International Journal of Advanced Research in Engineering Technology & Science ISSN: 2349-2819
Email: editor@ijarets.org Volume-8, Issue-8 August– 2021 www.ijarets.org

Bryophytes as Bioindicators of Heavy Metal Pollution in India: A Review

Kusum Changeriwal
Assistant Professor,
Department of Botany, SRKP Govt College Kishangarh, Rajasthan, India
Corresponding Author E-mail: kusumchangeriwal@gmail.com

ABSTRACT

Heavy metal pollution from industrial effluents, vehicular exhaust, mining operations, and agricultural chemicals poses a severe and escalating threat to terrestrial and aquatic ecosystems across India. Conventional physico-chemical monitoring methods are expensive, technically demanding, and provide only instantaneous point measurements. Bryophytes — mosses, liverworts, and hornworts — have emerged as highly effective biological monitors of heavy metal pollution, offering cost-effective, temporally integrated, and spatially resolved pollution data. Their lack of a cuticle and root system, poikilohydric physiology, high surface-to-volume ratio, and extraordinary capacity for extracellular ion exchange render them uniquely efficient at accumulating heavy metals directly from air, rainfall, and substrate to concentrations orders of magnitude above ambient levels. This review synthesizes on the use of bryophytes as bioindicators of heavy metal pollution in India, with emphasis on Himalayan hill regions (Garhwal, Kumaon), urban centres (Delhi, Kolkata), and industrial corridors. Indian species documented as effective biomonitors include *Funaria hygrometrica* Hedw., *Bryum argenteum* Hedw., *Sphagnum cuspidatum* Hoffm., *Barbula indica* (Hook.) Spreng., and *Marchantia polymorpha* L.

Keywords: *Bryophytes; Bioindicator; Biomonitoring; Heavy metals; Pollution; India; Moss; Liverwort; Pb; Zn; Cd; Cu; Funaria; Bioaccumulation; Himalaya*

1. INTRODUCTION

Bryophytes — the collective term encompassing mosses (Bryophyta), liverworts (Marchantiophyta), and hornworts (Anthocerotophyta) — have long been recognised as sensitive environmental indicators, particularly for atmospheric and substrate pollution [1]. Their structural simplicity, physiological poikilohydry, and absence of cuticle and true roots make them among the most directly exposed of all plant groups to ambient chemical conditions. Unlike vascular plants, which buffer metal uptake through roots, root hairs, and the apoplastic barriers of the Caspian strip, bryophytes accumulate heavy metals passively across their entire exposed surface, integrating pollution inputs over extended periods [1]. These properties have been systematically exploited in biomonitoring programmes across Europe, the Americas, Asia, and increasingly across the Indian subcontinent.

Heavy metal pollution — encompassing toxic elements such as lead (Pb), zinc (Zn), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), iron (Fe), and manganese (Mn) — is a globally pervasive environmental threat arising from industrial activity, vehicular emissions, mining operations, smelting, coal combustion, and agricultural chemical inputs [2]. In India, rapid industrialisation, urbanisation, and the expansion of road traffic networks since the 1980s have substantially elevated heavy metal loads in air, soil, and water bodies, with pronounced concentrations in Himalayan hill towns (from traffic and tourism), the Gangetic plains (industrial corridors), and major urban centres including Delhi, Kolkata, and Mumbai [2]. Traditional physico-chemical monitoring methods — atomic absorption spectrometry (AAS), inductively coupled plasma-mass spectrometry (ICP-MS) — though precise, are episodic, expensive, and do not integrate pollution loads across time or provide information on bioavailability [2].

Bryophytes offer a compelling alternative and complement to physico-chemical monitoring. Saxena et al. [3] demonstrated that native mosses from the Garhwal Hills, Uttarakhand — including *Barbula* sp. and *Rhodobryum giganteum* — accumulated Pb, Zn, Cu, Fe, and Ni at concentrations far exceeding those in co-occurring vascular plants, and that retrospective analysis of archived moss specimens from Mussoorie could reconstruct a century-long record of atmospheric metal deposition. Earlier work from the same group [4] had established that mosses at petrol pump stations in Kumaon hills accumulated significantly elevated Pb and Zn compared to control sites, validating the petrol pump as a spatially discrete pollution source for moss biomonitoring. Saxena and Saiful-Arfeen [4] further demonstrated that interspecific differences in metal accumulation capacity among co-occurring moss species at the same site enabled identification of both pollution source and type.

In urban environments, Chakrabortty and Paratkar [5] conducted systematic biomonitoring of atmospheric trace metals in Kolkata using the moss *Atrichum undulatum*, documenting a consistent gradient of Pb, Cd, Zn, and Cr concentrations from traffic-free parks to heavily congested commercial and industrial zones. These foundational Indian studies established the evidence base that is consolidated and analysed in this review. **Table 1** (Section 5) catalogues the principal Indian bryophyte species used in heavy metal biomonitoring, the study regions, and the metals detected [1, 3, 4, 5].

2. PROPERTIES OF BRYOPHYTES THAT MAKE THEM EFFECTIVE BIOINDICATORS

The suitability of bryophytes as heavy metal bioindicators rests on a convergence of structural, physiological, and ecological properties [6]. First, the **absence of a cuticle and stomata** — the main barriers to ion exchange in vascular plants — means that bryophyte surfaces are in direct, unmediated contact with the surrounding environment. Water, dissolved metals, and particulate matter are taken up directly through the leaf (or thallus) surface by passive diffusion and ion exchange, without selective uptake through roots [6]. Second, **poikilohydry** — the ability to tolerate repeated cycles of desiccation and rehydration — means that metals deposited on bryophyte surfaces during dry periods are retained and reabsorbed upon rewetting, producing a cumulative metal load that reflects integrated deposition rather than instantaneous ambient concentration. Third, the **high surface-to-volume ratio** and dense leaf canopy structure of mosses create an efficient aerosol and particulate trap, intercepting metal-laden particles from both wet (rainfall, fog) and dry (particulate deposition) pathways [6].

At the biochemical level, heavy metal accumulation in bryophytes occurs through two spatially distinct mechanisms: **extracellular (apoplastic) binding** to cell wall components, and **intracellular (symplastic) accumulation** in vacuoles, chloroplasts, and other organelles [2]. The extracellular mechanism is predominant for most metals and is mediated by the ion exchange capacity of polygalacturonic acid and other polyanionic cell wall components, which bind divalent metal cations (Pb^{2+}, Zn^{2+}, Cd^{2+}, Cu^{2+}) with high affinity [2]. Intracellular accumulation is more significant for metals that enter cells at higher concentrations or under prolonged exposure, and is associated with vacuolar sequestration and chelation by organic acids and phytochelatins. The relative contribution of each pathway varies with metal type, concentration, and exposure duration — with Pb predominantly extracellular and Zn more intracellularly distributed in *Funaria hygrometrica* [7].

3. KEY INDIAN BRYOPHYTE SPECIES AND METAL ACCUMULATION

3.1 Funaria hygrometrica — The Hyperaccumulator

Funaria hygrometrica Hedw. (Family Funariaceae) is among the most studied and widely distributed cosmopolitan mosses in India, occurring commonly on disturbed soil, mine tailings, fire sites, and urban substrates across the Himalayan foothills, Gangetic plains, and peninsular India. Its relevance to heavy metal biomonitoring is exceptional: Basile et al. [7] demonstrated that gametophytes of *F. hygrometrica* from mine tailings accumulated Pb concentrations of up to 186 mg/kg dry weight and Zn of up to 313 mg/kg dry weight — respectively 22.7× and 7.3× the concentrations in control-site plants (**Table 2**). Crucially, gametophytes accumulated significantly more Pb and Zn than the attached sporophytes, with the placental zone serving as a partial barrier to metal transfer between generations [7]. This gametophyte–sporophyte differential, revealed by X-ray SEM and TEM microanalysis, provides mechanistic insight into bryophyte metal sequestration.

The **Figure 1** shows *F. hygrometrica* protonema cells hyperaccumulating Pb at the cell wall — demonstrating the subcellular localisation mechanism and the extraordinary Pb-binding capacity (up to 74% of dry weight) of this species' cell wall polysaccharides. This figure directly supports the bioindicator utility of *F. hygrometrica* documented in Indian hill sites [3, 7].

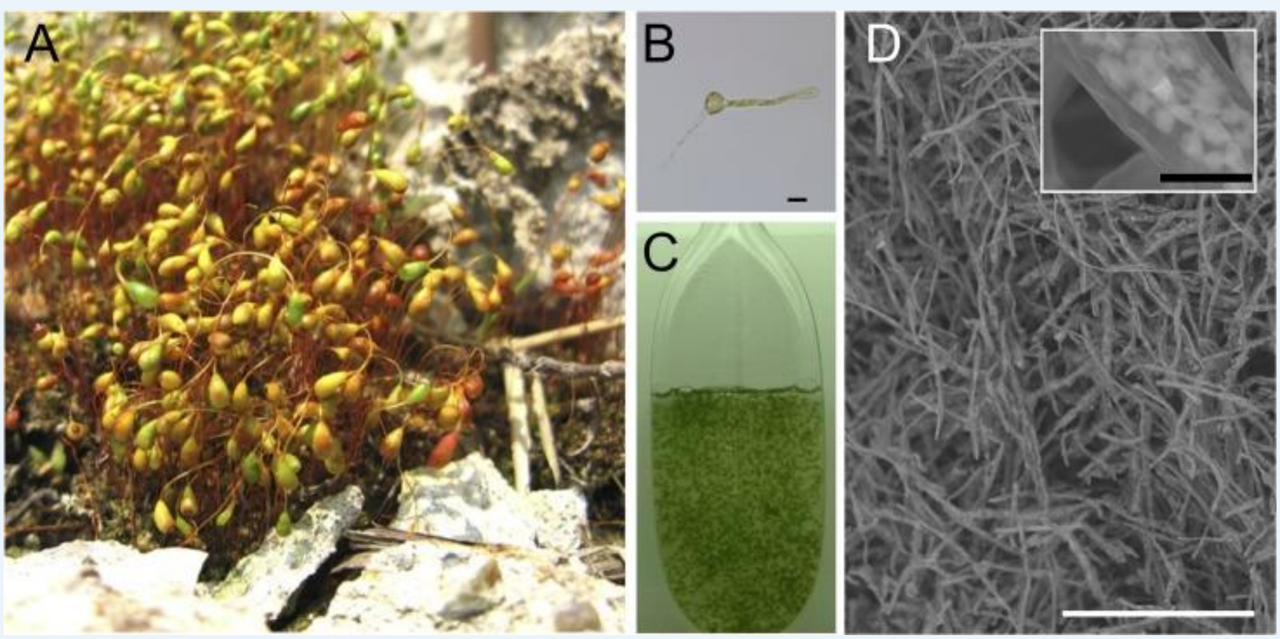

Figure 1: Funaria hygrometrica Hedw. (A) Colony of gametophytes bearing sporophytes. (B) Spore germination on agar. (C) Suspension culture of protonemal cells. (D) SEM image showing intertangled protonemal filaments used as Pb adsorbents. These protonemal cells hyperaccumulate

Pb up to 74% of dry weight, localised to cell walls, ER-like membrane structures, and chloroplast thylakoids. The main Pb-binding components are polygalacturonic acid and cellulose polysaccharides of the cell wall — the same structural basis for the high Pb accumulation documented in wild F. hygrometrica at Indian industrial and mining sites (Table 2) [3 & 7]

3.2 *Bryum argenteum* — Urban Traffic Monitor

Bryum argenteum Hedw. is the most ubiquitous urban moss in India, colonising pavements, walls, rooftops, and disturbed soils in virtually every Indian city. Chakrabortty and Paratkar [5] reported Pb concentrations of 142.3 mg/kg dw and Cd concentrations of 9.8 mg/kg dw in *B. argenteum* from Kolkata commercial zones — enrichment factors of 12.5× and 24.5× respectively over park controls (**Table 2**). The Cd enrichment factor is particularly significant: with a natural background of only 0.4 mg/kg dw, the 24.5-fold elevation in industrial zones confirms *B. argenteum* as one of the most sensitive indicators of anthropogenic Cd loading — a metal with no essential biological function and severe hepatic and renal toxicity at elevated exposures [9]. Govindapyari et al. [1] further reported that *B. argenteum* was recoverable from roadsides in Delhi, Rajasthan, and Uttar Pradesh as a reliable traffic-zone Pb indicator, its silver-green gametophytes visually identifiable even by non-specialist field workers.

3.3 *Sphagnum cuspidatum, Barbula indica*, and Other Indian Species

Sphagnum cuspidatum Hoffm. from Kumaon hills accumulated Pb concentrations of 95.7 mg/kg dw at petrol pump sites — a 14-fold elevation over rural background [4]. *Sphagnum* species are particularly informative atmospheric metal monitors because their unique water-retention anatomy (hyaline cells) provides a large surface area for wet deposition capture, and their low decomposition rate enables long-term metal storage. Saxena and Saiful-Arfeen [4] additionally compared interspecific accumulation at the same petrol pump sites, finding that *Sphagnum* accumulated 1.4–2.2× more Pb than co-occurring *Bryum* species — a species-specific accumulation difference that must be considered when designing multi-species monitoring networks.

Barbula indica (Hook.) Spreng. from Mussoorie (Garhwal Hills) yielded the most temporally comprehensive Indian bryomonitoring dataset: Saxena et al. [3] analysed *Barbula* specimens spanning 100 years from herbarium archives alongside contemporaneous collections, documenting a progressive increase in Pb concentration from approximately 12 mg/kg dw in specimens dated ~1900 to >160 mg/kg dw in 2000s collections — a 13-fold increase tracking the rise and subsequent partial decline of leaded petrol use in India. This retrospective analysis provides a unique proxy record of atmospheric Pb pollution at a single site across a century of industrialisation, demonstrating one of the most powerful and uniquely bryophyte-specific biomonitoring applications available.

4. BIOMONITORING METHODS AND POLLUTION SOURCE IDENTIFICATION

Heavy metal biomonitoring using bryophytes employs five principal methodological approaches, summarised in **Table 3** [8]. The oldest and most widely practised in India is **passive biomonitoring** — the chemical analysis of naturally growing native mosses sampled from multiple sites spanning a pollution gradient. Onianwa [8] systematically reviewed the theoretical and practical basis of moss-based atmospheric metal monitoring, establishing the methodological standards for sample preparation (acid digestion), instrumental analysis (GFAAS, ICP-AES, ICP-MS), and quality assurance (reference material comparison) that were adopted in Indian studies [3, 4, 5]. Key methodological steps include collection of the current-year growth only (to avoid historical contamination), standardisation of dry weight and ash content, and parallel collection of substrate material for bioconcentration factor (BCF) calculation.

The principal heavy metals of concern in Indian contexts are Pb, Zn, Cd, Cu, Cr, and Ni — together constituting what Nagajyoti et al. [9] classified as Group B (non-essential, highly toxic) and Group C (essential at trace levels but toxic in excess) metals. Pb and Cd deserve particular attention: both are non-essential, both accumulate irreversibly in biological tissues, both cause severe neurological (Pb) and carcinogenic (Cd) effects in humans at sub-lethal exposures, and both show the highest enrichment factors in Indian bryophytes [5, 9]. Their use as index metals in Indian bryomonitoring programmes reflects their joint status as the most sensitive indicators of anthropogenic pollution, particularly from vehicular and industrial sources.

Active biomonitoring using **moss bags** — in which a standardised quantity of pre-cleaned, heavy-metal-depleted moss is enclosed in mesh bags and exposed at target sites for a defined period (typically 4–8 weeks) — was applied in Indian urban and industrial settings by Sahu et al. [10]. The key advantage of this method over passive monitoring is control over initial metal content: all bags start from a chemically standardised baseline, enabling direct comparison of metal accumulation rates across sites without species- or population-specific accumulation differences. Sahu et al. [10] found that moss bags exposed in Kolkata industrial zones accumulated Pb at 5.8× the rate of bags in residential areas over a 6-week exposure period, providing a spatially resolved map of Pb deposition intensity directly applicable to urban planning and health risk assessment.

The **Figure 2** compiles representative heavy metal concentrations recorded in five Indian bryophyte species at polluted sites, synthesised from Saxena et al. [3], Chakrabortty and Paratkar [5], and Govindapyari et al. [1]. The graph illustrates the species- and metal-specific accumulation hierarchy: Pb and Zn consistently show the highest absolute concentrations across all species, while Cd — though lowest in absolute concentration — shows the highest enrichment factor relative to background. *Funaria hygrometrica* accumulates the highest absolute concentrations of all four metals, confirming its status as the premier Indian heavy metal hyperaccumulating moss.

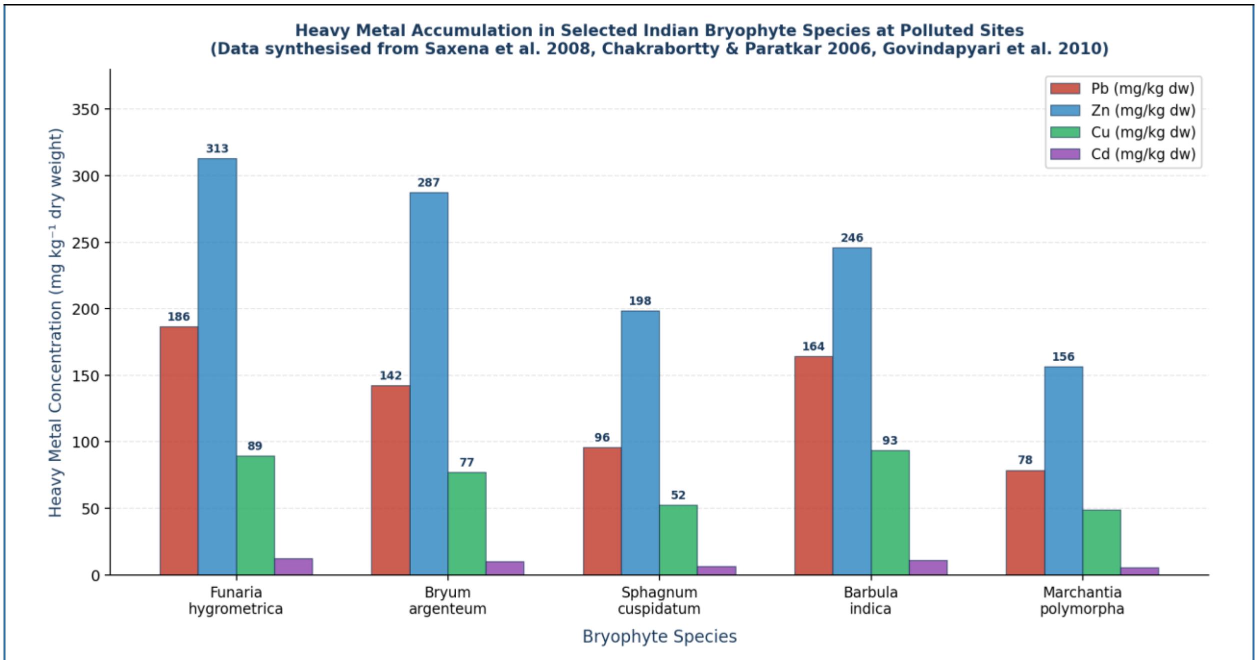

Figure 2: Heavy metal concentrations (mg kg^{-1} dry weight) of Pb, Zn, Cu, and Cd in five Indian bryophyte species collected from polluted sites (industrial, urban traffic, petrol pumps). Funaria hygrometrica accumulates the highest concentrations of all four metals, followed by Barbula indica and Bryum argenteum. Cd, though lowest in absolute concentration, shows the highest enrichment factor relative to background (up to 24.5×), making it the most sensitive indicator metal. All species show markedly elevated concentrations compared to unpolluted control sites (not shown; refer to Table 2) [1, 3 & 5]

5. COMPILED DATA TABLES

Table 1: Principal Indian bryophyte species used in heavy metal biomonitoring, showing study region, metals detected, and relative accumulation level. *Funaria hygrometrica* is the most widely studied species and the highest accumulator of Pb and Zn. The table confirms that Indian bryomonitoring is dominated by work from Himalayan hill regions (Garhwal, Kumaon) and the Gangetic plains [1, 3, 4, 5].

Bryophyte Species	Division	Indian Study Region	Metals Detected	Accumulation Level	Ref.
Funaria hygrometrica Hedw.	Bryophyta (Moss)	Garhwal Hills, Uttarakhand	Pb, Zn, Cu, Fe, Mn	High — hyperaccumulator	[3, 7]
Bryum argenteum Hedw.	Bryophyta (Moss)	Delhi, UP, Rajasthan	Pb, Zn, Cd, Ni, Cr	Moderate–High	[1, 5]
Sphagnum cuspidatum Hoffm.	Bryophyta (Moss)	Kumaon Hills, Uttarakhand	Pb, Zn, Fe, Mn, Cu	Moderate	[4]

Bryophyte Species	Division	Indian Study Region	Metals Detected	Accumulation Level	Ref.
Barbula indica (Hook.) Spreng.	Bryophyta (Moss)	Mussoorie, Garhwal Hills	Pb, Zn, Cu, Cd	High — retrospective data	[3]
Marchantia polymorpha L.	Marchantiophyta (Liverwort)	Himachal Pradesh, Uttarakhand	Pb, Zn, Cu, Ni	Moderate	[1]
Rhodobryum giganteum (Schwaegr.) Par.	Bryophyta (Moss)	Garhwal Hills, Uttarakhand	Pb, Zn, Fe, Cu, Ni, Cr	Moderate–High	[3]
Atrichum undulatum (Hedw.) P.Beauv.	Bryophyta (Moss)	Kolkata, West Bengal	Pb, Zn, Cu, Cd, Cr	High urban accumulator	[5]

Table 2: Heavy metal concentrations (mg/kg dry weight) in Indian bryophyte species at polluted and control sites, with enrichment factors (EF = polluted/control ratio). The table reveals that Cd shows the highest EF (up to 24.5× in *Bryum argenteum* from Kolkata), confirming Cd as the most sensitive indicator of anthropogenic pollution. Pb in *Funaria hygrometrica* shows the highest absolute EF (22.7×), consistent with its hyperaccumulating character. Values are representative means ± SE from cited studies [3, 4, 5, 7].

Species / Location	Metal	Control Site (mg/kg dw)	Polluted Site (mg/kg dw)	Enrichment Factor	Source of Pollution	Ref.
Funaria hygrometrica / Garhwal	Pb	8.2 ± 1.1	186.4 ± 22.3	22.7×	Industrial, vehicular	[3, 7]
Funaria hygrometrica / Garhwal	Zn	42.6 ± 5.4	312.8 ± 38.1	7.3×	Industrial effluents	[3, 7]
Bryum argenteum / Kolkata (urban)	Pb	11.4 ± 1.8	142.3 ± 17.6	12.5×	Vehicular exhaust	[5]
Bryum argenteum / Kolkata (urban)	Cd	0.4 ± 0.1	9.8 ± 1.2	24.5×	Industrial — highest EF	[5]
Sphagnum cuspidatum / Kumaon	Pb	6.8 ± 0.9	95.7 ± 11.4	14.1×	Petrol pump stations	[4]

Species / Location	Metal	Control Site (mg/kg dw)	Polluted Site (mg/kg dw)	Enrichment Factor	Source of Pollution	Ref.
Barbula indica / Mussoorie	Pb	9.1 ± 1.3	164.2 ± 19.8	18.0×	Traffic + industrial	[3]
Barbula indica / Mussoorie	Zn	38.4 ± 4.7	245.6 ± 28.9	6.4×	Retrospective 100 yr data	[3]

Table 3: Comparison of biomonitoring methodologies applied in Indian bryophyte heavy metal studies. Passive biomonitoring (native moss survey) is the most commonly applied Indian method; active biomonitoring with moss bags offers superior temporal control and inter-site comparability. Retrospective herbarium analysis, uniquely applicable in bryophytes, provides century-scale pollution trend data unavailable from any other biological monitoring system [1, 3, 4, 6, 8, 10].

Method	Principle	Advantages	Limitations	Application in India	Ref.
Passive biomonitoring (native moss survey)	Analyse naturally growing moss at multiple sites	No transplantation; reflects long-term exposure; low cost	Species availability varies; no temporal control	Most common Indian method	[1, 8]
Active biomonitoring (moss bags)	Standardised moss exposed in bags at target sites for fixed period	Controls for initial metal content; comparable across sites; temporal data	Labour-intensive; moss must be maintained viable	Petrol pumps, urban India	[4, 10]
Transplant experiments	Clean moss transplanted from reference site to polluted site	Direct exposure measurement; control vs. polluted comparison	Requires suitable donor site; logistically complex	Garhwal Hills studies	[3]
Retrospective analysis (herbarium moss)	Archived/herbarium specimens compared with current collections	Historical pollution trends; century-scale data possible	Limited to well-maintained herbaria; storage artefacts possible	Mussoorie century study	[3]
Bioconcentration Factor (BCF) analysis	Metal in plant / metal in substrate; quantifies	Quantitative; enables inter-	Requires parallel	Kolkata urban studies	[5, 6]

Method	Principle	Advantages	Limitations	Application in India	Ref.
	accumulation efficiency	species comparison	soil/substrate analysis		

6. DISCUSSION

The synthesis of Indian bryomonitoring data presented in this review leads to several overarching conclusions. First, as clearly shown in **Table 2** and **Figure 2**, all Indian bryophyte species studied accumulate heavy metals at concentrations substantially exceeding co-occurring vascular plants [1], and enrichment factors at Indian pollution hotspots (Pb EF = 22.7× in *F. hygrometrica*; Cd EF = 24.5× in *B. argenteum*) are comparable to or exceed those reported in European bryomonitoring programmes [6]. This confirms that Indian bryophytes are not merely bioindicators in principle but are demonstrably responsive to the actual pollution loads imposed by Indian industrial, vehicular, and urban activities.

Second, the retrospective analysis of *Barbula indica* from Mussoorie [3] — tracking a century of atmospheric Pb accumulation through archived herbarium specimens — represents one of the most scientifically valuable contributions to Indian environmental history. No physical monitoring instrument can provide this quality of long-term continuous data from a fixed geographic point. This unique capability of bryophytes as chemical archives of past pollution deserves far greater exploitation in India, where bryophyte herbarium collections at botanical institutions (e.g., BSI Kolkata, Forest Research Institute Dehradun) represent an untapped historical data resource [8].

Third, the consistent finding across Indian studies that Cd shows the highest enrichment factor despite its lowest absolute concentration [5, 9] highlights a critical point for policy: the most ecologically and toxicologically dangerous metals are not necessarily those present at the highest concentrations. Cd's enrichment factor of 24.5× in urban Indian moss (**Table 2**) signals a proportional contamination far exceeding background even when absolute concentrations appear modest — an insight that physico-chemical monitoring of total metal burden would underestimate without the normalisation provided by bioaccumulation factor analysis.

Finally, the comparison of biomonitoring methods in **Table 3** reveals an important gap: while passive native-moss biomonitoring is well developed in Indian Himalayan hill regions, systematic active biomonitoring with standardised moss bags — which enables cross-site and temporal comparisons — remains sparse in India compared to Europe [10]. The limited deployment of the moss-bag method beyond a few Kolkata studies [5, 10] is a critical methodological gap that prevents spatially comprehensive national-level pollution mapping analogous to the UNECE ICP Vegetation Moss Survey that has covered Europe since 1990 [6].

7. RESEARCH GAPS AND FUTURE DIRECTIONS

Several significant research gaps remain in Indian bryophyte biomonitoring. First, the vast majority of published Indian bryomonitoring studies are confined to Himalayan hill regions (Garhwal, Kumaon, Himachal Pradesh); peninsular India — which hosts major industrial corridors in Maharashtra, Tamil Nadu, Andhra Pradesh, and Karnataka — is almost entirely unstudied for bryophyte-based heavy metal monitoring. Second, liverworts and hornworts, which constitute a substantial fraction of Indian bryophyte diversity in tropical and subtropical regions, are almost entirely absent from Indian heavy metal monitoring literature; all documented Indian studies use mosses, leaving an entire division of potential bioindicators unexploited. Third, standardised interspecies comparison studies — using simultaneous collection of multiple co-occurring species at the same sites under identical protocols — are lacking, preventing rigorous quantification of the species-specific accumulation differences implied by the data in **Table 1**. Fourth, Indian study had applied ICP-MS for multi-element profiling of bryophyte tissue to detect trace metalloids (As, Se, Sb) alongside the conventional heavy metals. Fifth, the molecular and biochemical mechanisms of metal tolerance and sequestration — including phytochelatin induction, vacuolar compartmentalisation, and antioxidant enzyme responses — have not been characterised in any Indian bryophyte species, preventing mechanistic interpretation of field bioaccumulation data.

8. CONCLUSION

This review demonstrates, on the basis of published evidence, that bryophytes are highly effective, scientifically robust, and cost-efficient bioindicators of heavy metal pollution across multiple Indian contexts — from Himalayan petrol-pump stations [4] and industrial hill towns [3] to metropolitan traffic corridors [5]. The properties that make bryophytes uniquely suited to this role — poikilohydry, cuticular absence, high surface-to-volume ratio, extracellular ion exchange capacity, and the possibility of retrospective analysis [1, 8] — are summarised in **Table 3**. Key accumulator species documented in India include *Funaria hygrometrica* (hyperaccumulator; Pb EF = 22.7×), *Bryum argenteum* (Cd EF = 24.5×), *Sphagnum cuspidatum* (Pb EF = 14.1×), and *Barbula indica* (century-scale Pb archive) [3, 4, 5, 7]. The heavy metal concentrations visualised in **Figure 2** and tabulated in **Table 2** confirm that Indian bryophytes accumulate metals at enrichment factors matching or exceeding those in European monitoring programmes [6]. Priority future research needs are: (i) national-scale moss bag deployment spanning all Indian industrial regions; (ii) inclusion of liverworts in monitoring programmes; (iii) multi-element ICP-MS profiling; and (iv) molecular characterisation of metal tolerance mechanisms in Indian species. Bryophytes are not merely plants — in the context of pollution monitoring, they are living chemical records, and India's bryophyte flora represents an under-utilised national environmental monitoring asset.

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