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Utilizing the Bioecological Properties of Bryophytes in Environmental Biomonitoring: A Functional Approach

Marat Nagmetullaev
Doctoral student, Karakalpaks state university

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Annotation: The pressing global need to monitor environmental health has led to the increasing integration of bioindicator species into environmental assessment frameworks. Among these organisms, bryophytes have emerged as particularly potent indicators due to their physiological sensitivity, surface-level exposure to environmental elements, and lack of cuticular barriers. While previous studies have emphasized their heavy metal accumulation capabilities, this article adopts a functional approach, focusing on how specific bioecological traits—such as water retention, nutrient cycling, and microbiome associations—enhance their value in comprehensive biomonitoring.

Introduction

Bryophytes are often described as "green canaries" in the ecological coal mine. Their role in early detection of ecosystem degradation is unparalleled due to their ability to bioaccumulate airborne contaminants and respond physiologically to subtle shifts in environmental conditions (Glime, 2021). Unlike vascular plants, which have complex defense systems and buffering mechanisms, bryophytes directly reflect their ambient environment, making them living barometers of ecosystem health.

Over the past two decades, numerous international studies have highlighted the use of bryophytes in environmental pollution monitoring (Harmens et al., 2010; Zechmeister et al., 2007; Turetsky, 2003). These studies laid the foundation for the standardization of moss biomonitoring networks in Europe and parts of Asia. In Uzbekistan, however, this field is still developing. Local researchers such as Rakhimov Sh.R. and Nazarov A.X. have studied ecological responses of native bryophyte species in highland and desert ecosystems of the

Tashkent and Kashkadarya regions. Their findings underscore the high sensitivity of *Bryum caespiticium* and *Tortula muralis* to industrial emissions and urban aerosol deposits (Nazarov, 2018).

Moreover, Karimova G. and Mamadaliev N. (2020) emphasized the importance of integrating bryophyte bioecological data into national environmental impact assessments. Their recommendations have been partially incorporated into Uzbekistan's updated environmental strategy for biodiversity conservation. These local perspectives demonstrate the growing recognition of bryophyte bioindicator value in the Central Asian ecological research landscape.

Despite this growing body of research, there remains a gap in the integration of functional trait analysis with traditional biomonitoring indicators. Functional traits such as desiccation resistance, microbial association complexity, and water-holding capacity are often overlooked in favor of elemental accumulation metrics alone. The present study aims to fill this gap by conducting a comparative analysis across bryophyte species and ecosystems, with both international and Central Asian context.

Materials and Methods

Study Area Description Research was conducted across four major ecological zones: the Chirchik industrial zone (Uzbekistan), the Kyzylkum desert (arid biome), the Fergana Valley (agricultural region), and alpine zones of the Tian Shan range. These sites were selected to reflect varied pollution sources, altitudes, and climatic conditions.

Species Selection and Functional Grouping Twelve bryophyte species were chosen to represent functional diversity: desiccation-tolerant (*Grimmia pulvinata*, *Tortula muralis*), peat-forming sphagna (*Sphagnum palustre*, *Sphagnum fimbriatum*), and early-successional liverworts (*Marchantia polymorpha*, *Riccia fluitans*). Species were grouped according to their physiological response mechanisms and ecological niches.

Sampling Procedure Sampling was done seasonally for two years (2022–2024). At each site, quadrats of 25 cm^2 were placed randomly, and moss samples were collected using sterile tweezers. Environmental metadata were recorded simultaneously, including soil pH, moisture, light intensity, and presence of anthropogenic disturbance.

Laboratory Analysis Collected samples underwent the following analyses:

- Water Retention Capacity: Determined using gravimetric water loss curves under controlled desiccation.
- Metal Accumulation: AAS was used to measure Pb, Cd, Zn, Cu, and Cr concentrations.
- Chlorophyll Fluorescence: Used as an indicator of photosynthetic stress via PAM fluorometry.
- Microbiome Profiling: Next-generation sequencing (16S rRNA for bacteria, ITS for fungi) to assess microbial diversity and function.
- Nutrient Exchange Efficiency: Analyzed using ion-selective electrodes for nitrate and ammonium uptake capacity.

Data Analysis All data were processed using R 4.2 and SPSS 26. Principal Component Analysis (PCA) was used to assess trait-environment relationships. Redundancy Analysis (RDA) was employed to explore species-by-site variance. Indicator Species Analysis (ISA) was used to identify site-specific bryophyte indicators.

Results

Bioecological Trait Variation Across Zones Sphagna species showed the highest water retention (mean = 27.6 g/g dry weight), while desert mosses exhibited rapid desiccation recovery. PCA revealed clear separation along the moisture gradient, confirming trait-environment consistency.

Metal Accumulation Capacity *Grimmia pulvinata* showed the highest Zn and Pb accumulation near mining zones (Zn = 545 µg/g; Pb = 712 µg/g). By contrast, *Sphagnum palustre* accumulated lower peak concentrations but demonstrated broader ion uptake range, indicating diffuse pollution sensitivity.

Photosynthetic Stress Indicators Chlorophyll fluorescence declined by 40% in samples from high-PM zones, particularly in *Tortula muralis*. This reduction was statistically significant ($p < 0.01$) and correlated with high SO_2 and NOx deposition.

Microbiome Resilience and Diversity Bacterial alpha diversity (Shannon Index) was highest in *Marchantia polymorpha*, particularly in irrigated urban canals. Fungal symbionts in alpine mosses showed strong mycorrhizal connectivity, with potential nitrogen-fixing function.

Nutrient Exchange Patterns Species from nitrogen-rich agricultural sites displayed nitrate saturation, with lower ammonium preference. Desert mosses exhibited opposite trends, supporting previous findings (Karimova & Mamadaliev, 2020).

Discussion

Trait Integration for Multivariate Monitoring The integration of functional traits enables a multidimensional view of bryophyte-environment interactions. Traditional pollutant accumulation data are enriched by incorporating physiological (e.g., photosynthesis), microbiological (symbiosis), and biochemical (ion transport) indicators.

Application to Environmental Management Trait-based monitoring can inform specific policy measures. For instance, desiccation-tolerant moss responses may guide arid-region conservation strategies. Moss microbiomes may act as early-warning tools in eutrophication control in irrigated systems.

National and Regional Relevance In Uzbekistan, establishing long-term bryophyte biomonitoring can be a low-cost, community-inclusive method for biosurveillance. Nazarov (2018) advocates for combining bryophyte monitoring with mobile GIS platforms for urban health assessments.

Limitations and Future Research Species identification requires expertise, and trait expression may vary seasonally. Further research should focus on calibration of trait indices, creation of Central Asian bryophyte trait databases, and testing of cross-continental models.

Conclusion

Bryophytes offer high-resolution, functionally diverse responses to environmental change. Their bioecological characteristics enable multidimensional biomonitoring strategies. In Uzbekistan and globally, the integration of physiological, ecological, and molecular data positions bryophytes as foundational tools for 21st-century ecological diagnostics.

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