A Rússia e a Romênia se destacam na adoção no período desta pesquisa (2020–2025), mas as Américas e a África apresentam falta de incentivos, destacando a necessidade de maior apoio global.

Palavras-Chave: Poluição Atmosférica, Metais, *Tillandsias*, Musgos, Líquenes

Abstract

This work is focused on the biomonitoring of trace element atmospheric pollutants using *Tillandsias,* mosses, and lichens. A scientometric analysis was conducted by using two databases: Scopus and Web of Science, resulting in the selection of 249 records. Passive biomonitoring was dominant (~52%), while active monitoring represented ~36%. A comparison of the usage of moss, *Tillandsia*, and lichen was performed, showing successful cases. Main characterization techniques included ICP-MS/OES, INAA, 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.

Keywords: Air pollution, Metals, *Tillandsias*, Mosses, Lichens

Introdução

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 limit for particulate matter with an aerodynamic diameter of 2.5 µm ($PM_{2.5}$) is about 5 µg/m³. However, $PM_{2.5}$ is considered the largest environmental risk factor for human health. 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).

There are a few options to perform elemental analysis in a commercial version. In this context, bioindicators and biomonitors have been increasingly recognized as cost-effective solutions for elemental analysis and as Nature-based Solutions (NbS) (Theophilo et al., 2021; Dunlop et al., 2024). In the field of air pollution biomonitoring, mosses, lichens, *Tillandsia* (from the Bromeliaceae family), tree barks, 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, where 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). 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. 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 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), Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES), Atomic Absorption Spectrometry (AAS), and Instrumental Neutron Activation Analysis (INAA) (Ishimaru, Santos, and Saiki, 2021; Swislowski et al., 2022). 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). 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, university and country interaction networks, evaluated environments, analyzed pollutants, and characterization techniques.

Materials and methods / experimental details / methodology

Eligibility Criteria

The eligibility criteria included articles published in journals, conference proceedings, books, and book chapters, which involved air pollution biomonitoring, excluding soil and water pollution. 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.

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 presented in Table 1.

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. 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.

Table 1 – Search Keywords used to perform research in the two databases, Web of Science and Scopus.

Database	**Search Keywords**
Web of Science	atmosphere OR air AND pollution (All Fields) and biomonitor OR biomonitoring or monitoring and air (All Fields) and tillandsia or bromeliads or bromeliad or lichen or moss and air (All Fields) and metals or metal or heavy metal or particulate or heavy metals or climate (All Fields) and 2026 or 2025 or 2024 or 2023 or 2022 or 2021 or 2020 (Publication Years).
Scopus	(TITLE-ABS-KEY(atmosphere OR air AND pollution) AND TITLE-ABS-KEY(biomonitor OR biomonitoring) OR TITLE-ABS-KEY(tillandsia) OR TITLE-ABS-KEY(bromeliads)) AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE,"English"))

Source: The authors (2025).

Using R Studio and the *Bibliometrix* package (Aria and Cuccurullo, 2017) and (Stem and 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, publicly available at https://osf.io/pyq4v/overview.

Statistical and bibliometric Analysis Performed with the Bibliometrix Package in R Studio

The *Bibliometrix* package (Aria and 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, or Vosviewer.

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

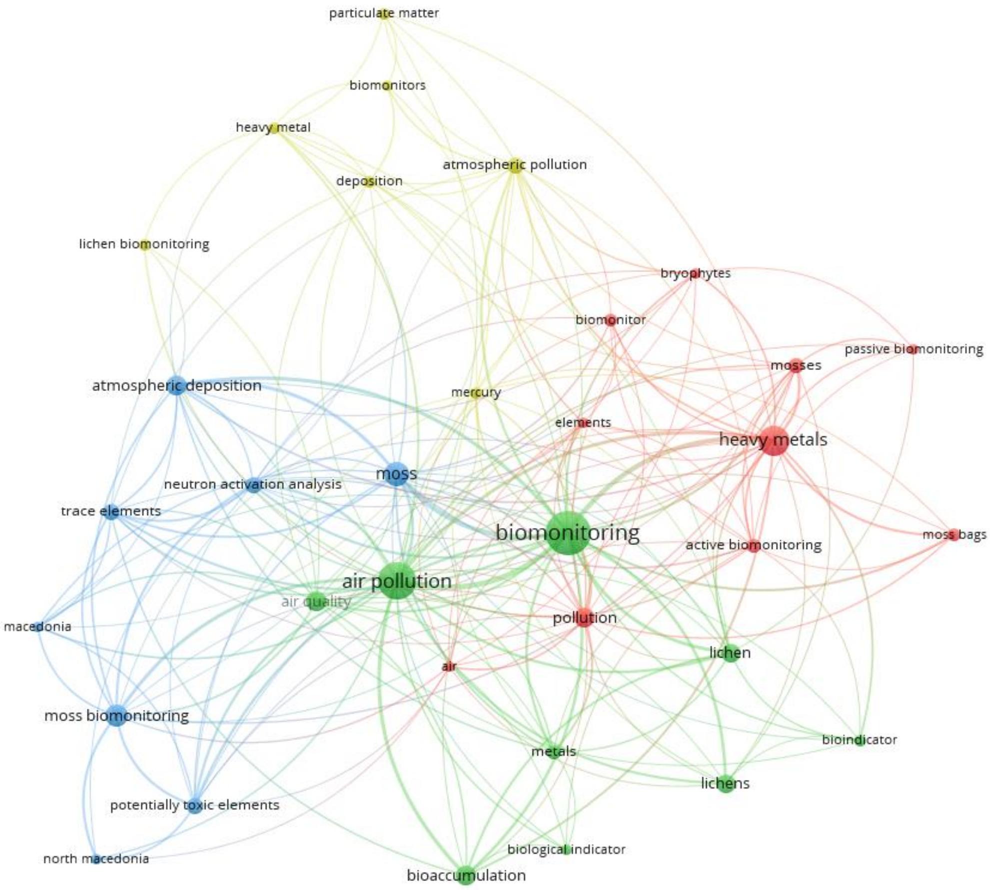
Keywords, Groups of Biomonitors, and Country Publication

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)*. Below, in Figure 1, is presented a word cloud with the keywords, where the larger the circles, the higher the frequency of the words.

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, as shown in Figure 2.

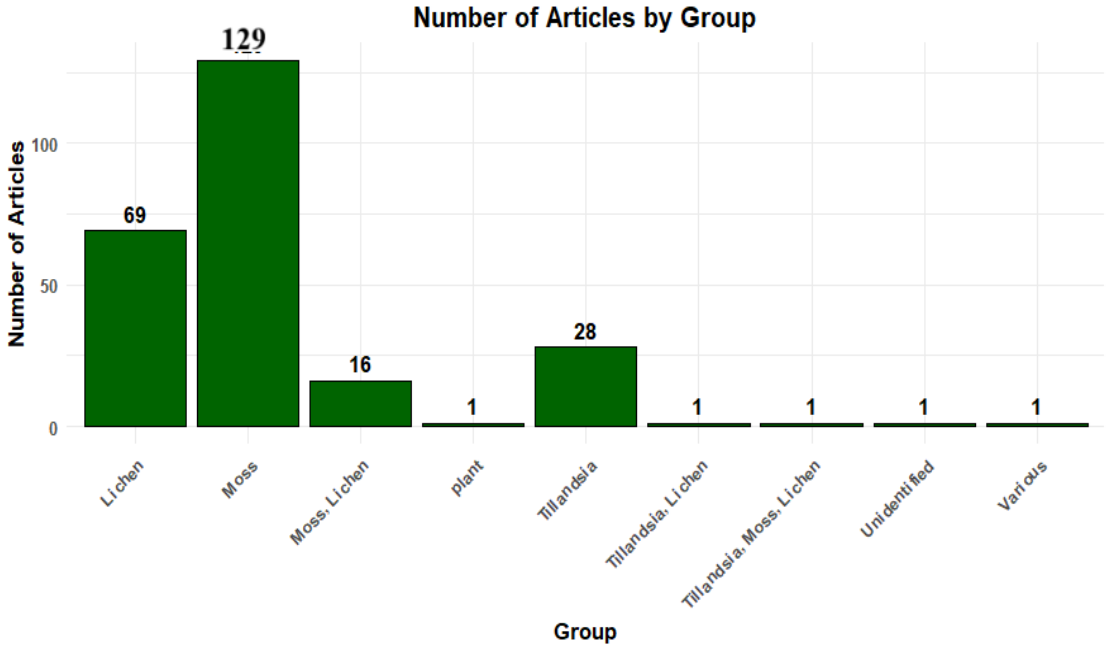
Moss was the principal group, since it is native to Asia and Europe. These countries usually adopt passive biomonitoring; however, biomonitors (*Tillandsia*, moss, and lichens) still remain underutilized as a tool for air quality monitoring, particularly in less affluent regions, despite their low cost and suitability for 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. Figure 3 presents the number of publications per country, showing that Asia and Europe present the highest number of publications, while in America and Africa, this technique is underutilized.

Figure 1: The word cloud.



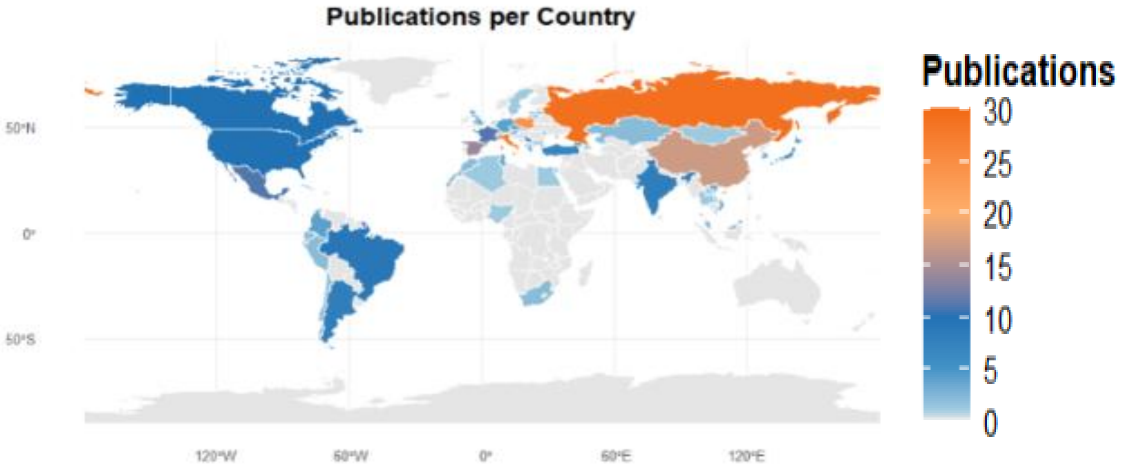
Source: The authors (2025).

Figure 2: Number of papers per group.



Source: The authors (2025).

Figure 3: Number of publications per country.

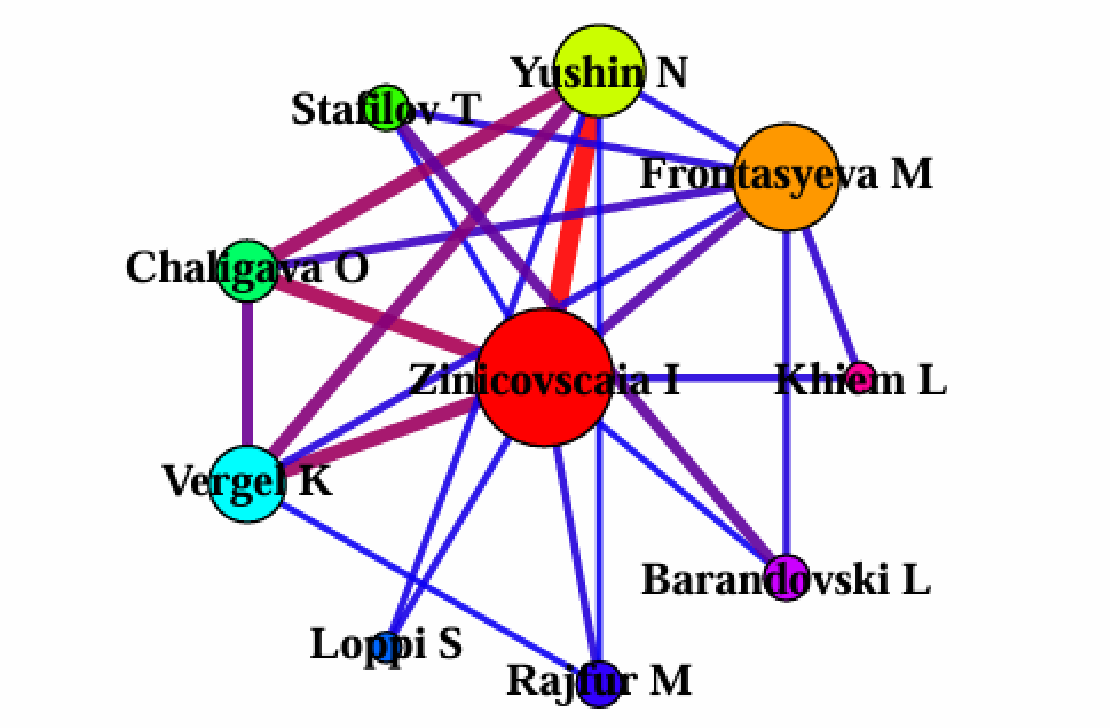


Source: The authors (2025).

Authors and University Network, Characterization techniques, and Pollutants

According to this research, the number of scientific 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 4 presents the 10 most productive authors and the network; the thickness and the color of lines connecting the edges are proportional to the number of publications (dark blue with one or two papers, purple with three or five papers, and red with more than five papers). 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). Concerning the number of their interactions, Zincovscaia I and Yushi N have the highest number of published papers in collaboration (21), being followed by Zincovscaia I and Chaligova O., with 14 collaborations, and Zincovscaia I and Vergel K. with 13 collaborations.

Figure 4: Co-authorship network – top 10 authors.



Source: The authors (2025).

Using the affiliation name tag (*AU_UN*) created by the *Bibliometrix* package, the top 10 most collaborative universities were identified (Figure 5). 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. It can be seen that Russia and Romania have the highest number of interactions. 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), 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).

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 2.

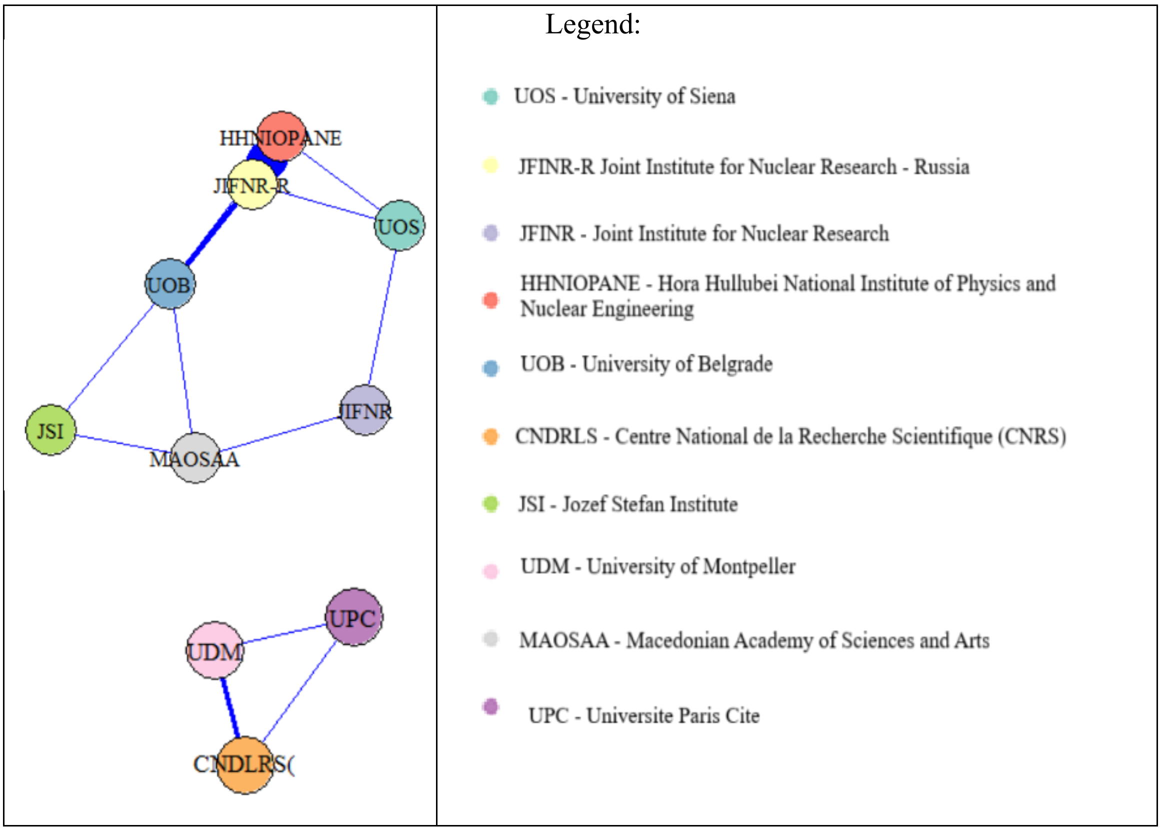
Meanwhile, the most frequently used techniques to evaluate elemental pollutants are ICP techniques, INAA, and AAS, as can be seen in Figure 6. Each method has a different detection limit, L_c; most of the time, this limit is also dependent on the trace element, but also the sample matrix and mass. These 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. 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 6. 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.

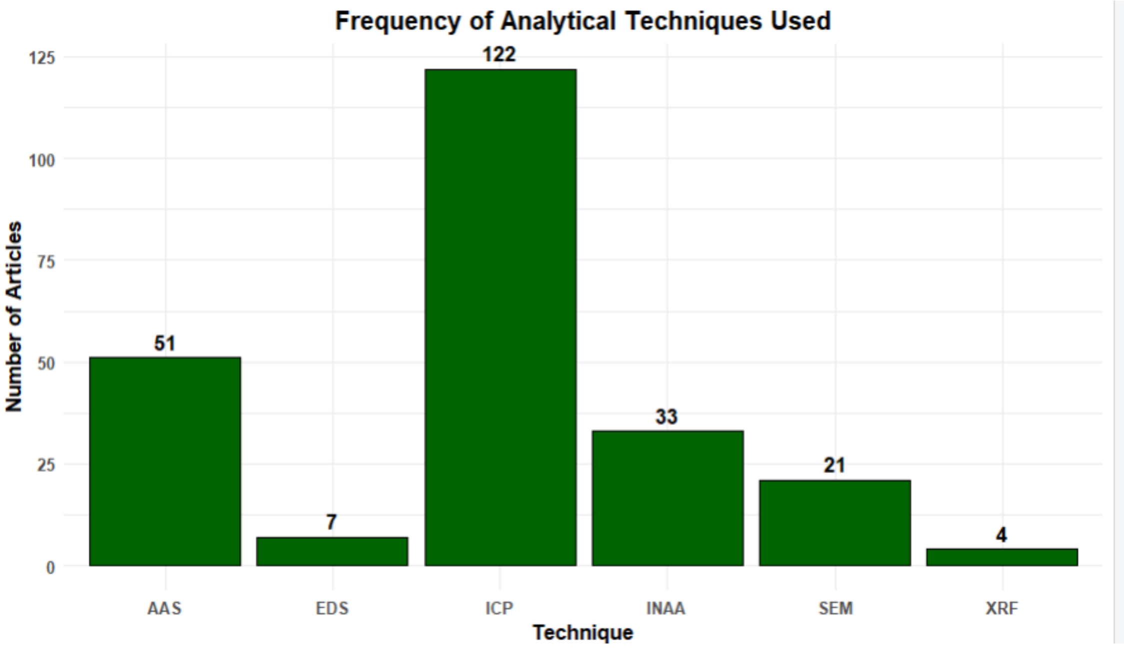
Considering the toxicity of the environment, it can be concluded that the four types of classification (industrial, urban, rural, and natural) have more than one factor listed in Table 2. For instance, the classification of urban environment includes traffic, oil combustion, lubricating oil, sometimes e-cigarettes, and others.

Figure 5: Top 10 most collaborative universities.



Source: The authors (2025).

Figure 6: Most frequent analytical techniques.



Source: The authors (2025).

Table 2: Toxicological trace elements and typical sources.

Icon	Category	Typical Sources	Trace Elements	Reference
⛏	Mining & Smelting	Mining, smelting of cinnabar ore, deposits of Pb and Zn, manufacturing of sodium hydroxide and chlorine by electrolysis of brine, Paper & 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	Chen, Maciejczyk, Thurston, 2022 Zheng et al., 2024
🚗	Traffic & Vehicle Wear	Traffic, brakes, tire wear, motor oil, gasoline additives	Ba, Ca, Cr, Cu, Fe, Mn, Ni, Zn, Cd, Pb	Chen, Maciejczyk, Thurston, 2022
🛢	Oil & Coal Combustion	Oil combustion, lubricating oil, coal combustion	V, Ni, Ca, Zn, Al, Fe, Mg, Na, Si, Ti	Chen, Maciejczyk, Thurston, 2022
🎆	Fireworks	Fireworks displays	Cu, Pb, Sr, Ti	Chen, Maciejczyk, Thurston, 2022

🚬	Tobacco Products	e-cigarettes Conventional cigarettes, e-cigarettes, and heated tobacco products	Cr, Mn, Ni, Pb, Cu, Zn, Cd 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 Świsłowski et al., 2022 Świsłowski et al., 2022
🌱	Pesticides & Fertilizers	Pesticides, insecticides, fertilizers	Cd, Ni, Pb	Morakinyo, Mukhola, Mokgobu, 2021
⛏	Coal Mines	Coal mines	Ag, Ge, Ni, Se, U, V, Zr	Petryshen, 2023
🗑	Landfill	Landfill	Ni, Pb, Zn	Stafilov et al., 2023

Source: The authors (2025).

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. 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). In conclusion, biomonitoring is a powerful Nature-based Solution for large areas and low-income regions.

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