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Bryophytes: Ecosystem Engineers in Soil, Carbon, and Water Cycles

Anupriya Gautam [1] and Tripti Sharma*

[1]Department of Bioscience and Biotechnology, Banasthali Vidyapith, Rajasthan, India

*Corresponding author Email: stripti@banasthali.in

Abstract

Mosses, liverworts, and hornworts are constituents of bryophytes, the oldest groups of terrestrial plants, i.e., avascular cryptogams. These plants are vital components of ecosystems, as they carry out vivacious ecological functions regardless of their small size and simple thallus organization. In unadorned or disturbed soils, they are the main colonists beside lichens, starting the soil formation through the accumulation of organic matter with the aid of microbial communities. By accumulating carbon in both terrestrial and some aquatic systems, bryophytes subsidize climate upholding and play a key role in the overall carbon cycle. These miniature plants also have a huge impact on hydrological procedures through soil erosion alleviation, surface runoff reduction, and water retention. Away from their roles in ecosystem engineering, these simple plants are becoming more broadly recognized for their ability to reinstate habitat, act as bioindicators of climatic stress, and reinforce ecosystem elasticity in the face of environmental stress. The biology, ecological roles, and physiology of bryophytes are abridged in this review, highlighting their worth for safeguarding tactics, restoration ecology, and climate change alleviation. In the era of global ecological challenges, a better consideration of these earliest land plants can help to manage ecosystems sustainably and reinforce efforts to safeguard biodiversity.

Keywords: Bryophytes, Carbon sequestration, Climate resilience, Ecosystem engineering, Soil formation.

1. Introduction

Derivative from the Greek words 'bryon' (meaning "moss") and 'phyton' (meaning "plant"), bryophytes are non-vascular, poikilohydric plants that belong to some of the most primitive terrestrial flora ancestries. These plants are notable by very simple thallus organization, the total absence of true vascular tissues, and dependency on surface water for hydration, with gametophyte-dominated life cycle. The earliest identified liverwort fossil is from the Upper Devonian of New York, signifying their extensive evolutionary history. Fossil evidence indicates that bryophyte-like organisms colonized land during the Ordovician period (~488–444 Ma). Despite their diminutive size and lucid morphology, bryophytes are crucial to many different ecosystems[1]. They are ecologically tough and able to inhabit cruel and fringe environments due to their great ability for rejuvenation and confrontation to desiccation. By alleviating soils, affecting hydrological fluctuations, and helping in the cycling of nutrients and carbon, these plants function as ecosystem engineers. In both terrestrial and riparian settings, moss mats and liverwort carpets can control microclimatic conditions, buffer temperature changes, and hold onto water. Furthermore, bryophytes frequently develop close relationships with microbial communities, such as cyanobacteria, fungi, and bacteria, which improve nutrient uptake and stress tolerance.

Beyond their ecological significance, bryophytes are significant model systems in plant biology and evolution, providing information on developmental biology, stress physiology, secondary metabolite production, and early land plant adaptations. They are perfect for research on desiccation tolerance, carbon assimilation, and biotechnological applications due to their straightforward morphology, quick life cycle, and genetic tractability. Largely, the ecological, evolutionary, and physiological characteristics of bryophytes emphasize their significance as foundational constituents of terrestrial ecosystems and as key subjects for investigation in plant science, climate resilience, and environmental restoration.

2. Materials and Methods

To summarize the present understanding of bryophytes as ecosystem engineers in the soil, carbon, and water cycles, a thorough literature review was carried out. Keywords including bryophytes, mosses, liverworts, hornworts, ecosystem engineering, soil formation, carbon sequestration, water retention, and microbial interactions were used to search scientific databases, including WoS, Scopus, PubMed, and ScienceDirect. Included were peer-reviewed studies, reviews, and meta-analyses that addressed the ecology, physiology, and functional roles of bryophytes in ecosystems. To highlight bryophyte contributions to soil stabilization, nitrogen cycling, hydrology, microbial relationships, and climate regulation, data from pertinent studies were selected and arranged thematically. The results were incorporated into a conceptual framework that provided a comprehensive knowledge of the ecological and environmental implications of bryophyte characteristics and microbial interactions in relation to ecosystem functioning.

3. Biology and Life Cycle

Bryophytes include three major lineages — mosses (*Bryophyta*), liverworts (*Marchantiophyta*), and hornworts (*Anthocerophyta*) — with mosses being the most species-rich. They undergo alternation of generations in their life cycle, dominated by the haploid gametophyte, which can be thalloid or leafy. Rhizoids substitute for roots, and they lack vascular tissues, relying instead on surface water absorption. They reproduce sexually via oogamy (antheridia and archegonia), producing a sporophyte (foot, seta, capsule) in which meiosis yields haploid spores.

3.1 Distribution and Habitat Diversity

Bryophytes are cosmopolitan, with particularly high species richness in tropical regions[2]. They inhabit diverse microhabitats: soils, rocks, tree trunks, peatlands, urban walls, and even concrete. Their success depends on factors such as moisture availability (critical for reproduction), substrate pH, canopy cover, and elevation[3,4]. Their capacity to desiccate and revive (poikilohydry) allows them to persist in extremely dry or cold environments.

4. Ecosystem Functions

4.1 *Soil Formation*

Bryophytes are pioneer species on bare substrates, influencing pedogenesis through physical, chemical, and biological pathways. Bryophytes contribute to soil formation through a synergistic combination of physical, chemical, and biological processes. Their mats physically stabilize surfaces by trapping particles, reducing erosion, and binding loose sediments through rhizoids and mucilage, which act as a natural glue and create a stable microenvironment that moderates temperature extremes and promotes mineral weathering and microbial activity[5-8]. Chemically, bryophytes secrete organic acids such as oxalic, citric, and malic acids that dissolve minerals and mobilize nutrients, while their cell walls—rich in uronic acids and phenolic compounds—facilitate cation exchange, proton release, and enhanced mineral hydrolysis[11]. They also support diverse microbial consortia, including cyanobacteria, bacteria, and fungi, which further accelerate mineral breakdown through siderophore production and extracellular enzymes[12-14]; additionally, decomposing bryophyte litter contributes humic substances that stabilize organic matter and drive long-term soil development[15-17]. Biologically, bryophytes host diverse surface- and rhizoid-associated microbes that fix nitrogen, mobilize phosphorus and iron, and enhance nutrient cycling[12, 14], while their persistent litter horizon and bryophyte-based biological soil crusts promote microbial activity[15, 16], soil aggregation, and overall soil stabilization[18]. These systems work synergistically: physical break-up exposes minerals, chemical exudates dissolve them, and microbial groups strengthen and supplement the emerging soil.

4.2 *Carbon Sequestration*

Bryophytes—especially *Sphagnum* mosses—are among the most influential yet often overlooked drivers of global carbon dynamics. Despite making up only 3% of the planet's land area, sphagnum-dominated peatlands can store an astounding 500–600 Gt of carbon[19] due to their consistently wet, acidic, and oxygen-poor conditions, which prevent decomposition and preserve organic matter. In tundra and alpine ecosystems, bryophyte carpets serve as natural insulation layers outside of peatlands, keeping soils cool, delaying microbial degradation, and encouraging long-term carbon retention[20]. Through symbiosis with nitrogen-fixing cyanobacteria, which enrich these systems with biologically available nitrogen and increase moss productivity and carbon sequestration, their ecological influence is further reinforced[21]. Bryophytes are essential to Earth's carbon balance and climate regulation because, in contrast to vascular plants, which store a large amount of their carbon in transient above-ground biomass, they channel a significant portion into stable, long-lived below-ground carbon pools. Though, peatland desiccation owing to climate change or human caused disturbance can reverse their competence from carbon sinks to sources, freeing centuries of stored carbon[22]. Restoration efforts, such as *Sphagnum* farming and peatland rewetting, are being pursued as climate mitigation strategies.

4.3 *Hydrological Regulation*

As organic hydrological sponges, bryophytes stabilize microclimates and buffer water fluxes in a variety of ecosystems. They are able to retain water amounts several times their dry mass[23] thanks to their complex capillary networks, specialized hyaline cells in *Sphagnum*, and dense cushions. They moderate runoff, extend base-flow, and lessen hydrological extremes by capturing and retaining rain, dew, and fog and releasing moisture gradually into the soil and atmosphere[24]. Features unique to a species enhance this function: hummock-shaped while epiphytic mosses in cloud forests collect fog and progressively drip water along trunks and forest floors, maintaining localized humidity[25], sphagnum sustains high water tables in peat lands. Bryophytes also indirectly influence carbon dynamics, plant community succession patterns, and decomposition rates due to their significant impact on soil moisture and microclimate[25].

5. Ecological and Practical Importance

In addition to their ecological benefits, bryophytes are valuable in science, industry, and commerce. As pioneer species, they lay the foundation for subsequent plant communities by starting ecological succession on disturbed or degraded substrates[26]. Their carpets and mats provide vital microhabitats for various microbial assemblages, amphibians, and invertebrates. Bryophytes are useful tools for environmental monitoring because they are sensitive bioindicators that efficiently accumulate pollutants like heavy metals and airborne contaminants. Molecular biology, genetics, and stress physiology all make extensive use of model species such as *Physcomitrium patens*[27]. Bryophytes offer natural solutions for rebuilding ecology by calming soil, controlling water, and aiding in carbon sequestration[28]. Sphagnum peat is still economically significant in horticulture, even though many species of bryophytes are still utilized in traditional medicine and crafts.

6. Future Directions

To fully unlock the ecological and biotechnological potential of bryophytes, future research must advance along several complementary fronts. At the molecular scale, integrating transcriptomic, proteomic, and genetic approaches will be essential for elucidating the mechanisms underlying desiccation tolerance, osmoprotection, and carbon stabilization[29, 30]. Long-term climate-change experiments are equally critical, particularly those examining how bryophyte communities—most notably peatlands—respond to warming, shifting precipitation patterns, wildfires, and permafrost thaw[22]. In addition to developing efficient rebuilding techniques for ecological restoration, applied efforts should concentrate on expanding dissemination methods like cryopreservation, tissue culture, and spore banking31. Advances in remote sensing and tomography, such as drone or NDVI-based mapping to measure moisture and bryophyte cover at landscape scales and micro-CT scanning to visualize internal water routes, provide new tools for biological monitoring[32]. Lastly, more accurate forecasts of their upcoming effects on the world's water and carbon cycles will be possible by integrating comprehensive bryophyte physiological data with ecosystem-level models.

7. Discussion

In addition to being a source of several phytochemicals that are important for medicine[33, 34], bryophytes are a special class of early-diverging land plants that maintain intricate relationships with their associated microbiomes, which are essential to ecosystem function and environmental resilience. The ecological and physiological significance of these relationships is highlighted by recent research, especially in stressful and harsh environments. In their thorough analysis of bryophyte–microorganism relationships, Dangar et al.[35] show how microbial communities maximize nutrient uptake, improve stress tolerance, and support bryophyte survival in a variety of environmental circumstances. In addition, Pandey et al.[36] described the isolation of endophytic bacteria from bryophyte gametophytes in Mount Abu, highlighting the variety and possible functional roles of these microorganisms in plant health and nutrient cycling.

A crucial interface for interactions between bryophytes and microbes has been identified as the rhizoid-associated microbiome. The bryophyte rhizoid-sphere microbiome is highly responsive to water deficit, as demonstrated by Berdaguer et al.[37], suggesting a dynamic microbial contribution to bryophyte resource management and drought tolerance. The production of secondary metabolites in bryophytes and stress physiology are closely related to these interactions. In their review of stress-response pathways, Kulshrestha et al.[38] emphasized the production of specialized metabolites like polyphenols, which both protect against abiotic stress and regulate microbial communities. Furthermore, Liu et al.[39] showed the complex molecular mechanisms underlying resilience by using proteomic and transcriptomic analyses to show that desiccation-tolerant mosses, such as *Racomitrium canescens*, quickly modify gene expression during rehydration. Beyond survival strategies mediated by microbes, bryophytes play an important role in global biogeochemical cycles.

Bryophytes and lichens play a significant role in carbon sequestration, especially in high-latitude ecosystems, according to Porada et al.[40] model of global carbon uptake. Bryophytes that form peatlands, primarily Sphagnum species, are known to play a crucial role in controlling the climate. Leifeld and Menichetti[41] stress that by preserving carbon-rich substrates and reducing CO_2 emissions, peatland restoration—aided by bryophytes—can offer practical natural climate solutions. Understanding and tracking bryophyte cover, which is essential for ecological modeling and conservation tactics, has improved thanks to remote sensing. For high-latitude vegetation monitoring, Assmann et al.[42] showed the value of multispectral sensors and UAV-based NDVI mapping, offering a reliable method to measure bryophyte distribution at landscape scales. Additionally, ecosystem microclimate regulation is directly impacted by the thermal characteristics of bryophyte mats. Soudzilovskaia et al.[43] showed that dominant species of bryophytes apply sturdy control over soil temperature vacillations through heat transfer characters and water content, proving their impact on local soil microenvironments and ecosystem liveliness balance.

Ultimately, bryophytes have revealed their potential in practical and environmentally friendly management. Singh and Choudhary[44] appraised their utility in phytoremediation, highlighting the capability of bryophytes to bioaccumulate unsafe heavy metals, destroy organic pollutants, and restore polluted habitats, aligning them as capable agents for ecological refurbishment and environmental sustainability. Mutually, these studies emphasize the versatile roles of bryophytes—from facilitating plant–microbe interactions and stress physiology to controlling carbon cycling, environmental remediation, and microclimate. The amalgamation of molecular, ecological, physiological, and remote sensing methods provides a complete frame to recognize bryophyte ecology and clout their ecosystem services in the perspective of worldwide environmental change.

8. Conclusion

Bryophytes, often overlooked because of their diminutive size and simple morphology, are in fact powerful ecosystem engineers that play a critical role in maintaining ecosystem structure and function. Through a combination of physical, chemical, and biological mechanisms, these plants contribute to soil formation, enhance nutrient cycling, sequester substantial amounts of carbon, and regulate hydrological processes, including water retention and runoff control. Their presence supports diverse microbial communities and provides essential habitats for invertebrates and other small organisms, highlighting their broader ecological significance. Conserving and bring back bryophyte-rich habitats not only protects these earliest plants but also offers a innate and cost-effective solution for climate modification and ecosystem resilience. Moreover, bryophytes grant distinctive perceptions into the evolution of land plants, serving as living models for identifying adaptation to land environments. Moving forward, interdisciplinary research combining molecular biology, ecology, physiology, and landscape-level studies will be vital to fully explaining the evolutionary, ecological, and climate-related ability of bryophytes. By connecting fundamental research with applied safeguarding strategies, we can make sure that these small, yet influential plants continue to maintain ecosystems and impact to a more durable biosphere in the face of global environmental change.

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Author contributions

TS –Research concept and design, **AG** –Collection and assembly of data, Data analysis and interpretation, writing the article, **AG, TS** –Critical revision and final approval of the article.

Data Availability

Not Applicable.

Conflicts of interest

The authors declare that there are no conflicts of interest related to this article. No ethical issues

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