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REVIEW

Global ambient air quality monitoring: *Can mosses help?* A systematic meta-analysis of literature about passive moss biomonitoring

Sriroop Chaudhuri[1] · **Mimi Roy**[1]

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Abstract

Surging incidents of air quality-related public health hazards, and environmental degradation, have prompted the global authorities to seek newer avenues of air quality monitoring, especially in developing economies, where the situation appears most alarming besides difficulties around 'adequate' deployment of air quality sensors. In the present narrative, we adopt a systematic review methodology (PRISMA, *Preferred Reporting Items for Systematic reviews and Meta-Analyses*) around recent global literature (2002–2022), around moss-based passive biomonitoring approaches which might offer the regulatory authorities a complementary means to fill 'gaps' in existing air quality records. Following the 4-phased search procedure under PRISMA, total of 123 documents were selected for review. A wealth of research demonstrates how passive biomonitoring, with strategic use of mosses, could become an invaluable regulatory (and research) tool to monitor atmospheric deposition patterns and help identifying the main drivers of air quality changes (e.g., anthropogenic and/or natural). Besides individual studies, we briefly reflect on the European Moss Survey, underway since 1990, which aptly showcases mosses as 'naturally occurring' sensors of ambient air quality for a slew of metals (heavy and trace) and persistent organic pollutants, and help assessing spatio-temporal changes therein. To that end, we urge the global research community to conduct targeted research around various pollutant uptake mechanisms by mosses (e.g., species-specific interactions, environmental conditions, land management practices). Of late, mosses have found various environmental applications as well, such as in epidemiological investigations, identification of pollutant sources and transport mechanisms, assessment of air quality in diverse and complex urban ecosystems, and even detecting short-term changes in ambient air quality (e.g., COVID-19 Lockdown), each being critical for the authorities to develop informed and strategic regulatory measures. To that end, we review current literature and highlight to the regulatory authorities how to extend moss-based observations, by integrating them with a wide range of ecological indicators to assess regional environmental vulnerability/risk due to degrading air quality. Overall, an underlying motive behind this narrative was to broaden the current regulatory outlook and purview, to bolster and diversify existing air quality monitoring initiatives, by coupling the moss-based outputs with the traditional, sensor-based datasets, and attain improved spatial representation. However, we also make a strong

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Extended author information available on the last page of the article

case of conducting more targeted research to fill in the ‘gaps’ in our current understanding of moss-based passive biomonitoring details, with increased case studies.

Keywords Passive moss biomonitoring · Air quality monitoring and assessment · European Moss Survey (EMS) · Heavy and trace metal · Persistent organic pollutants (POP) · Enrichment factor · Contamination factor · Ecological risk index

1 Introduction

In recent times, air quality has emerged as a single largest environmental threat (Lelieveld et al., 2019; Venter et al., 2020), with surging cases of air pollution inflicted mortality, and major cause of public health emergency in Central and Southern Asia (Kaur & Pandey, 2021; Shaddick et al., 2020). Manisalidis et al. (2020) labeled air pollution as *"one of our era’s greatest scourges, on account not only of its impact on climate change but also its impact on public and individual health due to increasing morbidity and mortality."* Mounting woes over public health damage due to air pollution has raised grave regulatory concerns with recent discovery of close ties COVID-19 virus spread (Kumar & Chaudhuri, 2021, 2022a; Pozzer et al., 2020). Such situation has brought up the concerned authorities (e.g., environmental systems’ managers, air quality regulators, public health officials, to name a few), as much as the global research community, up to a daunting task: *How to bolster existing air quality monitoring networks so as to preempt more targeted and data-driven interventions for air pollution prevention and control* (Kumar & Chaudhuri, 2022b). The question becomes even more critical for developing economies where adequate (and appropriate) technology, finance, institutional support, and manpower are lacking to investigate ambient air quality, and how it changes across space and time (Chaudhuri & Kumar, 2022; Chen et al., 2017; Gao et al., 2020).

As the need of improved air quality monitoring soared, a growing idea has been to test and adopt moss-based approaches, which, many authorities believe, offers certain means to ‘expand’ existing monitoring network (Kapusta & Godzik, 2020). It is as Kosior et al. (2020) maintained, "*Today, moss biomonitoring is a part of pollution monitoring programs in most European countries as it gives evidence of the anthropogenic impact in urban areas due to vehicular traffic and fossil fuel combustion"*. Moss-based biomonitoring of atmospheric pollution was pioneered by the Swedish research groups in the 1960s (Donovan et al., 2016). In Europe, the International Cooperation Program on the Impact of Air Pollution on Natural Ecosystems and Crops (ICP Vegetation) has been conducting moss-based biomonitoring of various heavy and trace metals since 1995 (Godzik, 2020). The program operates within the framework of the United Nations Convention on Long-Range Transboundary Air Pollution (CLRTAP) with the aim of identifying main pollution hotspots across Europe, generating regional maps, and growing deeper understanding of long-range transboundary pollutant transport mechanisms (Uzhinsky et al., 2019). As part of the initiative, mosses are being collected every five years from numerous sites (approximately, one sample/1000 km^2), at up to 7300 sites, for spatio-temporal assessments of air quality at transnational scale (Frontasyeva et al., 2020; ICP Vegetation, 2020). A total of 13 elements are reported for the Atlas (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn, Al, Sb, and N). In 2005, determination of the nitrogen concentration in mosses was included for the first time. Since 2010, some countries also began assessing a selected suite of persistent organic pollutants (POPs), particularly, the polycyclic aromatic hydrocarbons (PAHs), at a selected number of sites. Data interpretation is based on the Multivariate statistical analysis, the description of sampling sites (MossMet information package) and distribution maps for each element. For heavy metals, majority of these surveys used *Pleurozium schreberi* (e.g., in 39.6% cases), followed by *Hypnum cupressiforme* (23.1%), *Hylocomium splendens* (19.9%), *Pseudoscleropodium purum* (6.3%), with other species accounting for the rest (11.2%) (Frontasyeva et al., 2020). For nitrogen, *Pleurozium schreberi* was the most frequently sampled species (33.4%), followed by *Hypnum cupressiforme* (29.8%), *Pseudoscleropodium purum* (18%), *Hylocomium splendens* (13.1%), and other species (5.6%).

Till date, a small but rapidly growing body of literature has demonstrated the ability of moss-based data for spatio-temporal modelling of a variety of trace and heavy metals and organic pollutant species, that helped ideating changes in atmospheric deposition patterns from local to national scale (Schlutow et al., 2021; Schröder & Nickel, 2019; Abulude et al., 2021; Badamasi, 2017; Blagnyte and Paliulis, 2010). Mosses have also been used to evaluate temporal changes in air quality. Wojtun et al. (2013) analyzed Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn levels in various Sphagnum species from ombrotrophic bogs in the Sudety mountains (SW Poland) between 1988 and 2011 to observe declining trends in level of pollution. Prime advantage of mosses, which should make them attractive to the regulatory authorities in developing economies, is that they come as low-cost, 'naturally-occurring' markers of ambient air quality (Gillooly et al., 2016), and able to detect a wide range pollutant species. In recent times, mosses have been used to assess urban air quality (Kosior et al., 2015); rural–urban differences in atmospheric deposition patterns (Lequy et al., 2022); atmospheric microfiber deposition (microplastic) (Roblin & Aherne, 2020); long-ranged, transboundary pollutant transport phenomena (Oishi, 2016, 2017, 2019), atmospheric circulation (Vosel et al., 2021), to name a few.

In view of the above, we present this narrative by systematically reviewing recent global literature, to make aware the authorities about the practices, advancements, and developments, as currently underway around moss-based passive biomonitoring of ambient air quality in different parts of the world. To that end, a main 'intended' readership of this narrative, besides the global research community, is the concerned authorities in developing countries (e.g., South-Southeast Asia where air pollution has emerged as a major threat to public health, infrastructure and economy). For them, mosses, with several favorable physiological traits and almost cosmopolitan occurrences, could offer a *natural means* to 'densify' existing air quality monitoring network (better spatio-temporal representation) (Lazo et al., 2018; Schröder et al., 2016), which is essential to ensure 'representativeness' of air quality data. The latter is difficult to achieve with traditional, sensor-based networks—only very sparsely installed due to high resource requirements (Godzik, 2020).

To that end, we call into discussion the literature coming out of Europe, Asia (China) and USA, without any territorial preferences, highlighting the use of a variety moss species, across a wide spectrum of pollutants (metals and organics). The implicit idea was for the authorities (interested in adopting moss-based biomonitoring) to obtain a bird's eye view of how different types of mosses have been strategically put to use in different types of environmental research, to be able to make 'informed choices' befitting their own context-specific requirements. We begin by highlighting physiological traits of mosses and go on to develop the narrative around two broad themes: (i) overview of moss records for metals (trace and heavy) and persistent organic pollutants (POPs); and (ii) selected environmental applications. Next, we try to summarize our current understanding about passive moss biomonitoring. In the concluding section, we reflect on certain areas of moss research that yet needs targeted investigation in coming years, as an appeal to the global research community.

In the present narrative, we, however, limit our discussions to ‘passive’ moss biomonitoring only. The main argument being, although both ‘active’ and ‘passive’ approaches have their own advantages and challenges,[1] a major ‘shortcoming’ around the former is relatively higher resource requirements (e.g., moss bag preparation, preservation, sample collection). As a main target group for this article is the authorities in developing economies (who already face resource shortage to establish robust sensor-based monitoring network), passive monitoring could be more appealing, which has inherently cheaper with lower resource demand (Lazo et al., 2018; Steinnes et al., 2011). In a recent study, Lequy et al. (2022) used the *Grimmia pulvinata* species, collected from in 77 and 51 cemeteries within ~50 km of Paris and Lyon city centers, to demonstrate that passive biomonitoring can satisfactorily proxy air quality even at finer resolutions over large areas.

2 Methodology

We identified relevant literature using the multi-stage, sequential PRISMA literature extraction method (Preferred Reporting Items for Systematic Reviews and Meta-analyses) (Chaudhuri et al., 2021a, Diener and Mudu, 2021; Tomson et al., 2021; Moher et al., 2009). The PRISMA[2] methodology comprises of a 27-item checklist (view Supplementary Material), within a 4-stage, sequential literature extraction method (Fig. 1). The initial article identification was performed across various search engines including SCOPUS, PubMed, Science Direct, Springer Lin, Blackwell and Social Citation Index, Web of Science (WoS), EconLit, JSTOR, and complemented with Google Scholar. For selection of search words/phrases, we took up the guidelines prescribed by Diener and Mudu (2021), which comprised of: (a) assessment of terminology use for over 60 topical papers, (b) trial searches to improve specificity and sensitivity and to calibrate the search term to include pre-defined key articles, (c) adjustment of search terms for selected databases, and (d) a series of supplemental searches, including hand searches in key thematic journals and reference tracking for selected papers. The search terms finally used were as follows: “pollutant”; “biomonitor”; “biomonitor*”; “moss”; “moss-based *”; “metals”; “heavy *”; “trace *”; “rare earth”; “POP”; “PAH”; “transport”; “urban”; “traffic”; “sampling”.

The asterisk symbol (‘*’) was used as wildcard to expand the search horizon. After the initial search (exploratory search), each search words/phrase was further combined (i) in

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[1] Passive monitoring uses moss that grows naturally in a particular area, while active monitoring is achieved by transplanting moss from other locations and establishing in moss bags. The choice of methods, however, should be guided by the target of the study. for example, the passive approach appears more appropriate for extensive studies across larger geography (i.e., regional or national studies) and time-scales, active monitoring is more useful for smaller areas, and where mosses do not grow naturally (Aboal et al., 2020; Aničić et al., 2009; Ares et al., 2012; Gribacheva et al., 2021).

[2] PRISMA was the outcome of a 3-day meeting in Ottawa, Canada, in June 2005 with a wide range of participants, including review authors, methodologists, practitioners, and editors (Moher et al., 2009). Since then, PRISMA has been a preferred method of locating appropriate literature in many recent studies, in varied streams of research (Liu et al., 2021; Rowinski and von Schreeb, 2021; Montana et al., 2021). Over the recent past the PRISMA methodology evolved, in response to certain growing needs: (i) iterative cycle of identifying and reviewing literature based on suitability to the study concerned; (ii) as a realization that conducting, and reporting research in a systematic fashion are distinct concepts; (iii) study-level vs. outcome-level assessment of risk of bias; and (iv) importance of reporting biases.

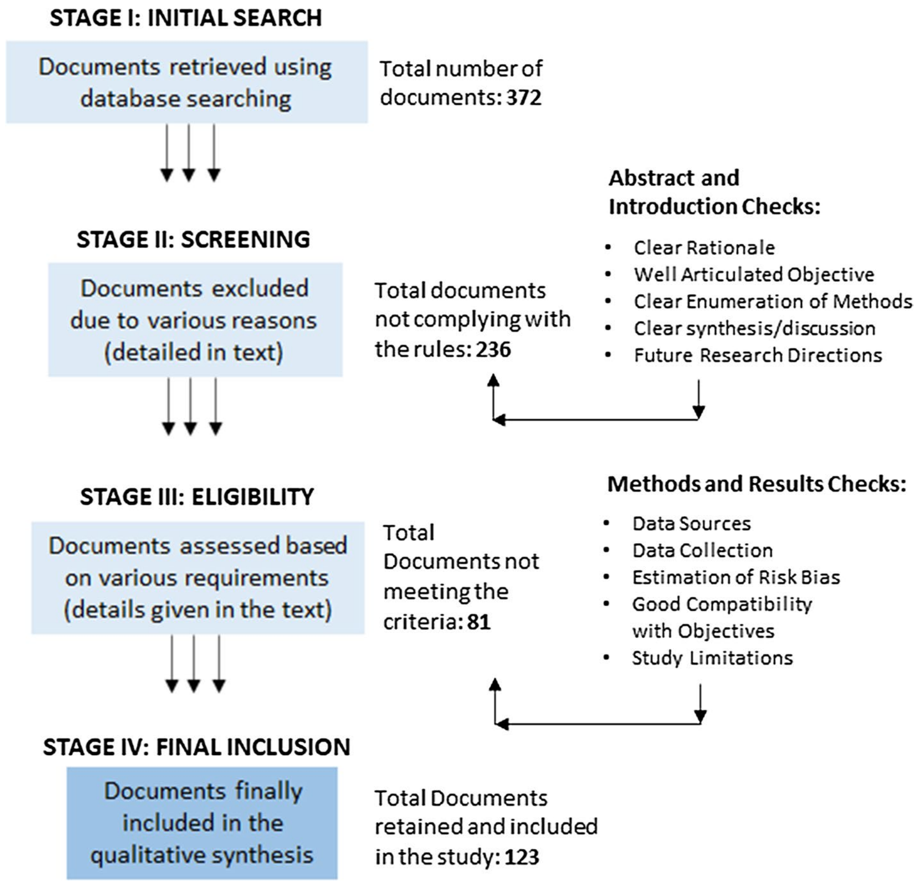

Fig. 1 Broad overview of literature selection procedure followed by the PRISMA methodology

various permutation combinations to develop new search terms; and (ii) with "air quality" or "air pollution" or "atmospheric pollution"; or "atmospheric deposition". Motivated by the results of this exploratory search, we also combined certain specific moss species with the search words/phrases, such as "*Sphagnum*"; "*Hypnum*"; "*Pleurozium*", as a large number of studies used these moss varieties. Retrieved documents included peer-reviewed manuscripts, book chapters, thesis, dissertations, and gray literature.[3]

After carrying out the above, a total of 372 documents were identified. Following the PRISMA methodology, these documents were further subject to two stages of 'refinement'. In the first stage, the documents were 'screened', based on checking the Abstract and Introduction parts of the study, keeping the following in mind (Chaudhuri et al., 2021b):

- Published in foreign language (*non-English*) (28 documents)

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[3] Research documents produced by organizations outside of the traditional commercial or academic publishing and distribution channels. Common gray literature publication types include reports, working papers, government documents, white papers and evaluations.

- Abstract only; unavailability of full text (71 documents)
- Duplication of results (49 documents excluded)
- Studies involving active biomonitoring (moss bag/transplants)
- Objective(s) not well-aligned with the present study
- Experimental/review methods not clearly enumerated

In the next stage, documents remaining from the screening stage were further passed through certain eligibility criteria (Chaudhuri et al., 2020):

- Reasonable enumeration of geochemistry of metal/POP removal
- Too many confounding variables
- Lack of future research directions

Finally, a set of 123 documents in total were retained for review.

3 Results and discussion

3.1 Why moss?

Mosses have certain unique physiological traits, which make them ideal natural recorders of ambient air quality. Ectohydric mosses obtain nutrition directly from wet (precipitation) and/or dry deposition, i.e., directly from atmospheric processes (Frontasyeva et al., 2020). As they lack real root system (the rhizoids just provide anchorage to the substrate), there is no uptake of nutrients from mineral substrates (e.g., soil) (Chakrabortty & Paratkar, 2006). It probably implies that elemental (pollutant) concentrations in moss tissues are keyed to their occurrence in ambient atmosphere (however, the degree of correlation between the two still requires more scientific investigation for statistical validation).

Other 'favorable' traits of the mosses include (Mahapatra et al., 2019; Dragovic and Mihailovič, 2009; Chakrabortty & Paratkar, 2006): lack cuticle (or it is very thin)—high permeability to ionic transport across cell wall; high surface-to-volume ratio (5–10 times higher than vascular plants); undeveloped vascular bundles (transport of minerals between segments is limited); minimal morphological changes during life cycle; totipotency (ability of a single cell to divide and produce all the differentiated cells in an organism); multiple reproductive cycles via spores and/or vegetative fragments and/or vegetative reproduction (Martin and Mallik, 2017); rapid colonization. In addition, mosses provide time-integrated exposure assessment of airborne pollutants, unlike traditional sensors that only catches snapshots of pollution. Moss growth segments provide estimate of integrated exposure to toxic metals over longer periods, and not just the current state at the time of collection; critical where pollutant levels change rapidly (and mostly in unregulated fashion, as is the case of most industrial and urban hubs of developing countries in South-Southeast Asia). Such opportunities owe to slow growth rates of moss species that allow them longer time window to bind metals and increases the concentration of several metals inside the cells or cell walls (Gonzalez et al., 2014). Sensor-based approaches, on the other hand, are unable to capture time-integrated, biological exposure effects of pollutants.

From regulatory purposes, another advantage is, mosses have ubiquitous geographic occurrence, which includes the Polar Regions as well (Cowden et al., 2015; Cannone et al., 2013; Real et al., 2009; Zhu et al., 2007; Schlensog et al., 2004). Mosses are poikilohydric organisms with high degree of phenotypic plasticity (Turetsky et al., 2012) with well-developed features that make them resilient to environmental stresses (Roads et al., 2014); and thrive extreme change and disturbance (Cannone et al., 2013). Mosses are resistant to water scarcity (Turetsky et al., 2012), and survive complete desiccation and temperatures ranging as high as 110 °C (Dragovič & Mihailovič, 2009). It owes to their poikilohydric trait that helps mosses dry out during water shortage, derive moisture from atmosphere and remain in dormant stage for extended period of time (Vanderpoorten & Goffinet, 2009).

3.2 Role in pollutant uptake

3.2.1 Metals

A growing number of studies around the world demonstrate that moss-based measurements can provide, reliable means for air quality monitoring at national as well sub-national level (Table 1). Applications range from continental to national/sub-national level while spanning from decade to years. Moss-based metal biomonitoring initiatives have become increasingly popular in Russia (Yushin et al., 2020; Zinicovscaia et al., 2021) and China in the recent past (Jiang et al., 2018, 2020; Lee et al., 2005; Sun et al., 2009). In a study in the Wanshan District in Guizhou Province, southwestern China, Liang et al. (2019) analyzed 221 moss samples. The results indicated strong influence of historical intensive Hg mining activities as potential cause of elevated levels of arsenic in ambient air. To that end, the moss-result also helped arsenic speciation—the total arsenic load was dominated by the inorganic fraction (arsenate + arsenate, accounting for ~ 87% of the total), while the organics forming only a minor fraction (monomethylarsonic acid and dimethylarsinic acid).

The European Moss Survey (EMS) probably showcases best long-term moss-based biomonitoring approach for metals (1990-ongoing). The EMS results indicate that continental average median concentrations of various heavy/trace species (As, Al, Pb, V, Cd, Cr, Ni, Fe, Cu, Zn, Hg), declined substantially over time (1990 vs. 2005/2006 and 2010/2011), marking significant improvements in ambient air quality (Fig. 2). The improving trend continues through recent phases of the survey as well (EMS = 2015/16). Compared to 1990, highest reductions have been achieved for Pb (77% in 2010/2011 while 83% in 2015/16); followed by V (51 and 53%), and Cd (52 and 63%). By 2015/16, most nations have managed to 'tame down' ambient metal levels, due to enactment of various air quality regulatory measures at national level (Fig. 3). Overall, the EMS records reveal lower concentrations of heavy metals in northern Europe, while more elevated levels in eastern and southeastern parts of the continent, resulting in a northwest to southeast gradient, a pattern closely corroborating with earlier observations of 2010/11 (Harmens et al., 2015a, 2015b). For regulatory authorities, such long-term assessments make mosses ideal candidates for basing regulatory interventions upon. For example, EMS records of 2015/16 reveals that even though concentrations of various metals are broadly on the decline, there yet remain concerns regarding elevated levels of As (in Italy, Finland, Sweden, Switzerland); Cd (all EMS nations, except Poland); Cr (all, except Iceland); Ni (All, except Austria and Iceland); Pb and Vn (all countries). The EMS also revealed that the ambient iron levels have declined in all nations over time, as did Cu and Zn (excepting Iceland and Italy) (Fig. 4).

Interestingly, recent investigation has started emerging that employed moss surveys to illustrate how mosses are effective to document short-term changes as well (weeks-months)

Table 1 Selected case studies for moss-based metal biomonitoring survey (*Source*: Compiled from various studies)

Study and region	Species analyzed	Moss Species and sampling number (*N*)	Salient features
Jovan et al. (2022) Study Region: Seattle, Washington, USA	21 elements including As, Cd, Cr, Co, Pb, Ni	*Orthotrichum lyellii* *(N=19)*	• Moss records identified pollution hot spots around the central industrial core with various possible emission sources, including that of As, Cd, Cr, Co, Pb, Ni • Moss records of pollutants can used to organize community-based community-centric environmental advocacy for future investigations to evaluate residents' exposure to heavy metals • Moss records of pollutants can be used in environmental justice
Zinicovscaia et al. (2021) Study Region: *Moldova*	35 elements (Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, As, Br, Se, Rb, Sr, Sb, Cs, Ba, La, Ce, Sm, Eu, Tb, Hf, Ta, Th, and U)	*Hypnum cupressiforme* Hedw *(N=41)*	• Comparative evaluation between 2010 and 2015/2016 surveys • Concentrations of Cr, As, Se, Br, Sr, Sb, Cd, Pb, Cu changed significantly over time • Air pollution mainly owes to anthropogenic activities including transport-, industrial-, agricultural-, and mining-related emissions; Al, Fe, Ni, V and As, had natural sources • Moss records are suitable for long-term air quality assessment, besides pollutant source tracking (distinguishing between natural and anthropogenic sources)

Table 1 (continued)

Study and region	Species analyzed	Moss Species and sampling number (*N*)	Salient features
Jovan et al. (2021) Study Region: *Portland City, Oregon, USA*	4 groups of PAHs, based on molecular weight (MW): the Naphthalene, Low, Medium, and High MW species	*Orthotrichum lyellii* *(N*=350*)*	• Distribution of PAHs are keyed to short-term weather and nuance of sample collection (height on the sampled tree, tree taxonomic family, whether collected from a branch or bole), influenced distribution of all groups • All PAH groups were highest over downtown Portland, along major highways, and lowest in parks and outer neighborhoods • Moss records can provide important clues of urban air quality—proximity to roads increases pollution loads • Strategic plantation of trees can be potential pollution prevention and abatement
Barandvski et al. (2020) Study Region: *North Macedonia*	41 elements (Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Zr, Mo, Ag, Cd, In, Sb, I, Cs, Ba, La, Ce, Sm, Eu, Tb, Hf, Ta, U)	*Hypnum cupressiforme, Homalothecium lutescens, Homalothecium sericeum* *(N*=72*)*	• Moss biomonitoring as part of the UNECE ICP Vegetation Program • Three sampling periods—2002, 2005, 2010 • Concentrations of Al, As, Co, Cs, Fe, Hf, Na, Rb, Sc, Ta, Th, Ti, U, V, Zr declined between 2002 and 2010 • Cr and Ni increased (2002—2005) • Elevated ambient levels of Ni, Cr, Pb, Zn, Cd • Air quality is mainly sourced to mining and related activities • Moss records can aid in understanding the current, as well as future trends in air pollution

Table 1 (continued)

Study and region	Species analyzed	Moss Species and sampling number (N)	Salient features
Vergel et al. (2020) Study Region: *Central Russia*	30 elements	*Pleurozium schreberi* ($N = 126$)	• Median values of the elements were compared with the results obtained for other regions in Russia • Computation of Geo-accumulation Index and Pollution Load Index for As, Sb, Pb, V, Cd, W, Fe, Cr, Ni and Co indicated growing environmental degradation and public health threats of declining air quality • Moss records can be used to understand key drivers of air pollution (e.g., industrial, vehicular and thermal power plant emissions) • Such understanding can be used to institute regulatory measures
Hristozova et al. (2020) Study Region: *Bulgaria*	37 elements (Al, As, Ba, Br, Ca, Ce, Cl, Co, Cr, Cs, Fe, Hf, I, K, La, Mn, Na, Nd, Ni, Rb, Sb, Sc, Se, Sr, Ta, Tb, Th, Ti, Tm, U, V, W, Yb, Zn, Cd, Cu, Pb)	Multiple moss species ($N = 57$)	• Comparative assessment between 2005/2006 and 2015/2016 survey results • Changes in concentrations of various species indicated: decreased industrial output in the country, increased coal combustion and transport pollution, and construction of roads

Table 1 (continued)

Study and region	Species analyzed	Moss Species and sampling number (N)	Salient features
Qarri et al. (2019) Study Region: *Albania*	As, Ni, Cu, Zn, V, Cd, Hg, Pb	*Hypnum cupressiforme Hedw* ($N=55$)	• High ecological threats associated with elevated levels of As, Cd, Cr, Hg, Ni, and Pb in ambient air • Al (aluminum) and Fe likely originated from natural sources • As, Cd, Hg, Pb, Cu, Zn, Ni, and Cr, sourced to anthropogenic activities • Moss records can be used decipher long-ranged, transboundary pollutant transport phenomena • Moss records are suitable proxies for changing ecological conditions and can be used for future management interventions
Zhou et al. (2017) Study Region: *Taizhou, East China*	Cd, Cr, Cu, Hg, Ni, Pb, Zn	*Haplocladium microphyllum* ($N=60$)	• High ecological risk due to elevated levels (exceeding environmental limits) of each metal species • Metal concentrations were significantly higher than that of EMS results • Moss records can help regulatory authorities assess ecological threats as well as growing public health concerns, and develop appropriate management measures

Table 1 (continued)

Study and region	Species analyzed	Moss Species and sampling number (*N*)	Salient features
Maxhuni et al. (2016) Study Region: *Republic of Kosovo*	Cd, Cr, Cu, Fe, Hg, Ni, Mn, Pb, Zn	*Pseudocleropodium purum* and *Hypnum cupressiforme* ($N=25$)	• Moss biomonitoring as part of the UNECE ICP Vegetation Program • Several hot spots of Cr, Ni, Pb, Zn owing to anthropogenic activities (heavy vehicular traffic and industrial emissions) • Above concentrations significantly higher than respective median values of Europe sampled in 2010 • Moss records could be used to compare atmospheric deposition patterns across continental scale
Yan et al. (2016) Study Region: *Wuxi District, eastern China*	Cd, Cr, Cu, Hg, Ni, Pb, Zn	*Haplocladium microphyllum*, *H. angustifolium* ($N=49$)	• Metal enrichment ratio in the moss samples varied as Cd > Zn > Pb > Cu > Cr > Ni • Significantly higher concentrations than that European Moss Survey results for 2010 • Computation of various environmental indicators based on moss records can provide useful insights in ecological risks • Moss records could be used to compare atmospheric deposition patterns across continental scale

Table 1 (continued)

Study and region	Species analyzed	Moss Species and sampling number (*N*)	Salient features
Macedo-Miranda et al. (2016)	Cr, Zn, Cd, Pb	*Fabriona ciliari,* *Leskea angustata* *(N* = 11*)*	• Moss records indicate a scale of bioaccumulation pattern: average concentrations varied in the order of: Zn > Pb > Cr > Cd • Moss records can be used to track sources of various pollutants individually (e.g., Cr: Terrigenous origin; Zn: Pedological-soil or substrate contribution and anthropogenic activities; Pb: Predominantly anthropogenic origin • Research is needed to understand bioaccumulation capacity of differen varieties of mosses (e.g., higher concentration capacities in *Fabriona ciliaris* than *Leskea angustata*)

The main ideas behind selecting the case studies were as follows: (i) include latest research across continents; (ii) diversity in outcomes; (iii) present a wide array of pollutant species—metals and organics; and (iv) highlight use of different varieties of mosses. It falls in line with the main objective of the present research: to offer the authorities (interested in adopting passive moss biomonitoring), a holistic overview of current advances around the world to be able to decide for themselves what will serve best, their contextual need

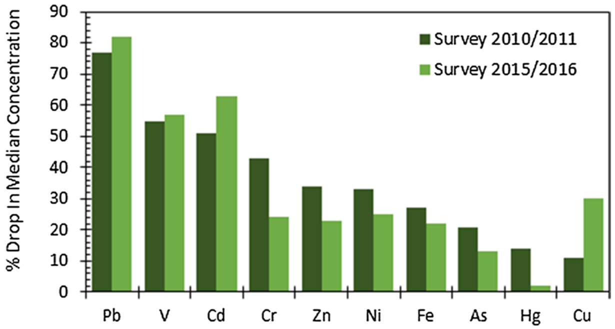


Fig. 2 Average percentage drop in median concentrations in various metals, compared to survey results in 1990. In the EMS, As and Hg data began reporting since 1995 (*Data Source*: Frontasyeva et al., 2020 for 2015/2016 and Harmens et al., 2015a, 2015b for 2010/2011 survey results, respectively)

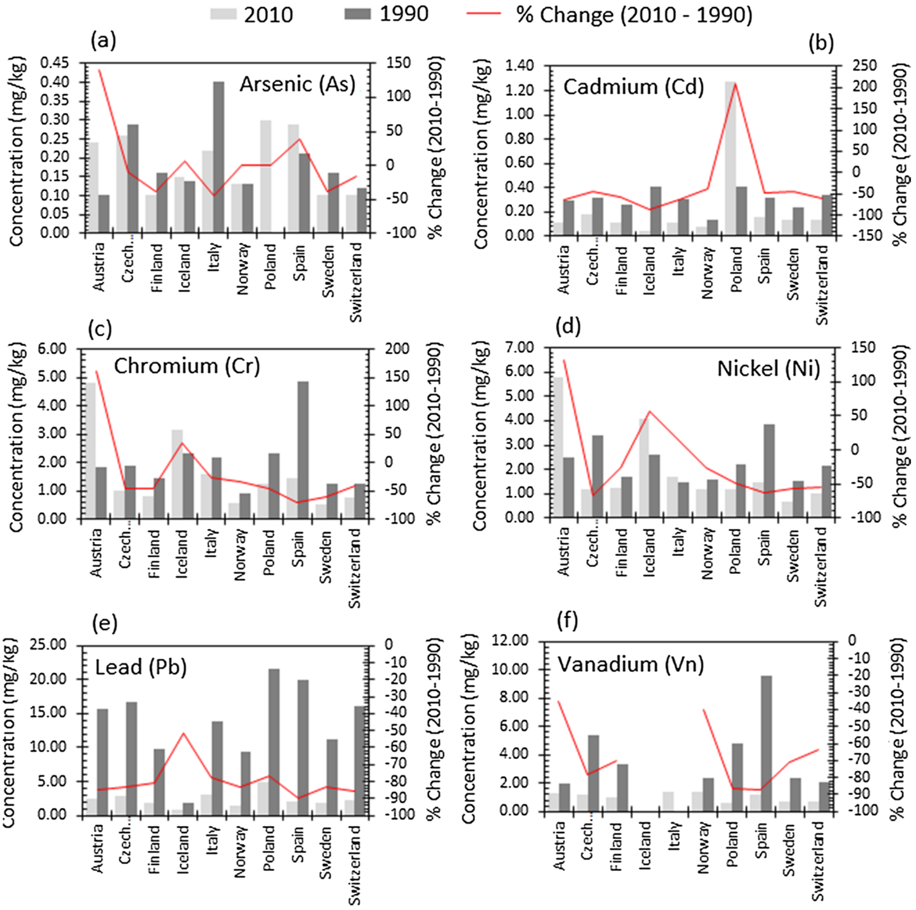
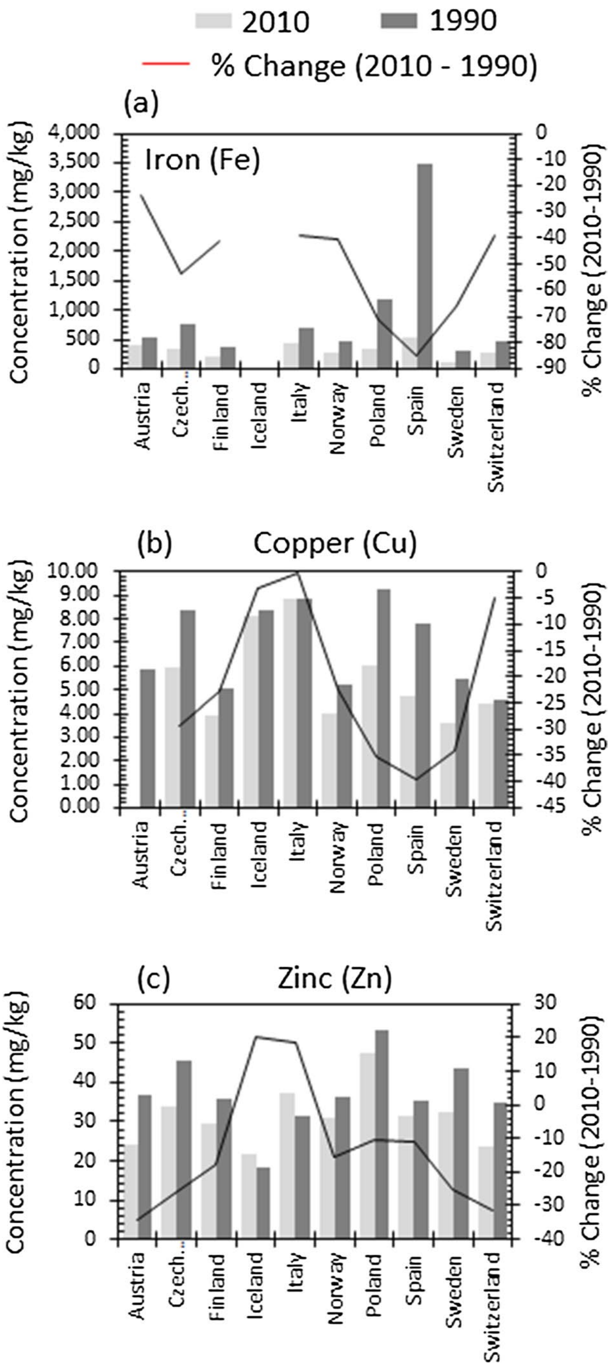


Fig. 3 Average median concentrations (mg/kg) of various elements in moss samples from selected countries, obtained from European Moss Survey data, conducted as part of the ICP Vegetation Program in 2010 and 1990. Percentage changes are shown in secondary y-axis [{(2010 − 1990)/1990)}*100]; negative values indicate reduction in elemental concentrations in 2010, compared to 1990. Arsenic concentrations were available for 2010 and 2000. (*Data Source*: https://icpvegetation.ceh.ac.uk/Data-and-Maps/Data)

Fig. 4 Average median concentrations (mg/kg) of various elements in moss samples from selected countries, obtained from European Moss Survey data, conducted as part of the ICP Vegetation Program in 2010 and 1990. Percentage changes are shown in secondary y-axis [{(2010 – 1990)/1990)}*100]; negative values indicate reduction in elemental concentrations in 2010, compared to 1990. (*Data Source*: https://icpvegetation.ceh.ac.uk/Data-and-Maps/Data)



in ambient air quality; examples of which include impacts of pre- and post-SARS-CoV-2 Lockdown and firecrackers during the New Year's Eve (Table 2).

3.2.2 Persistent organic pollutants (POPs)

A rich body of literature demonstrates effectiveness of moss biomonitoring to detect changes in ambient levels of persistent organic pollutants (POPs) (Kosior et al., 2015; Wu et al., 2014). In a long-term study, Martinez-Swatson et al. (2020) used historical records of three species of moss namely, (Herbarium C)—*Dicranum scoparium* Hedw., *Hylocomium splendens* (Hedw.) Schimp, and *Racomitrium lanuginosum* (Hedw.) Brid, to document atmospheric deposition patterns of 19 PAH species in Greenland, since the beginning of nineteenth century, which closely mirrored that of the global trend.

The POPs include a wide spectrum of organics including polycyclic aromatic hydrocarbons (PAHs), polychlorobiphenyls (PCBs), dioxins and furans (PCDD/Fs), and polybrominated diphenyl ethers (PBDEs), and have deleterious impacts on the environment and public health (Harmens et al., 2013). The POPs are of special significance to regulatory authorities as they have demonstrated adversities toward environment and health. Recent literature, the POPs have even labeled the POPs as "global pollutants" due long-range transboundary transport (Hageman et al., 2015), and risks of bioaccumulation and biomagnification through food webs (Li et al., 2007).

Under the circumstances, mosses could open up newer avenues for the authorities to track spatio-temporal distribution of POPs across a wide range of ecological settings, thus facilitating research and development (e.g., pollution prevention and abatement). For example, Carballeria et al. (2006) monitored PCDD/F levels in *Pseudoscleropodium purum* tissues collected in the surroundings of several types of industries, incinerators and burning rubbish dumps), and maintained that *"mosses are effective for) detection of strong and weak pollution sources and that these measurements are sensible enough to assess changes in the pollution intensity along time, as well as to describe the spatial gradients of pollution created around point sources, and the differences in the relative abundance of isomers (homologue profiles) among different sources."*

In a nationwide assessment of POPs in Germany, as part of the European Moss Survey initiatives in 2015, Dreyer et al. (2018) analyzed 400 moss samples following a harmonized methodology. Results indicated that (i) mosses have appreciable bioaccumulation potential for a wide array of POPs (e.g., PAHs, PCBs, PCDD/Fs, HBCDs) and thus aid in monitoring atmospheric concentrations, and (ii) compared to nearby tree leaf samples, mosses have high accumulation potential for pollutants of high octanol–air partition coefficient (KOA) and octanol–water partition coefficient (KOW). Mosses have been effective to detect short-term changes in ambient POPs as well. Colabuono et al. (2015) used mosses to detect atmospheric deposition patterns after a fire incident, at the Brazilian Antarctic Station (The Comandante Ferraz Station) located on King George Island in Admiralty Bay. Moss analyses revealed sudden surge in a suit of endocrine disrupting compounds (EDC) including hexachlorobenzenes (HCBs) and PAHs, besides several metal species (Pb, Zn and Cu) in ambient air after the incident, which declined after a few months. The moss results even helped source tracking of the POPs—volatilization of Arctic grade diesel fuel, and low molecular weight PAHs (LMW-PAH)—major components of Antarctic soils. Li et al. (2011) used mosses to detect changes in ambient levels of various PCDD/Fs, PCBs, and PBDEs in and around a big steel industrial park of Anshan, Northeast China. Results indicated distinct seasonal patterns—significantly

Table 2 Short-term variations in air quality using moss biomonitoring survey (*Source*: Compiled from various studies)

Study and Region	Pollutants Monitored	Moss Species and Sample Number (*N*)	Salient Features
Yushin et al. (2020) Study Region: *Moscow City, Russia*	Cd, Cr, Cu, Fe, Ni, Pb	*Pleurozium schreberi* ($N=19$)	• Comparative assessment of pre- and post- SARS-CoV-2 Lockdown ambient air quality in 2020 (as compared to *business-as-usual* scenario 2019) • Compared to same time period in 2019, Cd content during 2020 Lockdown decreased by 2–46%, while the iron content increased by 3–127% • Cu, Ni, and Pb levels dropped at most sites, except for western part of Moscow city, where most engineering and metal processing plants are located • Negative impacts of the industrial emissions on ambient air quality persisted at the level of 2019 or even increased • SARS-CoV-2 Lockdown policy significantly improved ambient air quality; the latter began dropping with resumption of life-as-usual condition • Moss records could be effective sensors for short-term changes in air quality to base policy decisions upon

Table 2 (continued)

Study and Region	Pollutants Monitored	Moss Species and Sample Number (*N*)	Salient Features
Zupanic and Bozau (2021) Study Region(s): *Germany—Harz Mountains;* *Slovenia—Pokljuka and Pohorje*	Al, Ca, Fe, Ba, Cd, Co, Cr, Cu, Hg, La, Mo, Nd, Ni, Pb, Sc, Sr, Ti, Zn	*Sphagnum* sp. ($N = 48$ total) (Germany, $N = 11$ Slovenia, $N = 10$)	• Impact of SARS-CoV-2 Lockdown in Harz Mountains (Germany) and Pokljuka (Slovenia) in 2020 (compared to 2019) • In Germany Cu, Hg, Pb, Co, Ni, Sc and Ti levels dropped due to Lockdown in 2020 • In Slovenia, concentrations of all species dropped in 2020, excepting Fe, Cr, Ni, Sc, and Ti, which increased during Lockdown • SARS-CoV-2 Lockdown led to a decrease in long-range pollutants bound to finest particles and increased the influence of local soil dusting • Effects prevailed over lower precipitation regimes in 2020, compared to 2019

high ambient PCDD/Fs levels in winter than that of summer, while the opposite for the PCBs and PBDEs. Such information may help the regulatory authorities preempt strategic pollution control mechanisms.

3.3 Pollutant uptake mechanisms

3.3.1 Metal

What is known so far about metal uptake by mosses is broadly guided by three key factors: (i) pollutant types, (ii) characteristics of the moss species, and (iii) local eco-environmental conditions (Table 3). Process-level research demonstrates that metals are sequestered by three main mechanisms: as aqueous solution, gas or solid particles and can adhere on cells' surfaces, outer walls (via ion exchange process) or be included into cells (via passive or active transport) (Wolterbeek, 2002). Weakly developed cuticles of mosses, through which metal ions easily penetrate the cell wall, coupled with and large surface to weight ratio of mosses, favors metal adsorption (Onianwa, 2001). Trace elements are deposited on the surface of mosses, as dry particulate matter or dissolved material; while heavy metals are retained primarily by adsorption mechanism, physico-chemical processes such as ion exchange or passive-active intracellular uptake (Macedo-Miranda et al., 2016). Ion exchange processes are influenced by a large number of factors, such as the number and type of free cation exchange sites, the age of the cells and their reaction to desiccation, moss growing conditions (temperature, precipitation pH), composition of the pollutants and extent of leaching (Blagnytė & Paliulis, 2010). The cell wall has a high polyuronic acid

Table 3 Main drivers of moss-pollutant uptake (*Source*: Compiled from Dołęgowska & Migaszewski, 2014)

Key Drivers	Critical Considerations
Pollutant Characteristics	• Particle size • Surficial chemistry (e.g., cation exchange sites) • Gaseous or particulate
Moss Traits	• Cells' pH • Cell wall structure and chemistry • Biomass productivity • Moss health • Level of phytotoxicity (pollution tolerance) • Moss tissue age • Moss growth patterns
Local Eco-environmental Conditions	• Temperature • Precipitation • Wind velocity • Relative humidity • Aridity • Vegetal coverage • presence of sea salt • Acidic precipitations • Local topography (elevation, slope, aspect) • Land management history (pollution sources) •Pollutant source distance and direction (w.r.t. wind velocity and direction)

content which makes moss a very good natural ion exchanger. Overall, pollutant entrapment by mosses is regulated by the chemical form of metals, principally ionic forms and by the affinity between the chemical form of metals and the biochemical structures in mosses (Klos et al. 2011).

3.3.2 POPs

Compared to moss-metal interactions, however, there is yet dearth of process-level investigations about organic pollutant uptake by mosses. PAHs uptake occurs through absorption and adsorption mechanisms depending on their availability in the environment, physical chemical properties (e.g., the partitioning between vapor and particle phases, the KOW coefficient), environmental conditions (e.g., temperature, humidity, radiation) and plant traits (Harmens et al., 2013). In a recent study, Spagnuolo et al. (2017) investigated phenathrene (a most abundant atmospheric PAH variety) uptake patterns by four moss species (*Amblystegium humile, Plagiomnium affine, Hypnum cupressiforme* and a clone of *Sphagnum palustre*), using fluorescent and confocal microscopy. Results implied 'particulate uptake' of phenanthrene, and a more 'physical' than chemical mechanism, with four mosses showing different uptake capacities. The latter could arise from differences in specific surface area and composition, frequency, and distribution of binding groups.

Recent studies indicate that the organic pollutant uptake by mosses is largely governed by the molecular weights[4] of the pollutant species (Dołęgowska & Migaszewski, 2014). For example, mosses 'preferentially' entrap high molecular weight PAHs (HMW-PAH; 5–6 rings), in contrast to plants and/or lichens, which tend to entrap more of low molecular weight species (LMW-PAH) (2-, 3-, 4-ringed PAHs) (Oishi, 2016). The difference owes mainly to high surface-to-mass ratio in mosses and structural differences in cell walls (González & Pokrovsky, 2014; Tretiach et al., 2007). The HMW-PAHs tend to be more of particulate nature, while the LMW-PAHs are generally gaseous. Therefore, plants uptake LMW-PAHs through absorption by the stomata on their leaf surfaces or diffusion through the cuticle layer. In contrast, particle-bound HMW-PAHs are more easily absorbed in mosses as they lack cuticles and they tend to uptake pollutants dissolved in precipitation as well as gaseous particles.

3.4 Environmental systems' analysis

Moss-based studies have rapidly evolved over the past two decades as complementary means to assess ambient air quality status, and (spatio-temporal) changes therein. It is Schröder et al. (2017) maintained that *"moss surveys should 'complement' modelled atmospheric deposition data as well as other biomonitoring approaches and offer a great potential for various terrestrial monitoring program dealing with exposure and effects."* In the following sections, we attempt to highlight to the concerned authorities (interested in moss-based biomonitoring) selected applications of mosses in environmental systems' monitoring and assessment that featured in most recent global literature.

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[4] A general observation has been that the PAHs of low molecular masses (128 ÷ 178 g/mol) occur in the atmosphere in the gaseous form and can be transported over long distances (Ciesielczuk et al., 2012). On the other hand, heavier PAHs (228 ÷ 278 g/mol) occur mostly as solids adsorbed on particles, (e.g., on soot particles), and are transported over relatively smaller distances (Lohmann et al., 2007; Wang et al., 2009).

3.4.1 Spatial monitoring and vulnerability assessment

Several recent studies have integrated moss-based records with various multivariate statistical methods to probe into potential origins (anthropogenic vs. natural/geogenic), species assemblages, and spatial structure of occurrences of various pollutant species, which aid in assessing eco-environmental risks (Chaligava et al., 2021; Kosior et al., 2020). In a recent study, Lazo et al. (2018) assessed 48 moss records of 37 elements across Albania. When analyzed with Factor Analysis (FA), results indicated that mosses are capable, not only of showcasing the spatial structure and variability of metal occurrences, but also providing clues for their origins and transport. Ren et al. (2021) used principal component analysis (PCA) upon moss-based radionuclide signatures (^{210}Pb (^{210}Pbex), ^{7}Be, ^{137}Cs, ^{40} K, ^{238}U, ^{226}Ra, ^{228}Ra and ^{228}Th) to ascertain spatial distribution of Fe, Zn, Cu, Al, Pb, Cd, Cr, Ni, V and Mn. Results indicated that moss records were able to distinguish between atmospheric deposition patterns in mainland China (higher environmental risk due to elevated metal concentrations) and that of the Arctic region.

When coupled with geographic information system (GIS) (Schroder and Nickel, 2019; Nickel & Schroder, 2017), moss records can help the authorities understand spatial structure (and variability) of pollutant species, which in turn can be used to establish vulnerability maps and develop spatially optimize regulatory interventions. For example, in an urban risk analysis study, in and around the Metropolitan Zone, Toluca Valley, Mexico, Avlia-Perez et al. (2016) integrated moss-based results (*Fabriona cilaris* and *Leskea angustata*) with geostatistical tools. The study identified regions with low urban vegetation coverage and closer to highways as high-risk areas. The authors inferred that strategic use of mosses can offer the local government (and environmental agencies) a low-cost, rapid risk evaluation tool, which could help re-imagining new, and re-defining the existing, public policies on air pollution prevention and control. For rapidly growing urban agglomerations, such approaches can help the authorities envision pre-emptive measures.

As an extension of the above, there is a rapidly growing body of research around the world that integrate moss-based biomonitoring results with various environmental indicators (Lazo et al., 2018) (Table 4). In the study conducted by Ren et al. (2021) in China, when the moss-based results were used to derive concentration ratios (CR) values of the radionuclides and the bioaccumulation factor (BCF) and enrichment factor (EF), it even helped identifying the most environmentally sensitive moss (*Bryum paradoxum*), which can be used for screening and monitoring radionuclides and metal pollution in urban atmospheres. Such approaches may provide baseline data for in-depth environmental systems' analysis as well as future targeting policies to protect various ecosystems from long-term inputs of various pollutant species guided by anthropogenic activities and atmospheric transportation (Bing et al., 2019).

3.4.2 Pollutant sources and drivers

An important aspect of any environmental systems' assessment is to ideate major pollutant sources/origins and factors/drivers (e.g., land management practices) leading to pollution. Kosior et al. (2015) used *Pleurozium schreberi*, isolated from rural, urban and industrial sites in Upper Silesia in southern Poland, to detect δ^{34}S and S concentrations in a 90-day experiment. The δ^{34}S enrichment (up to 4.7‰) signatures in the *P. schreberi* varied distinctly by land use sites and indicated that strategic use of these

Table 4 Various environmental indicators developed in on moss-based bioindicator studies (*Source*: Compiled from various studies)

Indicator Name	Indicator Development	Significance	Study
Contamination Factor (CF)	$CF = \frac{C_M}{C_B}$ *where,* C_M: Observed concentration of pollutant species in moss C_B: Background metal concentration in at site	$CF < 1$ = No Contamination CF 1–2 = Suspected CF 2–3.5 = Slight CF 3.5–8 = moderate CF 8–27 = Severe $CF > 27$ = extreme	Yushin et al. (2020), Jiang et al. (2018)
Enrichment Factor (EF)	$EF = \frac{C_M T_i}{C_B T_b}$ *where,* C_M: Observed concentration of pollutant species in moss T_i = Concentration of conservative reference element in moss sample C_B: Background metal concentration in at site T_b = Concentration of conservative reference element in reference	$EF \leq 2$ = Conservative EF 3–5 = Slightly Enriched EF 6–9 = Moderately $EF \geq 10$ = Highly Enriched *(potentially anthropogenic pollution)*	Jiang et al. (2018), Zarazúa-Ortega et al. (2013)
Rapid Accumulation Factor (RAF)	$EF = \frac{C_{i,1} - T_{i,0}}{C_{1,0}}$ *where,* $C_{i,0}$: Concentration of an analyte after exposure period $C_{i,1}$: Concentration of an analyte after exposure period	Higher the EF, higher the bioaccumulation potential of the pollutant	Demková et al. (2019)
Geo-accumulation Factor (I_{geo})	$I_{geo} = \log_2 \frac{C_M}{1.5 C_B}$ *where,* C_M: Observed concentration of pollutant species in moss C_B: Background metal concentration in at site *1.5* = Empirical value, to account for 'potential' heterogeneity in C_B	$I_{geo} \leq 0$ = Unpolluted I_{geo} 0–1 = Unpolluted—Moderately Polluted I_{geo} 1–2 = Moderately Polluted I_{geo} 2–3 = Moderate—Strongly Polluted I_{geo} 3–4 = Strongly I_{geo} 4–5 = Strongly—Extremely Polluted > 6 = Extremely Polluted	Krakovska et al. (2020)

Table 4 (continued)

Indicator Name	Indicator Development	Significance	Study
Pollution Loading Index (PLI) *[represents nth order geometric mean of the entire set of CF]*	$\mathrm{PLI} = \sqrt[n]{\coprod_{i=1}^{n} \mathrm{CF}}$ *where,* CF = Contamination Factor n = Total number of pollutant species	$\mathrm{PLI} < 1$ = Non Polluted PLI $1 \leq \mathrm{PLI} < 2$ = Slight Polluted PLI $2 \leq \mathrm{PLI} < 3$ = Moderately Polluted $\mathrm{PLI} < 3$ = Highly Polluted	Yushin et al. (2020)
Ecological Risk Index (ERI) *[“overall” ecological risk of multiple heavy metals]*	$\mathrm{ERI} = \mathrm{T}_{\mathrm{R}}^{\mathrm{i}}\mathrm{CF}$ where, CF = Contamination Factor $\mathrm{T}_{\mathrm{R}}^{\mathrm{i}}$ = Toxic-response coefficients (Xu et al., 2008); Cd = 30; Cr = 2; Cu = 5; Hg = 40; N = 5; Ni = 5; Pb = 5; Mn = 1; As = 10; Zn = 1	$\mathrm{RI} < 150$ = Low Risk $150 \leq \mathrm{RI} < 300$ = Moderate Risk $300 \leq \mathrm{RI} < 600$ = Considerable Risk $\mathrm{RI} \geq 600$ = Very High Risk	Zhou et al. (2017), Jiang et al. (2020)

species can help the authorities distinguish changes in air quality. From Mountain Gongaa, China, Xiao et al. (2021) found that metal accumulation in mosses could be keyed to elevation differences, with low lying areas sequestering more due to proximal sources of pollution. Bing et al. (2019) conducted a study involving eight trace metals (As, Cd, Cr, Cu, Ni, Pb, Sb, and Zn) to understand key driving factors affecting the distribution of trace elements in remote mountainous areas at national scale in China. Distribution of metals indicated: (1) higher levels than that in most European countries; (ii) significantly higher contamination levels in the eastern, southern and southwestern China; (iii) anthropogenic origins of As, Cd, Pb, Sb and Zn (mining-related activities, fuel combustion, industrial emissions), whereas natural for Cr, Cu and Ni; (iv) monsoonal precipitation was an important driving factor. Such observations can help the authorities assess current environmental systems' vulnerability and 'optimize' regulatory interventions for future. Zhou et al. (2021) carried out pollutant source tracking in Yancheng, a coastal city in central Jiangsu Province, China, using the species *Haplocladium microphyllum* (Hedw.) Broth. Prior to this study, there have been no reports on atmospheric heavy metal deposition in Yancheng. The authors reported levels of various heavy metals (d, Cr, Pb, Zn, V, Ni, and Cu) in Yancheng were significantly higher than those recorded in other similar studies in Eurasia and Alaska. Natural sources dominated the scenario (53% of the total load) followed by manufacturing and construction (33%); metal processing and chemical industries (12%); traffic emissions and fuel burning in industrial activities (2%). Metal processing and traffic emissions were the main sources of Pb contamination. Overall, moss-based assessment of atmospheric pollution appeared useful for developing various effective measures to prevent and reduce atmospheric HM deposition in Yancheng.

3.4.3 Urban air quality

For urban sustainability planners mosses can offer means to decipher changes in ambient air quality under various pollution scenarios (Kosior et al., 2015). For example, Goryainova et al. (2016), used *Sphagnum girgensohnii* to determine the small-scale vertical distribution of 25 major and trace elements in different types of street canyons (regular, deep and avenue types) in Belgrade and Moscow city. The results showed that in both cities, pollutants loadings were (i) higher in deep and regular street canyons, than that of the avenue type, even when the latter has a higher traffic flow; (ii) highest at the lowest heights compared to those of the upper floors; and (iii) lower on the off-street avenue side compared to the on-street side for all heights of moss exposure. Street canyons are very common geometry in most urban habitats in South-South Asia and known for pollution arising from complex atmospheric, meteorological and anthropogenic factors (Chaudhuri & Kumar, 2022). Zechmeister et al. (2006) maintained that could yield appreciable estimates of air quality in tunnel settings as well. It owes to the fact that confounding effects of other sources of pollution and the ’noise’ in the accumulation process (e.g., washout through wet deposition), which potentially disrupt the ’true signals’ of pollutants in traditional, sensor-based technologies, are minimized in cases of mosses. In tunnel environments, the pollutants are not lost by rain events and persist for longer periods of time. Zarazua-Ortega et al. (2013) collected *Fabronia ciliaris* from six urban sites in the Metropolitan Zone of the Toluca Valley in Mexico. Industrial and densely packed urban areas bore distinct signatures of heavy metals (Cr, Cu, Zn, Pb) owing mainly to intense vehicular emissions and fossil fuel combustion.

In the same area, Avlia-Perez et al. (2016) used *Fabriona cilaris* and *Leskea angustata*, to find that a confluence of anthropogenic activities including combustion, vehicular emissions, biomass burning, brick kiln emissions, agricultural and livestock activities, manufacturing industry and re-deposition by the action of the wind, impacted heavy metals (Cr, Cu, Pb, Zn) occurrence in ambient air.

3.4.4 Epidemiological research

In the post-COVID-19 era, epidemiological complications related environmental degradation has emerged as a major concern to authorities around the world. However, a key to establish statistically validated correlations between the two, fundamentally hinges on 'confidence' on data quality (completeness and representativeness of air quality records). It is a major stumbling block in developing countries due to dire resource constraints to establish robust monitoring networks. To that end, Lequy et al. (2018) maintained*, "To conduct epidemiological research on exposure to atmospheric metals we must expand the network of monitoring stations or find different ways of quantifying levels of atmospheric metals. Fortunately, such an alternative exists in an unexpected form: the moss biomonitoring approach, based on the ability of mosses to proxy levels of atmospheric metals."*

In France, Lequy et al. (2019) modelled and mapped atmospheric deposition patterns of 13 metals (Al, As, Ca, Cd, Cr, Cu, Fe, Hg, Na, Ni, Pb, V, and Zn) to ideate potential exposure concerns. Information were obtained from the BRAMM database that included moss survey results across four time periods (1996, 2000, 2006, and 2011) in 449–559 rural forest sites, involving 11,382 participant. The study found that exposure to metals having anthropogenic sources (Cd, Hg, Pb, Zn; arising from urban, traffic or industrial pollution) have elevated mortality risks, while those from natural sources were not. A previous study conducted by same group (Lequy et al., 2018), based on same database and same respondent population, found that exposure of all metals (i) had high spatial and temporal variability, and (ii) generally followed gradients of population density -higher concentrations in industrial regions, such as the Parisian region, the North of the Rhone valley. Schlutow et al. (2021) used moss-based biomonitoring to decipher human health impact of heavy metal deposition (As, Cd, Cu, Ni, Zn, Cr, Hg Pb) in Germany between 1990 and 2015. The spatio-temporal maps indicated that As, Ni, Zn, and Cr did not exceed the Ecosystem and Human Health Critical Loads in 2009–2011, but Hg and Pb did. The Critical Load for Cu was exceeded in 2010 in two regions. However, the study revealed that human health Critical Loads for Cd were not exceeded in 2010.

3.4.5 Pollutant transport

Vosel et al. (2021) has used moss-based records (Hylocomium splendens) of ^{137}Cs concentrations, to understand impacts of nuclear weapon tests on ambient air quality (Novaya Zemlya, western Siberia). Results of the study offer valuable insights into atmospheric circulation patterns, and pollutant transport mechanisms, in the northern hemisphere, which can initiate new research.

Several studies have used mass-based PAH to understand national/transnational transport. Recent studies employed moss-based biomonitoring to decipher transboundary atmospheric transport of PAHs (Martinez-Swatson et al., 2020). In a study in the Alpine areas and urban areas across central Japan (easternmost part of Asia), Oishi (2017) observed close association between the transport phenomena and molecular weights of PAHs: LMW-PAH has more localized emission sources while HMW-PAHs originated at more distance sources. Analyses of isomer ratios revealed that the PAH sources for alpine moss (HMW-PAHs) were similar to that for northern coastal cities, which are typically influenced by long-transported PAHs from East Asia. Using nitrogen contents and stable isotopic composition ($\delta^{15}N$) as a marker of N sources (and pollution), Oishi (2019) deciphered that N in the alpine moss (*Hylocomium splendens*) on the west slope seemed to be influenced by transboundary N pollutants through particulate matter (PM), which is brought to Japan from mainland Asia by prevailing westerly winds and northwest monsoons.

In a more recent study, Oishi (2022) indicated that Pb isotope ratios can offer better clues to long-ranged, transboundary transport or airborne pollutants. However, caution must be used to interpret results as (i) Pb isotope ratios were partially dependent on seasonal variations in precipitation; (ii) Pb isotope ratios were altered by soil-derived Pb in areas with Pb-enriched soil; and (iii) Pb uptake by mosses can be inhibited by other trace metals that compete with Pb for cation binding sites at the cell wall; such inhibitory action can alter the contribution of atmospheric Pb deposition to the total Pb content in mosses, thereby affecting the Pb isotope ratios.

4 Lessons learned

As the concern over public health hazard soars with increased atmospheric pollution, so has worldwide effort to find suitable means to monitor and assess ambient air quality across regional to national scale. There has been a boom in moss literature around the world through the past two decades. Since its continental-scale application began with the EMS in the 1990, mosses have been used as close proxy to ambient air quality and changes therein, offering the authorities, as much as research community, a complementary means to ideate pollutant behavior.

4.1 Understanding pollutant dynamics

According to Schröder et al. (2017), *"moss surveys provide spatially dense data on environmental concentrations of heavy metals and nitrogen which, together with other biomonitoring and modelling data, can be used for indicating deposition to terrestrial ecosystems and related effects across time and areas of different spatial extension."* In view of rising tolls of air quality induced public health damages, such moss-based approaches could potentially help the authorities ‘filling in gaps’ in existing data records, which is essential for conducting process-level research. It falls in line with recent observations made by Fores-Martin et al. (2021), *"monitoring ecosystem change at large spatial scales and over long-time frames is an essential endeavor of effective environmental management and conservation. However, resource limitations often preclude revisiting entire monitoring networks at high frequency."* It owes to some highly specialized physiological traits that provide the authorities time-integrated profile of pollutants, unlike traditional sensors.

Global experience demonstrates how mosses have widely been used in monitoring and assessment of a vast range of metals and organics, and provided valuable insights into their sources (e.g., vehicular and industrial emissions, fuel combustion, mining, to name a few). From epidemiological studies to ecological risk assessment, detection of short- to long-term air quality shifts, understanding of long-range pollutant transport patterns, mosses have shown great potential for monitoring environmental degradation and thus, ability to influence future regulatory decisions from regional to continental scale, while keeping in mind individual national priorities. Hristozova et al. (2019), as part of the UNECE ICP Vegetation program in Bulgaria, analyzed long-term moss records (1995/96–2015/16) of 47 metal species around a lead–zinc smelter. The authors maintained that such long-term studies could help the concerned authorities instituting new and efficient pollution-control equipment, evaluate health hazards and ecosystem risks, and develop appropriate regulatory measures thereof. Being highly sensitive recorder to short-term shifts in ambient air quality, mosses may also help instituting quick/emergency response plans at local scale. In addition, moss-based biomonitoring can even help adding new monitoring parameters to the current monitoring protocol.

4.2 Clues for effective sampling-monitoring design?

A critical outcome of the EMS has been that knowledge of spatial structure of metals thus generated by various researchers (Pesch et al., 2008), in future could help restructuring and refining environmental monitoring networks, which in turn, would enable quantitative description of possible effects on the information quality. Moreover, knowledge obtained from such ’site optimization’ approaches could be applied to other environmental monitoring programs as well, to envision better sampling protocols (transparent; ecologically, environmentally, and spatially representative; statistically validated; resource efficient) (Schröder & Nickel, 2019; Nickel and Schröder, 2017), including a potential ’revision’ of the current protocols followed by ICP vegetation. This, in turn, can lead to ’prioritization’ of pollution hotspots, and development of more informed/targeted pollution prevention and abatement programs.

4.3 Understanding air quality evolutionary patterns

Moss-based results can even help understanding evolutionary patterns of air quality at national scale. For example, Kapusta et al. (2020) was able to decipher the evolutionary sequence of air quality in Krakow region, southern Poland with 4 periods of sampling—1975, 1992, 1998, 2014. Using moss species of *Pleurozium schreberi* the authors showed significant reductions in ambient Cd, Pb, Fe, Cu and Zn concentrations over time (by factor of 10, 9, 3.5, 2 and 2, respectively). Biggest changes occurred at the very beginning (1975–1992) due to drops in industrial production and the introduction of environmentally friendly technologies. Between, 1998 and 2014, however, concentrations of some trace metals increased, due largely to urban sprawl and agricultural intensification (non-industrial sources).

4.4 Mosses or trees?

There has been a growing body of research assessing comparing mosses with trees to bioaccumulate airborne pollutants. In Wuhan, China, Jiang et al. (2018) found that *Haplocladium angustifolium*, was able to capture traffic-induced emissions 3–51 times better two evergreen tree species, *Cinnamomum bodinieri* and *Osmanthus fragrans*. Capozzi et al. (2020) compared between *Hypnum cupressiforme*, and leaves of *Robinia pseudoacacia* (black locust) to find significantly higher bioaccumulation potential of Hypnum for a wide array of heavy metals. *R. pseudoacacia*, with a smooth leaf surface and scarce trichomes, showed a limited ability in airborne element retention. From Campania and Tuscany, in Italy, De Nicola et al. (2013) observed that *Leptodon smithii* accumulated higher concentrations of trace elements (Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb and Zn) than tree leaves (holm oak; Quercus ilex), while the latter showed a higher accumulation capability for PAHs, especially for those with low molecular weight. The different bioaccumulation in leaves and moss were explained in terms of their distinctive morphological and ecophysiological characteristics. Compared to trees, what makes moss more suitable for air quality sensing are: (i) presence of highly reactive functional groups on cell wall that facilitate pollutant capture (Gonzalez et al., 2016; Gonlzalez and Pokrovsy, 2014); (ii) higher surface-to-volume ratio; and (iii) adaptation to low light due to their one-cell-thick leaves and lack of well-developed cuticle (Julinova & Bečkovský, 2019). Interestingly, presence of tree species can also 'influence' pollutant accumulation levels in mosses. (Kosior et al., 2015). For more in-depth understanding between mosses and trees, we suggest the authorities to consult relevant literature (Piraga et al., 2017; Tsikritzis et al., 2003; Dongarra et al., 2003). While scientific theories continue to surface, De Nicola et al. (2013) recommended combined use of moss and tree species to improved biomonitoring of airborne pollutants.

4.5 Potential co-benefits?

However, besides pollutant monitoring and assessment, mosses may even provide several co-benefits to the authorities as well. For example, mosses are known to prevent erosional soil loss and regulators of local ecosystem water budget (Cui, et al., 2009; Fernandez et al., 2006; Wang, et al., 2008). While the former helps to preserve soil fertility status (retention of soil nutrients and organic matter) and thus maintain crop yield, food security, and revenue generation (income and livelihood), the latter helps in countering water stress/scarcity issues. Mosses can alter not only their temperature but also the temperature of the soil. By evaporative cooling, where they transfer water from lower parts to growing tips, they can prevent overheating of the soil (Julinova & Bečkovský, 2019).

5 Concluding remarks: *concerns and future research*

A main impetus to present this narrative was to offer the concerned authorities, especially that in developing countries, where setting up robust (spatio-temporally intensive) air quality monitoring network has become essential to ensure human health sustainability and environmental protection. However, air quality monitoring using traditional sensors is marred by multiple logistic hardships, especially in developing countries where economic constraints directly interfere with environmental ideals. In the present narrative, we adopted a systematic review methodology (PRISMA) to scan recent global literature (2002–2022),[5] to offer the authorities a holistic overview of current practices and

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[5] Such review-based approaches, in recent times have become increasingly popular, as they summarize latest advances and innovations, future opportunities, while highlighting potential challenges for implementation (Li et al, 2021; Swislowski, et al., 2020). Research communities frequently resort to such 'summary documents' to understand exiting research gaps (Kesavan et al., 2022). On the other hand, In the policy-/decision-makers circle such documents are particularly prized to identify areas of priority action and mobilize resources (funds and infrastructure) judiciously (Chaudhuri and Kumar, 2022).

Table 5 Process-level concerns and potential future research directions around moss-based biomonitoring (*Source*: Compiled from various studies)

Issues	Future Research Requirements
Lack of Data	• There is yet lack of adequate empirical evidences, establishing statistically significant relationships between the levels of pollutants accumulated in moss and that in ambient air • A way to assess this is by installing high frequency (days to weeks) samplers near known pollutant sources that can be identified with the current moss data (Mudge et al., 2019). The rate of uptake into moss can be measured along with the time to equilibrium. Factors may be developed that enable an estimate of the emissions to be predicted • This would need to be done at several different sites with different emission types
Heterogeneity	Spatial heterogeneity in moss samples (e.g., occurrences of multiple moss species across a geographic stretch), could result in systems' 'mismatch', and eventually, difficulty in interpreting results (Krmar et al. 2013; Boquete et al. 2017)
Variability	• Oishi (2019) found significant impacts of slope aspect and altitude on nitrogen accumulation in in *Hylocomium splendens* in the Alpine regions in Japan • Targeted research necessary to ascertain likely impacts of natural local variability on bioaccumulation patterns of pollutants, such as ambient pH levels, meteorological factors, topography (slope, slope aspect, altitude)

advances in passive moss-based biomonitoring of ambient air quality. Although mosses offer a series of advantages over traditional sensor-based assessment of ambient air quality, there yet remain uncertainties around the approach (Wolterbeek et al., 2010) that need to be addressed with more process-level research, with increased case studies (Table 5).

5.1 Which species to pick?

For the authorities interested in adopting moss-based approaches, a critical question is which species to select? So far, global literature suggests certain moss species that have become the choice of the research community for tracking pollutant distribution, for several 'preferred' physiological traits and geographic occurrence (Schroder and Nickel, 2019; ICP Vegetation, 2014). This includes *Pleurozium schreberi* (BRID.) MITT. (abbreviated as Plesch), *Hypnum cupressiforme* HEDW. (abbreviated as Hypcup) and *Pseudoscleropodium purum* (HEDW.) M.FLEISCH (Synonym *Scleropodium purum* HEDW. LIMPR.) (abbreviated as Psepur). These species are appropriate for mapping trends of heavy metal bioaccumulation of atmospheric deposition throughout areas of large spatial extent based on a spatially dense network. However, there is yet some research necessary to understand potential use of other varieties, such as different species of Haplocladium.

5.2 Moss-pollutant interactions

A prime challenge for the research community in days ahead will be to advance our understanding about moss-pollutant interactions and species-specific differences in intercepting airborne pollutant dynamics. In a landmark research, Gonzalez et al. (2014) found that 5 major functional groups, phosphodiester, carboxyl, phosphoryl, amine and polyphenols, present in the cell wall of mosses, and responsible for metal adsorption behavior in mosses. The latter was direct functions of pH and metal concentrations. In comparative study, the authors found that of four commonly used moss species (*Hypnum* sp., *Sphagnum* sp., *Pseudoscleropodium purum* and *Brachytecium rutabulum*), the Sphagnum variety has strongest adsorption behavior. However, it will require more targeted research to unravel species-specific interaction mechanisms under various environmental conditions, and land management practices, to identify the best variety to befit local conditions. In this regard, Giraldez et al. (2022) stressed that a critical requirement for the authorities to use mosses for biomonitoring will hinge on the ability to establish ’background’ pollution levels. To that end, the authors proposed probabilistic approaches integrated with spatial statistical tools.

5.3 Are mosses reliable proxies of air quality?

In a related sense, Wu et al. (2014) emphasized on process-level research to establish statistically validated associations between the concentrations of pollutants in moss tissues and that in the atmosphere (different size particulates and vapor phases). A main point of concern herein is likelihood of ’false negative’—high atmospheric levels of pollutants and low concentrations observed in moss (Giraldez et al., 2022). Boquete et al. (2015) suggested that in order to understand the interrelationships between moss concentrations and that of bulk deposition, conscious efforts should be made to the experimental designs (e.g., analytic techniques, statistical methods) as well. In a more recent study, Bouquet et al. (2020) emphasized the need (i) to account for potential ’mismatch’ between the time that the moss tissue selected for analysis is exposed to atmospheric deposition, and the time during which bulk deposition is collected; and (ii) identify which moss tissues may provide better estimate of bulk deposition.

5.4 Phytotoxicity?

There is considerable debate around potential toxic effect of metal build-up in moss tissues, which can alter long-term performances as bioaccumulators; and may even lead to death of moss (Lazo et al., 2018). At process-level, mosses cannot prevent ions penetrating their tissues because they have high counter-gradient mechanisms by which they accumulate significant concentrations of metals in their bodies (metal toxicity) (Shakya et al., 2008; Chakrabortty & Paratkar, 2006). Basile et al. (2012), however, found that culturing the moss *Scorpiurum circinatum* (Brid.) Fleisch. & Loeske with metal solutions (Cd, Cu, Pb and Zn) for 30 days, there was not much ultrastructural changes, and cells were still alive and generally well preserved; moss cells survived to heavy metal toxicity by immobilizing most toxic ions extracellularly, likely in binding sites of the cell wall, which is the main site of metal detoxification.More recently, Bellini et al. (2020) observed that *Leptodictyum riparium* can counteracts severe Cd stress by activating Glutathione S-Transferase and Phytochelatin Synthase, thus minimizing the cellular damage caused by the metal. Overall, there is need for targeted research to further understand the dynamics of the bioconcentrated metal fraction (intracellular) in relation to moss metabolic activities and long-term performance as air quality sensors (Pérez-Llamazares et al., 2011).

5.5 Overall…?

For authorities interested in adopting moss biomonitoring, few critical questions are as follows: (i) what is the most efficient moss material and species that can be recommended for the moss biomonitoring of pollutants besides the endemic Sphagnum genera; (ii) what is the most appropriate exposure time of mosses to achieve the reliable uptake (above detection limit) of pollutants; (iii) how to establish quantitative relationship between the concentrations of compounds in ambient atmosphere and those measured in moss species; (iv) how do environmental/topographic parameters ’alter’ moss-pollutant interaction; (v) does climatic shifts/anomalies impact mosses as bioaccumulators of various pollutant species in ambient atmosphere, to name a few. In this regard, the authorities might take up the research directions clued by Markert (2008), regarding the effective use of biological systems for environmental pollution prevention and control:

- More frequent inclusion of multi-element total analyses for a thorough investigation of mutual correlations in the sense of the biological system of elements
- More work on (analytical) speciation issues to proceed into real effect-oriented environmental sciences
- There should and must be a focus on integrative bioindication methods because of a large number of environmental monitoring problems

To that end, it is as Wolterbeek (2002) summarized, *"… more explicit coupling of biomonitoring data to knowledge and databases on both emission registration, ecosystem performance and human health.”* This emphasizes the need of interdisciplinary research comprising of biomonitoring experts, environmental systems’ managers, pollution regulators, ecologists, epidemiologists, landscape planners’, spatial mappers (to name a few), for process-level interpretation of moss-pollutant interactions, for better use in air quality monitoring initiatives.

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Data availability This was a literature review-based study. Therefore, the clause of data availability was not applicable to this article as no ’new’ datasets were generated during the current study. The information about the European Moss Survey (EMS) and ICP Vegetation are open-sourced and available to all for free of cost.

Declarations

Conflict of interest The authors declare that there was no conflict of interest whatsoever.

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Authors and Affiliations

Sriroop Chaudhuri[1] · Mimi Roy[1]

✉ Sriroop Chaudhuri
schaudhuri@jgu.edu.in

Mimi Roy
mroy@jgu.edu.in

[1] Jindal School of Liberal Arts and Humanities; Center for Environment, Sustainability and Human Development (CESH), O.P. Jindal Global University, Sonipat, Haryana 131001, India