Revista de Estudos Interdisciplinares

TRENDS IN ATMOSPHERIC POLLUTION BIOMONITORING USING *TILLANDSIAS*, MOSSES, AND LICHENS: A SCIENTOMETRIC ANALYSIS

TENDÊNCIAS NO BIOMONITORAMENTO DA POLUIÇÃO ATMOSFÉRICA USANDO *TILLANDSIAS*, MUSGOS E LÍQUENES: UMA ANÁLISE CIENCIOMÉTRICA

Received on: 10/20/2025
Accepted on: 12/12/2025
Published on: 01/26/2026

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Abstract: This work addresses biomonitoring of trace atmospheric pollutants using *Tillandsias,* mosses, and lichens. A scientometric analysis was conducted using Scopus and Web of Science, with 249 records selected. Passive biomonitoring was dominant (~52%), while active monitoring represented ~36%. Moss was most used (~52%), likely due to its natural abundance in Asia, followed by lichens (28%) and *Tillandsias* (11%). Main characterization techniques included ICP-MS/OES, INAA, XRF, and AAS. Urban (35%) and industrial (38.4%) environments were the most studied. Despite some limitations, biomonitoring is a powerful, low-cost tool and a nature-based solution, especially suitable for low-income regions. Russia and Romania stand out in adoption in the period of this research (2020 – 2025), but the Americas and Africa show a lack of incentives, highlighting the need for greater global support. Factors that can interfere with analysis were also discussed (differences among species, requirements for active monitoring, interference of meteorological conditions, and particulate matter capture by plants).

Keywords: Air Pollution; Metals; *Tillandsias*; Mosses; Lichens.

Resumo: Este trabalho aborda o biomonitoramento de poluentes atmosféricos de traço utilizando *Tillandsia*, musgos e líquenes. Foram analisados 249 registros das bases Scopus e Web of Science. O método passivo predominou (~52%), enquanto o ativo foi de ~36%. O musgo foi o mais utilizado (~52%), provavelmente pela sua abundância na Ásia, seguido por líquens (28%) e *Tillandsia* (11%). As principais técnicas foram ICP-MS/OES, INAA, XRF e AAS. Os ambientes urbanos (35%) e industriais (38,4%) foram os mais estudados. Apesar de limitações, o biomonitoramento é uma ferramenta eficaz, de baixo custo e uma solução baseada na natureza, adequada para regiões de baixa renda. Rússia e Romênia destacam-se no período desta pesquisa (2020 – 2025), mas as Américas e a África apresentam falta de incentivos, evidenciando a necessidade de maior apoio global. Fatores que podem interferir nas análises também foram discutidos (diferenças entre as espécies, necessidades do monitoramento ativo, interferência de condições meteorológicas e captura de material particulado pelas plantas).

Palavras-chave: Poluição Atmosférica; Metais; *Tillandsias;* Musgos; Líquenes.

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INTRODUCTION

Importance of monitoring air quality

Air pollution arises from two primary sources: natural and anthropogenic. Monitoring and controlling it has become a global priority under the United Nations 2030 Agenda for Sustainable Development (United Nations, 2015), due to its global impacts on human health and the environment. Among the diseases associated with high levels of environmental pollution, the World Health Organization (WHO, 2025) identifies the following: lower respiratory tract infections (such as pneumonia and acute bronchitis), cancers of the trachea, bronchus, or lungs, ischemic heart disease, stroke, and chronic obstructive pulmonary disease (COPD). According to the WHO Global Air Quality 2025 guidelines (WHO, 2025), the recommended annual concentration limits for major air pollutants are as follows: particulate matter with an aerodynamic diameter inferior or equal to 2.5 μm ($PM_{2.5}$) at 5 μg/m³, particulate matter with an aerodynamic diameter inferior or equal to 10 μm (PM_{10}) at 10 μg/m³, and NO_2 at 10 μg/m³. For 24-hour exposure, the recommended limits are: SO_2 at 40 μg/m³ and CO at 4 μg/m³.

Focusing on particulate matter, PM_{10} is primarily produced by combustion processes, industrial activities, power generation, and aerosols, and the fine inhalable particulate matter $PM_{2.5}$ is present in haze, aerosols, smoke, and soot formed by gas reactions (Seinfeld, 1986). However, $PM_{2.5}$ is considered the largest environmental risk factor for human health (Mukherjee and Agraval, 2017; Murari *et al.*, 2016; McDuffie *et al.*, 2021). According to the WHO (2020), the 10 chemicals of major public health concern are: As, asbestos, benzene, Cd, dioxins, Pb, Hg, and hazardous pesticides, as well as excess F.

Meanwhile, Chen, Maciejczyk, and Thurston (2022) stated that transition metals (Ni, V, Fe, Cu) can participate in redox reactions, producing oxidative stress and therefore being harmful to health. The authors also cited in their review that Si, Fe, and K are principally associated with soil; B and Pb with motor vehicles; V and Ni with residual oil, Mn and Zn with metal/steel industries, and Se and S with coal combustion. Besides, microplastics and organic compounds are also factors to be concerned about (Roblin and Aherne, 2020; Wikuats, 2025).

Zheng *et al.* (2024), through field measurements using filters and subsequent characterization with Inductively Coupled Plasma Mass Spectrometry/Optical Emission Spectrometry (ICP-MS/ ICP OES) and Gas Chromatography (GC), quantified elemental pollution in the Chinese atmosphere. Their results showed that industrial sources emitted substantially more pollutants than residential ones (125.6 times higher) and transportation sectors (10.8 times higher) in the analyzed region. The highest elemental concentrations observed in the different environment studied were: (a) power plants (Cr, Fe, Sr, Pb, Zn); (b) industrial facilities—boilers and iron/steel production (Fe, Mn, Pb, Zn), cement plants (mainly Fe), and other industries (As, Cd, Cu, Fe, Pb, Zn); (c) residential areas (As, Cu, Fe, Pb, Zn); and (d) the transportation sector (Cu, Fe, Mn, Mo, Pb, Sb, Zn).

Hence, the need for monitoring air quality and controlling it in several types of environments (urban, industrial, indoor, residential, and so on) has become imperative. This monitoring has been performed by air quality monitoring stations (AQMS), mobile monitoring units that can be installed in vehicles, and Asea Brown Boveri (ABB) smart air quality stations. However, these systems are limited to the range of pollutants they are designed to detect (PM_{10}, $PM_{2.5}$, O_3, NO_2, SO_2, CO, and, in some cases, CH_4) and are costly to deploy at a large scale in a short time. The main advantage of these techniques is that the measurements are performed in real time, and some meteorological conditions that can interfere with the analysis are measured simultaneously (Singh *et al.,* 2021; Seesaard *et al.,* 2024; CETESB report, 2022). To change this scenario, portable units with low-cost sensors that measure pollutants together with meteorological conditions have been developed, making air quality monitoring more accessible (Santos; Matta, and Landulfo, 2025).

Meanwhile, there are a few options to perform elemental analysis in a commercial version. Zeb *et al.* (2018) performed it by using the low-volume samplers (LVS), where the particulates are collected by filters in a controlled flux and then analyzed. Alternatives to monitoring the elemental chemical composition and nature of particulate matter (PM) have gained significant research interest throughout the years (Madheshiya *et al.,* 2022; Badamasi, 2017; Sugimae, 1984; Liu, 2024). In this context, bioindicators and biomonitors have been increasingly recognized as a cost-effective solution for elemental analysis and a Nature-based Solution (NbS) (Theophilo *et al.,* 2021; Dunlop *et al.,* 2024). Biomonitors enable quantification of specific pollutants using various biological materials—such as honeybees, spider webs, bird feathers, and plant leaves—which have been used to monitor air, soil, and water pollution (Madheshiya *et al.*, 2022; Baczewska-Dabrowska; Gworek; Dmuchowski, 2023; Benitez *et al.*, 2024; Abas, 2021).

Biomonitoring with *Tillandsia*, moss, and lichen

In the field of air pollution biomonitoring, mosses, lichens, various species of *Tillandsia* (from the Bromeliaceae family), tree bark, and other materials—generally epiphytic—have been widely used. Epiphytic species attach themselves to other plants and typically absorb nutrients directly from the air, rainfall, and wind. They possess specialized leaves adapted to store water and nutrients without relying on soil. Their use as biomonitors has been well documented by various authors (Ishimaru; Santos and Saiki, 2021; Baczewska-Dabrowska; Gworek and Dmuchowski, 2023; Benitez *et al.*, 2024; Abas, 2021; Wolterbeek; Sarmento and Verburg, 2010**)**. To illustrate particle uptake by *Tillandsia usneoides* leaves, a summary is presented in Figure 6 of Appendix A, along with supporting images. The processes by which these organisms absorb nutrients and pollutants vary, and several factors influence this capacity. These include surface-to-volume ratio, morphology, the nature of specific pollutants, pollutant retention ability, leaf age, and more. The main advantages of biomonitoring are: a) a low-cost technique, making it possible to monitor hazardous places where expensive equipment cannot be installed; b) the opportunity to evaluate the environment on living organisms and to estimate the potential impact on other organisms, and c) to allow long term monitoring and to determine spatial and temporal trends in the occurrence (Badamsi, 2017).

Biomonitoring can be either passive or active. In passive biomonitoring, samples are collected directly from the target area and subsequently analyzed, depending on the availability of native species, the season, and the ease of taxonomic identification (Calas *et al.*, 2025; Boubibh *et al.*, 2025; Sfetsas *et al.*, 2025). After collection, researchers must decide whether to wash the samples with deionized water or analyze them unwashed (Boonpeng *et al.*, 2021). The main advantage of this approach is that it requires no laboratory preparation before exposure, although spatial representation is limited due to the low density of stations. However, passive biomonitoring must comply with established field collection protocols, such as those described in the *Istituto Superiore per la Protezione e la Ricerca Ambientale*, ISPRA (2020) and International Cooperative Program on Effects of Air Pollution on Natural Vegetation and Crops, ICP vegetation - *Moss Manual* (2020). On the other hand, in active biomonitoring, the most common approach is to prepare bags of the desired species for transplantation to the monitoring site (Ares *et al.*, 2012), and it does not depend on the existence of chosen species in the future studied area, since the samples are transplanted to the area, as it will be discussed afterward. One disadvantage of biomonitoring is that this is not a real-time measurement, since the organisms must be exposed for about 4 weeks at least (in an active biomonitoring case), then the samples are collected and analyzed by a chosen characterization technique.

The most varied chemical analytical techniques have been used, such as X-ray Fluorescence (XRF), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Atomic

Absorption Spectrometry (AAS), and Instrumental Neutron Activation Analysis (INAA) (Ishimaru; Santos; Saiki, 2021; Ogrizek; Kroflic; Sala, 2022; Swislowski *et al.*, 2022; Liubomyr *et al.*, 2025). Focusing on image characterization, Scanning Electron Microscopy with Dispersive X-ray Spectroscopy (SEM – EDS) or Transmission Electron Microscopy (TEM) has been used (Schreck *et al.*, 2025; Parente *et al.*, 2023; Buitrago; Chaparro; Duque Trujillo, 2023; Broström *et al.*, 2020; De Oliveira *et al.*, 2022). Meanwhile, the structural analysis has been performed by X-ray Diffraction (XRD) or Transmission Electron Microscopy (TEM) (Zheng, 2024). In general, authors employ multiple techniques to complement information, as seen in Zeb *et al.* (2018), who characterized particle matter in urban regions using Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray (EDX) Spectroscopy.

This study aims to provide an overview of air pollution biomonitoring using three organism types—*Tillandsia*, lichen, and moss—and their elemental analysis over the period from 2020 to 2025, by updating the most recently used keywords, number of publications, authors, top journals, university and country interaction networks, evaluated environments, analyzed pollutants, and characterization techniques.

MATERIALS AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY

Eligibility Criteria

As can be seen in the supplementary materials (https://osf.io/w6dh2/overview), the eligibility criteria included articles published in journals, conference proceedings, books, and book chapters written in English, which involved air pollution biomonitoring. Studies employing *Tillandsia*, moss, or lichen as biomonitors were included if they focused on the following subject areas: Chemical Engineering, Environmental Science, Chemistry, Multidisciplinary, Forestry, Nuclear Science and Technology, and Atmospheric Sciences. Articles focusing on soil or water pollution, as well as those with a public health focus, were excluded.

Information Sources and Search

To conduct the scientometric survey, two databases were used: Web of Science and Scopus. Publications from 2020 to June 2025 were considered, and the search keywords were adapted to the specific requirements of each database. The searches were carried out between April 2025 and June 2025, and the search strategy combined terms related to air pollution, biomonitoring, and specific organisms (*Tillandsia*, moss, and lichen), as well as target pollutants (metals, particulate matter, and related elements). The full search string used in each database is available in the Supplementary Material (https://osf.io/w6dh2/overview).

Study Selection and Data Collection Process

The searches were performed in the databases via the CAPES (Brazilian Federal Agency for Support and Evaluation of Graduate Education) portal. The selected documents were exported to an Excel spreadsheet (Scopus) and a plain text file (Web of Science). PRISMA 2020 search model, outlining the study stages, was followed (Page *et al.*, 2022). Initially, a total number of 1026 papers were found, where 831 were retrieved from Scopus and 195 were retrieved from Web of Science and b) In sequence, 56 papers were removed from Scopus and 18 from Web of Science, when only the categories Chemical Engineering, Environmental Science, Chemistry, Multidisciplinary, Forestry, Nuclear Science and Technology, and Atmospheric Sciences were selected. Then, with 776 papers from Scopus and 177 from Web of Science, their abstracts were analyzed, and papers related to medicine, soil, and water were excluded, focusing only on *Tillandsia*, moss, and lichen (Scopus (n =521) and Web of Science (n=47)), resulting in a total of 385 papers with the two bases together.

Using R Studio and the *Bibliometrix* package (Aria; Cuccurullo, 2017) and (Stem; Briet, 2025), the files were merged, then 89 duplicate records were removed, and a set of 295 documents was obtained. Then, a manual review was performed carefully, excluding the papers that were not accessible (with no identified DOI); moreover, papers that were not directly related to the evaluation of toxic elements in air were also removed, resulting in a total of 249 papers. This study was prospectively registered in the Open Science Framework (OSF) before data extraction and analysis. The registration, including the research questions, inclusion criteria, analysis plan, and supplementary material (including considered papers, the type of environment classification, analyzed chemical elements, the characterization technique, times cited, year of publication, and source), is publicly available at https://osf.io/w6dh2/overview.

STATISTICAL AND BIBLIOMETRIC ANALYSIS PERFORMED WITH THE BIBLIOMETRIX PACKAGE IN R STUDIO

The *Bibliometrix* package (Aria; Cuccurullo, 2017) provides tools for bibliometric analysis through functions such as summary and plot. To obtain collaboration networks and data correlations, analyses were performed in R Studio using packages such as *biblionetwork*, by programming in R or Excel. Additional filtering was initially conducted in R Studio using the title, keywords, and abstract fields, followed by careful manual verification. Table 1 and Table 2 present the applied filters for environmental criteria and species groups (*Tillandsia*, moss, and lichen), respectively.

Table 1 – List of filters of types of environments: industrial, urban, rural, and natural.

Filters			
For industrial	**For urban**	**For rural**	**For natural**
"industrial", "factory", "plant", "manufacture", "pollution", "industrialized";	"urban", "city", "town", "suburb", "residential", "metropolitan", "downtown";	"rural", "countryside", "village", "agriculture", "farm", "pasture";	"forest", "park", "wetland", "natural reserve", "protected area", "mountain" "mine"

Source: the authors (2025).

Table 2 – Filter for groups: *Tillandsia*, Moss, and Lichen.

Filters		
For *Tillandsia*	**For Moss**	**For Lichen**
"*Tillandsia*", "bromeliad(s)", "*usneoides*", "Spanish moss", "*recurvata*", "*capillaris*", "*bergeri*", "*aeranthos*", "*stricta*", "*ionantha*", "*cyanea*", "*fasciculata*", "*bulbosa*", "*xerographica*", " *bartrami*i"	"moss", "bryophyte(s)", "*sphagnum*", "*polytrichum*", "*hypnum*", "acrocarp", "pleurocarp", "funariaceae", "mniaceae", "dicranaceae", "bryales", "*musci*", "acrocarpous", "*pleurocarpous*", "bartramiaceae")	"lichen", "lichens"

Source: the authors (2025).

RESULTS AND DISCUSSION

Results of this bibliometric investigation were: a) Keywords and Groups of Biomonitors and Country Interactions; b) Number of publications and University Network, and c) Pollutants, Types of Environments, Characterization Techniques, and Types of Biomonitoring.

Keywords, Groups of Biomonitors, and Country Interactions

According to the summary provided by *Bibliometrix*, when selecting the top 30 keywords, the most frequent terms are biomonitoring (in 89 publications), air pollution (in 68 publications), and heavy metals (in 40 publications). Arranging them in decreasing order of frequency: *biomonitoring* (89), *air pollution* (68), *heavy metals* (40), *moss* (30), *moss biomonitoring* (23), *bioaccumulation* (19), *atmospheric deposition* (18), *air quality* (17), *pollution* (17), *lichens* (15), *lichen* (16), *neutron activation analysis* (14), *atmospheric pollution* (13), *potentially toxic elements* (12), *trace elements* (12), *active biomonitoring* (11) and *mosses* (11). This suggests that biomonitoring research has likely focused not only on heavy metals but also on pollutants in general, given that the number of publications using the keyword biomonitoring is significantly higher than those using *heavy metal(s)*.

Figure 1 presents the world map as a function of the number of publications, calculated by filtering the affiliations of authors' countries. Duplicated country names (e.g., *Macedonia* and *North Macedonia*) were avoided in the R-based count. The most productive countries were Romania (31 publications), Italy (29), Russia (29), and Poland (24). In the Americas, the numbers are lower, with the United States and Canada (10), Mexico (11), Brazil (9), Argentina (8), and Colombia (4) during the study period (up to June 2025).

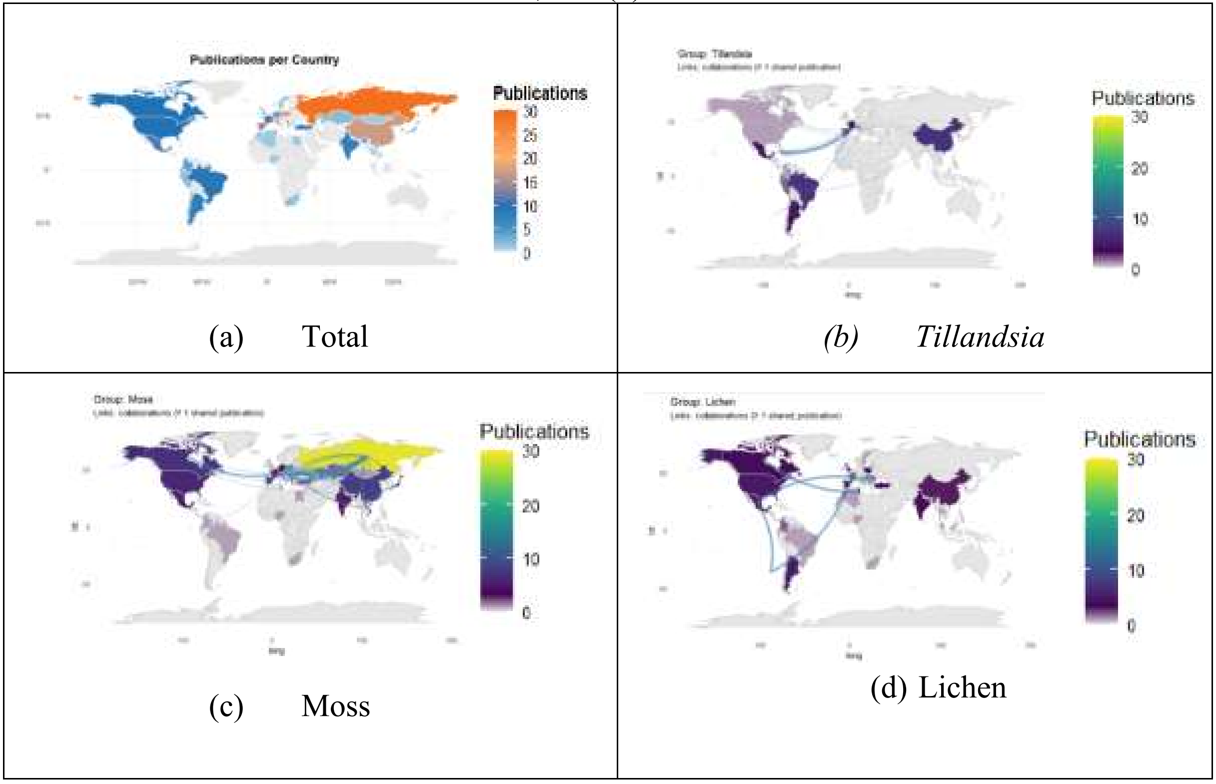
According to the analyzed results, it was found that there are 28 publications about only *Tillandsia*, 129 publications about only moss, 69 publications with only lichen, a combination of moss and lichen about 16 publications, a combination of *Tillandsia* and lichen about 1 publication, and with the three organisms (moss + lichen + *Tillandsia*) about 1 paper, and about 5 papers are generic (no counting of these words in title, in keywords or abstracts), resulting in a total of 249 papers. Figures 1b, 1c, and 1d present world maps showing the number of publications for *Tillandsia (*including Spanish Moss*)*, moss, and lichen, respectively. Country interactions are also represented by connecting lines.

In Figure 1b, it can be observed that the highest number of publications about *Tillandsia* is from Brazil and China (7 each), France and Mexico (4 each), Spain (3), and the others are fewer than three. Concerning the interactions it can be seen that we have 2 interactions between Cuba and Spain, and the others are only one in each case, Argentina and Colombia, Argentina and Mexico, Brazil and China, Brazil and Italy, Brazil and Mexico, Brazil and Peru, Canada and Cuba, Canada and Monaco, Canada and Spain, Chile and France, Chile and Spain, Chile and Italy, Cuba and Monaco, France and Spain, Mexico and United States and Monaco and Spain.

In Figure 1c, the highest number of publications for moss is found to Russia (29), Romania (28), Poland (20), Macedonia (14), Slovenia (11), Georgia (9), Moldova (8), Spain (8), China and Canada (7 each), and the others are inferior to 7. The main interactions can be cited Romania and Russia (21), Macedonia and Slovenia (10), Georgia and Romania (9), Georgia and Russia (9), Macedonia and Romania (5), Romania and Slovenia (4), Moldova and Romania (5), Russia and Vietnam (4), Moldova and Russia (4), and the others are inferior to 4.

In contrast, Figure 1d shows that Italy has the highest number of publications on lichens, with 18, followed by Argentina, India and Turkey (4 each), and the others are lower than 4. Concerning interactions among countries that study lichen, it can be noticed that all the interactions have weight 1 (Chile and France, Chile and Mexico, France and Mexico, Italy and Slovakia).

Figure 1 – Summary of the group of biomonitors publications: (a) total; (b) *Tillandsia* and (c) Moss, and (d) lichens.



(a) Total | *(b) Tillandsia* | (c) Moss | (d) Lichen

Source: the authors (2025).

These results suggest that biomonitors (*Tillandsia*, moss, and lichens) remain underutilized as a tool for air quality monitoring, particularly in less affluent regions, despite their low cost and suitability for deployment in remote areas without the need for specialized technology. The highest costs in this type of monitoring are related to the characterization techniques used to quantify elemental pollutants, and it can be considered an example of a solution based on nature (Dunlop *et al.*, 2024) that aims at achieving sustainable goals. There are only a few works in Brazil that use moss as a monitoring species, probably due to the ease of finding bromeliads as *Tillandsia*, in Latin America, but the mosses are typical of the Asian Continent, as shown in Figure 1c.

In contrast to Asia, American countries presented a limited number of interactions among countries. Their maximum number of publications in *Scopus* and *Web of Science* databases is between 10 and 12. Moreover, the necessity of monitoring air in all types of environments (industrial, urban, indoors, and so on) is imperative according to the standards of health proposed by WHO (2025). Despite the government action plans all over the world having increased over the years, there is still much to be done (WHO, 2025), as most countries have not reached the desirable proposed conditions yet There is a lack of projects in America similar to the United Nations Economic Commission for Europe International Cooperative Program on Effects of Air Pollution on Natural Vegetation and Crops (UNECE ICP Vegetation site; Harmens *et al.*, 2015), and after, being followed by other countries such as Ukraine, Romania, Bulgaria, Poland, Belarus, and Russia, in the project of ICP vegetation “Mosses as Biomonitors of Air Pollution” since 2020/2022 (Fronstayeva *et al.*, 2020).

Number of publications and University Network

According to this research, the Scientific number of publications per year was 35 in 2020, 54 in 2021 (presenting a significant increase), 42 in 2022, 39 in 2023, 55 in 2024, and 24 in 2025. The reduction in the number of publications in 2022 and 2023 can probably be attributed to COVID-19, which necessitated social distancing and thus stagnated research that was dependent on social convivence. It can also be noted that the number of publications in 2025 refers only to the first 6 months of the year, since the investigation of this work was completed by June 2025. Concerning this scenario, Figure 2 presents the most productive authors. The 10 most productive authors are: Zinicovscaia I (31), Yushin N (21), Rajfur M (18), Stafilov T (18), Chaligova O, Fronstayeva M, and Vergel K (16 each), Swislowski P (14), Loppi S (13), and Sajn N (11).

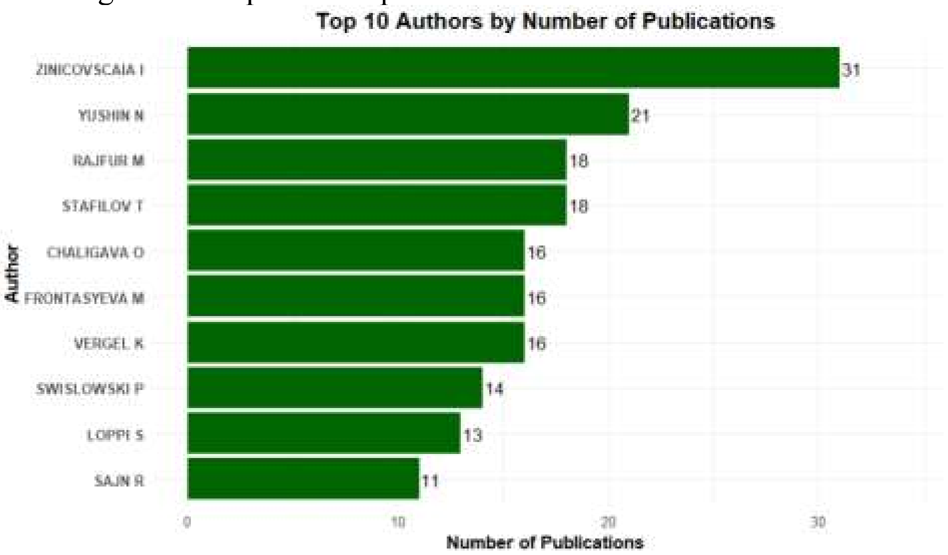
Figure 3 presents the top 10 journals with the highest number of publications. Analyzing Figure 3, the journal with the largest number of publications is *Atmosphere* (26 publications, having an impact factor of 2.50), followed by *Environmental Science and Pollution Research* (22 publications and an impact factor of 5.59). *Science of the Total Environment* and *Environmental Monitoring and Assessment* (15 and 14 publications, respectively, with corresponding impact factors of 9.75 and 3.00). However, when considering the most cited papers, journals such as *Ecological Indicators*, *Science of the Total Environment*, *Applied Sciences* (Switzerland), *Chemosphere*, and *Plants* stand out. According to statistical analysis, Abas (2021) and Robin and Aberne (2020) are the most cited papers, with 95 and 65 citations, respectively. Next are Winkler *et al.* (2020) (44 citations), Contardo *et al.* (2020) (40 citations), and Zinicovscaia *et al.* (2025) (35 citations).

Using the affiliation name tag (*AU_UN*) created by the *Bibliometrix* package, the top 10 most collaborative universities were identified (Figure 4). In this network, the thickness of connection lines is proportional to the number of interactions. The most collaborative institutions are the Joint Institute for Nuclear Research – Russia (JINR-R) and the Horia Hulubei National Institute of Physics and Nuclear Engineering (HHNIPNE, Romania), with 20 joint publications. All other institutions have fewer than five collaborations. These results are consistent with Figure 1c, where it can be seen that Russia and Romania have the highest number of interactions.

Pollutants, Types of Environments, Characterization Techniques, and types of biomonitoring

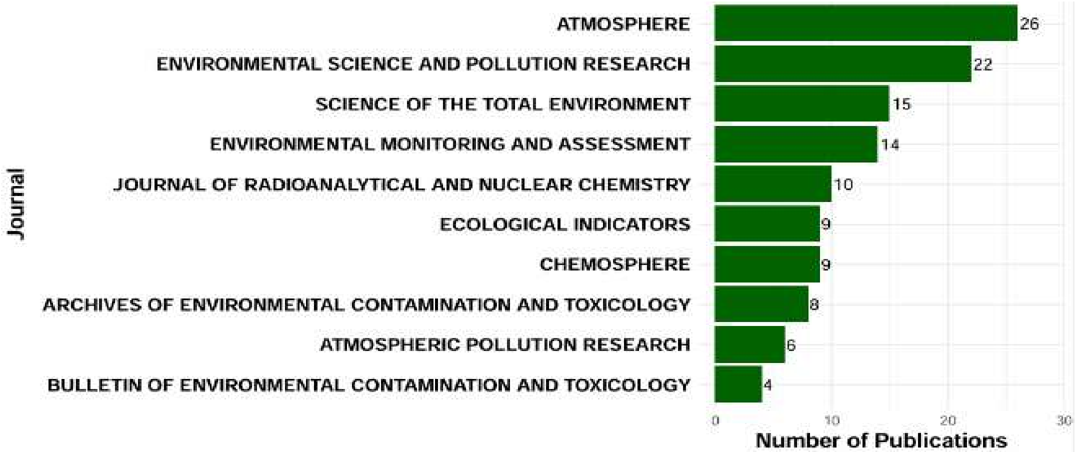
According to Wikuats (2025), particulate matter is compounded principally by elemental carbon, organic matter, and black carbon, being followed by inorganic ions (S), geological minerals (Al, Si, Ca, Fe), and trace elements. This work is focused on analyzing trace elements of pollutants. Biomonitoring with *Tillandsia*, Moss, and Lichen requires analyzing these trace elements measured by techniques, which provide concentrations in their majority at the µg/g or ng/g levels. This fact makes it difficult to compare with the toxic limits proposed by the agencies (EPA, WHO), where the unit is $\mu g/m^3$ or ng/m^3, since there is no direct conversion. One option is to work with closed chambers, as Tomson, Michael, and Agranovski (2025) did, who studied and compared the efficiency of a *Tillandsia* panel to a particle counter filter, showing that *Tillandsia* panels achieved an efficiency of 74% for 10 µm air particulate at air velocities of 1.0 and 1.5 m/s without varying the pressure too much. Meanwhile, Popa and Rusănescu (2023) also established a comparison between conventional measurements and the ones performed with biomonitoring, showing a reasonable agreement.

Figure 2 – Top 10 most productive authors from 2020 to 2025.



Source: the authors (2025).

Figure 3 – Top 10 journals and the number of publications from 2020 to 2025.



Source: the authors (2025).

Another important parameter to analyze trace element contribution is the enrichment factor (EF), which allows for evaluating the anthropogenic enrichment due to air pollutants in the biomonitor (*Tillandsia*, moss, and lichen) in relation to Earth´s crust (Gaonkar *et al.*, 2019; McDonough *et al.*, 2022), as it can be seen in the Expression (1).

$$EF = \left(\frac{C_{chosen\ element}}{C_{reference\ element}}\right)_{Sample} \times \left(\frac{C_{chosen\ element}}{C_{reference\ element}}\right)_{Crustal} \quad (1)$$

Considering the toxicology of elements, one can associate metals as typical sources of pollutants, considering the following sources: a) mining, smelting of cinnabar ore, deposits of metal ores of Pb and Zn, manufacturing of sodium hydroxide and chlorine by electrolysis of brine, paper and pulp industries; b) industrial emissions; c) traffic; d) brakes, tire wear, motor oil, brake wear, gasoline additives; e) oil combustion; f) lubricating oil; g) fireworks; h) e-cigarettes; i) coal combustion; j) soil resuspension; k) pesticides, insecticides, and fertilizers and l) refinaries, as shown in Table 3.

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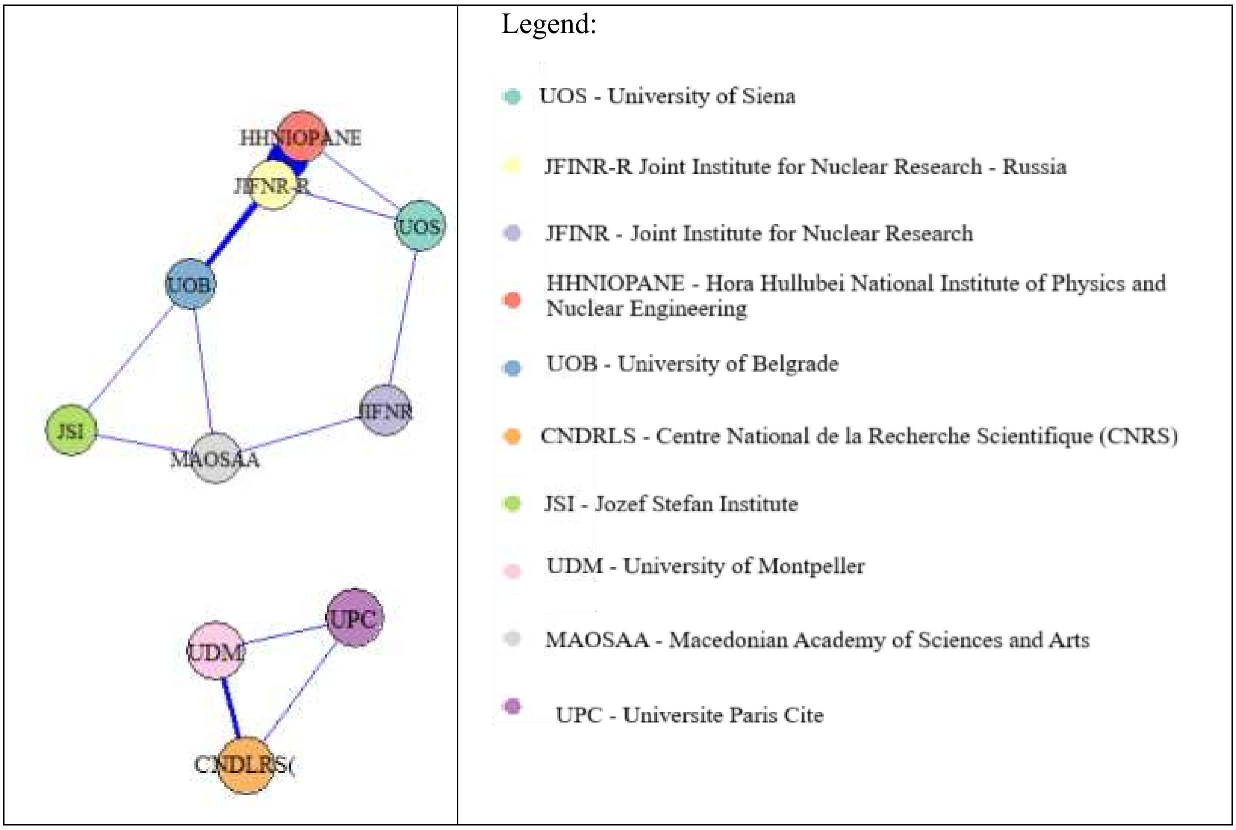
Figure 4 – Top 10 most collaborative universities.



Source: the authors (2025).

Meanwhile, the most frequently used techniques to evaluate elemental pollutants are ICP techniques, INAA, XRF, and AAS, as shown in Table 4 (adapted from Djingova; Ivanova and Kuleff, 1998). Each method has a different detection limit, L_c; most of the time, this limit is also dependent on the trace element, but also the sample matrix and mass. According to the literature, XRF has poor detection capabilities for atomic number elements ($Z < 12$): B, C, N, O, P, S; meanwhile, ICP has poor detection for C, N, H, O, Cl, F, Br, I, B, Hg and INAA presents difficulty to detect H, C, N, O, Pb, Cd, Ti, Hg, P, S, Cl and B. The sensitivities of these techniques for plant matrices are ng/g range, µg/g range, sub-µg/g to low µg/g range, ng/g, pg/g for AAS, XRF, INAA, ICP-OES, and ICP-MS, respectively (Rawat *et al.*, 2024; Djingova; Ivanova; Kuleff, 1998). These techniques present some limitations for performance; ICP and AAS, for instance, present difficulties in the digestion of samples (sometimes it is not completely digested), which increases the error in the measurements.

In INAA, peak overlapping must be avoided, and sample mass limitations can decrease accuracy. In XRF, peak overlapping should also be avoided, and matrix interference should be addressed. A recent comparison performed by Orlic *et al.* (2022) showed that non-destructive techniques, such as INAA and WD-XRF, could be used in plants with reasonable agreement, highlighting the importance of characterizing the desired samples together with certified reference materials (CRM) to check and analyze possible discrepancies in the analysis of the samples (Chahloul *et al.*, 2022; Dybczyñski *et al.*, 2004 and Mackey *et al.*, 2004). At the same time, Djingova and Kuleff (2000), in their book chapter, present a list of suitable techniques as a function of chemical elements and different matrices, including plants, and Frontasyeva, Harmens, and Uzhinskiy (2020) present a summary of chemical elements, analytical techniques, and countries in the period 2015/2016 at their project report.

According to the analysis of the selected papers, the majority of the studies is related to passive biomonitoring (130), being followed by the active type (89), both types (2), and unidentified (32), it can be highlighted the predominance of the passive method, probably due to the fact this method requires less work in laboratory, besides being cheaper and faster than the active one. The type of environments and the respective percentage are shown in Figure 5. In this figure, it can be seen that urban and industrial environments are the dominant ones, with 38.4% and 35%, since they are the ones that require more concerns about air pollution. The unidentified ones refer to review papers or book chapters and, therefore, are generic.

The 10 top-most frequent elements for the corresponding types of environment in decrescent order are: a) industrial (Ni < Pb < Cr < Zn < Fe< Cu < Cd < As < Co < Mn); b) urban (Pb < Zn < Cu < Cd < Fe < Cr < Ni < Al < Mn < Co); c) rural (Cr < Pb < Ni < Zn < Cd < Al < Cu < Fe < As <Mn and d) natural (Zn <Fe < Pb < Cd < As < Ni < Cr < Cu < Mn < V). However, there are a lot of factors that can interfere with these measurements, as discussed below. Wind, rain, geography, and the season of the year are factors that are sometimes overlooked. In case of natural environments, mine and volcanic regions can also alter the results of pollutants in the environment. Therefore, it is necessary to choose the most suitable characterization technique for the desired elements to be analyzed according to each type of environment, or to use more than one technique, since techniques have different grades of sensitivity.

Table 3 – Toxicological trace elements and typical sources.

Typical Sources	**Trace Elements**	**Reference**
Mining, Smelting of cinnabar ore, deposits of metal ores of Pb and Zn, manufacturing of sodium hydroxide and chlorine by electrolysis of brine, Paper and pulp industries	Hg	Chen, Maciejczyk, Thurston, 2022

Industrial emissions iron/steel production cement production	As, Ca, Cd, Cr, Fe, Mn, Ni, Pb, S, Se, V, Zn (depending on the segment of industry) Fe, Mn, Pb, Zn Fe	Chen, Maciejczyk, Thurston, 2022 Zheng et al., 2024 Zheng et al., 2024
Traffic	Ba, Ca, Cr, Cu, Fe, Mn, Ni, Zn	Chen, Maciejczyk, Thurston, 2022
Brakes, tire wear, motor oil, brake wear, gasoline additives	Cd, Cr, Cu, Ni, Pb, Zn	Chen, Maciejczyk, Thurston, 2022
Oil Combustion	V and Ni	Chen, Maciejczyk, Thurston, 2022
Lubricating oil	Ca and Zn	Chen, Maciejczyk, Thurston, 2022
Fireworks	Cu, Pb, Sr, Ti	Chen, Maciejczyk, Thurston, 2022
e-cigarettes conventional cigarettes, e-cigarettes, and heated tobacco products jj	Cr, Mn, Ni, and Pb Conventional – Cu, Zn, and Pb e-cigarettes – Ni, Cu, Zn, and Pb Heated tobacco – Cu, Zn, Cd, and Pb	Chen, Maciejczyk, Thurston, 2022 Świsłowski et al., 2022
Coal combustion	Al, Ca, Fe, Mg, Na, Si, Ti	Chen, Maciejczyk, Thurston, 2022
Soil Resuspension	Al, Ca, Fe, Si, Ti Fe, K, and Si	Wikuats, 2025 Chen, Maciejczyk, Thurston, 2022
Pesticides, Insecticides, and Fertilizers	Cd, Ni, Pb	Morakinyo, Mukhola, Mokgobu, 2021
Refineries	Cd and Ni	Morakinyo, Mukhola, Mokgobu, 2021
Trace of fossil fuel or biomass (wood) combustion activity	Zn	Roth et al., 2021
Coal mines	Ag, Ge, Ni, Se, U, V, Zr	Petryshen, 2023
Landfill	Ni, Pb, Zn	Stafilov et al., 2023

Source: the authors (2025).

Table 4 – Comparison of ICP OES, INAA, AAS, and ED-XRF with respect to experimental detection limit, L_c in plant matrices (Djingova; Ivanova; Kuleff, 1998).

Element	Lc, mg/g ICP OES	Lc, mg/g INAA	Lc, mg/g AAS	Lc, mg/g ED-XRF
Al	2	$8x10^{-1}$	-	$1.500x10^{3}$
As	$5x10^{-1}$	8×10^{-3}	-	5
Au	-	1×10^{-4}	-	-
Ba	5	10	-	-
Ca	2	260	1	10
Cd	$3x10^{-1}$	$5x10^{-1}$	$4x10^{-3}$	-
Cl	-	35	-	$2.50x10^{2}$
Co	$6x10^{-1}$	$8 x10^{-4}$	2×10^{-2}	-
Cr	2	$9x10^{-2}$	$1x10^{-1}$	4

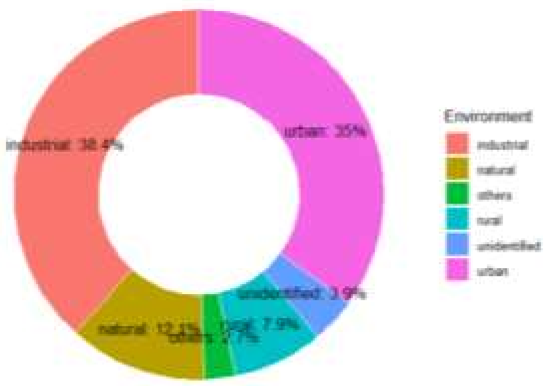
Cu	3	8	$2x10^{-2}$	3
Fe	2	5	6	3
Hg	-	$1x10^{-2}$	-	-
K	2	$2.60x10^{2}$	2	10
Mg	1	$1.20x10^{2}$	$1x10^{-1}$	-
Mn	1	$1x10^{-1}$	3	15
Na	7	2	0.2	-
Ni	$5x10^{-1}$	-	$2x10^{-2}$	-
Pb	1	-	$2x10^{-2}$	2
S	-	$2.5x10^{3}$	-	$2.50x10^{2}$
Se	-	$1x10^{-2}$	-	-
Sr	12	-	-	1
V	-	$4x10^{-2}$	-	-
Zn	6	$4x10^{-2}$	3	1

Source: the authors (2025) - adapted from Djingova, Ivanova, and Kuleff (1998).

Considering the toxicity of the environment, it can be concluded that the four types of classification (industrial, urban, rural, and natural) have more than one factor listed in Table 3. For instance, the classification of urban environment includes traffic, oil combustion, lubricating oil, sometimes e-cigarettes, and others.

The findings above highlight methodological diversity across studies. To deepen this discussion, three aspects are emphasized below: species differences, methodological preparation, and meteorological interferences.

Figure 5 – Types of environments.



Source: the authors (2025).

IMPORTANT FACTORS TO TAKE INTO ACCOUNT IN PLANT BIOMONITORING

Uptake of pollutants is dependent on the species

It has been verified by several authors that the pollutant concentration of the elemental analysis is dependent on the species used as a biomonitor.

Carrillo *et al.* (2022) conducted a comparative study using bryophytes (mosses), lichens, and *Tillandsia usneoides* to assess air and water pollution in urban areas and forested localities around the city of Loja in southern city of Ecuador. The authors evaluated concentrations of Cd, Cu, Mn, Pb, and Zn in four zones and found that all three biomonitors showed similar pollutant concentrations. However, *Tillandsia* proved slightly more effective, likely due to its longer leaves and higher surface-to-volume ratio. Conversely, in another study, Jafarova *et al.* (2023) compared the lichen *Evernia prunastri* with the moss *Pseudoscleropodium purum* for passive monitoring of airborne microplastics in Italy. They found that microplastic accumulation was significantly lower in lichens than in mosses, a difference attributed to the structural characteristics of these organisms.

Similarly, Wannaz and Pignata (2006) analyzed four *Tillandsia* species (*T. capillaris*, *T. tricholepis*, *T. permutata*, and *T. retorta*) through active biomonitoring in Córdoba, Argentina. They evaluated the absorption of metals (Co, Cu, Fe, Mn, Ni, Pb, and Zn) after three months of exposure and found notable differences in metal accumulation. *T. tricholepis* showed visible signs of damage, whereas the other species displayed varying uptake capacities.

Zambrano *et al.* (2019) investigated foliar water uptake in different *Tillandsia* species (*T. xerographica*, *T. caput-medusae*, *T. schiedeana*, and *T. Houston's* Cotton Candy). They found that *T. schiedeana* had the highest water content, followed by *T. Houston* > *T. xerographica* > *T. caput-medusae*. These results highlight structural differences—such as foliar density and trichome morphology – which are also likely to influence pollutant uptake and retention.

In another comparison, Gonzalez *et al.* (2025) studied *Tillandsia aeranthos* and *Tillandsia bergeri* and demonstrated that *T. bergeri* had a greater capacity for accumulating elements. Regarding external factors influencing pollutant accumulation, several studies have considered variables such as environment type, exposure duration, seasonality, rainfall, and wind direction. For example, Posada *et al.* (2023) compared *T. recurvata* and *T. usneoides* using the moss bag technique, shielding the samples with acrylic covers to minimize rainfall effects. Their results indicated that rainfall did not significantly affect magnetic particle monitoring.

However, caution is needed when interpreting the accumulation of elements that are also nutrients, as these may be selectively absorbed and stored in leaf tissues. For instance, Calas *et al.* (2025) compared *Tillandsia usneoides* with PM_{10} collected on filters in France. They found that 14 elements (including Al, As, Ba, Cd, Ce, Co, Cr, Fe, La, Li, Sb, Ti, U, and V) were present in both plant tissue and particulate matter. In contrast, no significant correlations were observed for Ca, Cd, Cu, Mg, Mn, Mo, Na, Ni, Rb, Sr, and Zn, and negative correlations were found for K and P.

Active Biomonitoring – Sample Preparation Requirements

In the so-called moss bag technique, samples are selected by removing dried leaves and controlling for mass. Some studies recommend washing the samples before exposure, while others do not. When preparing moss bags, weight loss should be considered, especially due to inappropriate mesh size, rainfall, and wind (Ares *et al.*, 2012; Chaudhuri, 2024; Agostini, 2020). For example, Zinicovscaia *et al.* (2025) used the moss bag technique to assess traffic-related pollutants in Russia, placing three bags at each site at a height of 1.5–2 m along three highways, at distances of 5, 50, and 100 m from the road.

Compaction of the moss should be avoided, and bag height should be selected according to research objectives – for example, lower heights are suitable for monitoring vehicular emissions and dust. However, a placement near the ground can easily lead to human interference, such as from children or curious passersby. The amount of material and exposure time are also relevant factors. Variations in application include the type of bag material (polystyrene, nylon, or organza), the sample mass-to-bag volume ratio, whether samples are washed or not, bag height, and exposure time (Ares *et al.*, 2012; Chaudhuri, 2024).

Capozzi *et al.* (2016) analyzed different moss bag shapes (flat, spherical, and rounded), mesh sizes, and weight-to-surface ratios when assessing pollutants, confirming previous findings (Ares *et al.*, 2012; Chaudhuri, 2024). They concluded that the primary factors affecting the results were moss density and the moss-to-surface area ratio of the bags. The authors also recommended an exposure time of more than six weeks; otherwise, results become overly dependent on site-specific conditions. In addition, they noted that seasonal differences (dry vs. humid) were less influential than anthropogenic activities, such as nearby construction.

Interference of meteorological conditions and particulate matter capture

A key focus of the biomonitoring principle is on capturing and retaining particulate matter by plants, as well as the influence of weather conditions. To understand the impact of meteorological factors on particulate settling and deposition, some authors analyzed the influence of rain, air humidity, temperature, wind direction, wind speed, rainfall, and dependence on the season of the year (Chaparro, 2021). For instance, generally, in winter, there is lower precipitation and temperature, and the particulate remains suspended, elevating the concentration of pollutants in the air.

Wróblewska and Jeong (2021) pointed out that plants with trichomes, foliar roughness, stomate densities, and wax on leaves can interfere with the adsorption capacity. According to these authors, the particulates are settled down on the leaves temporarily; in some cases, they are resuspended by wind. The quantity of resuspended particles (from leaves or even the soil) increases with the wind, depending on its velocity. The authors also indicate that metals as Pb, Cu, Zn, and Mn are more difficult to remove from foliar tissue, since they can interact with foliar structure, whether being encapsulated by foliar cuticle or even changing their structure.

The authors also suggest Expression (2) to calculate the deposit amount, where LAI is the leaf area index; v_D, velocity of deposition; C, concentration of pollutant; and t is exposition time. On the other hand, v_D is inversely proportional to aerodynamic resistance, friction on the leaf, and the size of the pollutant. Posada, Chaparro, and Duque-Trujillo (2023) showed that *Tillandsia recurvata* and *Tillandsia usneoides* can store airborne Fe particulates, even in heavily rainy cities, in agreement with Wróblewska and Jeong (2021).

$$\text{Deposit amount (g m}^{-2}\text{)} = LAI \times v_D \times C \times t \qquad (2)$$

Girotti *et al.* (2025) suggested that there is a trade-off between precipitation and pollutant circulation, where, during the day, the atmospheric stability is higher. Therefore, there is a difference in whether rainfall occurs during the day or at night. The authors also indicated that higher values of accumulated precipitation are associated with lower values of $PM_{2.5}$.

Meanwhile, according to Garsa *et al.* (2023), relative air humidity can interfere with the adhesion of particles and seems to have a higher impact on $PM_{2.5}$ than PM_{10}. Shao *et al.* (2019) emphasize the importance of having plants in the environment to capture inhalable particulate matter. The authors also compared the adsorbed pollutants by leaves to soil samples and proved that C, O, Si, Al, Ca, K, Mg, Nb, Fe, Na, and Ti were probably derived from soil dust.

CONCLUSION

This work discussed the use of biomonitoring, focusing on the toxicity of trace elements. The scientometric analysis was based on two databases, Scopus and Web of Science, from 2020 to 2025. Our analysis reveals that biomonitoring using *Tillandsia*, moss, or lichen remains underutilized, despite being a low-cost and nature-based solution, making it a viable option for low-income countries. The most collaborative institutions are the Joint Institute for Nuclear Research – Russia (JINR-R) and the Horia Hulubei National Institute of Physics and Nuclear Engineering (HHNIPNE, Romania), showing their high concern for air quality control and low-cost resources. In addition, their adherence to the ICP vegetation cooperative project after 2020 must have influenced this research result.

Passive monitoring is the most used method (about 52% of publications), while active monitoring occupies about 36%, probably due to the practicality of monitoring large areas and the lower time spent in laboratories. Once chosen biomonitoring to keep under control the trace pollutants of an area, some factors have to be considered (the requirements of the active monitoring or the directions of collecting material in case of passive monitoring; the species that are going to be used, keeping in mind different species can adsorb elements differently; and the interference of meteorological conditions in particle capture by plants). And finally, according to the statistics, the dominant environments of interest are industrial and urban, and the most studied elements are Pb, Zn, Cr, Fe, Ni, Cu, Cd, Mn, Co, and As, independently of the environment. In conclusion, biomonitoring is a powerful nature-based solution for large areas and low-income regions, and it has been adopted by many countries in Europe and Asia, as can be seen in the ICP vegetation projects, indicating the necessity of government support in the American and African countries, since monitoring atmospheric pollution is imperative for human and planet health.

ACKNOWLEDGEMENTS

The authors would like to thank the SEM staff from Maua Institute of Technology (Mauricio Pereira da Silva, Dr. Viviane Tavares de Moraes, and Vinicius Pellicci) for images obtained with FAPESP´s financial support under the process 2020/09163-3, as presented in Appendix A.

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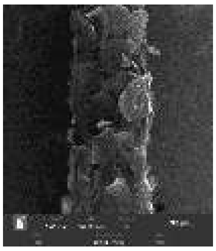
PPENDIX A – Examples of *Tillandsia usneoides* uptaking particles by using Scanning Electron Microscopy/ EDS – different ages of the leaves

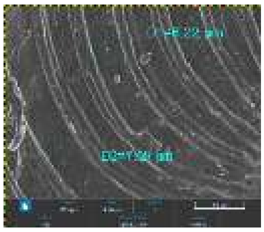
Figure 6 presents two *Tillandsia usneoides* leaf samples of different ages, being exposed in the garden of the IPEN reactor (natural environment). The samples were freeze-dried, cut into small pieces, mounted on a substrate using carbon tape, and coated with a thin layer of gold via sputtering as required for scanning electron microscopy (SEM) analysis. Figures 6a, 6b, 6c, 6d, and 6e present sample A1 (younger leaf) in the sequence: 200x magnification, 1000x magnification, 4000x magnification, qualitative EDS, and histogram of particle perimeters, in sequence. In Figures 6f, 6g, and 6h, the oldest leaf (sample A6) is presented with the magnifications 200x, 1000x, and 4000x, respectively. Images were acquired by the SEM staff from Mauá Institute of Technology, with the EDS spectrum. The analysis of images was made by the authors using ImageJ software (Abramoff, Magalhães, and Ram, 2004). According to Figure 6a, the total length of the analyzed segment is 1408 µm, with a width ranging from 500 µm to 583 µm. The fractal dimension, calculated using the box-counting method, is 1.79. In the 4000× image (Figure 6c), the grooves on the leaf surface are spaced approximately 6.22 µm to 7.09 µm apart, and the areas of individual particles are up to ~100 µm² (as shown in Figure 6e). In Figure 6f, the total length of this leaf is approximately 1405 µm, with widths ranging from 900 µm to 1150 µm depending on the curvature of the leaf wings. The average length of the wing cells in this sample is about 600 µm. These cells appear more elongated than those observed in Sample A1 (Figure 6a). The fractal dimension of Sample A6, also calculated in Image J using the box-counting method, is 1.67. Figure 6g shows that the groove spacing in the wing structure ranges from approximately 10.23 µm to 12.00 µm, higher than in sample A1. When comparing Sample A1 (younger leaf) to Sample A6 (older leaf), it is evident that the older leaf has a higher aspect ratio (ratio between width and height of the images 6a compared to 6f) and a higher surface volume ratio, but a lower fractal dimension, likely due to the increased elongation of its structure. However, further studies are necessary to determine how these morphological differences can influence particle uptake efficiency.

Figure 6 – Example of leaves of the biomonitor *Tillandsia* Usenoides.



(a) Sample A1 with 200x magnification.

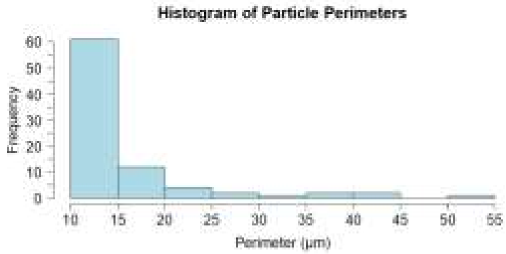
(b) Sample A1 with 1000x magnification.



(c) Sample A1 with 4000x magnification.

Element	Atomic %	Weight %
Calcium	0.96	2.80
Carbon	71.35	62.61
Oxygen	26.02	30.41
Potassium	0.49	1.39
Sulphur	1.19	2.79

d) Qualitative EDS measurement of one particle at the A1 sample. S and Ca are probably of crustal origin, C can have interference of matrix (since it is a leaf), O (probably because chemical elements are in oxide forms and also due to matrix), and K, probably due to wind or soil resuspension.



e) Histogram of particle perimeter Figure 5b (qualitative evaluation on the leaf – 82 particles)

f) Sample A6 with 200x magnification.

g) Sample A6 with 1000x magnification.

h) Sample A6 with 4000x magnification.

Source: EDS spectrum and Images made by SEM staff from Maua Institute of Technology. Analysis with Image J software made by the authors (2025).