# Bryophytes as an Accumulator of Toxic Elements from the Environment: Recent Advances

Jayanta Barukial and Porismita Hazarika

## Contents



**Abstract**

Toxic elements cause a serious threat to both the terrestrial and aquatic ecosystems. They are released into the environment by anthropogenic activities like the discharge of wastewaters viz. industrial effluents, home sewage, use of chemical fertilizers, burning of fossil fuel, mining of different ores, use of radioactive elements, and nuclear reactors which contribute to heavy metal influx into the environment. Bryophytes include liverworts, hornworts, and mosses which have a significant potential to absorb heavy metals, making them useful biomonitoring tools. Because of the lack of an efficient vascular system, heavy metals deposition has been seen in bryophytes. Bryophyte tissue is a potent ion exchanger with the environment; hence, they accumulate heavy metals from the sources. Metal

J. Barukial (✉)
Debraj Roy College, Golaghat, Assam, India

P. Hazarika
Dibrugarh University, Dibrugarh, Assam, India
e-mail: rs_porismitahazarika@dibru.ac.in



H. N. Murthy (ed.), *Bioactive Compounds in Bryophytes and Pteridophytes*, Reference Series in Phytochemistry, https://doi.org/10.1007/978-3-030-97415-2_6-1

absorption is extremely noticeable in bryophytes, especially in samples from contaminated streams. Mosses are the most important of the three groups of bryophytes in terms of bioaccumulation of hazardous substances from the environment. Moss species are more effective than vascular plant leaves for monitoring air pollution produced by heavy metals in urban areas. Hence, bryophytes are regarded as the best biomonitoring agent of environmental pollution. Currently, Moss bag techniques have been used to give a low-cost, flexible, and dense monitoring design that can show spatial and temporal trends but also vertical and horizontal gradients for a number of inorganic and organic pollutants. The moss bag approach will successfully overcome the issue of a lack of naturally grown mosses, allowing homogeneous biomonitoring of gaseous pollutants across all anthropogenically devastated areas. It has been utilized successfully for biomonitoring of potentially hazardous elements such as rare earth elements and persistent organic chemicals, primarily polycyclic aromatic hydrocarbons. In this context, a more in-depth research is necessary from the forthcoming researchers in this field.

**Keywords**

Bioaccumulation · Biomonitoring · Bryophytes · Ecosystem · Heavy metals · Moss bag · Toxic elements

**Abbreviations**

| | |
|---|---|
| $\text{Ag}^{-}$ | Silver |
| $\text{Al}^{-}$ | Aluminum |
| $\text{Ca}^{-}$ | Calcium |
| $\text{Cd}^{-}$ | Cadmium |
| $\text{CEC}^{-}$ | Cation Exchange Capacity |
| $\text{CF}^{-}$ | Contamination Factor |
| $\text{Co}^{-}$ | Cobalt |
| $\text{Cr}^{-}$ | Chromium |
| $\text{Cu}^{-}$ | Copper |
| $\text{Fe}^{-}$ | Iron |
| $\text{Hg}^{-}$ | Mercury |
| $\text{HM}^{-}$ | Heavy Metal |
| $\text{K}^{-}$ | Potassium |
| $\text{Mg}^{-}$ | Magnesium |
| $\text{Mn}^{-}$ | Manganese |
| $\text{Mo}^{-}$ | Molybdenum |
| $\text{Na}^{-}$ | Sodium |
| $\text{Ni}^{-}$ | Nickel |
| $\text{PAH}^{-}$ | Polycyclic Aromatic Hydrocarbon |
| $\text{Pb}^{-}$ | Lead |
| $\text{PTE}^{-}$ | Potentially Toxic Trace Elements |

| | |
|---|---|
| $Se^{-}$ | Selenium |
| $Sn^{-}$ | Tin |
| $Zn^{-}$ | Zinc |

# 1 Introduction

People are becoming more aware of the term "pollution" and are collecting harmful substances from their surroundings. They have since learned about the dangerous substances' negative effects on their health and the health of other living beings. Copper(Cu), Iron(Fe), Molybdenum(Mo), Zinc(Zn), and, in some cases, Aluminium(Al), Nickel(Ni), and Selenium(Se) are all trace metals that organisms need as micronutrients. However, in certain circumstances, these same components may accumulate in high concentrations in species, causing ecological devastation. Cadmium(Cd), Chromium(Cr), Cobalt(Co), Copper(Cu), Iron(Fe), Lead(Pb), Mercury(Hg), Nickel(Ni), Silver(Ag), Tin(Sn) and Zinc(Zn), as well as the lighter elements Aluminium(Al), Arsenic(As), and Selenium (Se) are the most usually linked to environmental toxicity [22].

## 1.1 Sources of Hazardous and Toxic Materials in the Environment

Both aquatic and terrestrial ecosystems are threatened by toxic trace metals. Heavy metals from various sources have poisoned both ecosystems. Heavy metals are one of the most studied contaminants in the environment. Depending on the dose and length of exposure, almost any heavy metal or metalloid could be hazardous to biota [1]. Metals with a specific density of more than 5 $gcm^{-3}$ are classified as heavy metals [39]. Heavy metals discharged into the atmosphere through mining, smelting, and other industrial activities eventually find their way back to the soil via dry and wet deposition. Heavy metals are released into the environment by the discharge of wastewaters such as industrial effluents and home sewage. Chemical fertilizers and fossil fuel burning both contribute to anthropogenic heavy metal influx into the environment. Phosphate fertilizers are particularly hazardous when it comes to heavy metal levels in commercial chemical fertilizers [1]. Heavy metals harm to water and soil because they are dumped into the water, moved down streams, and eventually trapped in the water's underlying bed; or they are washed away by overflow onto the water surface [21]. The toxic effects of these metals are an issue for ecological, evolutionary, nutritional, and environmental reasons [56]. The toxicity of persons exposed is influenced by the dose, manner of exposure, chemical species, as well as their age, gender, genetics, and nutritional status. Heavy metals are persistent in the environment and can bioaccumulate in food systems. Cadmium, lead, and mercury are examples of common air pollutants emitted mostly as a result of industrial activities. They contribute to soil deposition and build-up despite the low air levels. Cadmium has also been identified as a probable human carcinogen, capable of causing lung cancer. Lead poisoning impairs the growth and neurobehavioral development of fetuses, newborns, and toddlers as well as raises blood pressure in adults.

Mercury is harmful in both its elemental and inorganic forms, but the organic molecules, particularly methyl mercury, that accumulate in the food chain, that is, in predatory fish in lakes and oceans, are the primary routes of human exposure. Long-range transboundary, air pollution is only one source of exposure to these metals, but due to their persistence and potential for global atmospheric transmission, atmospheric emissions have an impact on even the most remote places [40].

### 1.2 Most Hazardous Toxic Elements with Environmental Impact

Many elements are regarded as heavy metals; however, some are significant in terms of the environment. Cr, Ni, Cu, Zn, Cd, Pb, Hg, and As are among the most ecologically hazardous heavy metals and metalloids [1, 5]. Cr, Mn, Ni, Cu, Zn, Cd, and Pb are the most prevalent heavy metal contaminants found in the environment [1, 42]. In 2009, China outlined four metals, that is, Cr, Cd, Pb, Hg, and the metalloids, as the highest priority pollutants for monitoring in the "12th 5 year plan for comprehensive prevention and control of heavy metals in the environment" [1, 23]. These metallic elements are considered systemic toxicants that can trigger organ damage even at low levels of exposure. They are also described as human carcinogens by the US Environmental Protection Agency and the International Agency for Research on Cancer [84].

## 2 Bryophytes and Toxic Elements

Because of their dispersion powers, bryophytes are more distributed widely than other plants [57, 80]. From an evolutionary standpoint, these are represented by the second most species-rich cluster of land-dwelling plants [37]. The mosses contain approximately 8000 species, liverworts 6000 species, and hornworts 200 species [31]. Bryophytes allocate important buffer structures for other groups of plants and thus play a crucial part in perpetuating ecosystems [36]. Bryophytes are widely used as touchstone species in air pollution, water pollution, and soil pollution. Besides, they are also used in various fields, such as material for seed beds, fuel, medicines, food, pesticides, moss gardening, treatment of waste, construction, genetic engineering, culturing, and soil conditioning [27, 65].

### 2.1 Sequestration of Toxic Elements by Bryophytes

A tolerant plant has a specific physiological system that enables it to work efficiently even when exposed to excessive heavy metal concentrations [83]. Bryophytes have a significant potential to absorb heavy metals, making them useful biomonitoring tools. However, depending on the element and bryophyte species employed, this capability may vary [4, 58]. Because of the lack of an efficient vascular system, heavy metals deposition has been seen in mosses and other bryophytes. This is owing to the relatively unrestricted exchange of solutes between active plant tissues and the atmosphere [30, 41]. Several investigations in the Goujiang Karst bauxite in South Western China found that gemmiferous bryophyte communities tolerate high-heavy metal substrates better than nongemmiferous communities, making gemmiferous bryophyte communities valuable in heavy metal pollution monitoring [80]. Pleurocarpous bryophytes are more susceptible to toxins than acrocarpous bryophytes. This sensitivity might be due to variations in the growth forms' water conducting systems and soluble metal absorption [48, 64]. Elevated pollution and poor water quality are likely to be problematic for aquatic bryophytes. The composition of bryophyte species is indicative of river hydromorphology in the assessment of surface water quality, while the abundance of elements in bryophyte tissue depicts water chemistry [25, 77].

Role of direct involvement of photochemical of bryophytes in the accumulation of toxic element is not established yet, but it has been revealed by some studies that the metal chelating properties involve in the sequestration of toxic elements by bryophytes. For assessing the antioxidant capacity that retains metals that induce lipid peroxidation, metal chelating activity is crucial. Chelating substances bind transition metals in the body for this reason, which prevents radical production [45]. Metal ion sequestration in the cell wall, vacuoles, and cytoplasm vesicles are all known to be involved in heavy metal tolerance in bryophytes. Heavy metal toxicity can be minimized by bryophytes by trapping toxic ions in internal and external spaces. One of the most well-known sites of metal detoxification is the cell wall [7, 8, 47]. According to some interpretations, heavy metal transport and deposition in metal-treated pollen grains may be facilitated via cell membrane pits, cytoplasm vesicles and multivesicular aggregates [20]. Herbarium moss samples might have been useful in predicting patterns in Pb and Cu deposition [67].

## 2.2 Ion Exchange Characteristics of Bryophytes

Bryophyte tissue is a potent ion exchanger, which *has been recognized for decades* [10, 74]. Metal tolerance in bryophyte is species-specific, although the mechanisms for the diverse levels of tolerance are unclear. In the mosses, the data indicate a hypothetic correlation between lamina cell shape and metal tolerance. Species with long, thin lamina cells may withstand high metal levels better than those with isodiametric cells [58]. *In comparison to tracheophyte roots, bryophyte tissues exhibit greater cell wall cation exchange capacities (CEC), which may be crucial in the sequestration and protoplasmic absorption of crucial cations like Mg*. The CEC of epilithic and wooded soil bryophytes reduces when the preferred substratum's Ca concentration and pH decline. It is likely that a lower CEC avoids excessive adsorption of the phytotoxicant AI, which becomes more readily accessible under acidic environments, although this concept is still not validated [9]. Cu2+, Pb2+ > Ni2+ > Co2+ > Zn2+,Mn2+ is the persistence ability order for heavy metal ions in *Hylocomium splendens* [63, 73]. At ambient levels, retention efficiency in *Sphagnum* falls in the order Fe3+ > Mg2+, Ca2+ > K+, Na+, as well as with cation exchange resins [10]. Unesterified polyuronic acids make up around 25% of the tissue dry weight in *Sphagnum acutifolium*, and there is a strong link between the quantity of these acids and the cation exchange capacity (CEC) of several *Sphagnum* species [19, 73]. The tissue abundance of pectic compounds, particularly uronic acid, is intrinsically linked to the cation exchange capacity (CEC) of *Sphagnum* [44].

## 3 Role of Bryophytes in Sequestration of Toxic Elements: Recent Advances

As a method for determining the levels of environmental health and assessing the harmful contaminants in the biosphere, bryo-monitoring is progressively gaining popularity [50]. Tyler and his colleagues came up with the notion of using mosses to quantify atmospheric heavy metal deposition in the late 1960s. The moss analysis approach provides a proxy, time-integrated estimate of heavy metal deposition patterns from the atmosphere to terrestrial systems [33]. As a result, many regions of the world employ these agents in the current situation to monitor the different kind of pollution [50] (listed in Table 1).

The European moss survey has been conducted every 5 years since 1990 [35]. The survey was conducted from 2000 to 2001 to investigate patterns of variation in heavy metal concentrations in mosses across Europe, identify the most contaminated places, create regional maps, and improve knowledge of long-range transboundary contamination [33]. The European moss study collects data on 10 heavy metal concentrations (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, and Zn) in naturally grown mosses, as well as the metals Al and Sb and nitrogen since 2005 [32, 34, 35, 71]. For 27 archival and native bryophyte specimens collected in Guangzhou from 1932 to 2018, five heavy metals (As, Cd, Cu, Pb, and Zn) were analyzed [81].

The Republic of Moldova's deposition of potentially harmful substances was assessed using the moss biomonitoring approach. The research was carried out under the auspices of the International Cooperative Program on Effects of Air Pollution on Natural Vegetation and Crops. In May 2020, samples of the moss *Hypnum cupressiforme* Hedw. were gathered from 41 sampling locations spread over the whole nation. Neutron activation analysis and atomic absorption spectrometry were used to estimate the mass fractions of 35 elements, including Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Br, Se, Rb, Sr, Sb, Cs, Ba, Cd, La, Ce, Sm, Eu, Tb, Hf, Ta, Th, Pb, and U [85].

The total contents of eight elements (Cu, Zn, Fe, Mn, Ni, Pb, Cd, and Cr) as determined by ICP-AES and Atomic Absorption Spectrophotometry (AAS) methods were compared in four types of indigenous mosses (*Brachythecium plumosum, Eurhynchium laxirete, Taxiphyllum taxirameum,* and *Haplocladium strictulum*), which were collected from various sampling sites in the Chengdu city, China. According to the study, *T. taxirameum* had a larger potential for metal

**Table 1** Name of the bryophytes that are involved in the accumulation of toxic elements

| Sl. No | Name | Family | Habitat |
|---|---|---|---|
| **Liverworts** | | | |
| 1 | *Riccia fluitans* L. | Ricciaceae | Aquatic |
| 2 | *Aneura pinguis* (L.) Dumort. | *Aneuraceae* | Terricolous |
| 3 | *Pellia endiviifolia* (Dicks.) Dumort. | Peliaceae | Terricolous |
| 4 | *Solenostoma crenulatum* Mitt. | Jungermanniaceae | Corticolous, saxicolous |
| **Mosses** | | | |
| 5 | *Pleurochaete squarrosa* (Brid.) Lindb. | Pottiaceae | Aquatic |
| 6 | *Hypnum cupressiforme*Hedw. | Hypnaceae | Terricolous/ Saxicolous |
| 7 | *Pseudoscleropodium purum* (Hedw.) M. Fleisch. | Brachytheciaceae | Terricolous |
| 8 | *Hylocomium splendens* (Hedw.) Schimp. | Hylocomiaceae | Saxicolous |
| 9 | *Bryum pseudotriquetrum* (Hedw.) Schwaegr. | Bryaceae | Saxicolous |
| 10 | *Bryum turbinatum* (Hedw.) Turner | Bryaceae | Saxicolous |
| 11 | *Chorisodontium aciphyllum* (Hook. f. & Wilson) Broth. | Dicranaceae | Saxicolous |
| 12 | *Racomitrium lanuginosum* (Hedw.) Brid. | *Grimmiaceae* | Saxicolous |
| 13 | *Rhizomnium punctatum* (Hedw.) T.J. Kop. | Mniaceae | Terricolous |
| 14 | *Taxiphyllum barbieri* (Cardot & Copp.) Z. Iwats. | Hypnaceae | Aquatic |
| 15 | *Pohlia nutans* (Hedw.) Lindb. | Bryaceae | Terricolous |
| 16 | *Leskea angustata* Taylor | Leskeaceae | Terricolous |
| 17 | *Fabronia ciliaris* (Brid.) Brid. | Fabroniaceae | Saxicolous / Corticolous |
| 18 | *Polytrichastrum formosum* (Hedw.) G.L. Sm. | Polytrichaceae | Terricolous / saxicolous |
| 19 | *Pleurozium schreberi* (Willd. ex Brid.) Mitt. | Hylocomiaceae | Terricolous |
| 20 | *Fontinalis antipyretica* L. ex. Hedw. | Fontinalaceae | Aquatic |
| 21 | *Philonotis fontana* (Hedw.) Brid. | *Bartramiaceae* | Terricolous / saxicolous |
| 22 | *Pohlia flexuosa* Harv. | Bryaceae | Saxicolous |
| 23 | *Cinclidotus fontinaloides* (Hedw.) P. Beauv. | *Cinclidotaceae* | Saxicolous |
| 24 | *Dialytrichia mucronata* (Brid.) Broth. | *Pottiaceae* | Corticolous/ saxicolous |
| 25 | *Hygroamblystegium fluviatile* (Hedw.) Loeske | Amblystegiaceae | Aquatic / saxicolous |
| 26 | *Hygroamblystegium tenax* (Hedw.) Jenn. | Amblystegiaceae | Aquatic / saxicolous |
| 27 | *Platyhypnidium riparioides* (Hedw.) Dixon | Brachytheciaceae | Aquatic |
| 28 | *Leptodictyum riparium* (Hedw.) Warnst. | Amblystegiaceae | Aquatic |
| 29 | *Scorpiurium circinatum* (Brid.) M. Fleisch. & Loeske | Brachytheciaceae | Saxicolous |

(continued)

**Table 1** (continued)

| Sl. No | Name | Family | Habitat |
|---|---|---|---|
| 30 | *Fontinalis hygrometrica* (Hedw.) P. Syd. | Fontinalaceae | Aquatic |
| 31 | *Fissidens bryoides* Hedw. | Fissidentaceae | Terricolous |
| 32 | *Cinclidotus aquaticus* (Hedw.) Bruch & Schimp. | Cinclidotaceae | Aquatic |
| 33 | *Cratoneuron filicinum* (Hedw.) Spruce | Amblystegiaceae | Terricolous |
| 34 | *Palustriella commutata* (Hedw.) Ochyra | Amblystegiaceae | Aquatic |
| 35 | *Ceratodon purpureus* (Hedw.) Brid. | Ditrichaceae | Saxicolous |
| 36 | *Sphagnum palustre* L. | Sphagnaceae | Aquatic |
| 37 | *Funaria hygrometrica* Hedw. | Funariaceae | Terricolous |
| 38 | *Brachythecium* species | Brachytheciaceae | Terricolous |
| 39 | *Eurhynchium* species | Brachytheciaceae | Terricolous |

accumulation than other species, and there were substantial inter- and intraspecies variances in heavy metal concentrations [17].

In order to determine the effects of growth substrates, geographic elevation, and moss species type on the accumulation characteristics of heavy metals as well as to pinpoint heavy metal sources, concentrations of Cr, Co, Ni, Zn, Sr, Cd, Ba, and Pb in various moss species from Mountain Gongga, China, were analyzed. The findings revealed substantial differences in both the composition and geographical distribution of these components. The findings demonstrated that elevation has an impact on the variance of heavy metals in moss. The kind of moss and growth substrate had less of an impact on the metal concentration of the mosses studied for this investigation. The PMF model's findings showed that the majority of the Co, Cr, and Ni in the mosses on Mountain Gongga came from substrate sources, while other elements were predominantly linked to human activities, Pb and Cd might be ascribed to atmospheric deposition [82].

After mineral exploitation, the restoration of natural vegetation in manganese mining regions has become a crucial task. In mining regions of South western China, bryophytes have a priceless impact on ecological restoration. The findings indicated that *Bryum atrovirens* obtained from two different types of regions had a considerable capacity to accumulate Mn, with cumulants of 5588.00 g/g and 4283.41 g/g, respectively. All mosses demonstrated a high capacity for Cd enrichment. It demonstrated that mosses were very resistant to heavy metals [60].

In both polluted and uncontaminated sites in Villavicencio (Colombia) and its surrounds, the presence and distribution of the bioaccumulation of lead in bryophytes have been assessed. Fifty-two samples of bryophytes in total were gathered, of which 43 came from locations spread around the city's urban areas (homes, businesses, and highways), while the remaining nine came from clean regions located outside the city. Nitric and hydrochloric acids were used to treat the samples, and the results were then analyzed using atomic absorption spectrometry. Pb concentrations were found to be between 1 and 6 times higher in the commercial sector than in the residential and highway sectors. The regional variations in lead deposition are reflected in the spatial patterns of lead concentrations in bryophytes. According to this study, mosses and liverworts can be used to detect pollution hotspots in a city [72].

Over the course of 5 years, a research was conducted using *Pleurozium schreberi* next to a national highway that crosses Poland from north to east in the vicinity of Natura 2000 regions. Three places that were noticeably different were used to harvest moss samples. The amount of Zn, Ni, Pb, Co, and Cd in moss was examined in this study in relation to the effects of road transportation [59].

As markers of metal contamination, two moss species – *Physcomitrium cyathicarpum* and *Barbula constricta* – growing in various parts of Delhi, India, have been utilized. Using atomic absorption spectroscopy, the levels of significant heavy metals including Cr, Co, Cd, Cu, Fe, Hg, Ni, and Pb have been estimated in the tissues of both moss species, with Fe, Ni, Cu, and Cr having the greatest levels followed by Co, Cd, Pb, and Hg. Fe, Co, Cu, and Cr concentrations were found to be high in both species growing in the North Delhi zone, followed by South and West Delhi, indicating that areas with an industrial belt, heavy traffic, and companies that produce chemical effluents [76].

In order to assess the capability for heavy metal accumulation in mosses at several sites in the Idukki District of Kerala, India, eighteen moss species and their soil substrata were examined. Statistics revealed substantial interspecies variations in metal concentrations ($p = 5\%$), where *Campylopodium khasianum* had a greater capability for metal accumulation. In all five of the chosen sampling locations, the substratum had the greatest Cr level, followed by Ni and Pb. Regardless of the sample sites, all the mosses exhibited substantial Cr (III) accumulation relative to other metals (Cd, Cu, Pb, and Ni). *Campylopodium khasianum*, one of 18 mosses, was shown to gather the most Cr, Cd, Ni, and Pb, indicating that it may be used to clean up soil polluted with these metals [75].

## 4 Several Bryophytes in the Deposition of Toxic Substances from the Environment

Metal absorption is extremely noticeable in bryophytes, especially in samples from contaminated streams [14]. Mosses are the most important of the three groups of bryophytes in terms of bioaccumulation of hazardous substances from the environment. Moss species are more effective than vascular plant leaves for monitoring air pollution produced by heavy metals in urban areas [18]. Mosses that can acquire large levels of heavy metals from the environment have evolved a natural response to these circumstances [13]. Moss proves to be a promising bioindicator for elements notably Al, Cr, Sc, Th, Pb, Cd, Cu, V, and partially Zn deposition [15].

## 4.1 Liverworts

*Pellia endiviifolia* (Dicks.) Dumort.and *Aneura pinguis* (L.) Dumort.can be utilized as reliable bioindicators of water quality [16]. *Marchantia polymorpha* L. may be utilized as an adequate air pollution indicator. A combination of indices such as chlorophyll, sugar, protein, catalase, and peroxidase in this species exposed for a short amount of time can reliably reveal pollution levels in the air. It may be regarded as a hyperaccumulator for lead since it demonstrated high levels of absorption. As a result, it can be utilized as a bioindicator or bioaccumulator species and can be used for indication or accumulation in various contaminated locations [66].

## 4.2 Mosses

*Fontinalis antipyretica* Hedw. can be utilized to detect zinc pollution in aquatic systems [53]. It acquires pollutants like heavy metals and other trace elements, making it a good indication of urban pollution in terms of the ecological threats posed. It may also be used to collect inorganic and organic contaminants [24–26, 77–79]. *Pohlia flexuosa* Harv. can tolerate large levels of hazardous metals without showing any signs of harm in its growth and development. For these metals, it possesses a tolerance and exclusion mechanism, notably for the nonessential elements As and Pb. As a result, its luxuriant and spontaneous development might be exploited as a phytostabilization pioneer plant in the black shale outcrop, where vascular plants are uncommon. Its ability to tolerate Cd toxicity may be due to the control of K and Zn uptake. *P. flexuosa* Harv, in particular, can grow and function properly in severely polluted soil (up to 486.0 mg $kg^{-1}$ Cd and 2220 mg $kg^{-1}$ Cu) [83]. In a biomonitoring study in remote areas of Italy and Northern Victoria, 15 chemical elements were discovered in five epigean moss species: *Hypnum cupressiforme* Hedw., *Pseudoscleropodium purum* (Hedw.) M. Fleisch., *Hylocomium splendens* (Hedw.)Schimp., *Bryum pseudotriquetrum* (Hedw.) Schwaegr., and *Chorisodontium aciphyllum* (Hook. f. & Wilson) Broth [6]. In a study conducted in Trieste, transplants of the mosses *Hypnum cupressiforme* Hedw. and *Pseudoscleropodium purum* (Hedw.) M. Fleisch. were compared as active biomonitors of some airborne trace elements (As, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Ti, V, Zn). *Pseudoscleropodium purum* (Hedw.) M. Fleisch. has a strong resistance to heavy metals in the atmosphere, accumulating and losing practically all elements at equal or greater rates, especially those connected to particulate, dry depositions. The physical absorption of the coarse component of the dust by the *P. purum (Hedw.) M. Fleisch.* transplants was the predominant mechanism of heavy metal accumulation [51, 86]. Largescale patterns connected to moist depositions might be detected using *Hypnum cupressiforme* Hedw. This species was shown to be capable of removing metal ions (Co, Ni, Zn, Cd, Pb, and Cu) from aqueous solutions based on biosorption studies. These two carpet-forming moss species were also used to investigate the atmospheric deposition of these components in Kosovo [13, 28, 54, 55]. *Racomitrium lanuginosum* (Hedw.) Brid. seems to have a wider potential for monitoring long-range atmospheric transit for these harmful substances [61]. Instrumental neutron activation analysis was used to evaluate the content of a total of 36 elements in *Brachythecium* sp. and *Eurhynchium* sp. [2]. *Taxiphyllum barbieri* (Cardot & Copp.) Z. Iwats., an aquatic moss, appears to be a good indicator species for metal toxicity because it showed clear sensitivity at the microscopic level [46]. Because it acquired significant levels of Cu and Ni, *Pohlia nutans* (Hedw.) Lindb. was thought to be a pollutant-resistant species. It not only survives extreme pollution, but also conquers severely polluted (barren) places in the absence of nonferrous smelters. It produces asexual reproductive structures that are highly specialized [68], which helps these species thrive in extremely polluted environments [48, 64, 73, 86]. *Leskea angustata* Taylor and *Fabronia ciliaris* (Brid.) Brid. are two epiphytic moss species that may be used to assess environmental pollution [49]. *Bryum turbinatum* (Hedw.) Turner and *Rhizomnium punctatum* (Hedw.) T.J. Kop. have high CFs for a variety of heavy metals and can be used to analyzed chemical contamination patterns [26]. *Polytrichastrum formosum* (Hedw.) G.L. Sm. is a suitable bioindicator for a variety of chemical components [52]. *Pleurozium schreberi* (Willd. ex Brid.) Mitt. is a sensitive bioindicator of heavy metal contamination in the environment. In Poland, this species is suggested for biomonitoring. They allow you to determine the degree of contamination, the source of contamination, and the direction of contamination spread [29, 43]. Metal accumulation by aquatic bryophytes from polluted mine streams is highly recorded. *Platyhypnidium riparioides* (Hedw.) Dixon, *Dialytrichia mucronata* (Brid.) Broth, *Hygroamblystegium fluviatile* (Hedw.) Loeske, *Hygroamblystegium tenax* (Hedw.) Jenn., and *Cinclidotus fontinaloides* (Hedw.) P. Beauv. could be used as trustworthy water quality bioindicators. Metal levels are high in *Philonotis fontana* (Hedw.) Brid. and *Solenostoma crenulatum* Mitt. (burton) [16, 77, 79]. *Leptodictyum riparium* (Hedw.) Warnst. is capable of retaining large levels of trace elements and has a high tolerance for human contamination [25]. Bioaccumulation in *Scorpiurum circinatum* (Brid.) Fleisch. & Loeske revealed that moss cells resisted heavy metal toxicity and immobilizing most harmful ions extracellularly, most likely in cell wall binding sites, which are the primary site of metal detoxification [8]. *Plagiomnium affine* (Blandow ex Funck) T.J. Kop.has been discovered to have a limited capacity to collect specific elements such as Zn, Cl, and others [58]. Pb and Zn accumulation is highest in the gametophyte and placenta of *Fontinalis hygrometrica* (Hedw.) P. Syd [7] specially in their cell walls, vacuoles, nuclei, and plastids [8]. *Sphagnum palustre* L. has proven to be a reliable bioindicator that may be used in biomonitoring research [70]. *Ceratodon purpureus* is a pollution-tolerant species that has been related to human influence [62]. *Pleurochaete squarrosa* (Brid.) Lindb. and *Hypnum cupressiforme* Hedw. were used in several biomonitoring assessments of heavy metal, nitrogen deposition, and $\delta$ 15 N signatures in a Mediterranean environment. In comparison to other pleurocarpous mosses, it is a viable biomonitor [38].

## 5 Perspective of Using Bryophytes in Accumulation of Toxic Elements

Moss analysis is a time-integrated surrogate measurement of metal deposition from the atmosphere to terrestrial systems. It is simpler and less expensive than traditional precipitation analysis because it eliminates the need for large numbers of precipitation collectors and a long-term program of sample collection and analysis. Because mosses have larger trace element concentrations than rainwater, analysis is easier and less prone to contamination. Although moss concentration measurements do not give a direct quantitative assessment of deposition, they may be calculated using one of many regression models that link moss survey findings to precipitation monitoring data [12, 33, 34]. Metal(loid) detoxification processes in bryophytes are probably worthy of further investigation. It is also worth noting that phytochelatin synthase (PCS) and phytochelatins (PCn) have recently been discovered in various bryophytes, indicating that PCn's involvement in metal detoxification and homeostasis in these plants might be important [11]. The moss bag approach successfully overcomes the issue of a lack of naturally grown mosses, allowing homogeneous biomonitoring of gaseous pollutants across all anthropogenically devastated areas. It has been utilized successfully for biomonitoring of potentially hazardous elements such as rare earth elements (PTEs) and persistent organic chemicals, primarily polycyclic aromatic hydrocarbons (PAHs). Moss bag techniques will be able to give a low-cost, flexible, and dense monitoring design that can show spatial and temporal trends but also vertical and horizontal gradients for a number of inorganic and organic pollutants. It might be used to monitor heavy metals in the air for a long time [3, 69].

## 6 Conclusion

It has been revealed that the mosses are more relevant to accumulating toxic elements than the other groups of bryophytes (Fig. 1). In terms of habitat, saxicolous and corticolous mosses are more relevant (Fig. 2). The family Amblystegiaceae has the potential in the tolerance of toxic metals from the environment followed by the family Brachytheciaceae and Bryaceae (Fig. 3). More in-depth research on these species, which play a significant role in phylogenesis, might uncover the presence of additional critical detoxifying systems that have been lost through time and/or better define the molecular processes underlying these plants' remarkable resistance to metal(loid)s. Understanding the present and developing successful solutions to meet future difficulties can be aided by a closer look into the past [11].

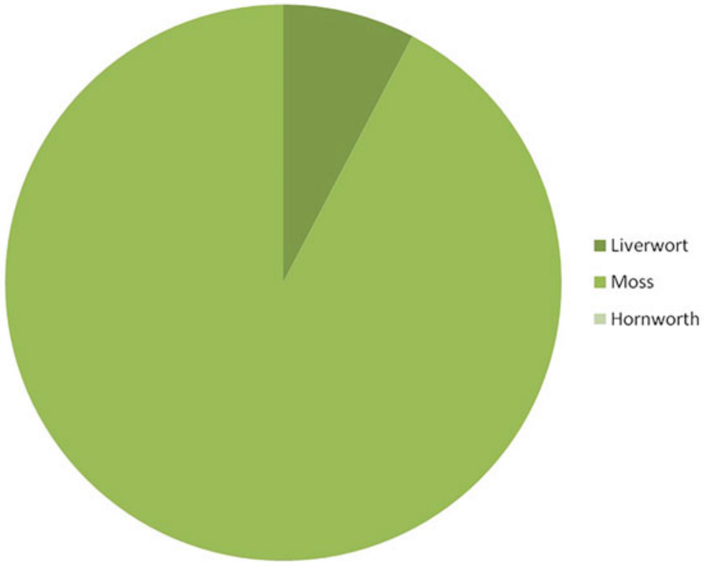


**Fig. 1** Pie diagram showing rate of involvement of different groups of bryophytes in term of toxic elements accumlation

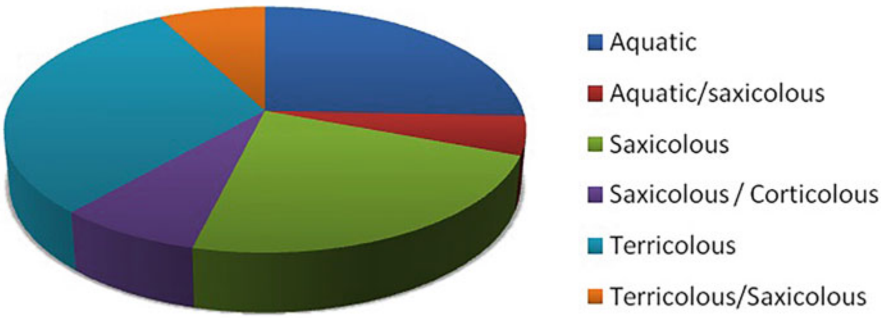


**Fig. 2** Pie diagram showing habitat-wise rate of involvement of bryophytes in context of toxic elements

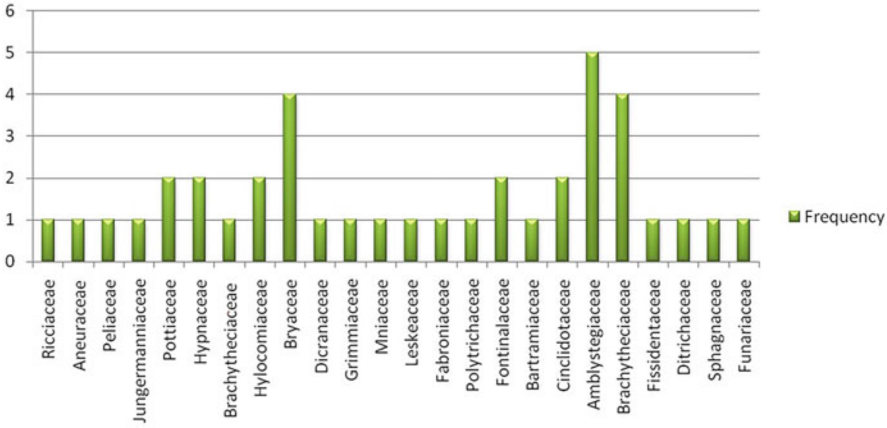


**Fig. 3** Bar digram showing accumulation rate of toxic elements by different families of bryophytes

## References


1. Ali H, Khan E, Ilahi I (2019) Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J Chem 2019:6730305
2. Aničić M, Tasić M, Frontasyeva MV, Tomašević M, Rajšić S, Mijić Z et al (2009) Active moss biomonitoring of trace elements with *Sphagnum girgensohnii* moss bags in relation to atmospheric bulk deposition in Belgrade, Serbia. Environ Pollut 157(2):673–679
3. Ares A, Aboal JR, Carballeira A, Giordano S, Adamo P, Fernández JA (2012) Moss bag biomonitoring: a methodological review. Sci Total Environ 432:143–158
4. Ares Á, Itouga M, Kato Y, Sakakibara H (2018) Differential metal tolerance and accumulation patterns of Cd, Cu, Pb and Zn in the liverwort *Marchantia polymorpha* L. Bull Environ Contam Toxicol 100(3):444–450
5. Barakat M (2011) New trends in removing heavy metals from industrial wastewater. Arab J Chem 4(4):361–377
6. Bargagli R, Brown DH, Nelli L (1995) Metal biomonitoring with mosses: procedures for correcting for soil contamination. Environ Pollut 89(2):169–175
7. Basile A, Cogoni AE, Bassi P, Fabrizi E, Sorbo S, Giordano S et al (2001) Accumulation of Pb and Zn in Gametophytes and Sporophytes of the Moss Funaria hygrometrica (Funariales). Ann Bot 87(4):537–543
8. Basile A, Sorbo S, Pisani T, Paoli L, Munzi S, Loppi S (2012) Bioacumulation and ultrastructural effects of Cd, Cu, Pb and Zn in the moss *Scorpiurum circinatum* (Brid.) Fleisch. & Loeske. Environ Pollut 166:208–211
9. Bates JW (1992) Mineral nutrient acquisition and retention by bryophytes. J Bryol 17(2):223–240
10. Bell P (1959) The ability of Sphagnum to absorb cations preferentially from dilute solutions resembling natural waters. J Ecol 47(2):351–355
11. Bellini E, Betti C, Sanità di Toppi L (2021) Responses to cadmium in early-diverging Streptophytes (Charophytes and bryophytes): current views and potential applications. Plan Theory 10(4):770
12. Berg T, Steinnes E (1997) Recent trends in atmospheric deposition of trace elements in Norway as evident from the 1995 moss survey. Sci Total Environ 208(3):197–206

13. Boquete MT, Fernández JÁ, Carballeira A, Aboal JR (2013) Assessing the tolerance of the terrestrial moss *Pseudoscleropodium purum* to high levels of atmospheric heavy metals: a reciprocal transplant study. Sci Total Environ 461–462:552–559
14. Burton M, Peterson P (1979) Metal accumulation by aquatic bryophytes from polluted mine streams. Environ Pollut (1970) 19(1):39–46
15. Čeburnis D, Steinnes E, Kvietkus K (1999) Estimation of metal uptake efficiencies from precipitation in mosses in Lithuania. Chemosphere 38(2):445–455
16. Ceschin S, Aleffi M, Bisceglie S, Savo V, Zuccarello V (2012) Aquatic bryophytes as Ecol. Indic. of the water quality status in the Tiber River basin (Italy). Ecol Indic 14(1):74–81
17. Chen Y, Yuan S, Su Y, Wang L (2010) Comparison of heavy metal accumulation capacity of some indigenous mosses in Southwest China cities: a case study in Chengdu city. Plant Soil Environ 56(2):60–66
18. Chen Y, Jiang Y, Huang H, Mou L, Ru J, Zhao J et al (2018) Long-term and high-concentration heavy-metal contamination strongly influences the microbiome and functional genes in Yellow River sediments. Sci Total Environ 637–638:1400–1412
19. Clymo R (1963) Ion exchange in Sphagnum and its relation to bog ecology. Ann Bot 27(2): 309–324
20. Dinis AM, Mesquita JF (2004) Uptake of heavy metal salt solutions by pollen grains of Magnolia× soulangeana (Magnoliaceae). Canada J Bot 82(12):1758–1767
21. Duruibe JO, Ogwuegbu M, Egwurugwu J (2007) Heavy metal pollution and human biotoxic effects. Int J Phys Sci 2(5):112–118
22. Freedman B (2018) Toxic elements. Environ Sci.Available via DIALOG.https://ecampusontario.pressbooks.pub/environmentalscience/chapter/chapter-18-toxic-elements/.
23. Fu Z, Guo W, Dang Z, Hu Q, Wu F, Feng C et al (2017) Refocusing on nonpriority toxic metals in the aquatic environment in China. ACS Publications, Washington, DC
24. Gecheva G, Yancheva V, Velcheva I, Georgieva E, Stoyanova S, Arnaudova D et al (2020) Integrated monitoring with moss-bag and mussel transplants in reservoirs. Water 12(6):1800
25. Gecheva G, Yurukova L, Ganeva A (2011) Assessment of pollution with aquatic bryophytes in Maritsa River (Bulgaria). Bull Environ Contam Toxicol 87(4):480–485
26. Gecheva G, Yurukova L, Cesa M, Cheshmedjiev S (2015) Monitoring of aquatic mosses and sediments: a case study in contaminated rivers, Bulgaria. Plant Biosyst 149(3):527–536
27. Glime JM (2007) Economic and ethnic uses of bryophytes. Flora N Am 27:14–41
28. González-Miqueo L, Elustondo D, Lasheras E, Santamaría J (2010) Use of native mosses as biomonitors of heavy metals and nitrogen deposition in the surroundings of two steel works. Chemosphere 78(8):965–971
29. Grodzinska K (1999) The environmental situation in the upper Vistula Basin (Southern Poland). In: Peakall DB, Walker CH, Migula P (eds) Biomarkers: a pragmatic basis for remediation of severe pollution in Eastern Europe. Springer Netherlands, Dordrecht, pp 29–48
30. Gupta A (1995) Heavy metal accumulation by three species of mosses in Shillong, North-Eastern India. Water Air Soil Pollut 82(3):751–756
31. Hallingback T, Hodgetts N (2000) Mosses, liverworts and hornworts. Status survey and conservation action plan for bryophytes. IUCN/SSC Bryophyte Specialist Group, Gland
32. Harmens H, Norris D (2008) Spatial and temporal trends in heavy metal accumulation in mosses in Europe (1990–2005): Programme Coordination centre for the ICP Vegetation, Centre for Ecology and Hydrology
33. Harmens H, Buse A, Büker P, Norris D, Mills G, Williams B et al (2004) Heavy metal concentrations in European mosses: 2000/2001 survey. J Atmos Chem 49(1):425–436
34. Harmens H, Norris DA, Koerber GR, Buse A, Steinnes E, Rühling Å (2007) Temporal trends in the concentration of arsenic, chromium, copper, iron, nickel, vanadium and zinc in mosses across Europe between 1990 and 2000. Atmos Environ 41(31):6673–6687
35. Harmens H, Norris D, Steinnes E, Kubin E, Piispanen J, Alber R et al (2010) Mosses as biomonitors of atmospheric heavy metal deposition: spatial patterns and temporal trends in Europe. Environ Pollut 158(10):3144–3156

36. Harris ES (2008) Ethnobryology: traditional uses and folk classification of bryophytes. Bryologist 111:169–217
37. Hassel K, Segreto R, Ekrem T (2013) Restricted variation in plant barcoding markers limits identification in closely related bryophyte species. Mol Ecol Resour 13(6):1047–1057
38. Izquieta-Rojano S, Elustondo D, Ederra A, Lasheras E, Santamaría C, Santamaría JM (2016) *Pleurochaete squarrosa* (Brid.) Lindb. as an alternative moss species for biomonitoring surveys of heavy metal, nitrogen deposition and δ15N signatures in a Mediterranean area. Ecol Indic 60: 1221–1228
39. Järup L (2003) Hazards of heavy metal contamination. Br Med Bull 68(1):167–182
40. Joint W, Organization WH (2007) Health risks of heavy metals from long-range transboundary air pollution. World Health Organization. Regional Office for Europe. Report No.: 9289071796. Available via https://apps.who.int/iris/handle/10665/107872
41. Kapfer J, Birks H, Astrup Felde V, Klanderud K, Martinessen TC, Ross L et al (2013) Long-term vegetation stability in northern Europe as assessed by changes in species co-occurrences. Plant Ecol Divers 6:289–302
42. Khan T, Muhammad S, Khan B, Khan H (2011) Investigating the levels of selected heavy metals in surface water of Shah Alam River (A tributary of River Kabul, Khyber Pakhtunkhwa). J Himal Earth Sci 44(2):71–79
43. Kłos A, Ziembik Z, Rajfur M, Dołhańczuk-Śródka A, Bochenek Z, Bjerke JW et al (2018) Using moss and lichens in biomonitoring of heavy-metal contamination of forest areas in southern and north-eastern Poland. Sci Total Environ 627:438–449
44. Knight A, Crooke W, Inkson R (1961) Cation-exchange capacities of tissues of higher and lower plants and their related uronic acid contents. Nature 192(4798):142–143
45. Kocazorbaz EK, Kerem T, Moulahoum H, Ün RN (2021) Phytochemical and bioactivity analysis of several methanolic extracts of nine bryophytes species. Sakarya Univ J Sci 25(4): 938–949
46. Kováčik J, Babula P, Hedbavny J (2017) Comparison of vascular and non-vascular aquatic plant as indicators of cadmium toxicity. Chemosphere 180:86–92
47. Krzesłowska M, Lenartowska M, Mellerowicz EJ, Samardakiewicz S, Woźny A (2009) Pectinous cell wall thickenings formation – a response of moss protonemata cells to lead. Environ Exp Bot 65(1):119–131
48. Lepp NW, Salmon D (1999) A field study of the ecotoxicology of copper to bryophytes. Environ Pollut 106(2):153–156
49. Macedo-Miranda G, Avila-Pérez P, Gil-Vargas P, Zarazúa G, Sánchez-Meza JC, Zepeda-Gómez C et al (2016) Accumulation of heavy metals in mosses: a biomonitoring study. Springer Plus 5 (1):715
50. Mahapatra B, Dhal NK, Dash AK, Panda BP, Panigrahi KCS, Pradhan A (2019) Perspective of mitigating atmospheric heavy metal pollution: using mosses as biomonitoring and indicator organism. Environ Sci Pollut Res 26(29):29620–29638
51. Mariet C, Gaudry A, Ayrault S, Moskura M, Denayer F, Bernard N (2011) Heavy metal bioaccumulation by the bryophyte Scleropodium purum at three French sites under various influences: Rural conditions, traffic, and industry. Environ Monit Assess 174(1):107–118
52. Markert B, Weckert V (1993) Time-and-site integrated long-term biomonitoring of chemical elements by means of mosses. Toxicol Environ Chem 40(1–4):43–56
53. Martins RJE, Boaventura RAR (2002) Uptake and release of zinc by aquatic bryophytes (Fontinalis antipyretica L. ex. Hedw.). Water Res 36(20):5005–5012
54. Maxhuni A, Lazo P, Kane S, Qarri F, Marku E, Harmens H (2016) First survey of atmospheric heavy metal deposition in Kosovo using moss biomonitoring. Environ Sci Pollut Res 23(1): 744–755
55. Mentese S, Yayintas O, Bas B, İrkin L, Yilmaz S (2021) Heavy metal and mineral composition of soil, atmospheric deposition, and mosses with regard to integrated pollution assessment approach. Environ Manag 67:1–19

56. Nagajyoti PC, Lee KD, Sreekanth T (2010) Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett 8(3):199–216
57. Patiño J, Vanderpoorten A (2018) Bryophyte biogeography. CRC Crit Rev Plant Sci 37(2–3): 175–209
58. Petschinger K, Adlassnig W, Sabovljevic M, Lang I (2021) Lamina cell shape and cell wall thickness are useful indicators for metal tolerance – an example in bryophytes. Plan Theory 10: 274
59. Radziemska M, Mazur Z, Bes A, Majewski G, Gusiatin ZM, Brtnicky M (2019) Using mosses as bioindicators of potentially toxic element contamination in ecologically valuable areas located in the vicinity of a road: a case study. Int J Environ Res Public Health 16(20):3963
60. Ren J, Liu F, Luo Y, Zhu J, Luo X, Liu R (2021) The pioneering role of bryophytes in ecological restoration of manganese waste residue areas, Southwestern China. J Chem
61. Riget F, Asmund G, Aastrup P (2000) The use of lichen (*Cetraria nivalis*) and moss (*Rhacomitrium lanuginosum*) as monitors for atmospheric deposition in Greenland. Sci Total Environ 245:137–148
62. Rola K, Osyczka P (2018) Cryptogamic communities as a useful bioindication tool for estimating the degree of soil pollution with heavy metals. Ecol Indic 88:454–464
63. Rühling Å, Tyler G (1970) Sorption and retention of heavy metals in the woodland moss Hylocomium splendens (Hedw.). Br Sch Oikos 21:92–97
64. Salemaa M, Derome J, Helmisaari H-S, Nieminen T, Vanha-Majamaa I (2004) Element accumulation in boreal bryophytes, lichens and vascular plants exposed to heavy metal and sulfur deposition in Finland. Sci Total Environ 324(1–3):141–160
65. Saxena D (2004) Uses of bryophytes. Resonance 9(6):56–65
66. Sharma S (2007) Marchantia polymorpha L.: a bioaccumulator. Aerobiologia 23(3):181–187
67. Shotbolt L, Büker P, Ashmore M (2007) Reconstructing temporal trends in heavy metal deposition: assessing the value of herbarium moss samples. Environ Pollut 147(1):120–130
68. Smith AJE (1978) Provisional atlas of the bryophytes of the British Isles. 2nd ed. Biological Records Centre
69. Ştefănuţ S, Öllerer K, Manole A, Ion MC, Constantin M, Banciu C et al (2019) National environmental quality assessment and monitoring of atmospheric heavy metal pollution-a moss bag approach. J Environ Manag 248:109224
70. Szczepaniak K, Astel A, Bode P, Sârbu C, Biziuk M, Raińska E et al (2006) Assessment of atmospheric inorganic pollution in the urban region of Gdańsk, Northern Poland. J Radioanal Nucl Chem 270(1):35–42
71. Thöni L, Yurukova L, Bergamini A, Ilyin I, Matthaei D (2011) Temporal trends and spatial patterns of heavy metal concentrations in mosses in Bulgaria and Switzerland: 1990–2005. Atmos Environ 45(11):1899–1912
72. Trujillo-González JM, Zapata-Muñoz YL, Torres-Mora MA, García-Navarro FJ, Jiménez-Ballesta R (2020) Assessment of urban environmental quality through the measurement of lead in bryophytes: case study in a medium-sized city. Environ Geochem Health 42(10):3131–3139
73. Tyler G (1990) Bryophytes and heavy metals: a literature review. Bot J Linn Soc 104(1–3): 231–253
74. Tyler G (2008) Bryophytes and heavy metals: a literature review. Bot J Linn Soc 104(1–3): 231–253
75. Uniyal P, Singh A, Sood A, Sharma P (2017) Assessment of accumulation of some heavy metals in mosses of Idukki District, Kerala (Western Ghats, India). Int J Plant Environ 3(01):15–19
76. Vats SK, Singh A, Koul M, Uniyal PL (2010) Study on the metal absorption by two mosses in Delhi Region (India). J Am Sci 6:176–181
77. Vázquez MD, Villares R, Carballeira A (2013) Biomonitoring urban fluvial contamination on the basis of physiological stress induced in transplants of the aquatic moss Fontinalis antipyretica Hedw. Hydrobiologia 707(1):97–108

78. Vázquez MD, Real C, Villares R (2020) Optimization of the biomonitoring technique with the aquatic Moss Fontinalis antipyretica Hedw: selection of shoot segment length for determining trace element concentrations. Water 12(9):2389
79. Vuori KM, Helisten H (2010) The use of aquatic mosses in assessment of metal pollution: appraisal of type-specific background concentrations and inter-specific differences in metal accumulation. Hydrobiologia 656(1):99–106
80. Wang S, Zhang Z, Wang Z (2015) Bryophyte communities as biomonitors of environmental factors in the Goujiang karst bauxite, southwestern China. Sci Total Environ 538:270–278
81. Wu L, Fu S, Wang X, Chang X (2020) Mapping of atmospheric heavy metal deposition in Guangzhou city, southern China using archived bryophytes. Environ Pollut 265(Pt B):114998
82. Xiao J, Han X, Sun S, Wang L, Rinklebe J (2021) Heavy metals in different moss species in alpine ecosystems of Mountain Gongga, China: geochemical characteristics and controlling factors. Environ Pollut 272:115991
83. Xu Y, Yang R, Zhang J, Gao L, Ni X (2021) Distribution and dispersion of heavy metals in the rock–soil–moss system in areas covered by black shale in the Southeast of Guizhou Province, China. Environ. Sci. Pollut. Res.(29)1:1-14.
84. Yedjou CG, Patlolla AK, Sutton DJ (2012) Heavy metals toxicity and the environment Paul B Tchounwou. Published in final edited form as: EXS.101: 133–164
85. Zinicovscaia I, Hramco C, Chaligava O, Yushin N, Grozdov D, Vergel K et al (2021) Accumulation of potentially toxic elements in mosses collected in the Republic of Moldova. Plan Theory 10(3):471
86. Zvereva E, Kozlov M (2011) Impacts of industrial polluters on bryophytes: a meta-analysis of observational studies. Water Air Soil Pollut 218:573–586