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Review article

Microplastic contamination of bryophytes: A review on mechanisms and impacts

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ABSTRACT

This systematic review investigates the interactions of microplastics (MPs) and nanoplastics (NPs) with bryophytes, incorporating findings from 11 articles identified through a comprehensive database search using a combination of keywords. The review explores mechanisms such as adsorption and internalization by which MPs and NPs are present in bryophytes and examines the ecological ramifications, including changes in bryophyte community structure and impacts on ecosystem functions such as nutrient cycling, soil formation, habitat provision, water balance, and erosion control. Despite providing valuable insights, this review highlights several critical knowledge gaps that warrant further investigation. Future research should address the following areas: the long-term effects of MPs and NPs on bryophyte health and survival, the mechanisms of MP and NP uptake and translocation within bryophytes, and the broader ecological consequences of plastic pollution on bryophyte-dominated ecosystems. Additionally, studies should explore the effectiveness of various mitigation and management strategies, including advanced waste management techniques and innovative technologies, in reducing plastic pollution and protecting these vital ecosystems.

1. Introduction

Microplastics (MPs) and nanoplastics (NPs) have become pervasive pollutants in various environments, raising concerns about their impact on ecosystems and human health. Studies have identified MPs as contaminants in aquatic habitats globally, with wastewater treatment plants serving as significant sources of MPs, particularly through sewage contaminated by fibers from washing clothes [1]. MPs are small plastic particles up to 5 mm in size [2]. NPs, on the other hand, are even smaller plastic particles, typically defined as being below 1000 nm or 100 nm, depending on the specific definition used [3]. Research has documented the presence of MPs in ocean habitats worldwide and in freshwater ecosystems [4], emphasizing the global distribution and environmental persistence of these pollutants. The prevalence of MP particles across marine, freshwater, or even atmospheric systems has captured the attention of scientists, politicians, and members of the public worldwide these days [5] because they cause detrimental effects on biota [6]. Among them, blue MPs were mainly comprised of fragments and lines (most probably fishing lines and plastic straws) [7]. When MPs are exposed in the natural environment, absorption of chemical contaminants and the formation of biofilms further enhance their complexity [8]. The issue raises concern since MPs are considered vectors of endocrine-disrupting compounds (EDCs) in the aquatic environment [9].

Bryophytes, which include mosses, liverworts, and hornworts, are vital for ecosystems due to their multifaceted roles. These small,

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often-overlooked non-vascular plants are foundational in many habitats, contributing significantly to biodiversity and ecological processes [10]. Bryophytes are essential for nutrient cycling as they decompose organic material, releasing nutrients back into the soil [11]. They aid in soil formation by trapping and stabilizing soil particles, preventing erosion, and maintaining soil moisture [12]. Furthermore, bryophytes provide microhabitats for numerous microorganisms, invertebrates, and fungi, enhancing habitat complexity and supporting a diverse range of species [13]. Their ability to retain water helps regulate water balance in ecosystems [12], and their sensitivity to environmental changes makes them valuable bioindicators for assessing ecosystem health and detecting pollution or climatic shifts [14].

However, the bryophyte community is increasingly threatened by the presence of MPs and NPs in the environment. MPs and NPs can infiltrate bryophyte habitats through air and water [15]. These plastics can physically damage plant tissues, obstructing their ability to absorb water and nutrients. Additionally, MPs and NPs may carry toxic substances that can be absorbed by bryophytes, leading to physiological stress, reduced growth, and impaired reproductive capabilities [16]. The accumulation of these plastics in bryophyte-dominated ecosystems can disrupt nutrient cycling and soil formation processes, ultimately affecting the entire ecological community. Understanding the impact of MPs and NPs on bryophytes is crucial for developing strategies to mitigate pollution and protect these essential components of ecosystems.

This review aims to comprehensively analyze the effects of MPs/NPs on bryophytes within diverse ecosystems. By synthesizing current knowledge and research findings, this review intends to elucidate the mechanisms of interaction between plastic particles and bryophytes, assess the physiological and ecological impacts on these organisms, and discuss the implications for broader ecosystem dynamics. Furthermore, it aims to identify research gaps, challenges, and future directions in this emerging field, offering insights to guide future studies and management strategies concerning plastic pollution's impact on bryophyte-dominated ecosystems.

2. Materials and methods

To retrieve peer-reviewed articles and conference proceedings on MP and NP interactions in bryophytes, a systematic review following PRISMA guidelines was conducted. Online searches were performed using Google Scholar, PubMed, ScienceDirect, and JSTOR databases. Additional references cited by various authors were included if they were not identified in the initial searches. The search strategy employed keywords such as "Detection," "Presence," "Abundance," "Accumulation," "Contamination," "Uptake," "Exposure," AND "Microplastics," AND "Bryophytes." This keyword combination initially yielded 390 publications in Google Scholar, six publications in PubMed, 39 publications in ScienceDirect, and 0 publications in JSTOR.

Literature was accessed and screened based on inclusion and exclusion criteria (Table 1). In reviewing data literacy, the publication year, title, and abstract were examined to identify relevant topics. The full text was then reviewed, focusing on MP and NP interactions in bryophytes, results, and conclusions to determine the suitability of the data as sources up to April 2024. Qualitative and quantitative analyses were conducted to provide a comprehensive overview of MP/NP research in bryophytes. All 11 selected relevant publications were read in full to gather necessary information for the analysis. The discussion of results emphasized identifying research gaps and opportunities in this emerging field.

3. Synthesis of evidence

In total, the author obtained 11 relevant publications dealing with the interaction between plastic particles and bryophytes, covering various database records up to 2024, as shown in Table 2.

3.1. *MP contamination across bryophyte families*

MPs and NPs have been identified in multiple species of bryophytes, all belonging to the group of mosses from various families, including Sphagnaceae, Hylocomiaceae, Fontinalaceae, Hypnaceae, Pottiaceae, Brachytheciaceae, and Grimmiaceae. Notably, some families such as Sphagnaceae, Hylocomiaceae, Hypnaceae, and Brachytheciaceae are mentioned multiple times, indicating recurring observations of MP contamination within these groups (Table 1).

3.2. *Comprehensive analysis of MPs/NPs in bryophytes*

3.2.1. *Sources and pathways of MP and NP pollution in bryophytes*

MPs and NPs originate from a variety of sources, broadly classified into primary and secondary categories. Primary MPs are manufactured at small sizes for specific industrial applications [28,29], such as in cosmetics (e.g., microbeads), personal care products,

Table 1
The exclusion and inclusion criteria in the literature search.

Criteria	Description
Exclusion	Editorials, letters, book, encyclopedia, Non-English publication, Duplicate publication
Inclusion	There is no limit on research location, Detecting microplastics in bryophytes, Microplastics contamination in bryophytes, Examining size, shape and type of microplastics in bryophytes, Accumulation of microplastics in bryophytes, Uptake of microplastics in bryophytes, Presence of microplastics in bryophytes, and Abundance of microplastics in bryophytes

Table 2
The presence of MPs in different species of bryophytes, the types and sizes of MPs, detection methods, sources of plastic particles, interactions of MPs with bryophytes, effects, and the localization of plastic particles in bryophytes.

Bryophyte species	Group of Bryophytes	Family	Types/Size of plastic particles	Detection method (s)	Source of plastic particles	Sample tested	External adsorption/ accumulation	Internal uptake	Effects occurred	Plastic particle tissue localization	(Putative) mechanisms	Reference
Sphagnum palustre L.	Moss	Sphagnaceae	Polystyrene nanoparticles (NPs)	Fluorescent microscopy	Freshwater ecosystems	Lab experiment	Yes	Yes	Cell membrane damage	Substantial clusters predominantly adhered to the surface of leaves, while individual nanoparticles were found within hyalocysts (empty cells with pores measuring 5–10 μm in diameter) and the cytoplasm.	The adsorption of nanoparticles is a result of particle aggregation, while their internalization occurs due to their small size.	[17]
Hylocomium splendens	Moss	Hylocomiaceae	MPs (0.83–1.20 mm), Synthetic dye Indigo ($C_{16}H_{10}N_2O_2$)	Stereo microscopy & Raman microscopy	Atmospheric deposition	Field sampling	NA	NA	NA	NA	NA	[18]
Fontinalis antipyretica	Moss	Fontinalaceae	MPs (5–25 mm), MPs (0.001–5 mm), commonly plyethylene and polyamide type 6	FT-IR microscropy	Freshwater ecosystems	Field experiment	NA	Yes?	NA	NA	NA	[19]
Pleurozium schreberi	Moss	Hylocomiaceae	MPs (0.03–4.51 mm), mainly fibres and fragments	Stereo microscopy	Atmospheric deposition	Field experiment	Yes	Yes?	NA	NA	NA	[20]
Hypnum cupressiforme	Moss	Hypnaceae	MPs (<5 mm), mostly microfibres	FT-IR microscropy	Atmospheric deposition	Field sampling	Yes	Yes?	NA	NA	NA	[21]
Hypnum cupressiforme	Moss	Hypnaceae	MPs (<5 mm), mostly filamentous	FT-IR microscropy	Atmospheric deposition	Field experiment	Yes	Yes	NA	NA	NA	[22]
Sphagnum spp.	Moss	Sphagnaceae	MPs (0.8–65.4 μm)	Dark-field color-spectral imaging microscopy	Atmospheric deposition	Commercial *Sphagnum* moss	NA	NA	NA	NA	NA	[23]
Cinclidotus aquaticus *Rhynchostegium raparioides*	Moss Moss	Pottiaceae Brachytheciaceae	MPs (polyethylene, polystyrene and polypropylene)	Stereo microscopy & Raman microscopy	Freshwater ecosystems	Microcosm experiment	Yes	NA	Mild response i.e., changes in fatty acid metabolism	Adsorbed to the surface of the moss	Adsorption	[24]
Pseudoscleropodium purum	Moss	Brachytheciaceae	MP fibers and fragments		Atmospheric deposition	Field sampling	Yes	NA	NA	NA	NA	[25]
Moss sample	Moss	NA	MPs (PET, PS, PP, and PE)	TED-GC-MS and Raman microspectroscopy	Atmospheric deposition	Field sampling	Yes	NA	NA	NA	NA	[26]
Grimmia critina	Moss	Grimmiaceae	MPs and microrubbers (MRs)	Stereo microscopy & Raman microscopy	Atmospheric deposition	Field sampling	Yes	NA	NA	NA	NA	[27]

Remark: NA = not available.

cleaning agents, and industrial abrasives (pellets and flakes) [30]. The intentional use of primary MPs, such as solid polymer particles in agriculture and cosmetics, is a subject of discussion regarding environmental safety and innovation [31], leading to their direct release into the environment [32]. Secondary MPs, on the other hand, result from the fragmentation of larger plastic debris due to environmental weathering processes like UV radiation, mechanical abrasion, and chemical degradation [33–36]. The pervasive use of plastics in modern society ensures that MPs and NPs are continually introduced into the environment [37] through waste mismanagement [38], runoff [39], and atmospheric deposition [40].

In this review, the main sources of plastic particles, including MPs and NPs, on bryophytes were predominantly from atmospheric deposition [18,20–23,25–27] and freshwater ecosystems [17,19,24]. Atmospheric deposition was identified as the source in seven studies, while freshwater ecosystems were cited in three studies (Table 2). This indicates that bryophytes, due to their widespread distribution and surface characteristics, are effective in capturing plastic particles from both air and water environments, underscoring their potential role as indicators of environmental plastic pollution.

Illustrating the pathway of plastic particles in the environment, Fig. 1 summarizes how bryophytes come into contact with MPs through deposition from the air, transport via water, and soil contamination. These pathways highlight the pervasive nature of MP pollution and its potential impact on bryophyte communities.

3.2.2. *Types and sizes of plastic particle detected on/in bryophytes*

The 11 publications on MPs and NPs in bryophytes report various types and sizes of plastic particles detected (Table 2). Polystyrene NPs and MPs ranging from 0.83 mm to 65.4 μm were identified, including synthetic dye Indigo ($C_{16}H_{10}N_2O_2$), polyethylene, polyamide type 6, and polypropylene. The sizes of MPs varied widely, from less than 5 mm–25 mm, with common forms being fibers and fragments. Several studies highlighted that MPs were predominantly microfibers and filamentous particles used in clothing [41–43]. Additionally, polyethylene terephthalate (PET), polystyrene (PS), and microrubbers (MRs) were detected among the identified plastic types. This variety in types and sizes underscores the extensive presence and potential for bioaccumulation and ecological implications of plastic pollution in bryophyte communities.

3.2.3. *Distribution of plastic particles in natural habitats and bryophytes*

The publication search in Table 2 indicated that wind and water currents might play significant roles in the transportation and dispersion of plastic particles [44] into bryophyte habitats such as forest species [21] and freshwater species [19]. These findings underscore the widespread distribution of MPs/NPs and their infiltration into seemingly undisturbed natural habitats, highlighting the urgent need for comprehensive research on their ecological impacts.

The distribution of MPs and NPs in natural habitats, particularly in river systems, is influenced by various factors. Land use types, such as runoff, rainstorms, atmospheric deposition, and sewage discharge, significantly impact the transport of them from land to rivers [45]. Estuaries, as transitional zones between rivers and oceans, play a crucial role in the migration of MPs and NPs [46]. Additionally, river flow speed and anthropogenic activities around rivers affect the distribution and accumulation of MPs and NPs in

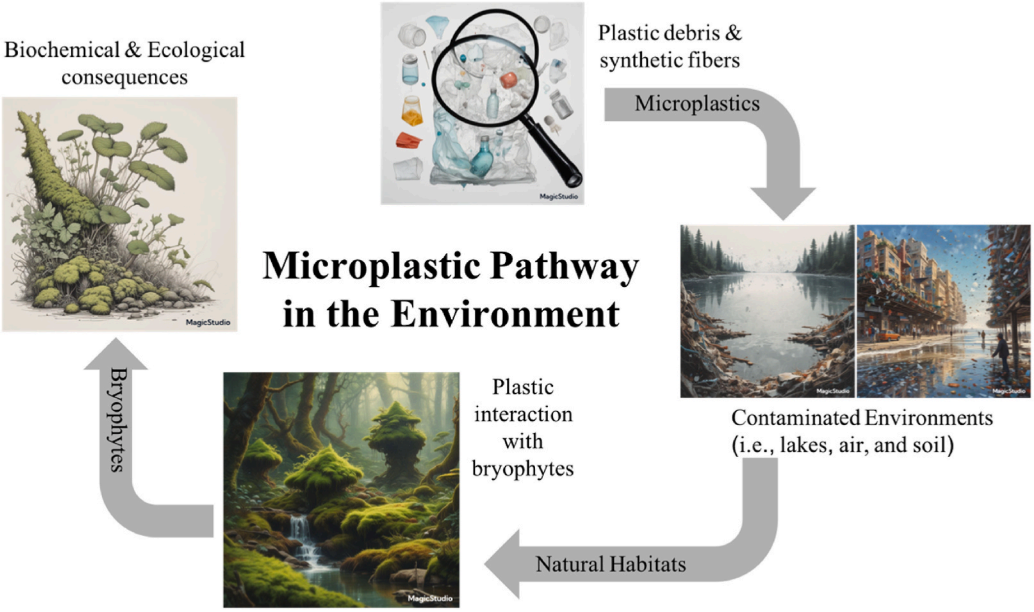

Fig. 1. The pathway of MPs contaminating the natural habitats of bryophytes. (Created with MagicStudio).

surface water and sediments [47].

Studies have shown that fibrous MPs are a predominant component in river sediments, with particle size influencing their retention in riverbed sediment [48,49]. Modeling approaches have also been employed to understand the pathways and transport of MPs in river systems, evaluating their impacts on water quality and exploring mitigation strategies [50].

Overall, these findings emphasize the pervasive nature of plastic pollution in natural environments and raise concerns about its potential impacts on bryophyte ecosystems. The wide range of plastic types and sizes detected suggests multiple sources and pathways for plastic contamination in these habitats. Understanding the distribution and accumulation patterns of MPs and NPs in bryophytes and their natural habitats is crucial for assessing their ecological consequences and developing effective mitigation strategies to protect these sensitive ecosystems. Further research is warranted to elucidate the mechanisms of interaction between MPs and NPs and bryophytes, as well as their broader implications for environmental health.

3.3. Specific mechanisms of MPs and NPs interaction with bryophytes

3.3.1. Adsorption and accumulation on bryophyte surfaces

Among the 11 publications on MPs and NPs in bryophytes, external adsorption and accumulation were examined. Eight studies confirmed the external adsorption and accumulation of plastic particles on bryophytes (Table 2), emphasizing their ability to adhere to the surfaces of these non-vascular plants. Three publications did not provide relevant data on this interaction, indicating gaps in the literature. This recurring observation of external adsorption and accumulation underscores the potential for bryophytes to serve as indicators of plastic pollution in various ecosystems.

Despite the limited understanding of the mechanisms of MPs and NPs interactions with bryophytes in literature published since 2000, recent research suggests that submicron plastics (SMPs <1 μm) physically interact with bryophytes through adsorption and accumulation on their surfaces [51]. Bryophytes have a high surface area relative to their volume [52], making them effective at capturing airborne and water-suspended particles, including MPs [17–27]. The leaf-like structures (phyllids) and rhizoids of bryophytes provide numerous sites for the physical adherence of MPs [53]. Environmental factors such as wind, water flow, and precipitation facilitate the deposition of these particles onto bryophyte surfaces. Once adhered, MPs can persist on bryophytes, potentially affecting their photosynthetic efficiency by shading light or altering their surface chemistry [53].

3.3.2. Uptake and internalization of plastic particles

In the 11 publications on plastic particles in bryophytes, internal uptake was a key focus. Five studies suggested the possibility of internal uptake of plastic particles by bryophytes, indicated by a "Yes/Yes?" due to varying levels of evidence and confirmation (Table 2). Six publications did not provide relevant data on internal uptake, highlighting significant gaps in the literature. The potential internalization of MPs and NPs in bryophytes warrants further research to understand the extent and implications of such uptake for these plants and the broader ecosystem. Once inside bryophyte cells, plastic particles are believed to travel through their internal structures, potentially interfering with cellular processes. Internalization of NPs might affect enzymatic activities in bryophytes, potentially leading to genotoxicity and oxidative damage, thereby impacting their health [54]. Understanding the pathways and impacts of MP and NP internalization in bryophytes is crucial for assessing ecological risks.

As shown in Table 2, both MPs and NPs have the potential to be easily taken up and internalized by bryophytes due to their small size [17,53]. Evidence shows that NPs can penetrate plant tissues through passive diffusion [17,51,55] or active transport mechanisms [56]. However, a review by Tang in vascular plants [54] suggested that MPs can also be internalized by specific plant cells through mechanisms such as endocytosis and taken up via roots, accumulating and being transported in vascular bundles via transpiration through stomata in leaves. These mechanisms may differ in non-vascular plants like bryophytes, as transpiration through stomata is not known [52]. In bryophytes, stomata are present only in the capsule wall of mosses and hornworts (but not in liverworts) during the sporophytic phase [57], where they are implicated in the drying and dehiscence of the sporangium [58] and in facilitating carbon uptake by sporophytes [59].

3.4. Physiological effects of MPs and NPs on bryophytes

3.4.1. Photosynthesis and growth

The literature on the physiological impacts of MPs and NPs on bryophytes is limited, as shown in Table 2. However, existing studies suggest that MPs and NPs may obstruct light penetration and gas exchange [60], thereby impairing photosynthesis in bryophytes. Capozzi et al. [17] found that polystyrene NPs reduced growth rates and chlorophyll levels in peat moss (*Sphagnum palustre*), indicating stress and disrupted photosynthesis. Molin et al. [61] associated MP pollution with reduced respiration in flowering vascular plants submerged in marine environments, such as seagrass (*Zostera marina*) and its epiphytes, suggesting similar effects in bryophytes. Cao et al. [62] demonstrated that 1 μm MP inhibited growth and reduced photosynthetic pigment content in the freshwater algae *Chlorella pyrenoidosa*, inducing oxidative stress and damaging cell membranes. Lee et al. [63] reviewed the broader effects of MPs and NPs on cellular mitochondrial function, noting increased reactive oxygen species (ROS) and decreased mitochondrial membrane potential [64]. Consequently, prolonged exposure to MPs and NPs could stunt growth and impair reproductive success in bryophytes.

3.4.2. Nutrient uptake and metabolism

Bryophytes rely on efficient nutrient uptake mechanisms, including cell wall cation exchange capacities (CEC) [65] and water absorption, facilitated by their unique physiological structures [66]. The presence of MPs/NPs on bryophyte surfaces can block nutrient absorption sites or alter nutrient availability in the surrounding environment. In a study by Changmai et al. [67], it was found that increasing concentrations of PVC-microplastic (2.5, 5, 7.5, and 10 % w/w) in the soil did not cause any observable phytotoxic symptoms, such as chlorosis or necrosis, in tomato plants. However, there was a dose-dependent reduction in plant growth-related parameters, including height, leaf area, stem diameter, and plant fresh and dry weight. It is possible that MPs/NPs internalized by bryophyte cells may interfere with cellular nutrient transport mechanisms, leading to nutrient imbalances and metabolic dysregulation. However, the study of changes in nutrient uptake and metabolism induced by MPs and NPs impairing essential physiological processes necessary for bryophyte growth, reproduction, and adaptation to environmental stresses is scarce in the current literature. Understanding the effects of MPs/NPs on the nutrient uptake of bryophytes is critical for evaluating their ecological impacts and developing strategies to mitigate plastic pollution in terrestrial ecosystems. Further research is necessary to elucidate the long-term consequences of plastic exposure on bryophyte populations and their interactions within ecological communities.

4. Ecological consequences

4.1. Alterations in bryophyte community structure and diversity

The infiltration of MPs and NPs into natural habitats can significantly alter the community structure and diversity of bryophytes. Bryophytes are particularly sensitive to environmental changes [68,69]. Studies have indicated that MPs can affect substrate quality and have ecotoxicological impacts on biota [70–72], raising questions about shifts in bryophyte species composition and abundance. The presence of MPs might favor certain bryophyte species that can tolerate or exploit these pollutants, thereby reducing overall species diversity. Changes in community structure could have cascading effects on ecosystems, as different bryophyte species contribute uniquely to their habitats. Zhang et al. [73] tested six common MPs (EPS, PET, HDPE, PP, PLA, and PA6) with either homogeneous or heterogeneous distribution in soil. Results showed that plant biomass was generally higher in homogeneous treatments for PET and PP, but lower for PLA. In heterogeneous treatments, biomass varied depending on the MP type. EPS decreased community evenness, while PET increased it. Therefore, future research should examine the numerous interactions between MPs and soil quality, as well as their ecotoxicological impacts on bryophyte communities, within the broader context of global environmental change.

4.2. Effects on bryophyte roles in nutrient cycling and moisture retention

Bryophytes play a crucial role in nutrient cycling and moisture retention within their ecosystems [66]. The introduction of MPs into bryophyte habitats can disrupt these essential functions. MPs can interfere with plants' ability to absorb water and nutrients [74], potentially altering their growth and physiological processes. Furthermore, the adsorption of organic pollutants by MPs can lead to the bioaccumulation of harmful substances in bryophyte tissues, affecting their health and their ability to participate in nutrient cycling [75]. This disruption can lead to a decrease in the efficiency of nutrient and water retention, impacting the broader ecological processes. Therefore, future research in environmental toxicology should address the toxicological assessment of the combined effects of MPs, NPs and their sorbed pollutants on bryophytes.

4.3. Implications for ecosystem functions where bryophytes are key species

Bryophytes are often key species in their ecosystems, contributing to soil formation, stabilizing substrates, and providing habitat for various microorganisms and invertebrates [12,13]. The ecological consequences of MP contamination in bryophyte-dominated habitats are profound. The impairment of bryophytes' health and function due to MP pollution can lead to weakened soil structure and increased erosion [76]. Moreover, the decline in bryophyte health can reduce habitat availability for other species [68], thereby diminishing biodiversity. The overall ecosystem function can be compromised, affecting everything from water filtration to the support of food webs. Understanding and mitigating the impact of MPs on bryophytes is crucial for preserving the integrity of these ecosystems.

5. Methodological approaches in studying MP/NP effects on bryophytes

5.1. Experimental designs and field studies

To understand the impacts of MPs and NPs on bryophytes, researchers have employed a variety of experimental designs and field studies (Table 2). Laboratory experiments often involve exposing bryophyte samples to known concentrations of MPs under controlled conditions, allowing for the detailed examination of physiological and/or biochemical responses [17–21]. These studies are complemented by field research, which involves collecting bryophyte samples from environments with varying levels of MP contamination [21–23,25]. Field studies provide valuable insights into real-world scenarios, capturing the complexity of natural ecosystems and the multitude of factors influencing bryophyte health and function. Combining laboratory and field approaches enables a comprehensive understanding of how MPs affect bryophytes across different contexts.

5.2. Techniques for detecting and quantifying MPs in bryophytes

Detecting and quantifying MPs in bryophytes is a critical aspect of this research. Table 2 summarizes the current techniques used for detecting and characterizing plastic particles in bryophytes. These diverse detection methods highlight the range of techniques available for identifying and analyzing MPs and NPs in bryophytes. Notably, several techniques such as stereomicroscopy, FT-IR, SEM, Pyr-GC/MS, and Raman spectroscopy are employed for the identification and quantification of MPs in environmental samples. Each technique has its limitations and quality control requirements for accurate results [77].

Advanced analytical techniques like Fourier-transform infrared (FT-IR) spectroscopy and Raman spectroscopy are commonly used to identify and characterize MPs in environmental samples [78]. Both methods are effective, allowing for precise determination of plastic type and size, but sometimes a combination is needed for reliable identification, especially for colored particles. For particles smaller than 400 μm, Raman imaging detected about 35 % more MPs than FT-IR imaging, particularly for those under 20 μm, although Raman imaging took longer. The study suggests dividing smaller MPs into two size ranges: 500–50 μm for quick FT-IR analysis and 50–1 μm for detailed Raman analysis [78].

Microscopic techniques, such as scanning electron microscopy (SEM) and fluorescence microscopy, are also employed to visualize and measure MPs within samples [77]. Additionally, the application of optical and electron microscopy for analyzing and characterizing MPs/NPs in aquatic environments is described by Girão [79]. Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) is particularly important for identifying MP-associated pollutants, such as toxic metals. These techniques provide detailed images of MP particles, helping to understand their distribution and interaction with bryophyte tissues. Combining these methods with chemical analysis enables researchers to quantify the concentration of MPs and assess their potential effects on bryophytes.

5.3. Limitations and challenges in current research methods

Despite the advancements in methodology, studying the effects of MPs and NPs on bryophytes presents several limitations and challenges. One significant challenge is the difficulty in replicating natural conditions within laboratory settings, which may not fully capture the complexity of field environments. Additionally, the detection and quantification of NPs remain particularly challenging due to their extremely small size and the limitations of current analytical techniques. Furthermore, there is a need for standardized protocols and methodologies to ensure consistency and comparability across different studies [77]. The variability in MP types, sizes, and environmental concentrations also adds to the complexity of research [80], making it difficult to draw broad conclusions. Addressing these challenges is essential for advancing our understanding of MP impacts on bryophytes and informing effective environmental policies and conservation strategies.

6. Mitigation and management strategies

6.1. Potential strategies to reduce MP pollution

Mitigating MP pollution requires a multifaceted approach that addresses both primary and secondary sources of contamination. One effective strategy involves improving waste management practices to minimize plastic leakage into the environment. Research indicates that an integrated waste management system focusing on the four R's hierarchy (reduce, reuse, recycle, recover) and enhancing the life-cycle of plastics is essential to reduce energy and resource consumption, prevent harmful emissions, and decrease the amount of mismanaged plastic waste reaching the oceans [81]. Additionally, strategies such as recycling and recovery of plastic waste, particularly polyethylene terephthalate (PET), play a significant role in reducing energy and resource depletion, avoiding harmful emissions, and minimizing the quantities of mismanaged plastic waste entering the environment [82]. Innovative technologies, such as electrocoagulation processes, natural coagulation, membrane filtration, and sand filtration in wastewater treatment plants [31,83–85], also hold promise in capturing MPs before they enter aquatic and terrestrial ecosystems. Immediate and vigorous action is essential to curb plastic waste generation and accumulation, underscoring the importance of international collaboration in achieving substantial reductions in plastic pollution [86].

6.2. Management practices to protect bryophyte habitats from MP contamination

Protecting bryophyte habitats from MP contamination requires tailored management practices that consider the unique ecological characteristics of these organisms. Conservation efforts should prioritize minimizing direct sources of MPs in sensitive habitats such as forests, wetlands, and freshwater ecosystems where bryophytes thrive. This includes implementing buffer zones around bryophyte-rich areas to reduce runoff carrying MPs, adopting sustainable land use practices that minimize disturbance to natural habitats, and promoting revegetation initiatives to enhance ecosystem resilience. Monitoring programs specifically targeting bryophyte communities can provide early detection of MP impacts, guiding adaptive management strategies to mitigate further contamination.

6.3. Future research directions and policy implications

Future research on MPs and bryophytes should focus on expanding our understanding of ecological interactions and long-term impacts. Key research priorities include investigating the mechanisms of MP uptake and accumulation in bryophyte tissues, assessing the bioaccumulation and transfer of MPs through food webs, and elucidating the synergistic effects of MPs with other environmental stressors. Integrating advanced analytical techniques and modeling approaches will be essential for quantifying MP loads in bryophyte habitats and predicting their ecological consequences. Policy implications should emphasize the integration of MP management into broader environmental policies, promoting interdisciplinary collaborations between scientists, policymakers, and stakeholders to develop effective mitigation strategies. Strengthening international regulations and standards for monitoring and reducing MP pollution will be critical for safeguarding bryophyte habitats and preserving ecosystem health for future generations.

7. Conclusion

In conclusion, this review underscores the pervasive presence of MPs and NPs in bryophyte-dominated ecosystems and highlights their profound impact on these crucial plant communities. The evidence synthesized reveals that MPs and NPs are widely distributed in bryophytes, originating from atmospheric deposition and freshwater systems, and affecting various bryophyte families. The interaction mechanisms, including adsorption, accumulation, and potential internalization of these particles, have been observed, though further research is needed to fully elucidate their implications. The physiological effects, such as altered photosynthesis, reduced growth, and disrupted nutrient uptake, point to significant challenges for bryophyte health and ecosystem functions. Ecological consequences extend to altered community structures, disrupted nutrient cycling, and compromised roles in moisture retention. Methodological advancements are needed to overcome challenges in detecting and quantifying these pollutants, and comprehensive field studies must be conducted to understand real-world impacts better. Future research should address the gaps identified, such as the mechanisms of internal uptake and long-term ecological impacts, and explore synergistic effects with other environmental stressors. Developing integrated management strategies and international policies is crucial to mitigating MP and NP pollution and protecting bryophyte habitats and broader ecosystem health.

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CRediT authorship contribution statement

Weerachon Sawangproh: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

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References

[1] J.J. Kelly, M.G. London, A.R. McCormick, M.G. Rojas, J.W. Scott, T.J. Hoellein, Wastewater treatment alters microbial colonization of microplastics, PLoS One 16 (1) (2021) e0244443, https://doi.org/10.1371/journal.pone.0244443.
[2] J.C. Prata, J. Padrão, M.T. Khan, T.R. Walker, Do's and don'ts of microplastic research: a comprehensive guide, Water Emerg. Contam. Nanoplastics 3 (2024) 8, https://doi.org/10.20517/wecn.2023.61.
[3] A. Jacqueline, S. Belz, A. Hoeveler, M. Hugas, H. Okuda, A. Patri, H. Rauscher, P. Silva, W. Slikker, B. Sokull-Kluettgen, W. Tong, E. Anklam, Regulatory landscape of nanotechnology and nanoplastics from a global perspective, Regul. Toxicol. Pharmacol. 122 (2021) 104885, https://doi.org/10.1016/j.yrtph.2021.104885.
[4] A.R. McCormick, T.J. Hoellein, S.A. Mason, J. Schluep, J.J. Kelly, Microplastic is an abundant and distinct microbial habitat in an urban river, Environ. Sci. Technol. 48 (20) (2014) 11863–11871, https://doi.org/10.1021/es503610r.
[5] T. Stanton, M. Johnson, P. Nathanail, R.L. Gomes, T. Needham, A. Burson, Exploring the efficacy of Nile red in microplastic quantification: a costaining approach, Environ. Sci. Technol. Lett. 6 (10) (2019) 606–611, https://doi.org/10.1021/acs.estlett.9b00499.
[6] B. Li, W. Liang, Q.X. Liu, S. Fu, C. Ma, Q. Chen, H. Shi, Fish ingest microplastics unintentionally, Environ. Sci. Technol. 55 (15) (2021) 10471–10479, https://doi.org/10.1021/acs.est.1c01753.
[7] E.D. Osorio, M.A.N. Tanchuling, M.B.L.D. Diola, Microplastics occurrence in surface waters and sediments in five river mouths of manila bay, Front. Environ. Sci. 9 (2021), https://doi.org/10.3389/fenvs.2021.719274.
[8] M. Kooi, A.A. Koelmans, Simplifying microplastic via continuous probability distributions for size, shape, and density, Environ. Sci. Technol. Lett. 6 (9) (2019) 551–557, https://doi.org/10.1021/acs.estlett.9b00379.
[9] J.S. Limbago, M.M.A. Bacabac, D.R.M. Fajardo, C.R.T. Mueda, A.U. Bitara, K.L.P. Ceguerra, .H.M.E. Nacorda, Occurrence and polymer types of microplastics from surface sediments of molawin watershed of the makiling forest reserve, los baños, laguna, Philippines, Environ. Nat. Resour. J. 19 (1) (2021) 57–67, https://doi.org/10.32526/ennrj/19/2020114.
[10] C. Cerrejon, O. Valeria, J. Munoz, N.J. Fenton, Small but visible: predicting rare bryophyte distribution and richness patterns using remote sensing-based ensembles of small models, PLoS One 17 (1) (2022) e0260543, https://doi.org/10.1371/journal.pone.0260543.
[11] N.J. Fenton, Y. Bergeron, D. Paré, Decomposition rates of bryophytes in managed boreal forests: influence of bryophyte species and forest harvesting, Plant Soil 336 (2010) 499–508, https://doi.org/10.1007/s11104-010-0506-z.
[12] A. Vanderpoorten, B. Papp, R. Gradstein, Chapter 13: sampling of bryophytes, in: J. Eymann, J. Degreef, Ch Häuser, J.C. Monje, Y. Samyn, D. VandenSpiegel (Eds.), Manual on Field Recording Techniques and Protocols for All Taxa Biodiversity Inventories (Vol. 8, Part 2), ABC Taxa, Belgian Development Cooperation, 2010, pp. 331–345.
[13] D.W. Carter, J.M. Arocena, Soil formation under two moss species in sandy materials of central British Columbia (Canada), Geoderma 98 (3–4) (2000) 157–176, https://doi.org/10.1016/S0016-7061(00)00059-8.
[14] Y. Oishi, T. Hiura, Bryophytes as bioindicators of the atmospheric environment in urban-forest landscapes, Landsc. Urban Plann. 167 (2017) 348–355, https://doi.org/10.1016/j.landurbplan.2017.07.010.

[15] A. Vaseashta, V. Ivanov, V. Stabnikov, A. Marinin, Environmental safety and security investigations of neurstonic microplastic aggregates near water-air interphase, Pol. J. Environ. Stud. 30 (4) (2021) 3457–3469, https://doi.org/10.15244/pjoes/131947.

[16] T. Gümüs, S. Meriç, A. Ayan, Ç. Atak, Perspective chapter: plant abiotic stress factors – current challenges of last decades and future threats. In: S. Hussain, T. H. Awan, E. A. Waraich, M. I. Awan (Eds.), Plant Abiotic Stress Responses and Tolerance Mechanism, London, UK: IntechOpen, pp. 1-27.

[17] F. Capozzi, R. Carotenuto, S. Giordano, V. Spagnuolo, Evidence on the effectiveness of mosses for biomonitoring of microplastics in fresh water environment, Chemosphere 205 (2018) 1–7, https://doi.org/10.1016/j.chemosphere.2018.04.074.

[18] B. Roblin, J. Aherne, Moss as a biomonitor for the atmospheric deposition of anthropogenic microfibres, Sci. Total Environ. 715 (2020) 136973, https://doi.org/10.1016/j.scitotenv.2020.136973.

[19] V. Carrieri, Z. Varela, J.R. Aboal, F. De Nicola, J.A. Fernández, Suitability of aquatic mosses for biomonitoring micro/meso plastics in freshwater ecosystems, Environ. Sci. Eur. 34 (2022) 72, https://doi.org/10.1186/s12302-022-00653-9.

[20] C. Bertrim, J. Aherne, Moss bags as biomonitors of atmospheric microplastic deposition in urban environments, Biology 12 (2) (2023) 149, https://doi.org/10.3390/biology12020149.

[21] F. Capozzi, M.C. Sorrentino, E. Cascone, M. Iuliano, G. De Tommaso, A. Granata, .V. Spagnuolo, Biomonitoring of airborne microplastic deposition in semi-natural and rural sites using the moss *Hypnum cupressiforme*, Plants 12 (5) (2023) 977, https://doi.org/10.3390/plants12050977.

[22] F. Capozzi, M.C. Sorrentino, A. Granata, A. Vergara, M. Alberico, M. Rossi, .S. Giordano, Optimizing moss and lichen transplants as biomonitors of airborne anthropogenic microfibers, Biology 12 (10) (2023) 1278, https://doi.org/10.3390/biology12101278.

[23] O. Hagelskjær, A. Crézé, G. Le Roux, J.E. Sonke, Investigating the correlation between morphological features of microplastics (5–500 μm) and their analytical recovery, Microplast. Nanoplast. 3 (2023) 22, https://doi.org/10.1186/s43591-023-00071-5.

[24] I. Grgić, K.A. Cetinić, Z. Karačić, A. Previšić, M. Rožman, Fate and effects of microplastics in combination with pharmaceuticals and endocrine disruptors in freshwaters: insights from a microcosm experiment, Sci. Total Environ. 859 (Pt 2) (2023) 160387, https://doi.org/10.1016/j.scitotenv.2022.160387.

[25] M. Jafarova, L. Grifoni, J. Aherne, S. Loppi, Comparison of lichens and mosses as biomonitors of airborne microplastics, Atmosphere 14 (6) (2023) 1007, https://doi.org/10.3390/atmos14061007.

[26] M. Wenzel, J. Schoettl, L. Pruin, B. Fischer, C. Wolf, C. Kube, .J. Tuerk, Determination of atmospherically deposited microplastics in moss: method development and performance evaluation, Green Anal. Chem. 7 (2023) 100078, https://doi.org/10.1016/j.greeac.2023.100078.

[27] N. Khodabakhshloo, S. Abbasi, P. Oleszczuk, A. Turner, Biomonitoring of airborne microplastics and microrubbers in Shiraz, Iran, using lichens and moss, Environ. Geochem. Health 46 (7) (2024) 244, https://doi.org/10.1007/s10653-024-01977-6.

[28] L. Geppner, J. Karaca, W. Wegner, M. Rados, T. Gutwald, P. Werth, M. Henjakovic, Testing of different digestion solutions on tissue samples and the effects of used potassium hydroxide solution on polystyrene microspheres, Toxics 11 (9) (2023) 790, https://doi.org/10.3390/toxics11090790.

[29] G. Thushari, J.D.M. Senevirathna, Plastic pollution in the marine environment, Heliyon 6 (8) (2020) e04709, https://doi.org/10.1016/j.heliyon.2020.e04709.

[30] J. Boucher, D. Friot, Primary Microplastics in the Oceans: A Global Evaluation of Sources, IUCN, Gland, Switzerland, 2017.

[31] T. Reza, Z.H. Mohamad Riza, S.R. Sheikh Abdullah, H. Abu Hasan, N. Ismail, A.R. Othman, Microplastic removal in wastewater treatment plants (wwtps) by natural coagulation: a literature review, Toxics 12 (1) (2023) 12, https://doi.org/10.3390/toxics12010012.

[32] C.B. Alvim, J.A. Mendoza-Roca, A. Bes-Piá, Wastewater treatment plant as microplastics release source–quantification and identification techniques, J. Environ. Manag. 255 (2020) 109739, https://doi.org/10.1016/j.jenvman.2019.109739.

[33] A.L. Andrady, Microplastics in the marine environment, Mar. Pollut. Bull. 62 (8) (2011) 1596–1605, https://doi.org/10.1016/j.marpolbul.2011.05.030.

[34] D.K. Barnes, F. Galgani, R.C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments, Philos. Trans. R. Soc. Lond. B Biol. Sci. 364 (1526) (2009) 1985–1998, https://doi.org/10.1098/rstb.2008.0205.

[35] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, .K.L. Law, Plastic waste inputs from land into the ocean, Science 347 (6223) (2015) 768–771, 0.1126/science.1260352.

[36] R. Yamashita, H. Takada, M.A. Fukuwaka, Y. Watanuki, Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, *Puffinus tenuirostris*, in the North Pacific Ocean, Mar. Pollut. Bull. 62 (12) (2011) 2845–2849, https://doi.org/10.1016/j.marpolbul.2011.10.008.

[37] Y. Li, Q. Zhang, J. Baartman, J. van Wijnen, N. Beriot, C. Kroeze, .M. Strokal, The plastic age: river pollution in China from crop production and urbanization, Environ. Sci. Technol. 57 (32) (2023) 12019–12032, https://doi.org/10.1021/acs.est.3c03374.

[38] M.T. Khan, I.A. Shah, M.F. Hossain, N. Akther, Y. Zhou, M.S. Khan, .I. Ihsanullah, Personal protective equipment (PPE) disposal during COVID-19: an emerging source of microplastic and microfiber pollution in the environment, Sci. Total Environ. 860 (2023) 160322, https://doi.org/10.1016/j.scitotenv.2022.160322.

[39] R. Treilles, J. Gasperi, A. Gallard, M. Saad, R. Dris, C. Partibane, .B. Tassin, Microplastics and microfibers in urban runoff from a suburban catchment of Greater Paris, Environ. Pollut. 287 (2021) 117352, https://doi.org/10.1016/j.envpol.2021.117352.

[40] K. Szewc, B. Graca, A. Dołęga, Atmospheric deposition of microplastics in the coastal zone: characteristics and relationship with meteorological factors, Sci. Total Environ. 761 (2021) 143272, https://doi.org/10.1016/j.scitotenv.2020.143272.

[41] A.K. Baldwin, A.R. Spanier, M.R. Rosen, T. Thom, Microplastics in lake mead national recreation area, USA: occurrence and biological uptake, PLoS One 15 (5) (2020) e0228896, https://doi.org/10.1371/journal.pon.0228896.

[42] S. Santonicola, M. Volgare, M.E. Schiano, M. Cocca, G. Colavita, A study on textile microfiber contamination in the gastrointestinal tracts of *Merluccius merluccius* samples from the Tyrrhenian Sea, Ital. J. Food Saf. 13 (2) (2024) 12216, https://doi.org/10.4081/ijfs.2024.12216.

[43] M.A. Brown, P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway, R. Thompson, Accumulation of microplastic on shorelines worldwide: sources and sinks, Environ. Sci. Technol. 45 (21) (2011) 9175–9179.

[44] M. Padervand, É. Lichtfouse, D. Robert, C. Wang, Removal of microplastics from the environment. a review, Environ. Chem. Lett. 18 (3) (2020) 807–828, https://doi.org/10.1007/s10311-020-00983-1.

[45] L. Zhang, X. Li, Q. Li, X. Xia, H. Zhang, The effects of land use types on microplastics in river water: a case study on the mainstream of the Wei River, China, Environ. Monit. Assess. 196 (4) (2024) 349, https://doi.org/10.1007/s10661-024-12430-7.

[46] Y. Cai, C. Li, Y. Zhao, A review of the migration and transformation of microplastics in inland water systems, Int. J. Environ. Res. Publ. Health 19 (1) (2021) 148, https://doi.org/10.3390/ijerph19010148.

[47] F.C. Alam, N.K. Sari, R. Anggraini, F.R. Setiawan, Microplastic distribution in surface water and sediments of way belau river, lampung, Indonesia, IOP Conf. Ser. Earth Environ. Sci. 1239 (1) (2023) 012002, https://doi.org/10.1088/1755-1315/1239/1/012002.

[48] P.L. Corcoran, S.L. Belontz, R. Kelly, M.J. Walzak, Factors controlling the distribution of microplastic particles in benthic sediment of the Thames River, Canada, Environ. Sci. Technol. 54 (2) (2019) 818–825, https://doi.org/10.1021/acs.est.9b04896.

[49] Y. Gao, R. Li, D. Li, H. Gui, T. Chen, Z. Zhang, Y. Zhang, Spatial distribution of microplastics in water and sediments of main rivers in taihu lake basin, ACS EST Water 3 (8) (2023) 2151–2160, https://doi.org/10.1021/acsestwater.2c00658.

[50] P. Whitehead, G. Bussi, J.M.R. Hughes, A.T. Castro-Castellon, M.D. Norling, E.S. Jeffers, A.A. Horton, Modelling microplastics in the river thames: sources, sinks and policy implications, Water 13 (6) (2021) 861, https://doi.org/10.3390/w13060861.

[51] M. Bandekar, F. Abdolahpur Monikh, J. Kekalainen, T. Tahvanainen, R. Kortet, P. Zhang, .J.V.K. Kukkonen, Submicron plastic adsorption by peat, accumulation in sphagnum mosses and influence on bacterial communities in peatland ecosystems, Environ. Sci. Technol. 56 (22) (2022) 15661–15671, https://doi.org/10.1021/acs.est.2c04892.

[52] D.H. Vitt, B. Crandall-Stotler, A. Wood, Bryophytes: survival in a dry world through tolerance and avoidance, in: N. Rajakaruna, R. Boyd, T. Harris (Eds.), Plant Ecology and Evolution in Harsh Environments, Nova Publishers, 2014, pp. 267–295.

[53] A. Mateos-Cardenas, F. van Pelt, J. O'Halloran, M.A.K. Jansen, Adsorption, uptake and toxicity of micro- and nanoplastics: effects on terrestrial plants and aquatic macrophytes, Environ. Pollut. 284 (2021) 117183, https://doi.org/10.1016/j.envpol.2021.117183.

[54] K.H.D. Tang, Effects of microplastics on agriculture: a mini-review, Asian J. Environ. Ecol. 13 (1) (2020) 1–9, https://doi.org/10.9734/ajee/2020/v13i130170.

[55] L. Giorgetti, C. Spanò, S. Muccifora, S. Bottega, F. Barbieri, L. Bellani, M.R. Castiglione, Exploring the interaction between polystyrene nanoplastics and *Allium cepa* during germination: internalization in root cells, induction of toxicity and oxidative stress, Plant Physiol. Biochem. 149 (2020) 170–177, https://doi.org/10.1016/j.plaphy.2020.02.014.

[56] M. Shen, Y. Zhang, Y. Zhu, B. Song, G. Zeng, D. Hu, .X. Ren, Recent advances in toxicological research of nanoplastics in the environment: a review, Environ. Pollut. 252 (2019) 511–521, https://doi.org/10.1016/j.envpol.2019.05.102.

[57] J.A. Paton, J.V. Pearce, The occurrence, structure and functions of the stomata in British bryophytes, Trans. Br. Bryol. Soc. 3 (2) (1957) 228–259, https://doi.org/10.1179/006813857804829560.

[58] A. Merced, K.S. Renzaglia, Structure, function and evolution of stomata from a bryological perspective, Bryophyte Diversity and Evolution 39 (1) (2017) 7–20, https://doi.org/10.11646/bde.39.1.4.

[59] J. Kubasek, T. Hajek, J. Duckett, S. Pressel, J. Santrucek, Moss stomata do not respond to light and CO_2 concentration but facilitate carbon uptake by sporophytes: a gas exchange, stomatal aperture, and ^{13}C-labelling study, New Phytol. 230 (5) (2021) 1815–1828, https://doi.org/10.1111/nph.17208.

[60] N. Tang, X. Li, X. Gao, X. Liu, W. Xing, The adsorption of arsenic on micro- and nano-plastics intensifies the toxic effect on submerged macrophytes, Environ. Pollut. 311 (2022) 119896, https://doi.org/10.1016/j.envpol.2022.119896.

[61] J.M. Molin, W.E. Groth-Andersen, P.J. Hansen, M. Kühl, K.E. Brodersen, Microplastic pollution associated with reduced respiration in seagrass (*Zostera marina* L.) and associated epiphytes, Front. Mar. Sci. 10 (2023) 1216299, https://doi.org/10.3389/fmars.2023.1216299.

[62] Q. Cao, W. Sun, T. Yang, Z. Zhu, Y. Jiang, W. Hu, H. Yang, The toxic effects of polystyrene microplastics on freshwater algae *Chlorella pyrenoidosa* depends on the different size of polystyrene microplastics, Chemosphere 308 (Pt 1) (2022) 136135, https://doi.org/10.1016/j.chemosphere.2022.136135.

[63] S.E. Lee, Y. Yi, S. Moon, H. Yoon, Y.S. Park, Impact of micro- and nanoplastics on mitochondria, Metabolites 12 (10) (2022) 897, https://doi.org/10.3390/metabo12100897.

[64] A. Das, The emerging role of microplastics in systemic toxicity: involvement of reactive oxygen species (ROS), Sci. Total Environ. 895 (2023) 165076, https://doi.org/10.1016/j.scitotenv.2023.165076.

[65] J.W. Bates, Mineral nutrient acquisition and retention by bryophytes, J. Bryolog. 17 (2) (1992) 223–240, https://doi.org/10.1179/jbr.1992.17.2.223.

[66] M.L. Slate, A. Antoninka, L. Bailey, M.B. Berdugo, D.A. Callaghan, M. Cardenas, K.K. Coe, Impact of changing climate on bryophyte contributions to terrestrial water, carbon, and nitrogen cycles, New Phytol. 242 (6) (2024) 2411–2429, https://doi.org/10.1111/nph.19772.

[67] U. Changmai, S.K. Sahana, N. Kumar, B. Borah, C. Chikkaputtaiah, R. Saikia, T. Phukan, Impact of polyvinyl chloride (PVC) microplastic on growth, photosynthesis and nutrient uptake of *Solanum lycopersicum* L.(Tomato), Environ. Pollut. 349 (2024) 123994, https://doi.org/10.1016/j.envpol.2024.123994.

[68] S. Boch, J. Müller, D. Prati, M. Fischer, Low-intensity management promotes bryophyte diversity in grasslands, Tuexenia 38 (2018) 311–328, https://doi.org/10.14471/2018.38.014.

[69] A. Désamoré, B. Laenen, M. Stech, B. Papp, L. Hedenäs, R.G. Mateo, A. Vanderpoorten, How do temperate bryophytes face the challenge of a changing environment? Lessons from the past and predictions for the future, Global Change Biol. 18 (9) (2012) 2915–2924, https://doi.org/10.1111/j.1365-2486.2012.02752.x.

[70] M. Arias-Andres, M.T. Kettner, T. Miki, H.P. Grossart, Microplastics: new substrates for heterotrophic activity contribute to altering organic matter cycles in aquatic ecosystems, Sci. Total Environ. 635 (2018) 1152–1159, https://doi.org/10.1016/j.scitotenv.2018.04.199.

[71] P.D. Dissanayake, S. Kim, B. Sarkar, P. Oleszczuk, M.K. Sang, M.N. Haque, .Y.S. Ok, Effects of microplastics on the terrestrial environment: a critical review, Environ. Res. 209 (2022) 112734, https://doi.org/10.1016/j.envres.2022.112734.

[72] J.N. Hitchcock, Microplastics can alter phytoplankton community composition, Sci. Total Environ. 819 (2022) 153074, https://doi.org/10.1016/j.scitotenv.2022.153074.

[73] X.M. Zhang, X.X. Cao, L.X. He, W. Xue, J.Q. Gao, N.F. Lei, M.H. Li, Soil heterogeneity in the horizontal distribution of microplastics influences productivity and species composition of plant communities, Front. Plant Sci. 13 (2022) 1075007, https://doi.org/10.3389/fpls.2022.1075007.

[74] M.A. Urbina, F. Correa, F. Aburto, J.P. Ferrio, Adsorption of polyethylene microbeads and physiological effects on hydroponic maize, Sci. Total Environ. 741 (2020) 140216, https://doi.org/10.1016/j.scitotenv.2020.140216.

[75] A. Menendez-Pedriza, J. Jaumot, Interaction of environmental pollutants with microplastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects, Toxics 8 (2) (2020) 40, https://doi.org/10.3390/toxics8020040.

[76] J.M. Glime, Roles of bryophytes in forest sustainability—positive or negative? Sustainability 16 (6) (2024) 2359, https://doi.org/10.3390/su16062359.

[77] G. Chen, Z. Fu, H. Yang, J. Wang, An overview of analytical methods for detecting microplastics in the atmosphere, TrAC, Trends Anal. Chem. 130 (2020) 115981, https://doi.org/10.1016/j.trac.2020.115981.

[78] A. Käppler, D. Fischer, S. Oberbeckmann, G. Schernewski, M. Labrenz, K.J. Eichhorn, B. Voit, Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both? Anal. Bioanal. Chem. 408 (2016) 8377–8391, https://doi.org/10.1007/s00216-016-9956-3.

[79] A.V. Girão, SEM/EDS and optical microscopy analysis of microplastics, in: T. Rocha-Santos, M.F. Costa, C. Mouneyrac (Eds.), Handbook of Microplastics in the Environment, Springer, Cham, 2022, pp. 57–78, https://doi.org/10.1007/978-3-030-39041-9_7.

[80] E. Uurasjarvi, S. Hartikainen, O. Setala, M. Lehtiniemi, A. Koistinen, Microplastic concentrations, size distribution, and polymer types in the surface waters of a northern European lake, Water Environ. Res. 92 (1) (2020) 149–156, https://doi.org/10.1002/wer.1229.

[81] J.C. Prata, A.L.P. Silva, J.P.d. Costa, C. Mouneyrac, T.R. Walker, T. Rocha-Santos, Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution, Int. J. Environ. Res. Publ. Health 16 (13) (2019) 2411, https://doi.org/10.3390/ijerph16132411.

[82] Y.V. Soong, M.J. Sobkowicz, D. Xie, Recent advances in biological recycling of polyethylene terephthalate (PET) plastic wastes, Bioengineering 9 (3) (2022) 98, https://doi.org/10.3390/bioengineering9030098.

[83] N. Kasmuri, M.S. Rosli, N. Zaini, S.E. Nayono, Reduction of microplastic in wastewater via electrocoagulation process, IOP Conf. Ser. Earth Environ. Sci. 1303 (1) (2024) 012020, https://doi.org/10.1088/1755-1315/1303/1/012020.

[84] H. Phu, H.T.N. Han, N.L.N. Thao, T.T. Ha, Microplastics and solutions to remove microplastics in wastewater from wastewater treatment plants in the Saigon–Dong Nai river basin, Vietnam, Vietnam J. Hydrometeorol. 12 (13) (2022) 1–13, https://doi.org/10.36335/vnjhm.2022(13).1-13.

[85] S. Wolff, F. Weber, J. Kerpen, M. Winklhofer, M. Engelhart, L. Barkmann, Elimination of microplastics by downstream sand filters in wastewater treatment, Water 13 (1) (2020) 33, https://doi.org/10.3390/w13010033.

[86] M. Kan, C. Wang, B. Zhu, W. Chen, Y. Liu, Y. Ren, M. Xu, Seven decades of plastic flows and stocks in the United States and pathways toward zero plastic pollution by 2050, J. Ind. Ecol. 27 (6) (2023) 1538–1552, https://doi.org/10.1111/jiec.13427.