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Plastic waste, circular economy, and atmospheric microplastics: A review of current challenges and the application of moss biomonitoring

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Abstract

Plastics have become indispensable materials in modern society; however, their continuous production and consumption have led to significant environmental challenges associated with plastic waste accumulation and the occurrence of microplastics. This review provides an overview of global plastic production, plastic waste generation, and waste management practices, with particular emphasis on circular economy strategies aimed at improving resource efficiency and reducing plastic pollution. The current situation in North Macedonia is also discussed, highlighting the challenges and opportunities related to plastic waste management and recycling. Special attention is given to microplastics as emerging environmental contaminants. Current knowledge regarding their sources, environmental distribution, and potential ecological and human health impacts is summarized. Recent studies indicate that atmospheric transport represents an important pathway for the dispersal and deposition of microplastic particles, contributing to their occurrence even in remote regions. The review further examines the application of moss biomonitoring as a cost-effective and efficient approach for assessing atmospheric microplastic deposition. Preliminary observations from a European monitoring initiative, including samples from North Macedonia, confirm the widespread presence of atmospheric microplastics and reveal spatial variations in their concentrations and polymer composition. These findings highlight the importance of harmonized monitoring methodologies and the integration of environmental monitoring with circular economy and waste management strategies to mitigate microplastic pollution.

Keywords: plastic waste; circular economy; environmental monitoring; atmospheric microplastics; moss biomonitoring

Introduction

The widespread use of plastics has transformed modern society, enabling advances in packaging, transportation, construction, medicine, and numerous other sectors. Their low cost, durability, and versatility have contributed to a continuous increase in global production, which has reached hundreds of millions of tonnes annually and is expected to continue growing in the coming decades (Geyer et al. 2017). However, the benefits of plastics are accompanied by significant environmental challenges associated with waste generation, inadequate disposal practices, and the persistence of plastic materials in the environment (Nayanathara Thathsarani Pilapitiya and Ratnayake 2024).

The accumulation of plastic waste has become a global concern, prompting increased interest in sustainable waste management strategies. In this context, the circular economy has emerged as an alternative to the traditional linear model of production and consumption. By promoting waste reduction, reuse, recycling, and resource efficiency, circular economy principles aim to minimize environmental impacts while maintaining the economic value of materials

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(Chanda 2021). Despite substantial progress in some regions, significant differences in recycling rates and waste treatment practices remain worldwide.

One of the most concerning consequences of plastic pollution is the formation of microplastics, which originate either from the direct release of small plastic particles or from the fragmentation of larger plastic debris. Due to their persistence and mobility, microplastics have been detected in aquatic ecosystems, soils, food, drinking water, and even human tissues (Frias and Nash 2019; Ragusa et al. 2021). Recent studies have further demonstrated that the atmosphere represents an important pathway for the transport and deposition of microplastics, enabling their dispersal over long distances and their occurrence even in remote regions (Zhang et al. 2020a).

The growing recognition of atmospheric microplastic pollution has created a need for reliable monitoring approaches capable of assessing their spatial distribution and potential sources. Among the available methods, moss biomonitoring has emerged as a promising tool because mosses efficiently accumulate airborne particles over time and have been widely used in atmospheric pollution studies (Stafilov et al. 2020; Bačeva Andonovska et al. 2023, 2024; Šajn et al. 2024). Their application for monitoring atmospheric microplastics offers a cost-effective approach for large-scale environmental assessments (Roblin and Aherne 2020; Jafarova et al. 2023; Cross et al. 2026a).

This review provides an overview of global plastic production, plastic waste generation, and waste management practices, with particular emphasis on circular economy strategies and the situation in North Macedonia. Furthermore, current knowledge on microplastic pollution, atmospheric transport, and biomonitoring approaches is summarized, and preliminary observations from moss-based monitoring of atmospheric microplastics in Europe, including North Macedonia, are presented.

Plastic Waste: Sources, Environmental Impacts and Circular Economy Approaches for plastic Waste Management

Plastics are among the most important materials of modern society and have become indispensable in numerous industrial sectors due to their versatility, durability, low cost, and ease of processing. Since their widespread commercialization during the twentieth century, synthetic polymers have transformed packaging, construction, transportation, healthcare, agriculture, textiles, and electronics, contributing significantly to technological progress and economic development. Their unique combination of lightweight structure, mechanical performance, chemical resistance, and design flexibility has enabled the replacement of traditional materials such as glass, metal, wood, and paper in a wide range of applications.

As a consequence of these advantages, global plastic production has increased continuously over the past seven decades. Production rose from less than 2 million tonnes in 1950 to approximately 464 million tonnes in 2018 and is projected to exceed one billion tonnes annually by 2050 if current consumption trends continue (Geyer et al. 2017). The growth of plastic production has been closely linked to population growth, urbanization, industrialization, and increasing consumer demand. Today, plastics are used in virtually every aspect of modern life, with packaging representing the largest application sector, followed by construction, consumer products, textiles, transportation, and electrical and electronic equipment (Heller et al. 2020).

The global plastics market is dominated by a relatively small number of commodity polymers, particularly polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) (Andrady and Neal 2009). These materials account for the majority of plastic products because they offer a favorable balance between performance, processability, and cost. Polyethylene and polypropylene are extensively used in packaging applications, PET is widely employed in beverage containers and food packaging, while PVC is commonly utilized in construction materials such as pipes, flooring, and window frames (Avery et al. 2025). Together, these polymers represent the backbone of global plastic production and consumption.

The widespread use of plastics, however, has resulted in the generation of unprecedented quantities of waste. Due to the short service life of many packaging products, large amounts of plastic enter the waste stream shortly after production and consumption. As illustrated in Figure 1, packaging-related polymers (PP and PE) contribute the largest share of global plastic waste generation. While plastics provide considerable societal benefits, their persistence and resistance to degradation have created significant environmental challenges. Most conventional plastics are derived from fossil resources and may remain in the environment for decades or even centuries after disposal.

The recyclability of plastics varies considerably among different polymer types. PET and high-density polyethylene (HDPE) are among the most successfully recycled materials due to established collection systems, relatively high market value, and the availability of mature recycling technologies (Benyathiar et al. 2022). In contrast, polymers such as PVC, polyurethane (PU), and PS remain difficult to recycle because of their complex composition, the presence of additives, contamination issues, and limited economic incentives for recovery (Jung et al. 2010, 2023). Consequently, substantial quantities of plastic waste continue to be disposed of in landfills, incinerated, or released into the environment.

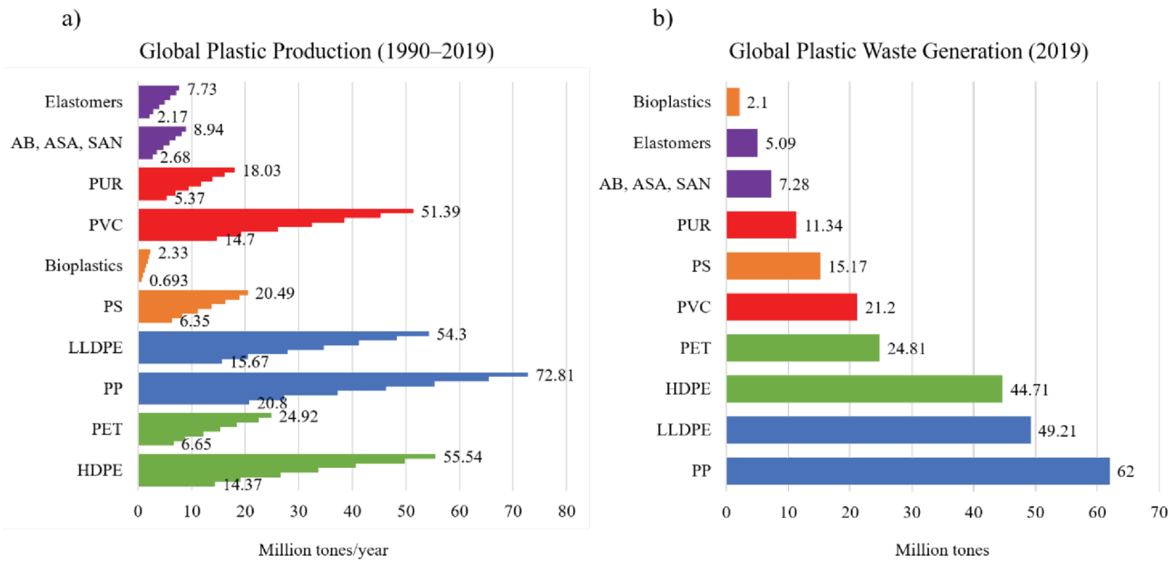

Figure 1. (a) Global production of different plastic types (1990–2019) and (b) plastic waste generation in 2019, based on data from *Our World in Data* (Ritchie et al. 2023). Polymers are color-coded to indicate recyclability: green for widely recycled, blue for moderately recycled, orange for limited recyclability, red for usually non-recycled, and violet for unknown recyclability.

The situation is becoming even more complex with the increasing development of advanced polymeric materials. Smart polymers, polymer composites, and nanocomposites often contain multiple polymer phases, nanoparticles, conductive fillers, sensors, or self-healing components that provide enhanced functionality. Although these materials offer significant technological advantages, their heterogeneous composition complicates identification, separation, and recycling processes. Furthermore, conventional recycling methods may alter or destroy the specific functionalities that justify their use, thereby limiting the feasibility of material recovery (Ivanoska-Dacikj et al. 2024; Ivanoska-Dacikj 2025). As advanced materials become more prevalent, new recycling technologies and design-for-recycling strategies will be required to ensure their sustainable end-of-life management.

These challenges have stimulated the transition from the traditional linear model of "take-make-dispose" toward a circular economy framework. The circular economy aims to minimize waste generation and maintain the value of products, materials, and resources within the economy for as long as possible. In the context of plastics, circularity can be achieved through several complementary approaches, including mechanical recycling, chemical recycling, organic recycling of biodegradable polymers, and the use of bio-based feedstocks (Chanda 2021). Mechanical recycling remains the most widely applied approach and involves the collection, sorting, cleaning, and reprocessing of plastic waste into new products. Chemical recycling technologies seek to convert plastic waste into monomers, fuels, or chemical feedstocks, thereby enabling the recovery of materials that are difficult to recycle mechanically. Organic recycling is applicable to biodegradable polymers under controlled composting conditions, while bio-based plastics offer opportunities to reduce dependence on fossil resources (Alrazen et al. 2025).

In addition to recycling technologies, circular economy strategies emphasize sustainable product design, reduction of unnecessary plastic use, increased incorporation of recycled content, extended producer responsibility (EPR) schemes, and the development of efficient collection and sorting systems. These measures not only reduce waste generation but also improve resource efficiency and contribute to climate change mitigation through reduced consumption of virgin raw materials. Nevertheless, the successful implementation of circular economy principles depends on technological innovation, supportive policy frameworks, economic incentives, and active participation from industry and consumers (Velenturf and Purnell 2021).

Although significant progress has been achieved in recent years, considerable challenges remain in closing the plastic life cycle. The effectiveness of circular economy strategies varies among regions due to differences in infrastructure, regulatory frameworks, and recycling capacities. Consequently, improving waste management systems and increasing recycling rates remain essential priorities for reducing plastic pollution and supporting the transition toward a more sustainable and resource-efficient economy.

Plastic Waste Management: Challenges and Limitations. Global Trends and North Macedonia

Despite growing recognition of the importance of circular economy principles, the management of plastic waste remains a major global challenge. The effectiveness of plastic waste management systems varies considerably among countries and regions, reflecting differences in infrastructure, economic development, technological capacity, regulatory frameworks, and public participation (Enache et al. 2025). As a result, significant disparities exist in recycling rates, landfill dependence, and the overall efficiency of resource recovery.

Globally, plastic waste is treated through a combination of recycling, energy recovery, landfill disposal, and, in some regions, uncontrolled dumping. Although recycling is considered one of the most effective strategies for reducing waste generation and conserving resources, a substantial proportion of plastic waste is still disposed of in landfills or inadequately managed. Consequently, large quantities of plastic continue to accumulate in the environment, representing a loss of valuable resources and a growing environmental burden.

Significant regional differences can be observed in plastic waste treatment practices. As illustrated in Figure 2, Europe has achieved comparatively high recycling rates through the implementation of comprehensive waste management systems, EPR schemes, deposit-return systems, and ambitious environmental legislation. In addition to material recycling, a considerable proportion of plastic waste is treated through energy recovery processes, reducing reliance on landfill disposal and supporting more circular material flows.

The United States of America continues to rely predominantly on landfill disposal, with approximately 74% of plastic waste being landfilled throughout the study period. Only a relatively small proportion is recycled or treated by incineration, and the overall distribution of waste treatment methods has changed little over the past two decades. These trends indicate that, despite advances in waste management, landfill remains the principal end-of-life option for plastic waste in the USA.

China has developed substantial recycling and waste-processing capacities, challenges related to landfill disposal, contamination of recyclable streams, and waste mismanagement remain significant (Brooks et al. 2018). The situation is particularly critical in many African countries, where insufficient collection systems, limited recycling infrastructure, and economic constraints result in low recycling rates and a high proportion of inadequately managed plastic waste (Ritchie et al. 2023).

These regional differences demonstrate that the successful implementation of circular economy

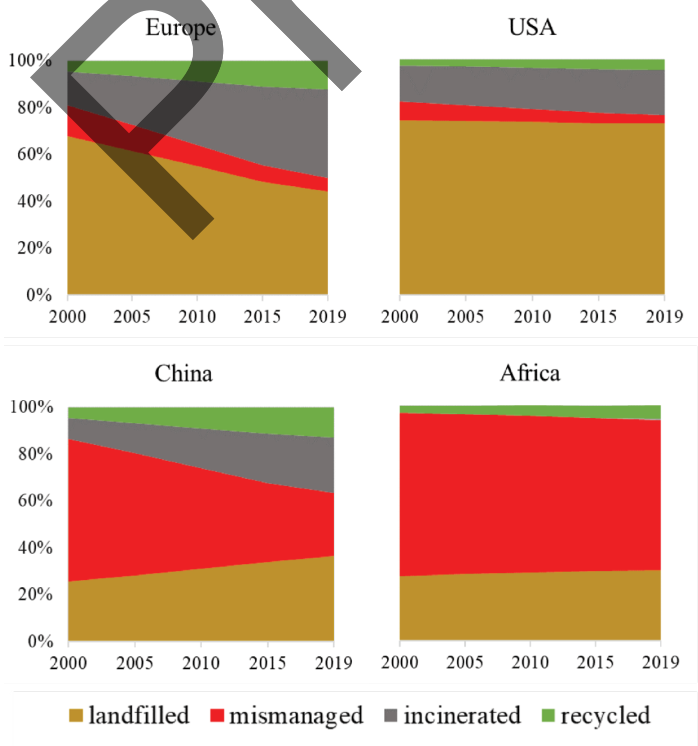

Figure 2. Plastic waste treatment in Europe, USA, China, and Africa: comparison of recycling, incineration, landfill disposal, and mismanaged waste rates, based on data from *Our World in Data* (Ritchie et al. 2023).

principles depends not only on technological solutions but also on effective governance, investment in infrastructure, and public engagement. While Europe has made substantial progress toward circular material flows through high recycling and energy recovery rates, the continued dependence on landfill disposal in the United States and the high proportion of mismanaged waste in many developing regions illustrate that significant challenges remain in reducing plastic leakage into the environment and improving resource recovery.

North Macedonia faces significant challenges in plastic waste management, reflecting broader difficulties in transitioning from a linear to a circular economy model. Despite ongoing efforts to align national environmental policies with European Union legislation, the country's recycling rate remains extremely low, estimated at approximately 0.3%, which is substantially below the European average (Switch to Green, 2024). The majority of municipal waste is disposed of in landfills, with the Drisla landfill near Skopje serving as the country's only sanitary landfill, while numerous illegal dumping sites continue to operate throughout the country. Limited waste collection coverage, insufficient sorting infrastructure, and a lack of domestic recycling capacities remain major barriers to effective waste management.

A considerable proportion of plastic waste generated in North Macedonia is exported for treatment, primarily to Turkey, highlighting the country's dependence on external recycling and recovery capacities (Municipal Waste Management in the Western Balkan Countries, 2022). Among plastic waste streams, PET bottles and HDPE packaging are the most commonly collected and recycled materials due to their relatively high market value and the availability of established recycling pathways. In contrast, polymers such as PP, PS, and PVC are rarely recovered because their collection, sorting, and recycling are technically more complex and economically less attractive (Jung et al. 2023). As a result, substantial quantities of potentially recyclable plastic materials continue to be landfilled or inadequately managed.

The challenges associated with plastic waste management are further compounded by increasing consumption of single-use plastics and the growing diversity of polymeric materials entering the market. Insufficient source separation and contamination of recyclable waste streams reduce recycling efficiency and increase treatment costs. Consequently, improving waste management infrastructure and establishing effective collection systems remain critical priorities for achieving higher recycling rates and reducing plastic leakage into the environment.

An important positive development has been the implementation of extended EPR schemes through organizations such as Pakomak, a non-profit packaging waste management company established in 2010 by leading Macedonian manufacturers. Pakomak coordinates the collection, recovery, and recycling of packaging waste in accordance with national legislation and European environmental standards. As a member of the ProEurope network and holder of the Green Dot license, the organization plays a key role in promoting producer responsibility and public awareness regarding waste management (Pakomak, 2023).

Particularly noteworthy is the introduction of reverse vending machines for the collection of PET bottles and aluminum beverage cans. These systems provide incentives for citizens to participate actively in waste separation and recycling, resulting in increased public engagement and improved collection rates. The positive response to such initiatives demonstrates the importance of combining technological solutions with economic incentives and environmental education to improve recycling performance.

The experience of North Macedonia illustrates that successful implementation of circular economy principles requires not only investment in recycling infrastructure but also stronger policy support, effective enforcement mechanisms, public participation, and regional cooperation. Expanding EPR schemes, improving waste collection and sorting systems, and increasing recycling capacities are essential steps toward reducing plastic pollution, conserving resources, and aligning national waste management practices with European sustainability objectives.

Microplastics: Formation, Distribution, Risks, and Removal Technologies

Microplastics are generally defined as plastic particles smaller than 5 mm and are increasingly recognized as contaminants of global environmental concern due to their persistence, mobility, and widespread occurrence in natural and human environments (Frias and Nash 2019; Thompson et al. 2024). Depending on their origin, microplastics can be classified as primary or secondary. Primary microplastics are intentionally manufactured in microscopic dimensions and are used in a wide range of products, including cosmetics, detergents, paints, fertilizers, plant protection products, and industrial applications. Secondary microplastics originate from the fragmentation and degradation of larger plastic items through exposure to ultraviolet radiation, mechanical abrasion, chemical weathering, and biological processes (Ari et al. 2025). While plastic leakage resulting from inadequate waste management remains a major source of microplastic pollution, significant quantities are also released unintentionally during the use of everyday products and materials. Major sources include tire wear particles, paints and coatings, plastic pellets, synthetic textiles, geotextiles, agricultural plastics, and packaging materials (Thompson et al. 2024). According to recent

European assessments, between 0.7 and 1.8 million tonnes of microplastics are unintentionally released into the environment annually in the European Union, greatly exceeding emissions from intentionally added microplastics (Schwarz et al. 2023).

The environmental distribution of microplastics reflects both the extensive use of plastic materials and the complexity of their transport pathways. Initially regarded primarily as a marine pollution problem, microplastics have now been detected in virtually all environmental compartments, including oceans, rivers, lakes, soils, sediments, glaciers, polar regions, and the atmosphere (Horton and Dixon 2018). Their occurrence in remote environments such as the Arctic demonstrates their ability to undergo long-range transport through both aquatic and atmospheric pathways. Atmospheric microplastics have attracted increasing attention because airborne particles can be transported over considerable distances before deposition (Evangeliou et al. 2020). In addition, many microplastics enter wastewater systems, where wastewater treatment plants retain a substantial fraction in sewage sludge. Since sewage sludge is frequently applied to agricultural land, this pathway may contribute to the transfer of microplastics from urban environments to terrestrial ecosystems.

The environmental risks associated with microplastics arise from both their physical properties and chemical composition. Due to their small size and large surface-to-volume ratio, microplastic particles can adsorb and transport a variety of contaminants, including heavy metals, persistent organic pollutants, and pathogenic microorganisms (Ziani et al. 2023). Consequently, microplastics can act as vectors for the transfer of hazardous substances within ecosystems. Numerous studies have documented the ingestion of microplastics by marine and freshwater organisms, invertebrates, birds, and mammals, with reported effects including reduced feeding efficiency, impaired growth, reproductive disturbances, oxidative stress, inflammation, and tissue damage (Jeong et al. 2024). Furthermore, plastic pellets, one of the major sources of microplastic pollution, are known to be ingested by marine species such as seabirds, sea turtles, and shellfish, potentially causing physical harm or mortality (Jeong et al. 2024).

In addition to ecological impacts, growing concern exists regarding human exposure to microplastics. Humans may be exposed through the consumption of contaminated food and drinking water, inhalation of airborne particles, and, to a lesser extent, dermal contact. Microplastics have been detected in human blood, lung tissue, placenta, breast milk, and other biological samples, demonstrating their ability to enter and circulate within the human body (Ragusa et al. 2021; Li et al. 2024). Although the long-term health consequences remain insufficiently understood, recent studies suggest potential links between microplastic exposure and oxidative stress, inflammation, cellular damage, endocrine disruption, and adverse immune responses (Li et al. 2024). The European Commission has identified the potential risks associated with microplastic pollution and highlighted the need for continued research into human and environmental health impacts (European Commission, 2023).

The growing evidence of the widespread occurrence and potential impacts of microplastics has led to increasing international concern and regulatory attention. Within the framework of the European Green Deal, the Circular Economy Action Plan, the Soil Strategy for 2030, and the Zero Pollution Action Plan, the European Union has identified microplastic pollution as a priority environmental challenge and established a target of reducing microplastic releases into the environment by 30% by 2030 (European Commission, 2023). Measures adopted or proposed include restrictions on intentionally added microplastics under the REACH Regulation, actions to prevent plastic pellet losses, initiatives addressing emissions from tires, textiles, and paints, and strengthened requirements for waste management and circular product design. Achieving this objective also requires the development of harmonized monitoring methodologies across environmental compartments, including marine waters, freshwater systems, wastewater, sewage sludge, soils, and drinking water, enabling comprehensive assessment of microplastic occurrence, transport pathways, and trends over time.

While preventing microplastic emissions remains the primary objective, the development of efficient treatment and removal technologies is equally important for mitigating existing environmental contamination. Conventional wastewater treatment can remove a considerable fraction of microplastics, but complete elimination remains challenging, especially for smaller particles and nanoplastics (Krishnan et al. 2023). Advanced approaches include membrane-based processes such as ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors, which are considered among the most effective technologies for retaining microplastic particles from water and wastewater (Acarer 2023). Nanotechnology-based strategies, including magnetic nanoparticles, functionalized adsorbents, and nanocomposite materials, have also been proposed for selective binding, aggregation, and magnetic separation of microplastics (Ouda et al. 2023). In addition, biological and enzymatic approaches are gaining attention, as selected microorganisms and engineered enzymes may contribute to the degradation or transformation of certain plastic polymers under controlled conditions (Cai et al. 2023). Although these methods remain at different stages of development, their integration with improved wastewater treatment and source-control measures may provide promising pathways for reducing microplastic emissions into the environment.

Atmospheric Microplastics and Moss Biomonitoring

Although microplastic research has traditionally focused on marine and freshwater environments, increasing evidence indicates that the atmosphere represents an important pathway for the transport, redistribution, and deposition of microplastic particles. Atmospheric microplastics originate from a variety of sources, including the abrasion of synthetic textiles, tire wear, degradation of packaging materials, construction products, and industrial emissions (Zhang et al. 2020b). Once released into the atmosphere, these particles can remain suspended for extended periods and be transported over considerable distances by wind and atmospheric circulation processes. Consequently, microplastics have been detected not only in densely populated urban areas but also in remote mountain regions, protected natural areas, polar environments, and marine ecosystems far from direct emission sources (Li et al. 2023).

The atmospheric transport of microplastics is increasingly recognized as a key mechanism contributing to their global distribution. Particle size, shape, density, and meteorological conditions influence atmospheric residence times and deposition patterns. Fibers, fragments, and films can be transported hundreds or even thousands of kilometers before being removed from the atmosphere through dry or wet deposition processes (Evangeliou et al. 2020). This long-range transport complicates source identification and highlights the transboundary nature of microplastic pollution, requiring coordinated international monitoring efforts and harmonized methodologies.

Given the widespread occurrence of atmospheric microplastics and the growing concerns regarding their ecological and human health impacts, reliable monitoring approaches are essential. Environmental monitoring provides valuable information on the spatial and temporal distribution of microplastics, potential emission sources, transport pathways, and deposition rates. Such information is critical for evaluating the effectiveness of waste management policies and circular economy strategies aimed at reducing plastic emissions into the environment (Prata et al. 2019; Fu et al. 2020). However, the monitoring of atmospheric microplastics remains challenging due to the lack of standardized sampling and analytical protocols, as well as the risk of contamination during sample collection and processing.

Among the available biomonitoring tools, mosses have attracted increasing attention because of their ability to accumulate airborne pollutants directly from the atmosphere. Mosses lack a well-developed root system and obtain most nutrients from atmospheric deposition, making them highly sensitive indicators of air quality. Their complex morphology, large surface area, and slow growth facilitate the retention and accumulation of particulate matter over extended periods (Roblin and Aherne 2020; Bertrim and Aherne 2023). For several decades, moss biomonitoring has been successfully applied throughout Europe for assessing the deposition of heavy metals, persistent organic pollutants, nitrogen compounds, and other atmospheric contaminants (Roblin and Aherne 2020; Stafilov et al. 2020; Bačeva Andonovska et al. 2023, 2024; Šajn et al. 2024).

The application of mosses for atmospheric microplastic monitoring is a relatively recent development (Roblin and Aherne 2020; Capozzi et al. 2023; Bertrim and Aherne 2023). Similar to airborne particulate matter, microplastic particles can become trapped on the moss surface or within its intricate structure, allowing their subsequent identification and quantification. Compared with conventional air-sampling devices, moss biomonitoring offers several advantages, including low cost, simplicity, broad spatial coverage, and the ability to integrate atmospheric deposition over longer periods. These characteristics make mosses particularly suitable for large-scale environmental surveys and regional assessments of atmospheric microplastic pollution.

Recent Evidence of Atmospheric Microplastic Deposition Across Europe

Recent efforts to harmonize atmospheric microplastic monitoring across Europe have provided valuable insights into the occurrence, composition, and distribution of airborne microplastics (Roblin et al. 2020; Cross et al. 2026b). Building upon the extensive European moss monitoring network originally established for assessing atmospheric deposition of trace elements and other pollutants, international initiatives have recently begun incorporating microplastics into biomonitoring programs. One such initiative is the MADAME (Microplastic Atmospheric Deposition Assessment using Moss in Europe) project, which involves approximately 30 countries and around 90 sampling locations (Mitacs 2024). By utilizing moss as a biomonitor, the project aims to establish a standardized framework for assessing atmospheric microplastic deposition at the continental scale and to improve understanding of the sources, transport pathways, and spatial distribution of airborne microplastics.

North Macedonia, with its long-standing experience in moss biomonitoring studies (Stafilov et al. 2020; Bačeva Andonovska et al. 2023, 2024; Šajn et al. 2024), participates in this initiative through the collection and analysis of moss samples. The inclusion of North Macedonia within a broader European monitoring network provides an opportunity to evaluate atmospheric microplastic contamination within a continental context and to contribute to the development of harmonized monitoring methodologies.

Preliminary findings reported within the framework of this initiative confirm the widespread occurrence of microplastics throughout Europe, including remote regions such as northern Scandinavia (Hayes et al. 2024 - preliminary findings from the MADAME project). The detection of microplastics in areas with limited industrial activity demonstrates that atmospheric transport is an important mechanism contributing to their long-range dispersal and deposition. Similar observations have been reported in mountain regions, polar environments, and other remote locations, further supporting the view that atmospheric microplastics represent a transboundary environmental issue that cannot be addressed solely through local mitigation measures (Evangeliou et al. 2020).

The identified microplastic particles consisted predominantly of fibers, foams, and packaging-related fragments, reflecting the diversity of emission sources associated with modern society. Analysis of polymer composition revealed the presence of a broad range of synthetic materials. Among the detected polymers, polybutylene terephthalate (PBT), PU, PVC, PE, and acrylonitrile-butadiene-styrene (ABS) were frequently reported (Figure 3) (Hayes et al. 2024 - preliminary findings from the MADAME project) The occurrence of these polymers suggests contributions from packaging materials, synthetic textiles, construction products, insulation materials, automotive components, and other consumer goods. Compared with several previous studies, a relatively higher proportion of packaging-related polymers was observed, indicating the continuing importance of packaging waste as a source of environmental microplastic contamination (Zhang et al. 2020a; Dahal and Babel 2025).

The preliminary European dataset also highlights considerable spatial variability in atmospheric microplastic deposition. Mean microplastic concentrations varied substantially among countries, ranging from less than 1 µg g⁻¹ dry moss in some regions to values exceeding 6 µg g⁻¹ in others (Figure 4a). Such differences likely reflect variations in population density, industrial activity, transportation intensity, waste management practices, meteorological conditions, and long-range atmospheric transport processes. Importantly, detectable concentrations were reported not only in urban environments but also in rural regions of Finland, Norway, and Ireland, demonstrating that atmospheric microplastic pollution is not restricted to highly populated or industrialized areas.

Within this European context, North Macedonia exhibited intermediate microplastic concentrations, approximately corresponding to the European average. Although the available dataset remains limited, these observations indicate that atmospheric microplastic contamination is also present under the diverse geographical and socio-economic conditions characteristic of the country. The findings are particularly relevant given the ongoing challenges associated with plastic waste management and recycling infrastructure discussed in previous sections.

The polymer composition reported for the analyzed samples provides additional information regarding potential emission sources (Figure 4b). PVC represented the dominant polymer fraction, followed by cellulose acetate (CA), PBT, and PU. Smaller contributions of polymethyl methacrylate (PMMA), PS, PP, and silicone were also identified. This diversity of polymer types reflects the complexity of atmospheric microplastic pollution and suggests contributions from multiple sectors, including packaging, construction, transportation, textiles, insulation materials, and cigarette filters.

These preliminary observations further emphasize the close relationship between plastic production, consumption patterns, waste management practices, and environmental contamination. The occurrence of microplastics across Europe, including remote regions,

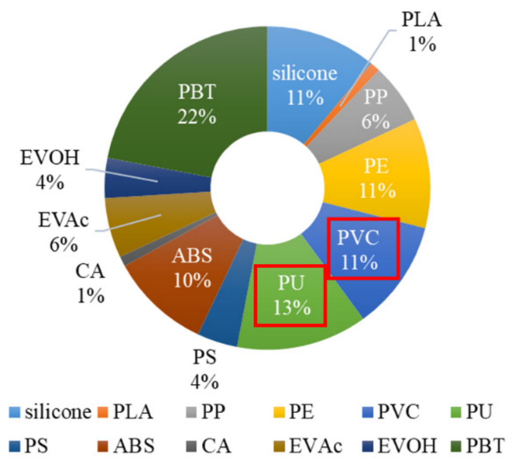

Figure 3. Relative abundance of polymer types identified in moss samples from the MADAME project (Hayes et al. 2024 - preliminary findings from the MADAME project).

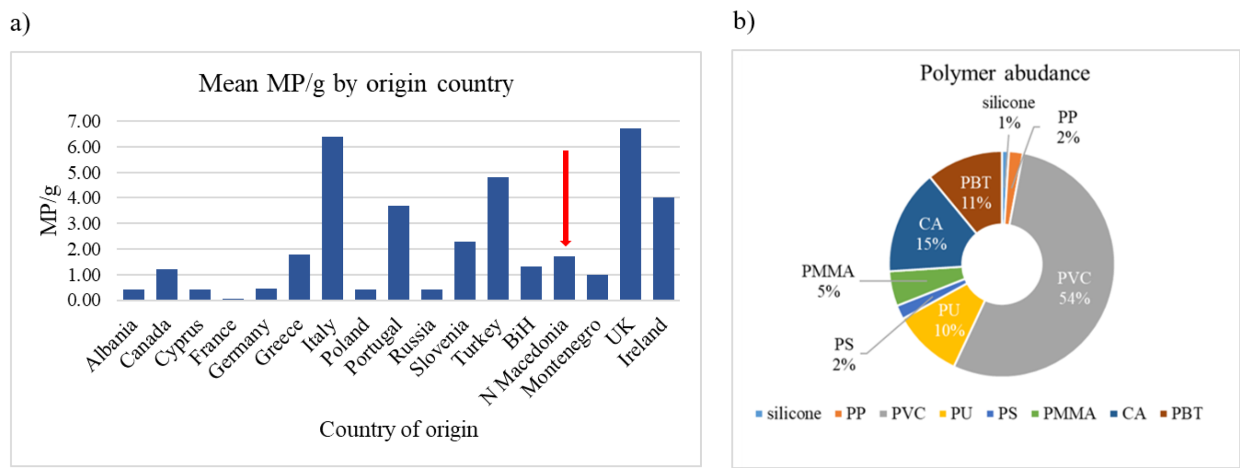

Figure 4. (a) Mean microplastic concentration (MP g⁻¹ dry moss) in moss samples from different European countries; (b) distribution of polymer types identified in the analyzed microplastic samples (Hayes et al. 2024 - preliminary findings from the MADAME project).

demonstrates that plastic pollution extends beyond visible waste accumulation and that atmospheric transport contributes significantly to its redistribution. Consequently, measures aimed at reducing plastic leakage into the environment–including improved waste management systems, increased recycling rates, extended producer responsibility schemes, sustainable product design, and the broader implementation of circular economy principles–are likely to contribute not only to waste reduction but also to the mitigation of atmospheric microplastic pollution.

From a monitoring perspective, the results demonstrate the potential of moss biomonitoring as a cost-effective tool for assessing atmospheric microplastic deposition over large geographical areas. Continued monitoring efforts, expanded spatial coverage, and methodological harmonization will be essential for establishing long-term trends, identifying major emission sources, and evaluating the effectiveness of future environmental and circular economy policies. For North Macedonia, participation in European monitoring initiatives represents an important opportunity to strengthen national environmental monitoring capacities and to contribute to a broader understanding of atmospheric microplastic pollution at the regional and continental levels.

Conclusion

The continuous growth of plastic production has intensified the challenges associated with plastic waste management and the widespread occurrence of microplastics in terrestrial, aquatic, and atmospheric environments. These issues highlight the close relationship between plastic waste generation, microplastic pollution, and the need to transition from a linear to a circular economy. Effective mitigation requires a combination of improved waste management, sustainable product design, increased recycling, and extended producer responsibility to reduce plastic leakage at its source. In parallel, emerging removal technologies, including advanced membrane systems, magnetic separation, and biological degradation, show promise for reducing microplastic contamination, although further research is needed before their large-scale implementation.

Recent studies demonstrate that atmospheric transport is an important pathway for the dispersal of microplastics, while moss biomonitoring has emerged as a promising and cost-effective approach for assessing their deposition over large geographical areas. Preliminary observations from Europe, including North Macedonia, confirm the widespread occurrence of atmospheric microplastics and demonstrate the potential of biomonitoring networks to provide valuable information on their distribution, composition, and possible sources.

Future efforts should focus on the harmonization of monitoring methodologies, the expansion of long-term environmental surveillance programs, and the integration of monitoring data into waste management and circular economy policies. Strengthening cooperation between researchers, policymakers, industry, and the public will be essential for developing effective strategies to reduce plastic emissions and mitigate the environmental and health risks associated with microplastic pollution. Such an integrated approach will contribute to achieving more sustainable resource management and supporting the transition toward a cleaner and more circular society.

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