrestrial Environments vol. 95, pp. 143–159. Springer. https://doi.org/10.1007/698_2020_449 . Series Title: The Handbook of Environmental Chemistry. http://link.springer.com/10.1007/698_2020_449 Accessed 2024-10-18

[9] Pramanik, S., Karak, N.: Polymer nanocomposites for adhesive, coating, and paint applications. In: Tripathy, D.K., Sahoo, B.P. (eds.) Properties and Applications of Polymer Nanocomposites, pp. 173–204. Springer. https://doi.org/10.1007/978-3-662-53517-2_8 . http://link.springer.com/10.1007/978-3-662-53517-2_8 Accessed 2024-05-20

[10] Stephens, B., Azimi, P., El Orch, Z., Ramos, T.: Ultrafine particle emissions from desktop 3d printers **79**, 334–339 https://doi.org/10.1016/j.atmosenv.2013.06.050 . Accessed 2024-05-20

[11] Hussain, K.A., Romanova, S., Okur, I., Zhang, D., Kuebler, J., Huang, X., Wang, B., Fernandez-Ballester, L., Lu, Y., Schubert, M., Li, Y.: Assessing the release of microplastics and nanoplastics from plastic containers and reusable food pouches: Implications for human health **57**(26), 9782–9792 https://doi.org/10.1021/acs.est.3c01942 . Accessed 2025-04-10

[12] Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C., Gieré, R.: Tire abrasion as a major source of microplastics in the environment **18**(8), 2014–2028 https://doi.org/10.4209/aaqr.2018.03.0099 . Accessed 2024-10-18

[13] Yang, T., Luo, J., Nowack, B.: Characterization of nanoplastics, fibrils, and microplastics released during washing and abrasion of polyester textiles **55**(23), 15873–15881 https://doi.org/10.1021/acs.est.1c04826 . Accessed 2025-04-10

[14] ISO, U.: TR 21960:2020; Plastics — Environmental aspects — State of knowledge and methodologies. https://www.iso.org/obp/ui/en/#iso:std:iso:tr:21960:ed-1:v1:en Accessed 2024-11-07

[15] Bank, M.S., Hansson, S.V.: The plastic cycle: A novel and holistic paradigm for the anthropocene **53**(13), 7177–7179 https://doi.org/10.1021/acs.est.9b02942 . Accessed 2024-10-10

[16] Hu, D., Shen, M., Zhang, Y., Li, H., Zeng, G.: Microplastics and nanoplastics: would they affect global biodiversity change? **26**(19), 19997–20002 https://doi.org/10.1007/s11356-019-05414-5 . Accessed 2024-10-11

[17] Rai, P.K., Lee, J., Brown, R.J.C., Kim, K.-H.: Micro- and nano-plastic pollution: Behavior, microbial ecology, and remediation technologies **291**, 125240 https://doi.org/10.1016/j.jclepro.2020.125240 . Accessed 2024-10-11

[18] Arif, Y., Mir, A.R., Zieliński, P., Hayat, S., Bajguz, A.: Microplastics and nanoplastics: Source, behavior, remediation, and multi-level environmental impact **356**, 120618 https://doi.org/10.1016/j.jenvman.2024.120618 . Accessed 2024-10-11

[19] Nizzetto, L., Bussi, G., Futter, M.N., Butterfield, D., Whitehead, P.G.: A theoretical assessment of microplastic transport in river catchments and their

retention by soils and river sediments **18**(8), 1050–1059 https://doi.org/10.1039/C6EM00206D . Accessed 2024-10-11

[20] Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C.: Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities **586**, 127–141 https://doi.org/10.1016/j.scitotenv.2017.01.190 . Accessed 2024-10-11

[21] Bläsing, M., Amelung, W.: Plastics in soil: Analytical methods and possible sources **612**, 422–435 https://doi.org/10.1016/j.scitotenv.2017.08.086 . Accessed 2024-10-11

[22] Pathan, S.I., Arfaioli, P., Bardelli, T., Ceccherini, M.T., Nannipieri, P., Pietramellara, G.: Soil pollution from micro- and nanoplastic debris: A hidden and unknown biohazard **12**(18), 7255 https://doi.org/10.3390/su12187255 . Accessed 2024-10-11

[23] Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B.: Microplastic contamination in an urban area: a case study in greater paris **12**(5), 592 https://doi.org/10.1071/EN14167 . Accessed 2025-02-13

[24] Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., De Frond, H., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M.: Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution **369**(6510), 1515–1518 https://doi.org/10.1126/science.aba3656 . Accessed 2024-10-11

[25] Cole, M., Galloway, T.S.: Ingestion of nanoplastics and microplastics by pacific oyster larvae **49**(24), 14625–14632 https://doi.org/10.1021/acs.est.5b04099 . Accessed 2024-10-11

[26] Koelmans, A.A., Kooi, M., Law, K.L., Van Sebille, E.: All is not lost: deriving a top-down mass budget of plastic at sea **12**(11), 114028 https://doi.org/10.1088/1748-9326/aa9500 . Accessed 2024-10-11

[27] Rios Mendoza, L.M., Karapanagioti, H., Álvarez, N.R.: Micro(nanoplastics) in the marine environment: Current knowledge and gaps **1**, 47–51 https://doi.org/10.1016/j.coesh.2017.11.004 . Accessed 2024-10-11

[28] Kanhai, L.D.K., Gardfeldt, K., Krumpen, T., Thompson, R.C., O'Connor, I.: Microplastics in sea ice and seawater beneath ice floes from the arctic ocean **10**(1), 5004 https://doi.org/10.1038/s41598-020-61948-6 . Accessed 2024-10-11

[29] Rezaei, M., Riksen, M.J.P.M., Sirjani, E., Sameni, A., Geissen, V.: Wind erosion as a driver for transport of light density microplastics **669**, 273–281 https://doi.org/10.1016/j.scitotenv.2019.02.382 . Accessed 2024-10-11

[30] Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D.: Atmospheric transport and deposition of microplastics in a remote mountain catchment **12**(5), 339–344 https://doi.org/10.1038/s41561-019-0335-5 . Accessed 2024-05-13

[31] Abbasi, S., Jaafarzadeh, N., Zahedi, A., Ravanbakhsh, M., Abbaszadeh, S., Turner, A.: Microplastics in the atmosphere of ahvaz city, iran **126**, 95–102 https://doi.org/10.1016/j.jes.2022.02.044 . Accessed 2024-12-05

[32] Luo, D., Wang, Z., Liao, Z., Chen, G., Ji, X., Sang, Y., Qu, L., Chen, Z., Wang, Z., Dahlgren, R.A., Zhang, M., Shang, X.: Airborne microplastics in urban, rural and wildland environments on the tibetan plateau **465**, 133177 https://doi.org/10.1016/j.jhazmat.2023.133177 . Accessed 2024-12-05

[33] Bullard, J.E., Ockelford, A., O'Brien, P., McKenna Neuman, C.: Preferential transport of microplastics by wind **245**, 118038 https://doi.org/10.1016/j.atmosenv.2020.118038 . Accessed 2024-10-11

[34] Bouwmeester, H., Hollman, P.C.H., Peters, R.J.B.: Potential health impact of environmentally released micro- and nanoplastics in the human food production chain: Experiences from nanotoxicology **49**(15), 8932–8947 https://doi.org/10.1021/acs.est.5b01090 . Accessed 2024-10-11

[35] EFSA Panel on Contaminants in the Food Chain (CONTAM): Presence of microplastics and nanoplastics in food, with particular focus on seafood **14**(6) https://doi.org/10.2903/j.efsa.2016.4501 . Accessed 2024-10-11

[36] Toussaint, B., Raffael, B., Angers-Loustau, A., Gilliland, D., Kestens, V., Petrillo, M., Rio-Echevarria, I.M., Van Den Eede, G.: Review of micro- and nanoplastic contamination in the food chain **36**(5), 639–673 https://doi.org/10.1080/19440049.2019.1583381 . Accessed 2024-10-11

[37] Rose, P.K., Yadav, S., Kataria, N., Khoo, K.S.: Microplastics and nanoplastics in the terrestrial food chain: Uptake, translocation, trophic transfer, ecotoxicology, and human health risk **167**, 117249 https://doi.org/10.1016/j.trac.2023.117249 . Accessed 2024-10-11

[38] Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., Tassin, B.: A first overview of textile fibers, including microplastics, in indoor and outdoor environments **221**, 453–458 https://doi.org/10.1016/j.envpol.2016.12.013 . Accessed 2024-10-13

[39] Perera, K., Ziajahromi, S., Bengtson Nash, S., Manage, P.M., Leusch, F.D.L.: Airborne microplastics in indoor and outdoor environments of a developing country in south asia: Abundance, distribution, morphology, and possible sources **56**(23), 16676–16685 https://doi.org/10.1021/acs.est.2c05885 . Accessed 2024-12-05

[40] Eberhard, T., Casillas, G., Zarus, G.M., Barr, D.B.: Systematic review of microplastics and nanoplastics in indoor and outdoor air: identifying a framework and data needs for quantifying human inhalation exposures https://doi.org/10.1038/s41370-023-00634-x . Accessed 2024-05-09

[41] Jiang, Y., Han, J., Na, J., Fang, J., Qi, C., Lu, J., Liu, X., Zhou, C., Feng, J., Zhu, W., Liu, L., Jiang, H., Hua, Z., Pan, G., Yan, L., Sun, W., Yang, Z.: Exposure to microplastics in the upper respiratory tract of indoor and outdoor workers **307**, 136067 https://doi.org/10.1016/j.chemosphere.2022.136067 . Accessed 2024-10-14

[42] Allen, S., Allen, D., Karbalaei, S., Maselli, V., Walker, T.R.: Micro(nano)plastics sources, fate, and effects: What we know after ten years of research **6**, 100057 https://doi.org/10.1016/j.hazadv.2022.100057 . Accessed 2024-05-14

[43] Allen, S., Allen, D., Moss, K., Le Roux, G., Phoenix, V.R., Sonke, J.E.: Examination of the ocean as a source for atmospheric microplastics **15**(5), 0232746 https://doi.org/10.1371/journal.pone.0232746 . Accessed 2024-10-17

[44] Allen, D., Allen, S., Abbasi, S., Baker, A., Bergmann, M., Brahney, J., Butler, T., Duce, R.A., Eckhardt, S., Evangeliou, N., Jickells, T., Kanakidou, M., Kershaw, P., Laj, P., Levermore, J., Li, D., Liss, P., Liu, K., Mahowald, N., Masque, P., Materić, D., Mayes, A.G., McGinnity, P., Osvath, I., Prather, K.A., Prospero, J.M., Revell, L.E., Sander, S.G., Shim, W.J., Slade, J., Stein, A., Tarasova, O., Wright, S.: Microplastics and nanoplastics in the marine-atmosphere environment **3**(6), 393–405 https://doi.org/10.1038/s43017-022-00292-x . Accessed 2024-09-25

[45] Allen, S., Allen, D., Baladima, F., Phoenix, V.R., Thomas, J.L., Le Roux, G., Sonke, J.E.: Evidence of free tropospheric and long-range transport of microplastic at pic du midi observatory **12**(1), 7242 https://doi.org/10.1038/s41467-021-27454-7 . Accessed 2024-10-22

[46] Wang, Y., Okochi, H., Tani, Y., Hayami, H., Minami, Y., Katsumi, N., Takeuchi, M., Sorimachi, A., Fujii, Y., Kajino, M., Adachi, K., Ishihara, Y., Iwamoto, Y., Niida, Y.: Airborne hydrophilic microplastics in cloud water at high altitudes and their role in cloud formation **21**(6), 3055–3062 https://doi.org/10.1007/s10311-023-01626-x . Accessed 2024-06-21

[47] Xu, X., Li, T., Zhen, J., Jiang, Y., Nie, X., Wang, Y., Yuan, X.-Z., Mao, H., Wang, X., Xue, L., Chen, J.: Characterization of microplastics in clouds over eastern china **11**(1), 16–22 https://doi.org/10.1021/acs.estlett.3c00729 . Accessed 2024-10-11

[48] González-Pleiter, M., Edo, C., Aguilera, , Viúdez-Moreiras, D., Pulido-Reyes, G., González-Toril, E., Osuna, S., De Diego-Castilla, G., Leganés, F., Fernández-Piñas, F., Rosal, R.: Occurrence and transport of microplastics sampled within

and above the planetary boundary layer **761**, 143213 https://doi.org/10.1016/j.scitotenv.2020.143213 . Accessed 2024-10-22

[49] Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., Sukumaran, S.: Plastic rain in protected areas of the united states **368**(6496), 1257–1260 https://doi.org/10.1126/science.aaz5819 . Accessed 2024-05-14

[50] Feng, S., Lu, H., Yao, T., Tang, M., Yin, C.: Analysis of microplastics in soils on the high-altitude area of the tibetan plateau: Multiple environmental factors **857**, 159399 https://doi.org/10.1016/j.scitotenv.2022.159399 . Accessed 2024-12-11

[51] Abbasi, S., Turner, A., Hoseini, M., Amiri, H.: Microplastics in the lut and kavir deserts, iran **55**(9), 5993–6000 https://doi.org/10.1021/acs.est.1c00615 . Accessed 2024-12-04

[52] Wang, F., Lai, Z., Peng, G., Luo, L., Liu, K., Huang, X., Xu, Y., Shen, Q., Li, D.: Microplastic abundance and distribution in a central asian desert **800**, 149529 https://doi.org/10.1016/j.scitotenv.2021.149529 . Accessed 2024-12-04

[53] Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G.: White and wonderful? microplastics prevail in snow from the alps to the arctic **5**(8), 1157 https://doi.org/10.1126/sciadv.aax1157 . Accessed 2024-12-05

[54] Huntington, A., Corcoran, P.L., Jantunen, L., Thaysen, C., Bernstein, S., Stern, G.A., Rochman, C.M.: A first assessment of microplastics and other anthropogenic particles in hudson bay and the surrounding eastern canadian arctic waters of nunavut **5**(1), 432–454 https://doi.org/10.1139/facets-2019-0042 . Accessed 2025-02-16

[55] Rillig, M.C., Kim, S.W., Zhu, Y.-G.: The soil plastisphere **22**(2), 64–74 https://doi.org/10.1038/s41579-023-00967-2 . Accessed 2024-10-11

[56] Sheng, D., Jing, S., He, X., Klein, A.-M., Köhler, H.-R., Wanger, T.C.: Plastic pollution in agricultural landscapes: an overlooked threat to pollination, biocontrol and food security **15**(1), 8413 https://doi.org/10.1038/s41467-024-52734-3 . Accessed 2024-09-30

[57] Revell, L.E., Kuma, P., Le Ru, E.C., Somerville, W.R.C., Gaw, S.: Direct radiative effects of airborne microplastics **598**(7881), 462–467 https://doi.org/10.1038/s41586-021-03864-x . Accessed 2024-10-11

[58] Aeschlimann, M., Li, G., Kanji, Z.A., Mitrano, D.M.: Potential impacts of atmospheric microplastics and nanoplastics on cloud formation processes **15**(12), 967–975 https://doi.org/10.1038/s41561-022-01051-9 . Accessed 2024-05-13

[59] Brahana, P., Zhang, M., Nakouzi, E., Bharti, B.: Weathering influences the

ice nucleation activity of microplastics **15**(1), 9579 https://doi.org/10.1038/s41467-024-53987-8 . Accessed 2024-11-07

[60] Revel, M., Châtel, A., Mouneyrac, C.: Micro(nano)plastics: A threat to human health? **1**, 17–23 https://doi.org/10.1016/j.coesh.2017.10.003 . Accessed 2024-10-11

[61] Prata, J.C., Da Costa, J.P., Lopes, I., Duarte, A.C., Rocha-Santos, T.: Environmental exposure to microplastics: An overview on possible human health effects **702**, 134455 https://doi.org/10.1016/j.scitotenv.2019.134455 . Accessed 2024-10-11

[62] Rahman, A., Sarkar, A., Yadav, O.P., Achari, G., Slobodnik, J.: Potential human health risks due to environmental exposure to nano- and microplastics and knowledge gaps: A scoping review **757**, 143872 https://doi.org/10.1016/j.scitotenv.2020.143872 . Accessed 2024-10-11

[63] Wang, X., Liu, K., Zhu, L., Li, C., Song, Z., Li, D.: Efficient transport of atmospheric microplastics onto the continent via the east asian summer monsoon **414**, 125477 https://doi.org/10.1016/j.jhazmat.2021.125477 . Accessed 2024-10-28

[64] Yee, M.S.-L., Hii, L.-W., Looi, C.K., Lim, W.-M., Wong, S.-F., Kok, Y.-Y., Tan, B.-K., Wong, C.-Y., Leong, C.-O.: Impact of microplastics and nanoplastics on human health **11**(2), 496 https://doi.org/10.3390/nano11020496 . Accessed 2024-04-22

[65] Zhao, B., Rehati, P., Yang, Z., Cai, Z., Guo, C., Li, Y.: The potential toxicity of microplastics on human health **912**, 168946 https://doi.org/10.1016/j.scitotenv.2023.168946 . Accessed 2024-10-16

[66] Canesi, L., Ciacci, C., Bergami, E., Monopoli, M.P., Dawson, K.A., Papa, S., Canonico, B., Corsi, I.: Evidence for immunomodulation and apoptotic processes induced by cationic polystyrene nanoparticles in the hemocytes of the marine bivalve mytilus **111**, 34–40 https://doi.org/10.1016/j.marenvres.2015.06.008 . Accessed 2024-10-11

[67] Xu, J.-L., Lin, X., Wang, J.J., Gowen, A.A.: A review of potential human health impacts of micro- and nanoplastics exposure **851**, 158111 https://doi.org/10.1016/j.scitotenv.2022.158111 . Accessed 2024-10-11

[68] Forest, V., Pourchez, J.: Can the impact of micro- and nanoplastics on human health really be assessed using in vitro models? a review of methodological issues **178**, 108115 https://doi.org/10.1016/j.envint.2023.108115 . Accessed 2024-10-11

[69] Yu, H., Qi, W., Cao, X., Hu, J., Li, Y., Peng, J., Hu, C., Qu, J.: Microplastic residues in wetland ecosystems: Do they truly threaten the plant-microbe-soil

system? **156**, 106708 https://doi.org/10.1016/j.envint.2021.106708 . Accessed 2024-10-11

[70] Sun, Y., Shi, J., Wang, X., Ding, C., Wang, J.: Deciphering the mechanisms shaping the plastisphere microbiota in soil **7**(4), 00352–22 https://doi.org/10.1128/msystems.00352-22 . Accessed 2024-10-11

[71] Buteler, M., Alma, A.M., Stadler, T., Gingold, A.C., Manattini, M.C., Lozada, M.: Acute toxicity of microplastic fibers to honeybees and effects on foraging behavior **822**, 153320 https://doi.org/10.1016/j.scitotenv.2022.153320 . Accessed 2024-10-11

[72] Viana, T.A., Botina, L.L., Bernardes, R.C., Barbosa, W.F., Xavier, T.K.D., Lima, M.A.P., Araújo, R.D.S., Martins, G.F.: Ingesting microplastics or nanometals during development harms the tropical pollinator partamona helleri (apinae: Meliponini) **893**, 164790 https://doi.org/10.1016/j.scitotenv.2023.164790 . Accessed 2024-10-11

[73] Shah, S., Ilyas, M., Li, R., Yang, J., Yang, F.-L.: Microplastics and nanoplastics effects on plant–pollinator interaction and pollination biology **57**(16), 6415–6424 https://doi.org/10.1021/acs.est.2c07733 . Accessed 2024-10-11

[74] Qi, Y., Yang, X., Pelaez, A.M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V.: Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (triticum aestivum) growth **645**, 1048–1056 https://doi.org/10.1016/j.scitotenv.2018.07.229 . Accessed 2024-10-11

[75] Yang, X., He, Q., Guo, F., Sun, X., Zhang, J., Chen, M., Vymazal, J., Chen, Y.: Nanoplastics disturb nitrogen removal in constructed wetlands: Responses of microbes and macrophytes **54**(21), 14007–14016 https://doi.org/10.1021/acs.est.0c03324 . Accessed 2024-10-11

[76] Shi, R., Liu, W., Lian, Y., Wang, X., Men, S., Zeb, A., Wang, Q., Wang, J., Li, J., Zheng, Z., Zhou, Q., Tang, J., Sun, Y., Wang, F., Xing, B.: Toxicity mechanisms of nanoplastics on crop growth, interference of phyllosphere microbes, and evidence for foliar penetration and translocation **58**(2), 1010–1021 https://doi.org/10.1021/acs.est.3c03649 . Accessed 2024-10-11

[77] Mao, C.-N., Gohil, K., Rastogi, D., Asa-Awuku, A.: The hygroscopicity of nanoplastic particles and implications for cloud formation and climate **58**(9), 1024–1032 https://doi.org/10.1080/02786826.2024.2361041 . Accessed 2024-10-11

[78] Ganguly, M., Ariya, P.A.: Ice nucleation of model nanoplastics and microplastics: A novel synthetic protocol and the influence of particle capping at diverse atmospheric environments **3**(9), 1729–1739 https://doi.org/10.1021/acsearthspacechem.9b00132 . Accessed 2024-10-11

[79] Busse, H.L., Ariyasena, D.D., Orris, J., Freedman, M.A.: Pristine and aged microplastics can nucleate ice through immersion freezing, 4–00146 https://doi.org/10.1021/acsestair.4c00146 . Accessed 2024-11-08

[80] Walker, T.R.: (micro)plastics and the UN sustainable development goals **30**, 100497 https://doi.org/10.1016/j.cogsc.2021.100497 . Accessed 2025-02-17

[81] Randhawa, J.S.: Advanced analytical techniques for microplastics in the environment: a review **47**(1), 174 https://doi.org/10.1186/s42269-023-01148-0 . Accessed 2025-02-17

[82] Adhikari, S., Kelkar, V., Kumar, R., Halden, R.U.: Methods and challenges in the detection of microplastics and nanoplastics: a mini-review **71**(5), 543–551 https://doi.org/10.1002/pi.6348 . Accessed 2024-12-29

[83] Stohl, A., Forster, C., Frank, A., Seibert, P., Wotawa, G.: Technical note: The lagrangian particle dispersion model FLEXPART version 6.2 **5**(9), 2461–2474 https://doi.org/10.5194/acp-5-2461-2005 . Accessed 2024-11-08

[84] Pisso, I., Sollum, E., Grythe, H., Kristiansen, N.I., Cassiani, M., Eckhardt, S., Arnold, D., Morton, D., Thompson, R.L., Groot Zwaaftink, C.D., Evangeliou, N., Sodemann, H., Haimberger, L., Henne, S., Brunner, D., Burkhart, J.F., Fouilloux, A., Brioude, J., Philipp, A., Seibert, P., Stohl, A.: The lagrangian particle dispersion model FLEXPART version 10.4 **12**(12), 4955–4997 https://doi.org/10.5194/gmd-12-4955-2019 . Accessed 2024-05-27

[85] Bakels, L., Tatsii, D., Tipka, A., Thompson, R., Dütsch, M., Blaschek, M., Seibert, P., Baier, K., Bucci, S., Cassiani, M., Eckhardt, S., Groot Zwaaftink, C., Henne, S., Kaufmann, P., Lechner, V., Maurer, C., Mulder, M.D., Pisso, I., Plach, A., Subramanian, R., Vojta, M., Stohl, A.: FLEXPART version 11: Improved accuracy, efficiency, and flexibility. https://doi.org/10.5194/egusphere-2024-1713 . https://egusphere.copernicus.org/preprints/2024/egusphere-2024-1713/ Accessed 2024-11-08

[86] Roland R. Draxler, G.D. Hess: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. (47), 295–308

[87] Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F.: NOAA's HYSPLIT atmospheric transport and dispersion modeling system **96**(12), 2059–2077 https://doi.org/10.1175/BAMS-D-14-00110.1 . Accessed 2024-05-14

[88] Danabasoglu, G., Lamarque, J. Bacmeister, J., Bailey, D.A., DuVivier, A.K., Edwards, J., Emmons, L.K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M.M., Large, W.G., Lauritzen, P.H., Lawrence, D.M., Lenaerts, J.T.M., Lindsay, K., Lipscomb, W.H., Mills, M.J., Neale, R., Oleson, K.W., Otto-Bliesner, B., Phillips, A.S., Sacks, W., Tilmes, S., Van Kampenhout, L.,

Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J.E., Kinnison, D., Kushner, P.J., Larson, V.E., Long, M.C., Mickelson, S., Moore, J.K., Nienhouse, E., Polvani, L., Rasch, P.J., Strand, W.G.: The community earth system model version 2 (CESM2) **12**(2), 2019–001916 https://doi.org/10.1029/2019MS001916 . Accessed 2025-02-17

[89] Yantosca, B., Sulprizio, M., Lundgren, L., Kelvinhb, Keller, C., Fritz, T., 22degrees, Ridley, D., Haipeng Lin, Bindle, L., Michael-S-Long, Eastham, S.D., Tsherwen, Downs, W., Fisher, J., Thackray, C., Holmes, C., GanLuo, Jiawei Zhuang, Murray, L., SpaceMouse, Laestrada, Shutter, J., Noelleselin, Long, M., Xin-Chen-Github, Emily-Ramnarine, Gianga, Dr. Jessica Haskins, Jourdan-He: Geoschem/geos-chem: GEOS-Chem 14.1.1. https://doi.org/10.5281/ZENODO.7696632 . https://zenodo.org/record/7696632 Accessed 2025-02-17

[90] Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., Prather, K.A.: Constraining the atmospheric limb of the plastic cycle **118**(16), 2020719118 https://doi.org/10.1073/pnas.2020719118 . Accessed 2024-05-17

[91] Evangeliou, N., Tichý, O., Eckhardt, S., Zwaaftink, C.G., Brahney, J.: Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: From global emissions to deposition **432**, 128585 https://doi.org/10.1016/j.jhazmat.2022.128585 . Accessed 2024-12-02

[92] Fu, Y., Pang, Q., Suo Lang Zhuo Ga, Wu, P., Wang, Y., Mao, M., Yuan, Z., Xu, X., Liu, K., Wang, X., Li, D., Zhang, Y.: Modeling atmospheric microplastic cycle by GEOS-chem: An optimized estimation by a global dataset suggests likely 50 times lower ocean emissions **6**(6), 705–714 https://doi.org/10.1016/j.oneear.2023.05.012 . Accessed 2024-08-13

[93] Long, X., Fu, T.-M., Yang, X., Tang, Y., Zheng, Y., Zhu, L., Shen, H., Ye, J., Wang, C., Wang, T., Li, B.: Efficient atmospheric transport of microplastics over asia and adjacent oceans **56**(10), 6243–6252 https://doi.org/10.1021/acs.est.1c07825 . Accessed 2024-10-17

[94] Yang, S., Zhang, T., Gan, Y., Lu, X., Chen, H., Chen, J., Yang, X., Wang, X.: Constraining microplastic particle emission flux from the ocean **9**(6), 513–519 https://doi.org/10.1021/acs.estlett.2c00214 . Accessed 2024-10-17

[95] Baensch-Baltruschat, B., Kocher, B., Stock, F., Reifferscheid, G.: Tyre and road wear particles (TRWP) - a review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment **733**, 137823 https://doi.org/10.1016/j.scitotenv.2020.137823 . Accessed 2024-10-18

[96] Beaurepaire, M., Dris, R., Gasperi, J., Tassin, B.: Microplastics in the atmospheric compartment: a comprehensive review on methods, results on their occurrence and determining factors **41**, 159–168 https://doi.org/10.1016/j.cofs.2021.04.010 . Accessed 2024-12-11

[97] Cerasa, M., Teodori, S., Pietrelli, L.: Searching nanoplastics: From sampling to sample processing **13**(21), 3658 https://doi.org/10.3390/polym13213658 . Accessed 2024-10-21

[98] Enyoh, C.E., Verla, A.W., Verla, E.N., Ibe, F.C., Amaobi, C.E.: Airborne microplastics: a review study on method for analysis, occurrence, movement and risks **191**(11), 668 https://doi.org/10.1007/s10661-019-7842-0 . Accessed 2024-12-10

[99] Ivleva, N.P.: Chemical analysis of microplastics and nanoplastics: Challenges, advanced methods, and perspectives **235**(19), 1030–1034 https://doi.org/10.1021/acs.chemrev.1c00178 . Accessed 2024-01-16

[100] Kiran, B.R., Kopperi, H., Venkata Mohan, S., Han, J.-Y., Baik, J.-J., Lee, H.: Micro/nano-plastics occurrence, identification, risk analysis and mitigation: challenges and perspectives **21**(1), 169–203 https://doi.org/10.1007/s11157-021-09609-6 . Accessed 2024-05-19

[101] Ko, K., Lee, J., Baumann, P., Kim, J., Chung, H.: Analysis of micro(nano)plastics based on automated data interpretation and modeling: A review **34**, 100509 https://doi.org/10.1016/j.impact.2024.100509 . Accessed 2024-10-03

[102] Le, V.-G., Nguyen, M.-K., Nguyen, H.-L., Lin, C., Hadi, M., Hung, N.T.Q., Hoang, H.-G., Nguyen, K.N., Tran, H.-T., Hou, D., Zhang, T., Bolan, N.S.: A comprehensive review of micro- and nano-plastics in the atmosphere: Occurrence, fate, toxicity, and strategies for risk reduction **904**, 166649 https://doi.org/10.1016/j.scitotenv.2023.166649 . Accessed 2024-11-07

[103] Luo, X., Wang, Z., Yang, L., Gao, T., Zhang, Y.: A review of analytical methods and models used in atmospheric microplastic research **828**, 154487 https://doi.org/10.1016/j.scitotenv.2022.154487 . Accessed 2024-12-29

[104] Luo, D., Chu, X., Wu, Y., Wang, Z., Liao, Z., Ji, X., Ju, J., Yang, B., Chen, Z., Dahlgren, R., Zhang, M., Shang, X.: Micro- and nano-plastics in the atmosphere: A review of occurrence, properties and human health risks **465**, 133412 https://doi.org/10.1016/j.jhazmat.2023.133412 . Accessed 2024-11-01

[105] Lusher, A.L., Munno, K., Hermabessiere, L., Carr, S.: Isolation and extraction of microplastics from environmental samples: An evaluation of practical approaches and recommendations for further harmonization **74**(9), 1049–1065 https://doi.org/10.1177/0003702820938993 . Accessed 2024-12-29

[106] Mariano, S., Tacconi, S., Fidaleo, M., Rossi, M., Dini, L.: Micro and nanoplastics identification: Classic methods and innovative detection techniques **3**, 636640 https://doi.org/10.3389/ftox.2021.636640 . Accessed 2024-10-16

[107] Mbachu, O., Jenkins, G., Pratt, C., Kaparaju, P.: A new contaminant superhighway? a review of sources, measurement techniques and fate of atmospheric microplastics **231**(2), 85 https://doi.org/10.1007/s11270-020-4459-4 . Accessed 2024-11-07

[108] Munyaneza, J., Jia, Q., Qaraah, F.A., Hossain, M.F., Wu, C., Zhen, H., Xiu, G.: A review of atmospheric microplastics pollution: In-depth sighting of sources, analytical methods, physiognomies, transport and risks **822**, 153339 https://doi.org/10.1016/j.scitotenv.2022.153339 . Accessed 2024-11-07

[109] Renner, G., Nellessen, A., Schwiers, A., Wenzel, M., Schmidt, T.C., Schram, J.: Data preprocessing & evaluation used in the microplastics identification process: A critical review & practical guide **111**, 229–238 https://doi.org/10.1016/j.trac.2018.12.004 . Accessed 2024-10-21

[110] Shao, L., Li, Y., Jones, T., Santosh, M., Liu, P., Zhang, M., Xu, L., Li, W., Lu, J., Yang, C.-X., Zhang, D., Feng, X., BéruBé, K.: Airborne microplastics: A review of current perspectives and environmental implications **347**, 131048 https://doi.org/10.1016/j.jclepro.2022.131048 . Accessed 2024-12-11

[111] Wright, S.L., Gouin, T., Koelmans, A.A., Scheuermann, L.: Development of screening criteria for microplastic particles in air and atmospheric deposition: critical review and applicability towards assessing human exposure **1**(1), 6 https://doi.org/10.1186/s43591-021-00006-y . Accessed 2024-12-29

[112] Xu, A., Shi, M., Xing, X., Su, Y., Li, X., Liu, W., Mao, Y., Hu, T., Qi, S.: Status and prospects of atmospheric microplastics: A review of methods, occurrence, composition, source and health risks **303**, 119173 https://doi.org/10.1016/j.envpol.2022.119173 . Accessed 2024-11-07

[113] Yang, J., Peng, Z., Sun, J., Chen, Z., Niu, X., Xu, H., Ho, K.-F., Cao, J., Shen, Z.: A review on advancements in atmospheric microplastics research: The pivotal role of machine learning **945**, 173966 https://doi.org/10.1016/j.scitotenv.2024.173966 . Accessed 2024-12-17

[114] Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., Sillanpää, M.: Atmospheric microplastics: A review on current status and perspectives **203**, 103118 https://doi.org/10.1016/j.earscirev.2020.103118 . Accessed 2024-10-03

[115] Zhang, N., Zhang, C., Qin, Y., Wang, J., Ge, X., Li, H., Dai, Y., Aruffo, E.: A review of atmospheric microplastics: Sources, characteristics, and detection method **10**(3), 412–429 https://doi.org/10.1007/s40726-024-00316-8 . Accessed 2024-10-18

[116] Azeem, I., Adeel, M., Ahmad, M.A., Shakoor, N., Jiangcuo, G.D., Azeem, K., Ishfaq, M., Shakoor, A., Ayaz, M., Xu, M., Rui, Y.: Uptake and accumulation of nano/microplastics in plants: A critical review **11**(11), 2935 https://doi.org/

10.3390/nano11112935 . Accessed 2024-12-06

[117] Bianco, A., Passananti, M.: Atmospheric micro and nanoplastics: An enormous microscopic problem **12**(18), 7327 https://doi.org/10.3390/su12187327 . Accessed 2024-05-10

[118] Horton, A.A., Dixon, S.J.: Microplastics: An introduction to environmental transport processes **5**(2), 1268 https://doi.org/10.1002/wat2.1268 . Accessed 2024-04-22

[119] O'Brien, S., Rauert, C., Ribeiro, F., Okoffo, E.D., Burrows, S.D., O'Brien, J.W., Wang, X., Wright, S.L., Thomas, K.V.: There's something in the air: A review of sources, prevalence and behaviour of microplastics in the atmosphere **874**, 162193 https://doi.org/10.1016/j.scitotenv.2023.162193 . Accessed 2024-12-05

[120] Abad López, A.P., Trilleras, J., Arana, V.A., Garcia-Alzate, L.S., Grande-Tovar, C.D.: Atmospheric microplastics: exposure, toxicity, and detrimental health effects **13**(11), 7468–7489 https://doi.org/10.1039/D2RA07098G . Accessed 2024-11-07

[121] Agathokleous, E., Iavicoli, I., Barceló, D., Calabrese, E.J.: Micro/nanoplastics effects on organisms: A review focusing on 'dose' **417**, 126084 https://doi.org/10.1016/j.jhazmat.2021.126084 . Accessed 2024-12-20

[122] Akanyange, S.N., Lyu, X., Zhao, X., Li, X., Zhang, Y., Crittenden, J.C., Anning, C., Chen, T., Jiang, T., Zhao, H.: Does microplastic really represent a threat? a review of the atmospheric contamination sources and potential impacts **777**, 146020 https://doi.org/10.1016/j.scitotenv.2021.146020 . Accessed 2024-12-29

[123] Can-Güven, E.: Microplastics as emerging atmospheric pollutants: a review and bibliometric analysis **14**(2), 203–215 https://doi.org/10.1007/s11869-020-00926-3 . Accessed 2024-12-29

[124] Carney Almroth, B., Eggert, H.: Marine plastic pollution: Sources, impacts, and policy issues **13**(2), 317–326 https://doi.org/10.1093/reep/rez012 . Accessed 2024-12-28

[125] Chang, X., Xue, Y., Li, J., Zou, L., Tang, M.: Potential health impact of environmental micro- and nanoplastics pollution **40**(1), 4–15 https://doi.org/10.1002/jat.3915 . Accessed 2024-12-20

[126] Chen, G., Feng, Q., Wang, J.: Mini-review of microplastics in the atmosphere and their risks to humans **703**, 135504 https://doi.org/10.1016/j.scitotenv.2019.135504 . Accessed 2024-12-29

[127] Haldar, S., Yhome, N., Muralidaran, Y., Rajagopal, S., Mishra, P.: Nanoplastics toxicity specific to liver in inducing metabolic dysfunction—a comprehensive

review **14**(3), 590 https://doi.org/10.3390/genes14030590 . Accessed 2024-10-15

[128] Jiang, B., Kauffman, A.E., Li, L., McFee, W., Cai, B., Weinstein, J., Lead, J.R., Chatterjee, S., Scott, G.I., Xiao, S.: Health impacts of environmental contamination of micro- and nanoplastics: a review **25**(1), 29 https://doi.org/10.1186/s12199-020-00870-9 . Accessed 2024-12-20

[129] Nafea, T.H., Chan, F.K.S., Xu, Y., Wang, C., Wang, X., Zhao, W., Ji, D., Xiao, H., He, J.: Microplastics aloft: A comprehensive exploration of sources, transport, variations, interactions and their implications on human health in the atmospheric realm **255**, 104864 https://doi.org/10.1016/j.earscirev.2024.104864 . Accessed 2024-12-06

[130] Pelegrini, K., Pereira, T.C.B., Maraschin, T.G., Teodoro, L.D.S., Basso, N.R.D.S., De Galland, G.L.B., Ligabue, R.A., Bogo, M.R.: Micro- and nanoplastic toxicity: A review on size, type, source, and test-organism implications **878**, 162954 https://doi.org/10.1016/j.scitotenv.2023.162954 . Accessed 2024-12-20

[131] Saha, S.C., Saha, G.: Effect of microplastics deposition on human lung airways: A review with computational benefits and challenges **10**(2), 24355 https://doi.org/10.1016/j.heliyon.2024.e24355 . Accessed 2024-10-14

[132] Shi, Q., Tang, J., Liu, R., Wang, L.: Toxicity *in vitro* reveals potential impacts of microplastics and nanoplastics on human health: A review **52**(21), 3863–3895 https://doi.org/10.1080/10643389.2021.1951528 . Accessed 2024-12-20

[133] Tang, K.H.D.: Climate change and plastic pollution: A review of their connections **1**(2), 110–120 https://doi.org/10.53623/tebt.v1i2.341 . Accessed 2025-02-20

[134] Yuan, Z., Li, H.-X., Lin, L., Pan, Y.-F., Liu, S., Hou, R., Xu, X.-R.: Occurrence and human exposure risks of atmospheric microplastics: A review **108**, 200–212 https://doi.org/10.1016/j.gr.2022.02.001 . Accessed 2024-11-07

[135] Zhu, Y., Che, R., Zong, X., Wang, J., Li, J., Zhang, C., Wang, F.: A comprehensive review on the source, ingestion route, attachment and toxicity of microplastics/nanoplastics in human systems **352**, 120039 https://doi.org/10.1016/j.jenvman.2024.120039 . Accessed 2024-12-20

[136] Petroff, A., Zhang, L.: Development and validation of a size-resolved particle dry deposition scheme for application in aerosol transport models **3**(2), 753–769 https://doi.org/10.5194/gmd-3-753-2010 . Accessed 2024-11-26

[137] Purwiyanto, A.I.S., Prartono, T., Riani, E., Naulita, Y., Cordova, M.R., Koropitan, A.F.: The deposition of atmospheric microplastics in jakarta-indonesia: The coastal urban area **174**, 113195 https://doi.org/10.1016/j.marpolbul.2021.113195 . Accessed 2024-12-04

[138] Shaw, D.B., Li, Q., Nunes, J.K., Deike, L.: Ocean emission of microplastic **2**(10), 296 https://doi.org/10.1093/pnasnexus/pgad296 . Accessed 2024-10-17

[139] Harb, C., Pokhrel, N., Foroutan, H.: Quantification of the emission of atmospheric microplastics and nanoplastics via sea spray **10**(6), 513–519 https://doi.org/10.1021/acs.estlett.3c00164 . Accessed 2024-05-17

[140] Yang, S., Lu, X., Wang, X.: A perspective on the controversy over global emission fluxes of microplastics from ocean into the atmosphere **58**(28), 12304–12312 https://doi.org/10.1021/acs.est.4c03182 . Accessed 2024-10-17

[141] Bucci, S., Richon, C., Bakels, L.: Exploring the transport path of oceanic microplastics in the atmosphere **58**(32), 14338–14347 https://doi.org/10.1021/acs.est.4c03216 . Accessed 2024-10-17

[142] Yang, S., Lu, X., Peng, Y., Wang, Z., Yang, X., Wang, X.: Microplastic emission from soil-air interface, 4–00189 https://doi.org/10.1021/acs.estlett.4c00189 . Accessed 2024-10-17

[143] Illuminati, S., Notarstefano, V., Tinari, C., Fanelli, M., Girolametti, F., Ajdini, B., Scarchilli, C., Ciardini, V., Iaccarino, A., Giorgini, E., Annibaldi, A., Truzzi, C.: Microplastics in bulk atmospheric deposition along the coastal region of victoria land, antarctica **949**, 175221 https://doi.org/10.1016/j.scitotenv.2024.175221 . Accessed 2024-12-06

[144] Kim, S.-K., Lee, H.-J., Kim, J.-S., Kang, S.-H., Yang, E.-J., Cho, K.-H., Tian, Z., Andrady, A.: Importance of seasonal sea ice in the western arctic ocean to the arctic and global microplastic budgets **418**, 125971 https://doi.org/10.1016/j.jhazmat.2021.125971 . Accessed 2024-12-11

[145] Ambrosini, R., Azzoni, R.S., Pittino, F., Diolaiuti, G., Franzetti, A., Parolini, M.: First evidence of microplastic contamination in the supraglacial debris of an alpine glacier **253**, 297–301 https://doi.org/10.1016/j.envpol.2019.07.005 . Accessed 2024-12-04

[146] Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., Li, D.: Source and potential risk assessment of suspended atmospheric microplastics in shanghai **675**, 462–471 https://doi.org/10.1016/j.scitotenv.2019.04.110 . Accessed 2024-10-21

[147] Liao, Z., Ji, X., Ma, Y., Lv, B., Huang, W., Zhu, X., Fang, M., Wang, Q., Wang, X., Dahlgren, R., Shang, X.: Airborne microplastics in indoor and outdoor environments of a coastal city in eastern china **417**, 126007 https://doi.org/10.1016/j.jhazmat.2021.126007 . Accessed 2024-05-13

[148] Li, Y., Shao, L., Wang, W., Zhang, M., Feng, X., Li, W., Zhang, D.: Airborne fiber particles: Types, size and concentration observed in beijing **705**, 135967 https://doi.org/10.1016/j.scitotenv.2019.135967 . Accessed 2024-10-27

[149] Zhu, X., Huang, W., Fang, M., Liao, Z., Wang, Y., Xu, L., Mu, Q., Shi, C., Lu, C., Deng, H., Dahlgren, R., Shang, X.: Airborne microplastic concentrations in five megacities of northern and southeast china, 1–03618 https://doi.org/10.1021/acs.est.1c03618 . Accessed 2024-10-27

[150] Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., Li, D.: Consistent transport of terrestrial microplastics to the ocean through atmosphere **53**(18), 10612–10619 https://doi.org/10.1021/acs.est.9b03427 . Accessed 2024-10-17

[151] Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., Chen, Q.: Characteristic of microplastics in the atmospheric fallout from dongguan city, china: preliminary research and first evidence **24**(32), 24928–24935 https://doi.org/10.1007/s11356-017-0116-x . Accessed 2024-05-14

[152] Huang, Y., He, T., Yan, M., Yang, L., Gong, H., Wang, W., Qing, X., Wang, J.: Atmospheric transport and deposition of microplastics in a subtropical urban environment **416**, 126168 https://doi.org/10.1016/j.jhazmat.2021.126168 . Accessed 2024-12-04

[153] Beaurepaire, M., Gasperi, J., Tassin, B., Dris, R.: COVID lockdown significantly impacted microplastic bulk atmospheric deposition rates **344**, 123354 https://doi.org/10.1016/j.envpol.2024.123354 . Accessed 2024-12-06

[154] Gaston, E., Woo, M., Steele, C., Sukumaran, S., Anderson, S.: Microplastics differ between indoor and outdoor air masses: Insights from multiple microscopy methodologies **74**(9), 1079–1098 https://doi.org/10.1177/0003702820920652 . Accessed 2024-10-27

[155] Yao, Y., Glamoclija, M., Murphy, A., Gao, Y.: Characterization of microplastics in indoor and ambient air in northern new jersey **207**, 112142 https://doi.org/10.1016/j.envres.2021.112142 . Accessed 2024-10-29

[156] Nagato, E.G., Noothalapati, H., Kogumasaka, C., Kakii, S., Hossain, S., Iwasaki, K., Takai, Y., Shimasaki, Y., Honda, M., Hayakawa, K., Yamamoto, T., Archer, S.D.J.: Differences in microplastic degradation in the atmosphere and coastal water environment from two island nations: Japan and new zealand **333**, 122011 https://doi.org/10.1016/j.envpol.2023.122011 . Accessed 2024-12-05

[157] Knobloch, E., Ruffell, H., Aves, A., Pantos, O., Gaw, S., Revell, L.E.: Comparison of deposition sampling methods to collect airborne microplastics in christchurch, new zealand **232**(4), 133 https://doi.org/10.1007/s11270-021-05080-9 . Accessed 2024-10-29

[158] Fan, W., Salmond, J.A., Dirks, K.N., Cabedo Sanz, P., Miskelly, G.M., Rindelaub, J.D.: Evidence and mass quantification of atmospheric microplastics in a coastal new zealand city **56**(24), 17556–17568 https://doi.org/10.1021/acs.est.2c05850 . Accessed 2024-12-06

[159] Dahal, Y., Babel, S.: Abundance and characteristics of atmospheric microplastics deposition in indoor and outdoor environments in bangkok, thailand https://doi.org/10.1007/s11869-024-01652-w . Accessed 2024-12-06

[160] Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W., Gomes, R.L.: Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres **666**, 377–389 https://doi.org/10.1016/j.scitotenv.2019.02.278 . Accessed 2024-10-29

[161] Wright, S.L., Ulke, J., Font, A., Chan, K.L.A., Kelly, F.J.: Atmospheric microplastic deposition in an urban environment and an evaluation of transport **136**, 105411 https://doi.org/10.1016/j.envint.2019.105411 . Accessed 2024-05-13

[162] Jenner, L.C., Sadofsky, L.R., Danopoulos, E., Chapman, E., White, D., Jenkins, R.L., Rotchell, J.M.: Outdoor atmospheric microplastics within the humber region (united kingdom): Quantification and chemical characterisation of deposited particles present **13**(2), 265 https://doi.org/10.3390/atmos13020265 . Accessed 2024-12-06

[163] Postma, J.V.: An inexpensive atmospheric microplastic collector for use in remote areas **13**(10), 101550 https://doi.org/10.1016/j.apr.2022.101550 . Accessed 2024-12-08

[164] Kernchen, S., Löder, M.G.J., Fischer, F., Fischer, D., Moses, S.R., Georgi, C., Nölscher, A.C., Held, A., Laforsch, C.: Airborne microplastic concentrations and deposition across the weser river catchment **818**, 151812 https://doi.org/10.1016/j.scitotenv.2021.151812 . Accessed 2024-10-28

[165] Klein, M., Fischer, E.K.: Microplastic abundance in atmospheric deposition within the metropolitan area of hamburg, germany **685**, 96–103 https://doi.org/10.1016/j.scitotenv.2019.05.405 . Accessed 2024-05-14

[166] Kernchen, S., Schmalz, H., Löder, M.G.J., Georgi, C., Einhorn, A., Greiner, A., Nölscher, A.C., Laforsch, C., Held, A.: Atmospheric deposition studies of microplastics in central germany **17**(10), 2247–2261 https://doi.org/10.1007/s11869-024-01571-w . Accessed 2024-12-06

[167] Trainic, M., Flores, J.M., Pinkas, I., Pedrotti, M.L., Lombard, F., Bourdin, G., Gorsky, G., Boss, E., Rudich, Y., Vardi, A., Koren, I.: Airborne microplastic particles detected in the remote marine atmosphere **1**(1), 64 https://doi.org/10.1038/s43247-020-00061-y . Accessed 2024-03-21

[168] Wang, X., Wei, N., Liu, K., Zhu, L., Li, C., Zong, C., Li, D.: Exponential decrease of airborne microplastics: From megacity to open ocean **849**, 157702 https://doi.org/10.1016/j.scitotenv.2022.157702 . Accessed 2024-12-05

[169] Ding, J., Sun, C., He, C., Zheng, L., Dai, D., Li, F.: Atmospheric microplastics in the northwestern pacific ocean: Distribution, source, and deposition **829**, 154337 https://doi.org/10.1016/j.scitotenv.2022.154337 . Accessed 2024-12-07

[170] Ding, Y., Zou, X., Wang, C., Feng, Z., Wang, Y., Fan, Q., Chen, H.: The abundance and characteristics of atmospheric microplastic deposition in the northwestern south china sea in the fall **253**, 118389 https://doi.org/10.1016/j.atmosenv.2021.118389 . Accessed 2024-10-21

[171] Seo, J.H., Shin, Y., Song, I.-g., Lim, J., Ok, Y.S., Weon, S.: Atmospheric microplastics: Challenges in site- and target-specific measurements **178**, 117859 https://doi.org/10.1016/j.trac.2024.117859 . Accessed 2024-12-11

[172] Syafei, A.D., Nurasrin, N.R., Assomadi, A.F., Boedisantoso, R.: Microplastic pollution in the ambient air of surabaya, indonesia **14**(2), 290–298 https://doi.org/10.12944/CWE.14.2.13 . Accessed 2024-10-27

[173] Truong, T.-N.-S., Strady, E., Kieu-Le, T.-C., Tran, Q.-V., Le, T.-M.-T., Thuong, Q.-T.: Microplastic in atmospheric fallouts of a developing southeast asian megacity under tropical climate **272**, 129874 https://doi.org/10.1016/j.chemosphere.2021.129874 . Accessed 2024-10-28

[174] Thinh, T.Q., Sang, T.T.N., University of Technology, Vietnam National University, Ho Chi Minh city, Vietnam, Viet, T.Q., University of Technology, Vietnam National University, Ho Chi Minh city, Vietnam, Tam, L.T.M., CARE (Asian Center for Water Research), University of Technology, Vietnam National University, Ho Chi Minh city, Vietnam, Dan, N.P., CARE (Asian Center for Water Research), University of Technology, Vietnam National University, Ho Chi Minh city, Vietnam, Strady, E., Univ. Grenoble Alpes, CNRS, IRD, Grenoble, France, Chung, K.L.T., Faculty of Geology and Petroleum Engineering, University of Technology, Vietnam National University, Ho Chi Minh city, Vietnam: Preliminary assessment on the microplastic contamination in the atmospheric fallout in the phuoc hiep landfill, cu chi, ho chi minh city **62**(3), 83–89 https://doi.org/10.31276/VJSTE.62(3).83-89 . Accessed 2024-10-29

[175] Roblin, B., Ryan, M., Vreugdenhil, A., Aherne, J.: Ambient atmospheric deposition of anthropogenic microfibers and microplastics on the western periphery of europe (ireland) **54**(18), 11100–11108 https://doi.org/10.1021/acs.est.0c04000 . Accessed 2024-10-29

[176] Dehghani, S., Moore, F., Akhbarizadeh, R.: Microplastic pollution in deposited urban dust, tehran metropolis, iran **24**(25), 20360–20371 https://doi.org/10.1007/s11356-017-9674-1 . Accessed 2024-12-11

[177] Su, L., Nan, B., Craig, N.J., Pettigrove, V.: Temporal and spatial variations of microplastics in roadside dust from rural and urban victoria, australia: Implications for diffuse pollution **252**, 126567 https://doi.org/10.1016/j.chemosphere.

2020.126567 . Accessed 2024-12-11

[178] Cabrera, M., Valencia, B.G., Lucas-Solis, O., Calero, J.L., Maisincho, L., Conicelli, B., Massaine Moulatlet, G., Capparelli, M.V.: A new method for microplastic sampling and isolation in mountain glaciers: A case study of one antisana glacier, ecuadorian andes **2**, 100051 https://doi.org/10.1016/j.cscee.2020.100051 . Accessed 2024-12-11

[179] Dos Santos Galvão, L., Fernandes, E.M.S., Ferreira, R.R., Dos Santos Rosa, D., Wiebeck, H.: Critical steps for microplastics characterization from the atmosphere **424**, 127668 https://doi.org/10.1016/j.jhazmat.2021.127668 . Accessed 2024-12-06

[180] Kyriakoudes, G., Turner, A.: Suspended and deposited microplastics in the coastal atmosphere of southwest england **343**, 140258 https://doi.org/10.1016/j.chemosphere.2023.140258 . Accessed 2024-12-05

[181] Ferrero, L., Scibetta, L., Markuszewski, P., Mazurkiewicz, M., Drozdowska, V., Makuch, P., Jutrzenka-Trzebiatowska, P., Zaleska-Medynska, A., Andò, S., Saliu, F., Nilsson, E.D., Bolzacchini, E.: Airborne and marine microplastics from an oceanographic survey at the baltic sea: An emerging role of air-sea interaction? **824**, 153709 https://doi.org/10.1016/j.scitotenv.2022.153709 . Accessed 2024-12-05

[182] Chen, Y., Meng, Y., Liu, G., Huang, X., Chai, G., Xie, Y.: Atmospheric deposition of microplastics at a western china metropolis: Relationship with underlying surface types and human exposure **355**, 124192 https://doi.org/10.1016/j.envpol.2024.124192 . Accessed 2024-12-05

[183] Fox, S., Stefánsson, H., Peternell, M., Zlotskiy, E., Ásbjörnsson, E.J., Sturkell, E., Wanner, P., Konrad-Schmolke, M.: Physical characteristics of microplastic particles and potential for global atmospheric transport: A meta-analysis **342**, 122938 https://doi.org/10.1016/j.envpol.2023.122938 . Accessed 2024-12-07

[184] Leonard, J., El Rassi, L.A., Samad, M.A., Prehn, S., Mohanty, S.K.: The relative importance of local climate and land use on the deposition rate of airborne microplastics on terrestrial land **318**, 120212 https://doi.org/10.1016/j.atmosenv.2023.120212 . Accessed 2024-12-06

[185] Liu, Z., Bai, Y., Ma, T., Liu, X., Wei, H., Meng, H., Fu, Y., Ma, Z., Zhang, L., Zhao, J.: Distribution and possible sources of atmospheric microplastic deposition in a valley basin city (lanzhou, china) **233**, 113353 https://doi.org/10.1016/j.ecoenv.2022.113353 . Accessed 2024-11-22

[186] Liu, Z., Liu, X., Bai, Y., Wei, H., Lu, J.: Spatiotemporal distribution and potential sources of atmospheric microplastic deposition in a semiarid urban environment of northwest china **30**(29), 74372–74385 https://doi.org/10.1007/

s11356-023-27581-2 . Accessed 2024-12-06

[187] Liu, P., Shao, L., Zhang, Y., Silvonen, V., Oswin, H., Cao, Y., Guo, Z., Ma, X., Morawska, L.: Atmospheric microplastic deposition associated with GDP and population growth: Insights from megacities in northern china **469**, 134024 https://doi.org/10.1016/j.jhazmat.2024.134024 . Accessed 2024-12-05

[188] Zheng, G., Li, P.: Resuspension of settled atmospheric particulate matter on plant leaves determined by wind and leaf surface characteristics **26**(19), 19606–19614 https://doi.org/10.1007/s11356-019-05241-8 . Accessed 2024-12-06

[189] Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., Gawronski, S.W.: Plant species differences in particulate matter accumulation on leaf surfaces **427-428**, 347–354 https://doi.org/10.1016/j.scitotenv.2012.03.084 . Accessed 2024-12-06

[190] Peñalver, R., Costa-Gómez, I., Arroyo-Manzanares, N., Moreno, J.M., López-García, I., Moreno-Grau, S., Córdoba, M.H.: Assessing the level of airborne polystyrene microplastics using thermogravimetry-mass spectrometry: Results for an agricultural area **787**, 147656 https://doi.org/10.1016/j.scitotenv.2021.147656 . Accessed 2024-12-06

[191] Liu, K., Wang, X., Song, Z., Wei, N., Li, D.: Terrestrial plants as a potential temporary sink of atmospheric microplastics during transport **742**, 140523 https://doi.org/10.1016/j.scitotenv.2020.140523 . Accessed 2024-12-06

[192] Liu, X., Lu, J., He, S., Tong, Y., Liu, Z., Li, W., Xiayihazi, N.: Evaluation of microplastic pollution in shihezi city, china, using pine needles as a biological passive sampler **821**, 153181 https://doi.org/10.1016/j.scitotenv.2022.153181 . Accessed 2024-12-06

[193] Sun, H., Lei, C., Xu, J., Li, R.: Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants **416**, 125854 https://doi.org/10.1016/j.jhazmat.2021.125854 . Accessed 2024-12-06

[194] Huang, X., Chen, Y., Meng, Y., Liu, G., Yang, M.: Are we ignoring the role of urban forests in intercepting atmospheric microplastics? **436**, 129096 https://doi.org/10.1016/j.jhazmat.2022.129096 . Accessed 2024-12-06

[195] Bertrim, C., Aherne, J.: Moss bags as biomonitors of atmospheric microplastic deposition in urban environments **12**(2), 149 https://doi.org/10.3390/biology12020149 . Accessed 2024-12-08

[196] Jafarova, M., Contardo, T., Aherne, J., Loppi, S.: Lichen biomonitoring of airborne microplastics in milan (n italy) **11**(12), 1815 https://doi.org/10.3390/biology11121815 . Accessed 2024-12-08

[197] Huang, Y., Zhu, Z., Li, T., Li, M., Cai, Z., Wang, X., Gong, H., Yan, M.: Mangrove plants are promising bioindicator of coastal atmospheric microplastics pollution **465**, 133473 https://doi.org/10.1016/j.jhazmat.2024.133473 . Accessed 2024-12-06

[198] Falakdin, P., Lopez-Rosales, A., Andrade, J., Terzaghi, E., Di Guardo, A., Muniategui-Lorenzo, S.: Comparison of microplastic type, size, and composition in atmospheric and foliage samples in an urban scenario **349**, 123911 https://doi.org/10.1016/j.envpol.2024.123911 . Accessed 2024-12-06

[199] Leonard, J., Borthakur, A., Koutnik, V.S., Brar, J., Glasman, J., Cowger, W., Dittrich, T.M., Mohanty, S.K.: Challenges of using leaves as a biomonitoring system to assess airborne microplastic deposition on urban tree canopies **14**(2), 101651 https://doi.org/10.1016/j.apr.2023.101651 . Accessed 2024-12-06

[200] Allen, S., Materić, D., Allen, D., MacDonald, A., Holzinger, R., Roux, G.L., Phoenix, V.R.: An early comparison of nano to microplastic mass in a remote catchment's atmospheric deposition **7**, 100104 https://doi.org/10.1016/j.hazadv.2022.100104 . Accessed 2024-12-06

[201] Villanova-Solano, C., Hernández-Sánchez, C., Díaz-Peña, F.J., González-Sálamo, J., González-Pleiter, M., Hernández-Borges, J.: Microplastics in snow of a high mountain national park: El teide, tenerife (canary islands, spain) **873**, 162276 https://doi.org/10.1016/j.scitotenv.2023.162276 . Accessed 2024-12-05

[202] Materić, D., Ludewig, E., Brunner, D., Röckmann, T., Holzinger, R.: Nanoplastics transport to the remote, high-altitude alps **288**, 117697 https://doi.org/10.1016/j.envpol.2021.117697 . Accessed 2024-05-26

[203] Wang, X., Li, C., Liu, K., Zhu, L., Song, Z., Li, D.: Atmospheric microplastic over the south china sea and east indian ocean: abundance, distribution and source **389**, 121846 https://doi.org/10.1016/j.jhazmat.2019.121846 . Accessed 2024-10-23

[204] Liu, K., Wang, X., Song, Z., Wei, N., Ye, H., Cong, X., Zhao, L., Li, Y., Qu, L., Zhu, L., Zhang, F., Zong, C., Jiang, C., Li, D.: Global inventory of atmospheric fibrous microplastics input into the ocean: An implication from the indoor origin **400**, 123223 https://doi.org/10.1016/j.jhazmat.2020.123223 . Accessed 2024-12-05

[205] Chen, Q., Shi, G., Revell, L.E., Zhang, J., Zuo, C., Wang, D., Le Ru, E.C., Wu, G., Mitrano, D.M.: Long-range atmospheric transport of microplastics across the southern hemisphere **14**(1), 7898 https://doi.org/10.1038/s41467-023-43695-0 . Accessed 2024-10-23

[206] Klein, S., Worch, E., Knepper, T.P.: Occurrence and spatial distribution of microplastics in river shore sediments of the rhine-main area in germany **49**(10),

6070–6076 https://doi.org/10.1021/acs.est.5b00492 . Accessed 2024-12-25

[207] Rochman, C.M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., Athey, S., Huntington, A., McIlwraith, H., Munno, K., De Frond, H., Kolomijeca, A., Erdle, L., Grbic, J., Bayoumi, M., Borrelle, S.B., Wu, T., Santoro, S., Werbowski, L.M., Zhu, X., Giles, R.K., Hamilton, B.M., Thaysen, C., Kaura, A., Klasios, N., Ead, L., Kim, J., Sherlock, C., Ho, A., Hung, C.: Rethinking microplastics as a diverse contaminant suite **38**(4), 703–711 https://doi.org/10.1002/etc.4371 . Accessed 2024-12-25

[208] Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E.: Lost at sea: Where is all the plastic? **304**(5672), 838–838 https://doi.org/10.1126/science.1094559 . Accessed 2024-05-20

[209] Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R.: Accumulation of microplastic on shorelines woldwide: Sources and sinks **45**(21), 9175–9179 https://doi.org/10.1021/es201811s . Accessed 2024-10-10

[210] Gupta, S., Kumar, R., Rajput, A., Gorka, R., Gupta, A., Bhasin, N., Yadav, S., Verma, A., Ram, K., Bhagat, M.: Atmospheric microplastics: Perspectives on origin, abundances, ecological and health risks **30**(49), 107435–107464 https://doi.org/10.1007/s11356-023-28422-y . Accessed 2024-12-25

[211] Dilara, P.A., Briassoulis, D.: Standard testing methods for mechanical properties and degradation of low density polyethylene (LDPE) films used as greenhouse covering materials: a critical evaluation **17**(8), 549–585 https://doi.org/10.1016/S0142-9418(97)00074-3 . Accessed 2024-12-25

[212] Dilara, P.A., Briassoulis, D.: Degradation and stabilization of low-density polyethylene films used as greenhouse covering materials **76**(4), 309–321 https://doi.org/10.1006/jaer.1999.0513 . Accessed 2024-12-25

[213] Mohamed Nor, N.H., Obbard, J.P.: Microplastics in singapore's coastal mangrove ecosystems **79**(1), 278–283 https://doi.org/10.1016/j.marpolbul.2013.11.025 . Accessed 2024-12-25

[214] Fendall, L.S., Sewell, M.A.: Contributing to marine pollution by washing your face: Microplastics in facial cleansers **58**(8), 1225–1228 https://doi.org/10.1016/j.marpolbul.2009.04.025 . Accessed 2024-10-10

[215] Chengappa S, K., Rao, A., K S, A., Jodalli, P.S., Shenoy Kudpi, R.: Microplastic content of over-the-counter toothpastes - a systematic review **12**, 390 https://doi.org/10.12688/f1000research.132035.1 . Accessed 2024-10-10

[216] Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M.: Microplastics in the

marine environment: A review of the methods used for identification and quantification **46**(6), 3060–3075 https://doi.org/10.1021/es2031505 . Accessed 2024-12-25

[217] Akhbarizadeh, R., Dobaradaran, S., Amouei Torkmahalleh, M., Saeedi, R., Aibaghi, R., Faraji Ghasemi, F.: Suspended fine particulate matter (PM2.5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: Their possible relationships and health implications **192**, 110339 https://doi.org/10.1016/j.envres.2020.110339 . Accessed 2024-10-27

[218] Aves, A., Ruffell, H., Evangeliou, N., Gaw, S., Revell, L.E.: Modelled sources of airborne microplastics collected at a remote southern hemisphere site **325**, 120437 https://doi.org/10.1016/j.atmosenv.2024.120437 . Accessed 2024-10-22

[219] Ryan, A.C., Allen, D., Allen, S., Maselli, V., LeBlanc, A., Kelleher, L., Krause, S., Walker, T.R., Cohen, M.: Transport and deposition of ocean-sourced microplastic particles by a north atlantic hurricane **4**(1), 442 https://doi.org/10.1038/s43247-023-01115-7 . Accessed 2024-12-06

[220] Stohl, A., Andrews, E., Burkhart, J.F., Forster, C., Herber, A., Hoch, S.W., Kowal, D., Lunder, C., Mefford, T., Ogren, J.A., Sharma, S., Spichtinger, N., Stebel, K., Stone, R., Ström, J., Tørseth, K., Wehrli, C., Yttri, K.E.: Pan-arctic enhancements of light absorbing aerosol concentrations due to north american boreal forest fires during summer 2004 **111**, 2006–007216 https://doi.org/10.1029/2006JD007216 . Accessed 2024-12-28

[221] Stohl, A., Prata, A.J., Eckhardt, S., Clarisse, L., Durant, A., Henne, S., Kristiansen, N.I., Minikin, A., Schumann, U., Seibert, P., Stebel, K., Thomas, H.E., Thorsteinsson, T., Tørseth, K., Weinzierl, B.: Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 eyjafjallajökull eruption **11**(9), 4333–4351 https://doi.org/10.5194/acp-11-4333-2011 . Accessed 2024-12-28

[222] Moxnes, E.D., Kristiansen, N.I., Stohl, A., Clarisse, L., Durant, A., Weber, K., Vogel, A.: Separation of ash and sulfur dioxide during the 2011 grímsvötn eruption **119**(12), 7477–7501 https://doi.org/10.1002/2013JD021129 . Accessed 2024-12-28

[223] Wotawa, G., De Geer, L.-E., Denier, P., Kalinowski, M., Toivonen, H., D'Amours, R., Desiato, F., Issartel, J.-P., Langer, M., Seibert, P., Frank, A., Sloan, C., Yamazawa, H.: Atmospheric transport modelling in support of CTBT verification—overview and basic concepts **37**(18), 2529–2537 https://doi.org/10.1016/S1352-2310(03)00154-7 . Accessed 2024-11-08

[224] Seibert, P., Frank, A.: Source-receptor matrix calculation with a lagrangian particle dispersion model in backward mode **4**(1), 51–63 https://doi.org/10.5194/acp-4-51-2004 . Accessed 2024-11-08

[225] Lehmann, M., Oehlschlägel, L.M., Häusl, F.P., Held, A., Gekle, S.: Ejection of marine microplastics by raindrops: a computational and experimental study **1**(1), 18 https://doi.org/10.1186/s43591-021-00018-8 . Accessed 2024-10-17

[226] Caracci, E., Vega-Herrera, A., Dachs, J., Berrojalbiz, N., Buonanno, G., Abad, E., Llorca, M., Moreno, T., Farré, M.: Micro(nano)plastics in the atmosphere of the atlantic ocean **450**, 131036 https://doi.org/10.1016/j.jhazmat.2023.131036 . Accessed 2024-10-17

[227] Oehlschlägel, L.M., Schmid, S., Lehmann, M., Gekle, S., Held, A.: Water–air transfer rates of microplastic particles through bubble bursting as a function of particle size **4**(1), 1 https://doi.org/10.1186/s43591-023-00079-x . Accessed 2024-10-17

[228] Rillig, M.C.: Microplastic in terrestrial ecosystems and the soil? **46**(12), 6453–6454 https://doi.org/10.1021/es302011r . Accessed 2024-10-18

[229] O'Connor, D., Pan, S., Shen, Z., Song, Y., Jin, Y., Wu, W.-M., Hou, D.: Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles **249**, 527–534 https://doi.org/10.1016/j.envpol.2019.03.092 . Accessed 2024-10-18

[230] Lwanga, E.H., Van Roshum, I., Munhoz, D.R., Meng, K., Rezaei, M., Goossens, D., Bijsterbosch, J., Alexandre, N., Oosterwijk, J., Krol, M., Peters, P., Geissen, V., Ritsema, C.: Microplastic appraisal of soil, water, ditch sediment and airborne dust: The case of agricultural systems **316**, 120513 https://doi.org/10.1016/j.envpol.2022.120513 . Accessed 2024-12-24

[231] Kole, P.J., Löhr, A.J., Van Belleghem, F., Ragas, A.: Wear and tear of tyres: A stealthy source of microplastics in the environment **14**(10), 1265 https://doi.org/10.3390/ijerph14101265 . Accessed 2024-10-18

[232] Prenner, S., Allesch, A., Staudner, M., Rexeis, M., Schwingshackl, M., Huber-Humer, M., Part, F.: Static modelling of the material flows of micro- and nanoplastic particles caused by the use of vehicle tyres **290**, 118102 https://doi.org/10.1016/j.envpol.2021.118102 . Accessed 2024-10-18

[233] Goßmann, I., Halbach, M., Scholz-Böttcher, B.M.: Car and truck tire wear particles in complex environmental samples – a quantitative comparison with "traditional" microplastic polymer mass loads **773**, 145667 https://doi.org/10.1016/j.scitotenv.2021.145667 . Accessed 2024-12-24

[234] Wang, T., Li, B., Zou, X., Wang, Y., Li, Y., Xu, Y., Mao, L., Zhang, C., Yu, W.: Emission of primary microplastics in mainland china: Invisible but not negligible **162**, 214–224 https://doi.org/10.1016/j.watres.2019.06.042 . Accessed 2024-10-17

[235] O'Brien, S., Okoffo, E.D., O'Brien, J.W., Ribeiro, F., Wang, X., Wright, S.L., Samanipour, S., Rauert, C., Toapanta, T.Y.A., Albarracin, R., Thomas, K.V.: Airborne emissions of microplastic fibres from domestic laundry dryers **747**, 141175 https://doi.org/10.1016/j.scitotenv.2020.141175 . Accessed 2024-12-09

[236] Xu, C., Zhang, B., Gu, C., Shen, C., Yin, S., Aamir, M., Li, F.: Are we underestimating the sources of microplastic pollution in terrestrial environment? **400**, 123228 https://doi.org/10.1016/j.jhazmat.2020.123228 . Accessed 2024-12-09

[237] Cakaj, A., Lisiak-Zielińska, M., Drzewiecka, K., Budka, A., Borowiak, K., Drapikowska, M., Cakaj, A., Qorri, E., Szkudlarz, P.: Potential impact of urban land use on microplastic atmospheric deposition: A case study in pristina city, kosovo **15**(23), 16464 https://doi.org/10.3390/su152316464 . Accessed 2024-12-06

[238] Jia, Q., Duan, Y., Han, X., Sun, X., Munyaneza, J., Ma, J., Xiu, G.: Atmospheric deposition of microplastics in the megalopolis (shanghai) during rainy season: Characteristics, influence factors, and source **847**, 157609 https://doi.org/10.1016/j.scitotenv.2022.157609 . Accessed 2024-12-04

[239] Yuan, Z., Pei, C., Li, H., Lin, L., Liu, S., Hou, R., Liao, R., Xu, X.: Atmospheric microplastics at a southern china metropolis: Occurrence, deposition flux, exposure risk and washout effect of rainfall **869**, 161839 https://doi.org/10.1016/j.scitotenv.2023.161839 . Accessed 2024-12-05

[240] Wesely, M.: A review of the current status of knowledge on dry deposition **34**(12), 2261–2282 https://doi.org/10.1016/S1352-2310(99)00467-7 . Accessed 2025-02-19

[241] Zannetti, P.: Dry and Wet Deposition, pp. 249–262. Springer. https://doi.org/10.1007/978-1-4757-4465-1_10 . http://link.springer.com/10.1007/978-1-4757-4465-1_10 Accessed 2025-02-19

[242] Zhang, H., Ahmadi, G., Fan, F.-G., McLaughlin, J.B.: Ellipsoidal particles transport and deposition in turbulent channel flows **27**(6), 971–1009 https://doi.org/10.1016/S0301-9322(00)00064-1 . Accessed 2024-12-25

[243] Marchioli, C., Fantoni, M., Soldati, A.: Orientation, distribution, and deposition of elongated, inertial fibers in turbulent channel flow **22**(3), 033301 https://doi.org/10.1063/1.3328874 . Accessed 2024-12-25

[244] Zhao, L., Challabotla, N.R., Andersson, H.I., Variano, E.A.: Rotation of nonspherical particles in turbulent channel flow **115**(24), 244501 https://doi.org/10.1103/PhysRevLett.115.244501 . Accessed 2024-12-25

[245] Challabotla, N.R., Zhao, L., Andersson, H.I.: Shape effects on dynamics of inertia-free spheroids in wall turbulence **27**(6), 061703 https://doi.org/10.1063/

1.4922864 . Accessed 2024-12-25

[246] Marchioli, C., Zhao, L., Andersson, H.I.: On the relative rotational motion between rigid fibers and fluid in turbulent channel flow **28**(1), 013301 https://doi.org/10.1063/1.4937757 . Accessed 2024-12-25

[247] Xiao, S., Cui, Y., Brahney, J., Mahowald, N.M., Li, Q.: Long-distance atmospheric transport of microplastic fibres influenced by their shapes **16**(10), 863–870 https://doi.org/10.1038/s41561-023-01264-6 . Accessed 2024-02-21

[248] Tatsii, D., Bucci, S., Bhowmick, T., Guettler, J., Bakels, L., Bagheri, G., Stohl, A.: Shape matters: Long-range transport of microplastic fibers in the atmosphere **58**(1), 671–682 https://doi.org/10.1021/acs.est.3c08209 . Accessed 2024-12-30

[249] Preston, C.A., McKenna Neuman, C.L., Aherne, J.: Effects of shape and size on microplastic atmospheric settling velocity **57**(32), 11937–11947 https://doi.org/10.1021/acs.est.3c03671 . Accessed 2024-10-23

[250] Ward, E., Gordon, M., Hanson, R., Jantunen, L.M.: Modelling the effect of shape on atmospheric microplastic transport **326**, 120458 https://doi.org/10.1016/j.atmosenv.2024.120458 . Accessed 2024-05-26

[251] Zhang, Y., Gao, T., Kang, S., Allen, S., Luo, X., Allen, D.: Microplastics in glaciers of the tibetan plateau: Evidence for the long-range transport of microplastics **758**, 143634 https://doi.org/10.1016/j.scitotenv.2020.143634 . Accessed 2024-11-22

[252] Aves, A.R., Revell, L.E., Gaw, S., Ruffell, H., Schuddeboom, A., Wotherspoon, N.E., LaRue, M., McDonald, A.J.: First evidence of microplastics in antarctic snow **16**(6), 2127–2145 https://doi.org/10.5194/tc-16-2127-2022 . Accessed 2024-10-22

[253] Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B.: Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? **104**(1), 290–293 https://doi.org/10.1016/j.marpolbul.2016.01.006 . Accessed 2024-11-25

[254] Gigault, J., Halle, A.t., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., El Hadri, H., Grassl, B., Reynaud, S.: Current opinion: What is a nanoplastic? **235**, 1030–1034 https://doi.org/10.1016/j.envpol.2018.01.024 . Accessed 2024-01-16

[255] Li, C., Wang, X., Zhu, L., Liu, K., Zong, C., Wei, N., Li, D.: Enhanced impacts evaluation of typhoon sinlaku (2020) on atmospheric microplastics in south china sea during the east asian summer monsoon **806**, 150767 https://doi.org/10.1016/j.scitotenv.2021.150767 . Accessed 2024-12-06

[256] Szewc, K., Graca, B., Dołęga, A.: Atmospheric deposition of microplastics in the

coastal zone: Characteristics and relationship with meteorological factors **761**, 143272 https://doi.org/10.1016/j.scitotenv.2020.143272 . Accessed 2024-12-04

[257] Mariraj Mohan, S.: An overview of particulate dry deposition: measuring methods, deposition velocity and controlling factors **13**(1), 387–402 https://doi.org/10.1007/s13762-015-0898-7 . Accessed 2024-11-26

[258] Zhang, C., Hu, Q., Su, W., Xing, C., Liu, C.: Satellite spectroscopy reveals the atmospheric consequences of the 2022 russia-ukraine war **869**, 161759 https://doi.org/10.1016/j.scitotenv.2023.161759 . Accessed 2024-11-20

[259] Seinfeld, J.H.: Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, 1st ed edn. New York Academy of Sciences Series. John Wiley & Sons, Incorporated

[260] Microplastics in the Ecosphere: Air, Water, Soil, and Food. https://doi.org/10.1002/9781119879534 . https://onlinelibrary.wiley.com/doi/book/10.1002/9781119879534 Accessed 2024-11-22

[261] Abbasi, S.: Microplastics washout from the atmosphere during a monsoon rain event **4**, 100035 https://doi.org/10.1016/j.hazadv.2021.100035 . Accessed 2024-12-04

[262] Sun, H., Jiao, R., Wang, D.: The difference of aggregation mechanism between microplastics and nanoplastics: Role of brownian motion and structural layer force **268**, 115942 https://doi.org/10.1016/j.envpol.2020.115942 . Accessed 2024-12-27

[263] Hee, Y.Y., Hanif, N.M., Weston, K., Latif, M.T., Suratman, S., Rusli, M.U., Mayes, A.G.: Atmospheric microplastic transport and deposition to urban and pristine tropical locations in southeast asia **902**, 166153 https://doi.org/10.1016/j.scitotenv.2023.166153 . Accessed 2024-12-04

[264] Rao, W., Fan, Y., Li, H., Qian, X., Liu, T.: New insights into the long-term dynamics and deposition-suspension distribution of atmospheric microplastics in an urban area **463**, 132860 https://doi.org/10.1016/j.jhazmat.2023.132860 . Accessed 2024-12-06

[265] Chen, Y., Niu, J., Xu, D., Zhang, M., Sun, K., Gao, B.: Wet deposition of globally transportable microplastics (<25 m) hovering over the megacity of beijing **57**(30), 11152–11162 https://doi.org/10.1021/acs.est.3c03474 . Accessed 2024-12-06

[266] Abbasi, S., Turner, A.: Dry and wet deposition of microplastics in a semi-arid region (shiraz, iran) **786**, 147358 https://doi.org/10.1016/j.scitotenv.2021.147358 . Accessed 2024-12-27

[267] Mao, C.-N., Gohil, K., Rastogi, D., Asa-Awuku, A.: The hygroscopicity of nanoplastic particles and implications for cloud formation and climate **58**(9), 1024–1032 https://doi.org/10.1080/02786826.2024.2361041 . Accessed 2024-07-25

[268] Petters, M.D., Kreidenweis, S.M.: A single parameter representation of hygroscopic growth and cloud condensation nucleus activity **7**(8), 1961–1971 https://doi.org/10.5194/acp-7-1961-2007 . Accessed 2024-09-18

[269] Yang, T., Wang, Y., Wu, Y., Zhai, J., Cong, L., Yan, G., Zhang, Z., Li, C.: Effect of the wetland environment on particulate matter and dry deposition **41**(8), 1054–1064 https://doi.org/10.1080/09593330.2018.1520307 . Accessed 2024-11-26

[270] Morrow, P.E.: Factors determining hygroscopic aerosol deposition in airways. **66**(2), 330–376 https://doi.org/10.1152/physrev.1986.66.2.330 . Accessed 2024-12-27

[271] Yuan, Y., Li, S., Chen, T., Ren, J.: Effects of ambient temperature and humidity on natural deposition characteristics of airborne biomass particles **20**(3), 1890 https://doi.org/10.3390/ijerph20031890 . Accessed 2024-12-27

[272] Bisal, F., Hsieh, J.: INFLUENCE OF MOISTURE ON ERODIBILITY OF SOIL BY WIND: **102**(3), 143–146 https://doi.org/10.1097/00010694-196609000-00001 . Accessed 2024-12-27

[273] Ford, H.V., Jones, N.H., Davies, A.J., Godley, B.J., Jambeck, J.R., Napper, I.E., Suckling, C.C., Williams, G.J., Woodall, L.C., Koldewey, H.J.: The fundamental links between climate change and marine plastic pollution **806**, 150392 https://doi.org/10.1016/j.scitotenv.2021.150392 . Accessed 2025-02-19

[274] Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G.: Arctic sea ice is an important temporal sink and means of transport for microplastic **9**(1), 1505 https://doi.org/10.1038/s41467-018-03825-5 . Accessed 2025-02-20

[275] Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C.: Global warming releases microplastic legacy frozen in arctic sea ice **2**(6), 315–320 https://doi.org/10.1002/2014EF000240 . Accessed 2025-02-20

[276] Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A.,

Sokona, Y., Sörensson, A.A., Tignor, M., Van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J.J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ürge-Vorsatz, D., Xiao, C., Yassaa, N., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., Van Der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., Romero, J., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Birt, A., Ha, M., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestvedt, J.S., Hansen, G., Ludden, C., Masson-Delmotte, V., Matthews, J.B.R., Mintenbeck, K., Pirani, A., Poloczanska, E., Leprince-Ringuet, N., Péan, C.: IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647 . Edition: First. https://www.ipcc.ch/report/ar6/syr/ Accessed 2025-02-20

[277] Wang, J., Lu, L., Wang, M., Jiang, T., Liu, X., Ru, S.: Typhoons increase the abundance of microplastics in the marine environment and cultured organisms: A case study in sanggou bay, china **667**, 1–8 https://doi.org/10.1016/j.scitotenv.2019.02.367 . Accessed 2025-02-20

[278] Abbasi, S., Rezaei, M., Ahmadi, F., Turner, A.: Atmospheric transport of microplastics during a dust storm **292**, 133456 https://doi.org/10.1016/j.chemosphere.2021.133456 . Accessed 2024-12-06

[279] Cai, L., Wang, J., Peng, J., Wu, Z., Tan, X.: Observation of the degradation of three types of plastic pellets exposed to UV irradiation in three different environments **628-629**, 740–747 https://doi.org/10.1016/j.scitotenv.2018.02.079 . Accessed 2024-11-27

[280] Shah, A.A., Hasan, F., Hameed, A., Ahmed, S.: Biological degradation of plastics: A comprehensive review **26**(3), 246–265 https://doi.org/10.1016/j.biotechadv.2007.12.005 . Accessed 2024-11-27

[281] Gardette, M., Perthue, A., Gardette, J.-L., Janecska, T., Földes, E., Pukánszky, B., Therias, S.: Photo- and thermal-oxidation of polyethylene: Comparison of mechanisms and influence of unsaturation content **98**(11), 2383–2390 https://doi.org/10.1016/j.polymdegradstab.2013.07.017 . Accessed 2024-11-30

[282] Gewert, B., Plassmann, M.M., MacLeod, M.: Pathways for degradation of plastic polymers floating in the marine environment **17**(9), 1513–1521 https://doi.org/

10.1039/C5EM00207A . Accessed 2024-11-30

[283] Singh, B., Sharma, N.: Mechanistic implications of plastic degradation **93**(3), 561–584 https://doi.org/10.1016/j.polymdegradstab.2007.11.008 . Accessed 2025-02-20

[284] Harvey, J.A.: Chemical and physical aging of plastics. In: Handbook of Environmental Degradation of Materials, pp. 153–163. Elsevier. https://doi.org/10.1016/B978-081551500-5.50009-4 . https://linkinghub.elsevier.com/retrieve/pii/B9780815515005500094 Accessed 2024-11-30

[285] Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J.: Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type **51**(8), 4368–4376 https://doi.org/10.1021/acs.est.6b06155 . Accessed 2024-11-30

[286] Zhu, K., Jia, H., Zhao, S., Xia, T., Guo, X., Wang, T., Zhu, L.: Formation of environmentally persistent free radicals on microplastics under light irradiation **53**(14), 8177–8186 https://doi.org/10.1021/acs.est.9b01474 . Accessed 2024-11-30

[287] Yang, R., Liu, Y., Yu, J., Wang, K.: Thermal oxidation products and kinetics of polyethylene composites **91**(8), 1651–1657 https://doi.org/10.1016/j.polymdegradstab.2005.12.013 . Accessed 2024-11-30

[288] Hüffer, T., Weniger, A.-K., Hofmann, T.: Sorption of organic compounds by aged polystyrene microplastic particles **236**, 218–225 https://doi.org/10.1016/j.envpol.2018.01.022 . Accessed 2024-11-27

[289] Liu, G., Zhu, Z., Yang, Y., Sun, Y., Yu, F., Ma, J.: Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater **246**, 26–33 https://doi.org/10.1016/j.envpol.2018.11.100 . Accessed 2024-11-30

[290] Zhou, L., Wang, T., Qu, G., Jia, H., Zhu, L.: Probing the aging processes and mechanisms of microplastic under simulated multiple actions generated by discharge plasma **398**, 122956 https://doi.org/10.1016/j.jhazmat.2020.122956 . Accessed 2024-11-30

[291] Brandon, J., Goldstein, M., Ohman, M.D.: Long-term aging and degradation of microplastic particles: Comparing in situ oceanic and experimental weathering patterns **110**(1), 299–308 https://doi.org/10.1016/j.marpolbul.2016.06.048 . Accessed 2024-11-30

[292] Yu, F., Qin, Q., Zhang, X., Ma, J.: Characteristics and adsorption behavior of typical microplastics in long-term accelerated weathering simulation **26**(5), 882–890 https://doi.org/10.1039/D4EM00062E . Accessed 2024-11-30

[293] Weinstein, J.E., Crocker, B.K., Gray, A.D.: From macroplastic to microplastic: Degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat **35**(7), 1632–1640 https://doi.org/10.1002/etc.3432 . Accessed 2024-11-30

[294] Ishigaki, T., Sugano, W., Nakanishi, A., Tateda, M., Ike, M., Fujita, M.: The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors **54**(3), 225–233 https://doi.org/10.1016/S0045-6535(03)00750-1 . Accessed 2024-12-01

[295] Krueger, M.C., Harms, H., Schlosser, D.: Prospects for microbiological solutions to environmental pollution with plastics **99**(21), 8857–8874 https://doi.org/10.1007/s00253-015-6879-4 . Accessed 2024-12-01

[296] Kumar, S., Teotia, U.V.T., Singh, Y.: A comprehensive review on microbial degradation of plastic waste **5**(4), 8–12 https://doi.org/10.18231/2348-0335.2017.0009 . Accessed 2024-12-01

[297] Emadian, S.M., Onay, T.T., Demirel, B.: Biodegradation of bioplastics in natural environments **59**, 526–536 https://doi.org/10.1016/j.wasman.2016.10.006 . Accessed 2024-11-30

[298] Jacquin, J., Cheng, J., Odobel, C., Pandin, C., Conan, P., Pujo-Pay, M., Barbe, V., Meistertzheim, A.-L., Ghiglione, J.-F.: Microbial ecotoxicology of marine plastic debris: A review on colonization and biodegradation by the "plastisphere" **10**, 865 https://doi.org/10.3389/fmicb.2019.00865 . Accessed 2024-12-01

[299] Mazhar, S.: Microbial degradation of plastic-a brief review **11**(2) https://doi.org/10.19045/bspab.2022.110044 . Accessed 2024-12-01

[300] Heris, Y.S.: Bacterial biodegradation of synthetic plastics: a review **48**(1), 87 https://doi.org/10.1186/s42269-024-01241-y . Accessed 2024-12-01

[301] Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L.: A global inventory of small floating plastic debris **10**(12), 124006 https://doi.org/10.1088/1748-9326/10/12/124006 . Accessed 2024-10-17

[302] Boucher, J., Friot, D.: Primary Microplastics in the Oceans: A Global Evaluation of Sources. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2017.01.en . https://portals.iucn.org/library/node/46622 Accessed 2024-10-17

[303] Kaandorp, M.L.A., Lobelle, D., Kehl, C., Dijkstra, H.A., Van Sebille, E.: Global mass of buoyant marine plastics dominated by large long-lived debris **16**(8), 689–694 https://doi.org/10.1038/s41561-023-01216-0 . Accessed 2024-10-17

[304] Cottom, J.W., Cook, E., Velis, C.A.: A local-to-global emissions inventory of macroplastic pollution **633**(8028), 101–108 https://doi.org/10.1038/s41586-024-07758-6 . Publisher: Springer Science and Business Media LLC. Accessed 2024-09-17

[305] Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., Stohl, A.: Atmospheric transport is a major pathway of microplastics to remote regions **11**(1), 3381 https://doi.org/10.1038/s41467-020-17201-9 . Accessed 2024-10-17

[306] Sonke, J.E., Koenig, A.M., Yakovenko, N., Hagelskjær, O., Margenat, H., Hansson, S.V., De Vleeschouwer, F., Magand, O., Le Roux, G., Thomas, J.L.: A mass budget and box model of global plastics cycling, degradation and dispersal in the land-ocean-atmosphere system **2**(1), 28 https://doi.org/10.1186/s43591-022-00048-w . Accessed 2024-10-17

[307] Yang, S., Brasseur, G., Walters, S., Lichtig, P., Li, C.W.Y.: Global atmospheric distribution of microplastics with evidence of low oceanic emissions **8**(1), 81 https://doi.org/10.1038/s41612-025-00914-3 . Accessed 2025-03-09

[308] Xu, L., Tian, X., Bai, X., Li, K., Zhang, G., Zhang, M., Rillig, M.C., Huang, Y., Hu, M.: Atmospheric microplastic input into wetlands: Spatiotemporal patterns, drivers, and unique ecological impacts **268**, 122601 https://doi.org/10.1016/j.watres.2024.122601 . Accessed 2024-12-04

[309] Brahney, J., Wetherbee, G., Sexstone, G.A., Youngbull, C., Strong, P., Heindel, R.C.: A new sampler for the collection and retrieval of dry dust deposition **45**, 100600 https://doi.org/10.1016/j.aeolia.2020.100600 . Accessed 2024-12-27

[310] Levermore, J.M., Smith, T.E.L., Kelly, F.J., Wright, S.L.: Detection of microplastics in ambient particulate matter using raman spectral imaging and chemometric analysis **92**(13), 8732–8740 https://doi.org/10.1021/acs.analchem.9b05445 . Accessed 2024-12-27

[311] Syafina, P.R., Yudison, A.P., Sembiring, E., Irsyad, M., Tomo, H.S.: Identification of fibrous suspended atmospheric microplastics in bandung metropolitan area, indonesia **308**, 136194 https://doi.org/10.1016/j.chemosphere.2022.136194 . Accessed 2024-12-05

[312] Saladin, S., Boies, A., Giorio, C.: Airborne tire wear particles: A critical reanalysis of the literature reveals emission factors lower than expected **11**(12), 1296–1307 https://doi.org/10.1021/acs.estlett.4c00792 . Accessed 2025-05-08

[313] Abbott, J.K., Sumaila, U.R.: Reducing marine plastic pollution: Policy insights from economics **13**(2), 327–336 https://doi.org/10.1093/reep/rez007 . Accessed 2024-12-28

[314] Schuyler, Q., Hardesty, B.D., Lawson, T.J., Wilcox, C.: Environmental context and socio-economic status drive plastic pollution in australian cities **17**(4), 045013 https://doi.org/10.1088/1748-9326/ac5690 . Accessed 2024-12-28

[315] Siddiqui, J., Pandey, G.: A review of plastic waste management strategies **2(12)**, 84–88

[316] Kovač Viršek, M., Palatinus, A., Koren, , Peterlin, M., Horvat, P., Kržan, A.: Protocol for microplastics sampling on the sea surface and sample analysis (118), 55161 https://doi.org/10.3791/55161-v . Accessed 2024-12-28

[317] ASTM: Practice for Collection of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and Fibers. ASTM International. https://doi.org/10.1520/D8332-20 . http://www.astm.org/cgi-bin/resolver.cgi?D8332-20 Accessed 2024-12-28

[318] ASTM: Practice for Coding Plastic Manufactured Articles for Resin Identification. ASTM International. https://doi.org/10.1520/D7611_D7611M-21 . http://www.astm.org/cgi-bin/resolver.cgi?D7611D7611M-21 Accessed 2024-12-28

[319] Guo, S., Popp, J., Bocklitz, T.: Chemometric analysis in raman spectroscopy from experimental design to machine learning–based modeling **16**(12), 5426–5459 https://doi.org/10.1038/s41596-021-00620-3 . Accessed 2024-10-21

[320] CA SWRCB: Standard Operating Procedures for Extraction and Measurement by Raman Spectroscopy of Microplastic Particles in Drinking Water. California State Water Board. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/microplastics/mcrplstcs_raman.pdf

[321] Dehaut, A., Cassone, A.-L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G., Lambert, C., Soudant, P., Huvet, A., Duflos, G., Paul-Pont, I.: Microplastics in seafood: Benchmark protocol for their extraction and characterization **215**, 223–233 https://doi.org/10.1016/j.envpol.2016.05.018 . Accessed 2024-12-29

[322] Masura, J., Baker, J., Foster, G., Arthur, C.: Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments. https://doi.org/10.25607/OBP-604 . Medium: 31pp. https://repository.oceanbestpractices.org/handle/11329/1076 Accessed 2024-12-29

[323] Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kühn, S., Lavers, J.L., Mallory, M.L., Trevail, A., Van Franeker, J.A.: Quantifying ingested debris in marine megafauna: a review and recommendations for standardization **9**(9), 1454–1469 https://doi.org/10.1039/C6AY02419J . Accessed 2024-12-29

[324] Dehaut, A., Hermabessiere, L., Duflos, G.: Current frontiers and recommendations for the study of microplastics in seafood **116**, 346–359 https://doi.org/10.1016/j.trac.2018.11.011 . Accessed 2024-12-29

[325] Cowger, W., Booth, A.M., Hamilton, B.M., Thaysen, C., Primpke, S., Munno, K., Lusher, A.L., Dehaut, A., Vaz, V.P., Liboiron, M., Devriese, L.I., Hermabessiere, L., Rochman, C., Athey, S.N., Lynch, J.M., De Frond, H., Gray, A., Jones, O.A.H., Brander, S., Steele, C., Moore, S., Sanchez, A., Nel, H.: Reporting guidelines to increase the reproducibility and comparability of research on microplastics **74**(9), 1066–1077 https://doi.org/10.1177/0003702820930292 . Accessed 2024-12-29

[326] Hermsen, E., Mintenig, S.M., Besseling, E., Koelmans, A.A.: Quality criteria for the analysis of microplastic in biota samples: A critical review **52**(18), 10230–10240 https://doi.org/10.1021/acs.est.8b01611 . Accessed 2024-12-29

[327] Wesch, C., Elert, A.M., Wörner, M., Braun, U., Klein, R., Paulus, M.: Assuring quality in microplastic monitoring: About the value of clean-air devices as essentials for verified data **7**(1), 5424 https://doi.org/10.1038/s41598-017-05838-4 . Accessed 2024-12-29

[328] Brander, S.M., Renick, V.C., Foley, M.M., Steele, C., Woo, M., Lusher, A., Carr, S., Helm, P., Box, C., Cherniak, S., Andrews, R.C., Rochman, C.M.: Sampling and quality assurance and quality control: A guide for scientists investigating the occurrence of microplastics across matrices **74**(9), 1099–1125 https://doi.org/10.1177/0003702820945713 . Accessed 2024-12-29

[329] Andrade, J.M., Ferreiro, B., López-Mahía, P., Muniategui-Lorenzo, S.: Standardization of the minimum information for publication of infrared-related data when microplastics are characterized **154**, 111035 https://doi.org/10.1016/j.marpolbul.2020.111035 . Accessed 2024-12-29

[330] Pfeiffer, F., Fischer, E.K.: Various digestion protocols within microplastic sample processing—evaluating the resistance of different synthetic polymers and the efficiency of biogenic organic matter destruction **8**, 572424 https://doi.org/10.3389/fenvs.2020.572424 . Accessed 2024-12-29

[331] Cabernard, L., Roscher, L., Lorenz, C., Gerdts, G., Primpke, S.: Comparison of raman and fourier transform infrared spectroscopy for the quantification of microplastics in the aquatic environment **52**(22), 13279–13288 https://doi.org/10.1021/acs.est.8b03438 . Accessed 2024-12-29

[332] Munno, K., De Frond, H., O'Donnell, B., Rochman, C.M.: Increasing the accessibility for characterizing microplastics: Introducing new application-based and spectral libraries of plastic particles (SLoPP and SLoPP-e) **92**(3), 2443–2451 https://doi.org/10.1021/acs.analchem.9b03626 . Accessed 2024-12-29

[333] Walton, W.H.: Feret's statistical diameter as a measure of particle size **162**(4113), 329–330 https://doi.org/10.1038/162329b0 . Accessed 2025-04-25

[334] Particle size measurement: the equivalent spherical diameter **419**(1856), 137–149 https://doi.org/10.1098/rspa.1988.0100 . Accessed 2025-04-25

[335] Allen, T.: Particle Size Measurement. Springer. https://doi.org/10.1007/978-94-009-0417-0 . http://link.springer.com/10.1007/978-94-009-0417-0 Accessed 2025-04-25

[336] Schnepf, U., Von Moers-Meßmer, M.A.L., Brümmer, F.: A practical primer for image-based particle measurements in microplastic research **3**(1), 16 https://doi.org/10.1186/s43591-023-00064-4 . Accessed 2025-04-25

[337] Blott, S.J., Pye, K.: Particle shape: a review and new methods of characterization and classification **55**(1), 31–63 https://doi.org/10.1111/j.1365-3091.2007.00892.x . Accessed 2025-04-25

[338] Ruiz-Jimenez, J., Zanca, N., Lan, H., Jussila, M., Hartonen, K., Riekkola, M.-L.: Aerial drone as a carrier for miniaturized air sampling systems **1597**, 202–208 https://doi.org/10.1016/j.chroma.2019.04.009 . Accessed 2024-12-29

[339] Burgués, J., Marco, S.: Environmental chemical sensing using small drones: A review **748**, 141172 https://doi.org/10.1016/j.scitotenv.2020.141172 . Accessed 2024-12-29

[340] Han, S., Youn, J.-S., Jung, Y.-W.: Characterization of PM10 and PM2.5 source profiles for resuspended road dust collected using mobile sampling methodology **45**(20), 3343–3351 https://doi.org/10.1016/j.atmosenv.2011.04.015 . Accessed 2024-12-29

[341] Kooi, M., Koelmans, A.A.: Simplifying microplastic via continuous probability distributions for size, shape, and density **6**(9), 551–557 https://doi.org/10.1021/acs.estlett.9b00379 . Accessed 2024-12-06

[342] Riemer, N., West, M., Zaveri, R.A., Easter, R.C.: Simulating the evolution of soot mixing state with a particle-resolved aerosol model **114**, 2008–011073 https://doi.org/10.1029/2008JD011073 . Accessed 2023-11-14

[343] Elert, A.M., Becker, R., Duemichen, E., Eisentraut, P., Falkenhagen, J., Sturm, H., Braun, U.: Comparison of different methods for MP detection: What can we learn from them, and why asking the right question before measurements matters? **231**, 1256–1264 https://doi.org/10.1016/j.envpol.2017.08.074 . Accessed 2025-02-23

[344] Primpke, S., Wirth, M., Lorenz, C., Gerdts, G.: Reference database design

for the automated analysis of microplastic samples based on fourier transform infrared (FTIR) spectroscopy **410**(21), 5131–5141 https://doi.org/10.1007/s00216-018-1156-x . Accessed 2025-02-23

[345] Abed, R.M.M., Muthukrishnan, T., Al Khaburi, M., Al-Senafi, F., Munam, A., Mahmoud, H.: Degradability and biofouling of oxo-biodegradable polyethylene in the planktonic and benthic zones of the arabian gulf **150**, 110639 https://doi.org/10.1016/j.marpolbul.2019.110639 . Accessed 2025-02-23

[346] Luo, R., Popp, J., Bocklitz, T.: Deep learning for raman spectroscopy: A review **3**(3), 287–301 https://doi.org/10.3390/analytica3030020 . Accessed 2024-10-21

[347] Lin, J.-y., Liu, H.-t., Zhang, J.: Recent advances in the application of machine learning methods to improve identification of the microplastics in environment **307**, 136092 https://doi.org/10.1016/j.chemosphere.2022.136092 . Accessed 2024-10-21

[348] Fan, X., Wang, Y., Yu, C., Lv, Y., Zhang, H., Yang, Q., Wen, M., Lu, H., Zhang, Z.: A universal and accurate method for easily identifying components in raman spectroscopy based on deep learning **95**(11), 4863–4870 https://doi.org/10.1021/acs.analchem.2c03853 . Accessed 2024-12-31

[349] Horgan, C.C., Jensen, M., Nagelkerke, A., St-Pierre, J.-P., Vercauteren, T., Stevens, M.M., Bergholt, M.S.: High-throughput molecular imaging via deep-learning-enabled raman spectroscopy **93**(48), 15850–15860 https://doi.org/10.1021/acs.analchem.1c02178 . Accessed 2024-12-31

[350] Hufnagl, B., Stibi, M., Martirosyan, H., Wilczek, U., Möller, J.N., Löder, M.G.J., Laforsch, C., Lohninger, H.: Computer-assisted analysis of microplastics in environmental samples based on FTIR imaging in combination with machine learning **9**(1), 90–95 https://doi.org/10.1021/acs.estlett.1c00851 . Accessed 2024-12-31

[351] Michel, A.P.M., Morrison, A.E., Preston, V.L., Marx, C.T., Colson, B.C., White, H.K.: Rapid identification of marine plastic debris via spectroscopic techniques and machine learning classifiers **54**(17), 10630–10637 https://doi.org/10.1021/acs.est.0c02099 . Accessed 2024-12-31

[352] Xie, L., Luo, S., Liu, Y., Ruan, X., Gong, K., Ge, Q., Li, K., Valev, V.K., Liu, G., Zhang, L.: Automatic identification of individual nanoplastics by raman spectroscopy based on machine learning **57**(46), 18203–18214 https://doi.org/10.1021/acs.est.3c03210 . Accessed 2024-12-31

[353] Beres, N.D., Burkart, J., Graf, E., Zeder, Y., Dailey, L.A., Weinzierl, B.: Merging holography, fluorescence, and machine learning for in situ, continuous characterization and classification of airborne microplastics. https://doi.org/10.5194/egusphere-2023-2853 . https://egusphere.copernicus.org/preprints/2023/

egusphere-2023-2853/ Accessed 2024-09-26

[354] Zhao, B., Richardson, R.E., You, F.: Advancing microplastic analysis in the era of artificial intelligence: From current applications to the promise of generative AI **1**(4), 100043 https://doi.org/10.1016/j.ynexs.2024.100043 . Accessed 2024-12-30

[355] Zolich, A., Faltynkova, A., Johnsen, G., Johansen, T.A.: Portable catamaran drone – an uncrewed sampling vehicle for micro-plastics and aquaculture research. In: OCEANS 2022, Hampton Roads, pp. 1–6. IEEE. https://doi.org/10.1109/OCEANS47191.2022.9977294 . https://ieeexplore.ieee.org/document/9977294/ Accessed 2025-02-23

[356] Pasquier, G., Doyen, P., Carlesi, N., Amara, R.: An innovative approach for microplastic sampling in all surface water bodies using an aquatic drone **8**(11), 11662 https://doi.org/10.1016/j.heliyon.2022.e11662 . Accessed 2025-02-23

[357] Alboody, A., Vandenbroucke, N., Porebski, A., Sawan, R., Viudes, F., Doyen, P., Amara, R.: A new remote hyperspectral imaging system embedded on an unmanned aquatic drone for the detection and identification of floating plastic litter using machine learning **15**(14), 3455 https://doi.org/10.3390/rs15143455 . Accessed 2025-02-23

[358] Faltynkova, A., Deschênes, C.E., Zolich, A., Wagner, M., Johansen, T.A., Johnsen, G.: Use of an uncrewed surface vehicle and near infrared hyperspectral imaging for sampling and analysis of aquatic microplastics **201**, 116214 https://doi.org/10.1016/j.marpolbul.2024.116214 . Accessed 2025-02-23

[359] Wei, J., Li, Z., Lyapustin, A., Wang, J., Dubovik, O., Schwartz, J., Sun, L., Li, C., Liu, S., Zhu, T.: First close insight into global daily gapless 1 km PM2.5 pollution, variability, and health impact **14**(1), 8349 https://doi.org/10.1038/s41467-023-43862-3 . Accessed 2025-02-23

[360] Peng, B., Hossain, K.B., Lin, Y., Zhang, M., Zheng, H., Yu, J., Meng, X., Wang, J., Cui, Y., Wu, B., Lou, L., Cai, M.: Assessment and sources identification of microplastics, PAHs and OCPs in the luoyuan bay, china: Based on multi-statistical analysis **175**, 113351 https://doi.org/10.1016/j.marpolbul.2022.113351 . Accessed 2024-12-31

[361] Iordachescu, L., Nielsen, R.V., Papacharalampos, K., Barritaud, L., Denieul, M.-P., Plessis, E., Baratto, G., Julien, V., Vollertsen, J.: Point-source tracking of microplastics in sewerage systems. finding the culprit **257**, 121696 https://doi.org/10.1016/j.watres.2024.121696 . Accessed 2024-12-31

[362] Zhang, M., Lin, Y., Booth, A.M., Song, X., Cui, Y., Xia, B., Gu, Z., Li, Y., Liu, F., Cai, M.: Fate, source and mass budget of sedimentary microplastics in the bohai sea and the yellow sea **294**, 118640 https://doi.org/10.1016/j.envpol.

2021.118640 . Accessed 2024-12-31

[363] Gan, J., Liu, P., Chakrabarty, R.K.: Deep learning enabled lagrangian particle trajectory simulation **139**, 105468 https://doi.org/10.1016/j.jaerosci.2019.105468 . Accessed 2025-02-21

[364] Hassanian, R., Myneni, H., Helgadóttir, , Riedel, M.: Deciphering the dynamics of distorted turbulent flows: Lagrangian particle tracking and chaos prediction through transformer-based deep learning models **35**(7), 075118 https://doi.org/10.1063/5.0157897 . Accessed 2025-02-21

[365] Hassanian, R., Helgadóttir, , Gharibi, F., Beck, A., Riedel, M.: Data-driven deep learning models in particle-laden turbulent flow **37**(2), 023348 https://doi.org/10.1063/5.0251765 . Accessed 2025-02-21

[366] Tian, Y., Livescu, D., Chertkov, M.: Physics-informed machine learning of the lagrangian dynamics of velocity gradient tensor **6**(9), 094607 https://doi.org/10.1103/PhysRevFluids.6.094607 . Accessed 2025-02-21

[367] Baharvand, S., Ahmari, H.: Application of machine learning approaches in particle tracking model to estimate sediment transport in natural streams **38**(8), 2905–2934 https://doi.org/10.1007/s11269-024-03798-9 . Accessed 2025-02-21

[368] Puzyrev, D., Harth, K., Trittel, T., Stannarius, R.: Machine learning for 3d particle tracking in granular gases **32**(5), 897–906 https://doi.org/10.1007/s12217-020-09800-4 . Accessed 2025-02-21

[369] Brecht, R., Bakels, L., Bihlo, A., Stohl, A.: Improving trajectory calculations by FLEXPART 10.4+ using single-image super-resolution **16**(8), 2181–2192 https://doi.org/10.5194/gmd-16-2181-2023 . Accessed 2025-02-21

[370] Lucas, D.D., Simpson, M., Cameron-Smith, P., Baskett, R.L.: Bayesian inverse modeling of the atmospheric transport and emissions of a controlled tracer release from a nuclear power plant **17**(22), 13521–13543 https://doi.org/10.5194/acp-17-13521-2017 . Accessed 2025-02-21

[371] Liao, H., Yuan, L., Wu, M., Chen, H.: Air quality prediction by integrating mechanism model and machine learning model **899**, 165646 https://doi.org/10.1016/j.scitotenv.2023.165646 . Accessed 2025-02-21

[372] Gunawardena, N., Pallotta, G., Simpson, M., Lucas, D.D.: Machine learning emulation of spatial deposition from a multi-physics ensemble of weather and atmospheric transport models **12**(8), 953 https://doi.org/10.3390/atmos12080953 . Accessed 2025-02-21

[373] Fillola, E., Santos-Rodriguez, R., Manning, A., O'Doherty, S., Rigby, M.:

A machine learning emulator for lagrangian particle dispersion model footprints: a case study using NAME **16**(7), 1997–2009 https://doi.org/10.5194/gmd-16-1997-2023 . Accessed 2025-02-21

[374] Qian, S., Qiao, X., Zhang, W., Yu, Z., Dong, S., Feng, J.: Machine learning-based prediction for settling velocity of microplastics with various shapes **249**, 121001 https://doi.org/10.1016/j.watres.2023.121001 . Accessed 2024-12-31

[375] Li, X., Tian, Z., Kong, Y., Cao, X., Liu, N., Zhang, T., Xiao, Z., Wang, Z.: The suspension stability of nanoplastics in aquatic environments revealed using meta-analysis and machine learning **471**, 134426 https://doi.org/10.1016/j.jhazmat.2024.134426 . Accessed 2024-12-31

[376] Mehmood, T., Tahir, M., Zhi, C.: The aging behavior of microplastics manufactured from diverse polymers is predicted by the johnsen index with regularized PLS **76**(7), 4041–4047 https://doi.org/10.1007/s11696-022-02141-z . Accessed 2024-12-31

[377] Shen, W., Wang, M., Riemer, N., Zheng, Z., Liu, Y., Dong, X.: Improving BC mixing state and CCN activity representation with machine learning in the community atmosphere model version 6 (CAM6) **16**(1), 2023–003889 https://doi.org/10.1029/2023MS003889 . Accessed 2024-12-31

[378] Behrens, G., Beucler, T., Iglesias-Suarez, F., Yu, S., Gentine, P., Pritchard, M., Schwabe, M., Eyring, V.: Simulating Atmospheric Processes in Earth System Models and Quantifying Uncertainties with Deep Learning Multi-Member and Stochastic Parameterizations. arXiv. Version Number: 2. https://doi.org/10.48550/ARXIV.2402.03079 . https://arxiv.org/abs/2402.03079 Accessed 2024-12-31

[379] Jiang, F., Zheng, Z., Coe, H., Healy, R.M., Poulain, L., Gros, V., Zhang, H., Li, W., Liu, D., West, M., Topping, D., Riemer, N.: Integrating simulations and observations: A foundation model for estimating the aerosol mixing state index, 4–00329 https://doi.org/10.1021/acsestair.4c00329 . Accessed 2025-05-05

[380] Yuan, Y., Lin, L.: Self-supervised pretraining of transformers for satellite image time series classification **14**, 474–487 https://doi.org/10.1109/JSTARS.2020.3036602 . Accessed 2024-09-10

[381] Cong, Y., Khanna, S., Meng, C., Liu, P., Rozi, E., He, Y., Burke, M., Lobell, D.B., Ermon, S.: SatMAE: Pre-training Transformers for Temporal and Multi-Spectral Satellite Imagery. arXiv. http://arxiv.org/abs/2207.08051 Accessed 2024-09-10

[382] Reed, C.J., Gupta, R., Li, S., Brockman, S., Funk, C., Clipp, B., Keutzer, K., Candido, S., Uyttendaele, M., Darrell, T.: Scale-MAE: A Scale-Aware Masked Autoencoder for Multiscale Geospatial Representation Learning. arXiv. http:

//arxiv.org/abs/2212.14532 Accessed 2024-09-10

[383] Nguyen, T., Brandstetter, J., Kapoor, A., Gupta, J.K., Grover, A.: ClimaX: A foundation model for weather and climate. arXiv. Version Number: 5. https://doi.org/10.48550/ARXIV.2301.10343 . https://arxiv.org/abs/2301.10343 Accessed 2024-06-11

[384] Chen, K., Han, T., Gong, J., Bai, L., Ling, F., Luo, J.-J., Chen, X., Ma, L., Zhang, T., Su, R., Ci, Y., Li, B., Yang, X., Ouyang, W.: FengWu: Pushing the Skillful Global Medium-range Weather Forecast beyond 10 Days Lead. arXiv. Version Number: 1. https://doi.org/10.48550/ARXIV.2304.02948 . https://arxiv.org/abs/2304.02948 Accessed 2024-09-10

[385] Bi, K., Xie, L., Zhang, H., Chen, X., Gu, X., Tian, Q.: Accurate medium-range global weather forecasting with 3d neural networks **619**(7970), 533–538 https://doi.org/10.1038/s41586-023-06185-3 . Accessed 2024-09-10

[386] Chen, L., Zhong, X., Zhang, F., Cheng, Y., Xu, Y., Qi, Y., Li, H.: FuXi: A cascade machine learning forecasting system for 15-day global weather forecast. arXiv. http://arxiv.org/abs/2306.12873 Accessed 2024-09-10

[387] Lam, R., Sanchez-Gonzalez, A., Willson, M., Wirnsberger, P., Fortunato, M., Alet, F., Ravuri, S., Ewalds, T., Eaton-Rosen, Z., Hu, W., Merose, A., Hoyer, S., Holland, G., Vinyals, O., Stott, J., Pritzel, A., Mohamed, S., Battaglia, P.: GraphCast: Learning skillful medium-range global weather forecasting. arXiv. http://arxiv.org/abs/2212.12794 Accessed 2024-09-10

[388] Pathak, J., Subramanian, S., Harrington, P., Raja, S., Chattopadhyay, A., Mardani, M., Kurth, T., Hall, D., Li, Z., Azizzadenesheli, K., Hassanzadeh, P., Kashinath, K., Anandkumar, A.: FourCastNet: A Global Data-driven High-resolution Weather Model using Adaptive Fourier Neural Operators. arXiv. http://arxiv.org/abs/2202.11214 Accessed 2024-09-10

[389] Man, X., Zhang, C., Feng, J., Li, C., Shao, J.: W-MAE: Pre-trained weather model with masked autoencoder for multi-variable weather forecasting. arXiv. http://arxiv.org/abs/2304.08754 Accessed 2024-09-10

[390] Webersinke, N., Kraus, M., Bingler, J.A., Leippold, M.: ClimateBert: A Pretrained Language Model for Climate-Related Text. arXiv. http://arxiv.org/abs/2110.12010 Accessed 2024-09-10