

Systematic review of the efficacy of lichens as atmospheric bioindicators of heavy metals in Peru

Revisión sistemática de la eficacia de los líquenes como bioindicadores atmosféricos de metales pesados en el Perú

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ABSTRACT

Atmospheric contamination by heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), copper (Cu) and zinc (Zn) represents a significant risk to public health and the environment. The objective of this review was to compare the efficacy of lichens as bioindicators of atmospheric contamination in Peru. National scientific studies that reported concentrations of heavy metals in lichens were compiled, identifying the evaluated species and the analytical techniques employed. The results of the review show that the lichen *Cladonia* accumulated 61.00 ppm of Pb, 99.34 ppm of Zn and 1.50 ppm of Cd, while *Physcia erumpens* reached 113.51 ppm of Cu. The concentrations of metals in several species exceeded the limits of environmental quality standards (ECA), which indicates that lichens are effective for monitoring contamination in urban and industrial areas. It was concluded that lichens, especially *Cladonia* and *Physcia erumpens*, proved to be effective, accessible and economical tools for air quality monitoring, providing a viable alternative in areas with limited resources.

Keywords: lichens, bioindicators, heavy metals, bioaccumulation, atmospheric contamination, environmental monitoring.

RESUMEN

La contaminación atmosférica por metales pesados como plomo (Pb), cadmio (Cd), arsénico (As), cobre (Cu) y zinc (Zn) representa un riesgo significativo para la salud pública y el medioambiente. El objetivo de esta revisión fue comparar la eficacia de los líquenes como bioindicadores de la contaminación atmosférica en el Perú. Se recopilieron estudios científicos nacionales que reportaron concentraciones de metales pesados en líquenes, identificando las especies evaluadas y las técnicas analíticas empleadas. Los resultados de la revisión muestran que el líquen *Cladonia* acumuló 61.00 ppm de Pb, 99.34 ppm de Zn y 1.50 ppm de Cd, mientras que *Physcia erumpens* alcanzó 113.51 ppm de Cu. Las concentraciones de metales en varias especies superaron los límites de los estándares de calidad ambiental (ECA), lo que indica que los líquenes son eficaces para monitorear la contaminación en áreas urbanas e industriales. Se llegó a la conclusión de que los líquenes, especialmente *Cladonia* y *Physcia erumpens*, demostraron ser herramientas eficaces, accesibles y económicas para el monitoreo de la calidad del aire, brindando una alternativa viable en zonas con recursos limitados.

Palabras clave: líquenes, bioindicadores, metales pesados, bioacumulación, contaminación atmosférica, monitoreo ambiental.

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Introduction

Atmospheric pollution by heavy metals, such as Pb, Cd, As, Hg, and Ni, remains a critical risk to public health and ecosystems due to their toxicity, persistence, and bioaccumulation capacity (Calderón-Guevara et al., 2023). The fraction of metals bound to inhalable particulate matter can penetrate deeply into the respiratory tract and accumulate in organs, increasing the risk of respiratory and cardiovascular diseases, as well as cancer, with children and older adults being more vulnerable (Khoshakhlagh et al., 2024; Liang et al., 2025). The main sources include mining and metallurgy, fossil fuel combustion, vehicular traffic, and the resuspension of urban and industrial dust, with impacts also occurring in indoor environments, where exposure can be prolonged (Okoro et al., 2025). In Andean countries with intense extractive activity and rapid urban growth, monitoring metals in the air is a priority; however, instrumental systems are often costly and have limited coverage, making complementary environmental monitoring strategies necessary, such as the use of lichens as bioindicators (Dahmardeh Behrooz et al., 2025).

In ecotoxicology, a bioindicator reflects qualitative changes in environmental conditions (presence or effect), whereas a biomonitor allows the quantification of contaminants accumulated in an organism over time (Szczepaniak & Biziuk, 2003). Lichens consist of a symbiosis between a mycobiont and a photobiont; they lack a cuticle and vascular tissues, absorb nutrients directly from the atmosphere, and retain particles through dry and wet deposition and ion exchange. These characteristics make them suitable for assessing airborne metals at different scales (Nash, 2008). Among the main advantages of lichens are their low sampling cost, their ability to integrate contaminant exposure over time, and their wide geographical distribution. Nevertheless, they have limitations associated with interspecific variability, microclimatic effects, and the need to standardize protocols (species and substrate selection, sample preparation, and analytical techniques) to ensure comparability among studies (Conti & Cecchetti, 2001).

At the international level, lichens have been shown to detect the presence of metals such as Pb, Cd, Zn, Cu, and As in urban and industrial areas. These organisms make it possible to identify areas with high contamination near emission sources and also to record improvements when environmental controls are implemented (Conti & Cecchetti, 2001). In Latin America, studies conducted in large cities and industrial areas have shown increased levels of these metals due to traffic and metallurgical activities, using lichen composition and the amount of metals they accumulate to assess contamination. Research involving transplanted lichens has demonstrated that they respond rapidly to changes in air pollution and wind direction (Lijteroff et al., 2009). In Peru, various studies have demonstrated the usefulness of lichens as bioindicators of atmospheric pollution. Doria et al. (2024) evaluated the bioaccumulation of heavy metals in lichens from the Atahualpa native community in Satipo and found elevated concentrations of Pb, Zn, and Cu, mainly associated with vehicular traffic and nearby industrial activity. The results showed that lichens respond sensitively to variations in air quality, confirming their effectiveness in identifying areas with a higher pollutant load and their potential for environmental monitoring.

Although the country has Environmental Quality Standards (EQS) for air, a significant gap persists regarding which lichen species are the most efficient and to what extent they can accumulate heavy metals. In Peru, research on lichens as bioindicators has increased in recent decades, particularly in regions where mining, industry, and vehicular traffic generate high levels of atmospheric pollution (Yaulilahua-Huacho et al., 2024). Various studies in departments such as Junín, Puno, Cusco, Arequipa, and Lima have demonstrated that lichens not only reflect air quality through the accumulation of metals such as Pb, Cu, Zn, and Cd, but also contribute to decontamination by retaining and binding these elements in their structures (Soto Sinche and Altuna Ríos, 2023). The dual function of these lichens as indicators and biological filters becomes a valuable tool for environmental monitoring and air quality management.

Despite the increase in local studies on bioindicators in departments such as Junín, Lima, and Cusco, a critical gap persists in the national literature: the lack of a systematic comparison to determine the hierarchy of effectiveness among species for specific metals. Currently, there is no technical consensus on which species

(e.g., *Cladonia* vs. *Physcia*) is superior for detecting particular contaminants under Peru's climatic conditions, which hinders the standardization of environmental monitoring protocols.

Therefore, the general objective of this study was to compare the effectiveness of lichens as bioindicators of atmospheric pollution for the detection and accumulation of heavy metals in various regions of Peru. The specific objectives were as follows: to evaluate the heavy metal accumulation capacity of different lichen species, to compare metal concentrations in lichens with Peruvian EQS and international regulations, and to determine which species presents greater effectiveness as a bioindicator. Based on this information, a comparative synthesis was developed to guide future lines of research and, fundamentally, to provide a low-cost atmospheric monitoring methodology with high social value for the protection of public health.

Materials and methods

Study area

The present study corresponds to a descriptive and comparative literature review based on the compilation and analysis of scientific studies conducted in Peru on the bioaccumulation of heavy metals in lichens used as bioindicators of atmospheric pollution. No specific geographical area was delimited, since the main purpose was to integrate and analyze the existing information on lichens used as bioindicators of heavy metals present in the atmosphere.

Data source

Stage 1. application of inclusion and exclusion criteria

Regarding the inclusion criteria, only studies conducted in Peruvian territory that presented quantitative results on the concentration of heavy metals in lichens, precisely identified the species analyzed, and described the methods used to determine such metals were considered. Studies such as theses were also considered, provided that they met the same conditions mentioned above and were prepared by professionals seeking a degree, master's degree, or doctoral degree in fields related to Biology, Forestry Engineering, Environmental Engineering, or Agricultural Engineering (Aguirre et al., 2022).

For the present review, an exhaustive search of the scientific literature published between 2017 and 2025 was conducted. After applying the inclusion and exclusion criteria, a total of ten final studies, identified in Table 1, were selected that met the technical rigor and availability of comparative data required for the comparative analysis.

Stage 2. Specialized search for research sources

The bibliographic search was conducted using combinations of keywords in Spanish and English, such as "lichens," "bioindicators," "heavy metals," "lead," "copper," "cadmium," "mercury," and "Peru." Boolean operators (AND, OR) were applied to optimize the retrieval of relevant studies.

Stage 3. Information sources

The information sources to be consulted were selected, including recognized scientific databases such as Scopus, Web of Science, SciELO, Renati, and Google Scholar, as well as institutional repositories of Peruvian universities and technical documents issued by national environmental agencies, such as the Ministry of the Environment (MINAM). This combination of sources made it possible to gather both peer-reviewed scientific publications and technical reports and theses with academic value and national applicability.

Stage 4. Selection and recording

The titles, abstracts, and full texts of the preselected publications were reviewed to determine their relevance, and those that met the established criteria were selected. Information was extracted from each document on

the title, author, year, region, coordinates, type of environment, lichen species, metal analyzed, instrumental technique used, unit of measurement, and reported concentration values. All records were incorporated into a general data matrix prepared in Microsoft Excel, which served as the basis for the subsequent analysis.

Information processing

Standardization of measurement units

Data standardization was carried out by homogenizing the concentration units to parts per million (ppm) of dry weight, in order to ensure consistency among the different studies. The consistency of the values was also reviewed, and duplicate or inconsistent records were removed.

Documentary analysis

The data were classified according to lichen species, metal evaluated, and geographical region of the study. This organization made it possible to identify general patterns, trends, and differences in the bioaccumulation capacity of lichens in response to different heavy metals and under different environmental conditions. The type of spatial and temporal coverage of the information collected was also verified, with the purpose of adequately representing the diversity of contexts investigated in the country.

Statistical analysis of the data

The information was analyzed descriptively and comparatively, based on the data collected from the selected sources. At this stage, the reported concentrations of heavy metals in the different lichen species were examined, considering variations according to the region, type of environment, and metal evaluated. The information was organized to visualize the differences among species and the general distribution of the reported values in the country.

Subsequently, an interpretive synthesis was prepared aimed at identifying which lichen species have a greater bioaccumulation capacity and, therefore, greater effectiveness as atmospheric bioindicators. The results obtained were compared with the EQS, in order to contextualize the levels detected and assess the environmental relevance of the reported values. For this process, Microsoft Excel software and the SPSS statistical program were used for descriptive statistical analysis, which allowed the calculation of measures of central tendency and dispersion of metal concentrations.

Results

The heavy metal concentration values presented in this section correspond to data collected from previously published studies, which were standardized and comparatively analyzed to identify bioaccumulation patterns in different lichen species.

Table 1 presents the key studies that constitute the bibliographic basis of this review, all focused on the use of lichens to detect the presence of heavy metals in various regions of Peru.

Heavy metal accumulation capacity in different lichen species compared with peruvian EQS and international Regulations of the Canadian Council of Ministers of the Environment (CCME) and South Africa

Figure 1a) shows that, with respect to As, *Cladonia* accumulated the highest amount, with 6.20 ppm, followed by *Usnea*, with 5.10 ppm, both below the EQS limit of 50 ppm. In Figure 1b), for Cd, *Cladonia* accumulated 1.50 ppm, exceeding the EQS limit of 1.4 ppm, while other species, such as *Parmotrema* and *Dirinaria appplanata*, showed much lower concentrations. In Figure 1c), regarding Cr, *Dirinaria cf. appplanata* showed the highest accumulation, with 9.56 ppm, followed by *Phycia erumpens*, with 7.02 ppm, both above the EQS of 0.4 ppm; whereas *Parmotrema* and *Cladonia* presented significantly lower concentrations. In Figure

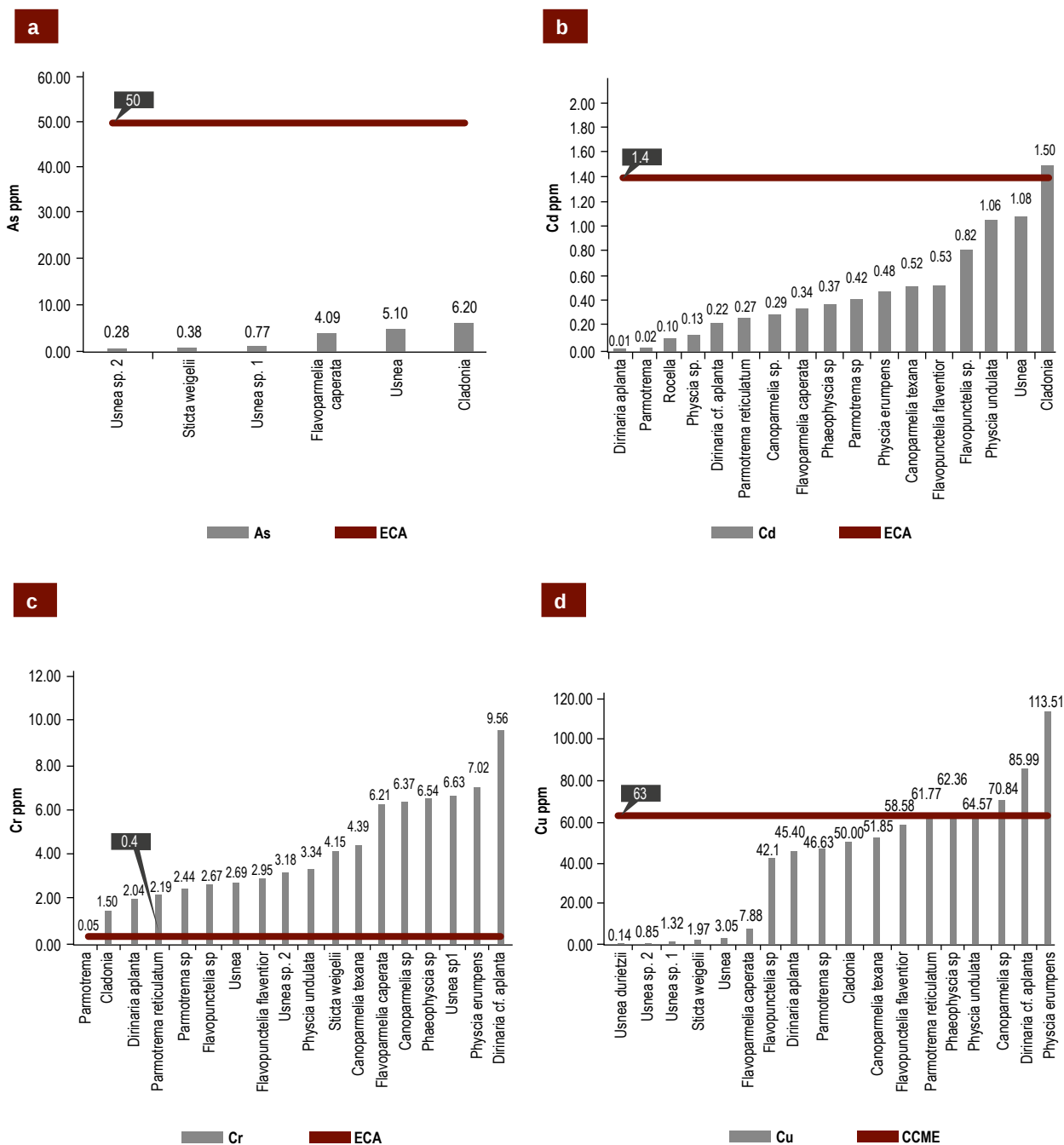
Table 1
Studies on lichens as bioindicators of heavy metals in Peru

No.	Study title	Author	Lichen species
1	biomonitoring in the Peruvian Andes metropolitan region using <i>Flavoparmelia caperata</i> lichen.	Huamán de la Cruz et al., 2018	<i>Flavoparmelia caperata</i>
2	Lichens as bioindicators of the presence of heavy metals in mountain ecosystems: experience in the Cordillera Blanca, Ancash, Peru.	Arroyo Sánchez, 2022	<i>Usnea</i> sp. 1, <i>Usnea</i> sp. 2 and <i>Sticta weigeli</i>
3	Bioaccumulation of heavy metals in tissues of aquatic and terrestrial vegetation evaluated in areas where mining environmental liabilities exist in Peru.	Cahuana y Aduvire, 2019	<i>Usnea</i> and <i>Cladonia</i>
4	Bioaccumulation of heavy metals: lead, cadmium, and chromium in medicinal plants collected in areas near high vehicular traffic in the city of Cusco.	Callo, 2022	<i>Usnea</i> , <i>Parmotrema</i> and <i>Flavoparmelia caperata</i>
5	Air quality through the <i>saxicolous lichen biota</i> in the Teatino archaeological zone—Lomas de Lachay National Reserve, Huacho, Lima, Peru, 2017.	Ferry López, 2018	<i>Xanthoria parietina</i> , <i>Hypogymnia physodes</i> and <i>Usnea</i> sp.
6	Use of lichens as bioindicators of atmospheric pollution in the Santo Toribio mining environmental liability, Ancash, Peru.	Valdivia and Ramírez, 2018	<i>Usnea durietzii</i>
7	Analysis of air pollution by heavy metals (lead and cadmium) using the lichen <i>Physcia</i> sp. in the district of Tingo María—Leoncio Prado—Huánuco, 2022.	Peña, 2023	<i>Physcia</i> sp.
8	Lichens as bioindicators of air quality in the district of San Miguel, Lima, Peru.	Cari Acosta, 2022	<i>Roccella</i>
9	Evaluation of air quality through the environmental purity index and analysis of heavy metals in the lichen <i>Xanthoparmelia</i> sp. (Vain.) Hale in the city of Puno.	Villamar Valdivia, 2018	<i>Xanthoparmelia</i> sp.
10	Biodiversity, atmospheric purity index (API), and bioaccumulation of metals (Pb, Cr, Cd, Cu, Ni, Zn) in lichens present in the Lomas de Amoquinto, Huacaluna (Moquegua), and Tacahuay (Tacna), 2020 and 2021.	Salinas Delgado, 2021	<i>Canoparmelia</i> sp., <i>Dirinaria</i> cf. <i>applanata</i> , <i>Dirinaria applanata</i> , <i>Flavopunctelia flaventior</i> , <i>Flavopunctelia</i> sp., <i>Parmotrema reticulatum</i> , <i>Parmotrema</i> sp., <i>Phaeophyscia</i> sp., <i>Physcia erumpens</i> and <i>Physcia undulata</i>

1d), for Cu, *Physcia erumpens* had the highest accumulation, with 113.51 ppm, followed by *Dirinaria* cf. *applanata* and *Canoparmelia* sp., with concentrations above 60 ppm, exceeding the CCME air quality standards, which are 63 ppm.

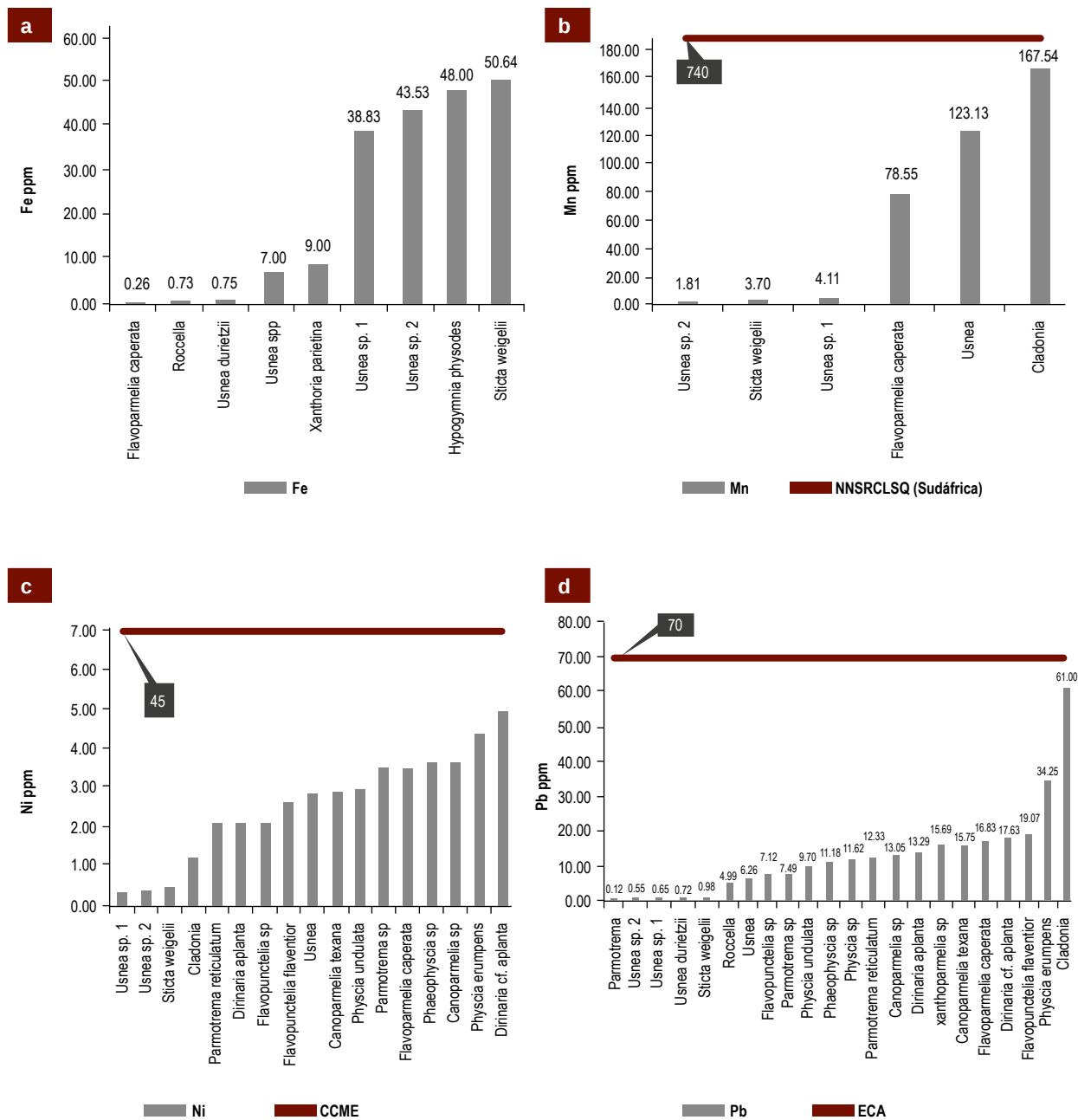
Figura 1

Concentration of heavy metals (As, Cd, Cr) in lichens, compared with the EQS; only Cu was compared with the CCME



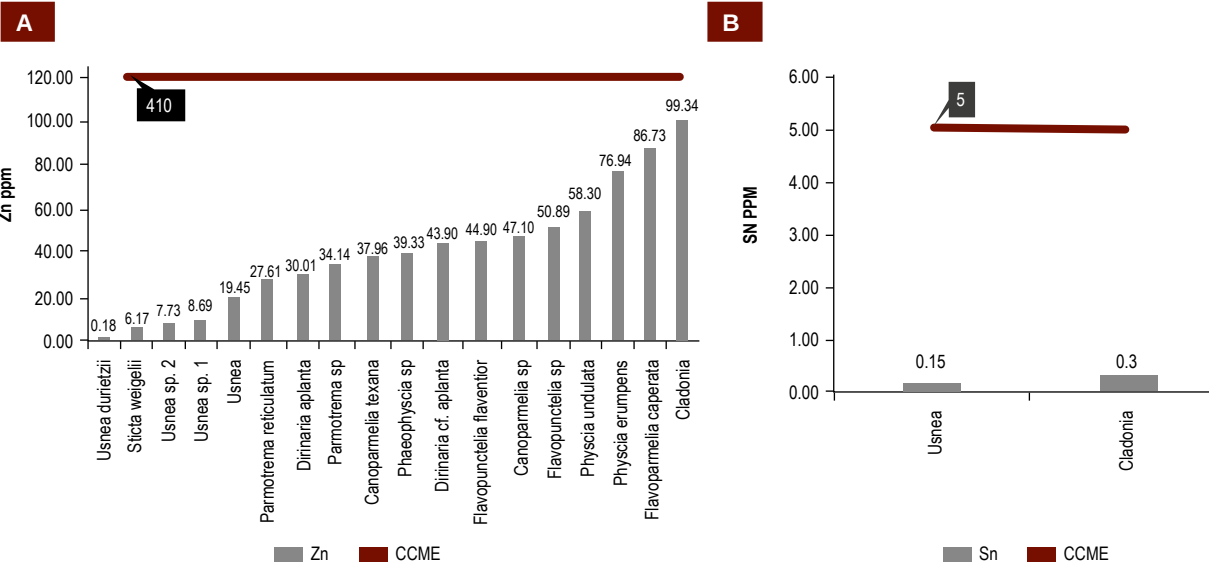
In Figure 2a), *Sticta weigelii* accumulated the highest amount of Fe, with 50.64 ppm, followed by *Usnea* sp. 2 and *Hypogymnia physodes*. In Figure 2b), *Cladonia* had the highest accumulation of Mn, with 167.54 ppm, significantly higher than in other species, such as *Flavoparmelia caperata* (78.55 ppm) and *Usnea* (123.13 ppm), and all below the South African standard (740 ppm). In Figure 2c), for Ni, *Dirinaria cf. applanata* accumulated 4.94 ppm, being the species with the highest concentration, followed by *Physcia erumpens* and *Canoparmelia* sp., with lower concentrations, all below the CCME standard of 45 ppm. In Figure 2d), *Cladonia* showed the highest accumulation of Pb, with 61.00 ppm, which was close to the EQS limit of 70 ppm, while other species accumulated Pb at lower concentrations.

Figura 2
Concentration of heavy metals Fe (a), Mn (b), Ni (c), and Pb (d) in lichens; Pb was compared with the EQS; Ni was compared with the CCME standard; Mn was compared with the South African standard (National Norms and Standards for the Remediation of Contaminated Land and Soil Quality) (GN R.331 of 2014), and Fe was not compared with any quality standard because the availability of iron in soil is so high that it makes it difficult to establish a generic standard value



In Figure 3a), for Zn, *Cladonia* accumulated 99.34 ppm, followed by *Flavoparmelia caperata*, with 86.73 ppm, standing out compared with other species with lower concentrations; all lichen species were below the CCME standard of 410 ppm. In Figure 3b), for Sn, *Cladonia* accumulated 0.30 ppm and *Usnea* 0.15 ppm; both values were low compared with the CCME standard of 5 ppm.

Figure 3
Concentration of heavy metals Zn (a) and Sn (b) in lichens, compared with the CCME standard



Analysis of the identification of the most efficient lichen species for heavy metal uptake

Figure 4 presents a comparison of lichen species according to their relative heavy metal bioaccumulation capacity, calculated based on the values reported in the studies analyzed, where *Cladonia* leads with 6 points, followed by *Physcia erumpens* and *Flavoparmelia caperata*, both with 5 points. *Usnea* and *Usnea sp. 1* have 4 points. The species with 3 points include *Dirinaria cf. applanata*, *Phaeophyscia sp.*, *Canoparmelia sp.*, and *Sticta weigeli*. The species with lower metal accumulation obtained 1 or 2 points, such as *Physcia undulata* and *Flavopunctelia sp.*

Figure 4
Points obtained by lichen species according to their capacity to accumulate heavy metals

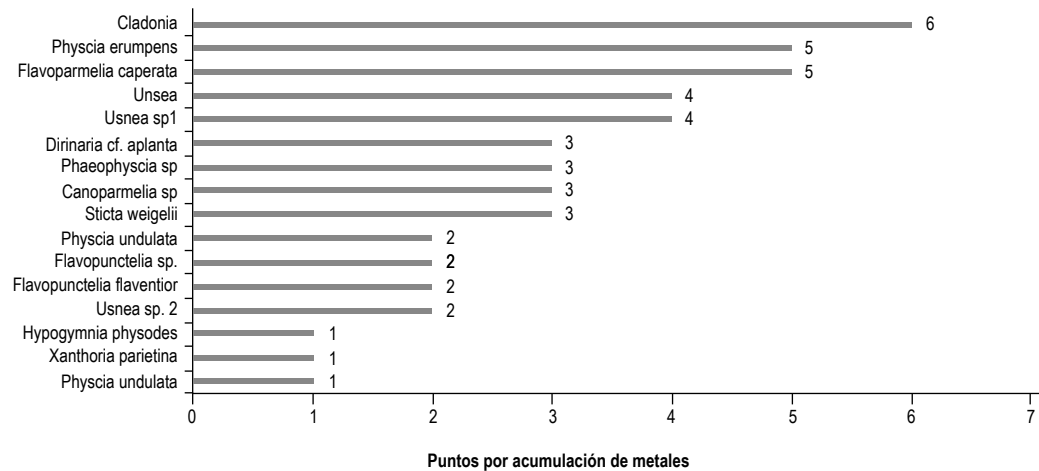
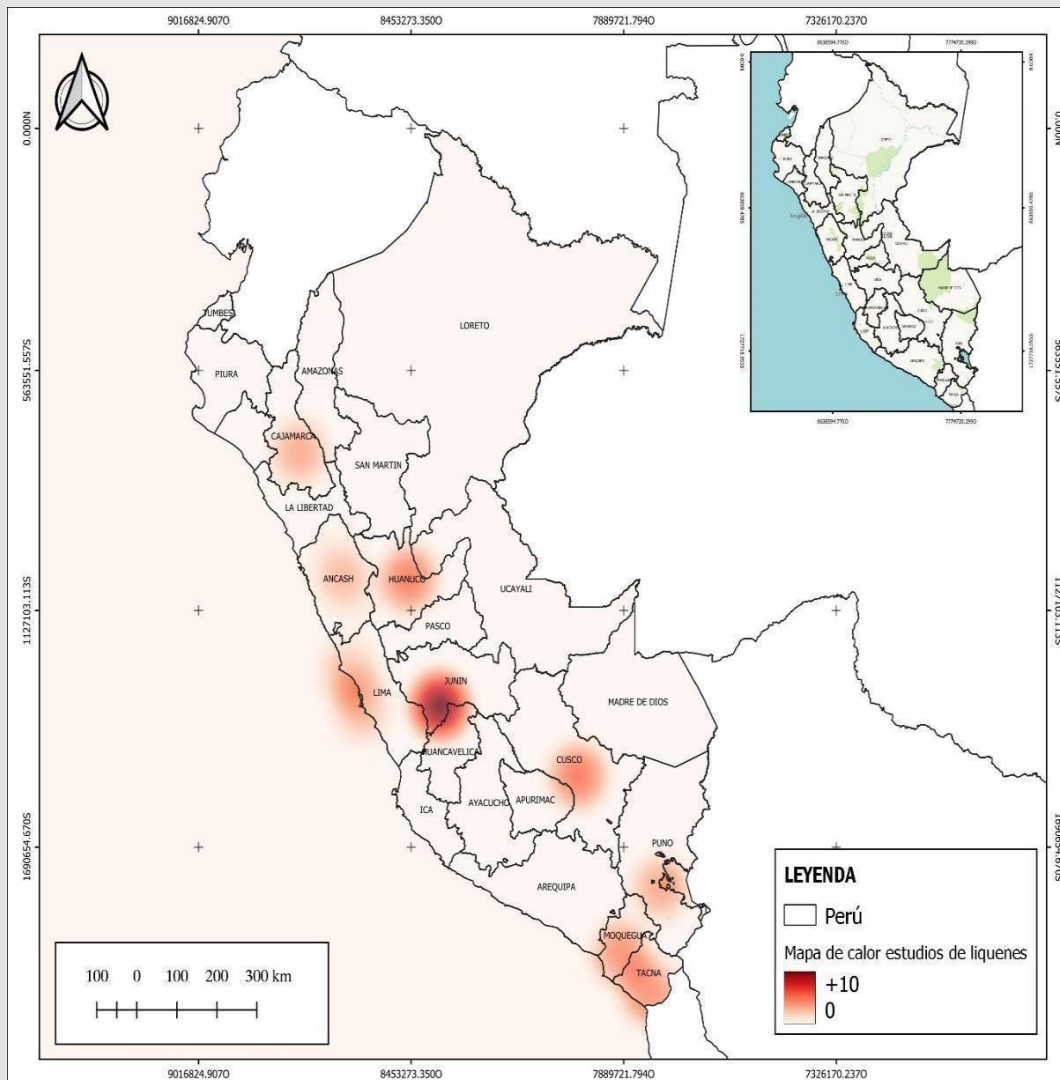


Figure 5 shows a heat map indicating the areas with the highest number of studies on lichens as bioindicators of atmospheric pollution in Peru. The regions with the highest number of studies are mainly located in Junín, with more than ten studies, followed by Lima, Cusco, and Tacna, with fewer than ten studies. This could be due to industrial and mining activities generating high levels of pollution in the aforementioned departments.

Figure 5

Heat map of the areas with the highest incidence of studies on lichen bioindicators



Discussions

The review of the studies analyzed made it possible to identify which lichen species has the greatest bioaccumulation capacity for certain metals: the morphology of *Cladonia*, which favors the retention of particles through dry deposition, is responsible for this organism accumulating more Pb and Zn than other species. This result is consistent with previous research conducted in the Andean region. However, when comparing the Cu levels found by Huamán de la Cruz et al. (2018) in *Physcia erumpens* with those recorded in this

analysis, an important contradiction is observed, since the former were notably lower than the latter. This discrepancy indicates that effectiveness depends not only on the species, but also on proximity to specific emission sources and local microclimatic variables, which are not always detailed in national studies. This makes it difficult to standardize these organisms as universal sensors. Similarly, Arroyo Sánchez (2022) found that *Usnea* stood out for the accumulation of metals such as As in mountain ecosystems, with values ranging from 6 to 9 ppm, showing a relationship with the results of this review. These similarities can be explained by the ability of lichens to accumulate heavy metals through dry and wet deposition, as stated by Conti & Cecchetti (2001), who explain that lichens, due to their biology and direct mode of nutrition from the air, tend to accumulate pollutants efficiently in areas with high atmospheric pollution, which is supported by Doria et al. (2024), who identified high concentrations of heavy metals in lichens near industrial activities in Satipo. This ability of lichens to serve as specific bioindicators of metals in urban and industrial environments reinforces their potential for monitoring air quality in contaminated areas, especially where instrumental monitoring is costly or inaccessible.

Of the ten metals evaluated, Cd, Cr, and Cu were the only ones that exceeded environmental standards. According to Arroyo Sánchez (2022), the concentration of Cd in soils reached a maximum of 0.98 ppm, below the limit of 1.4 ppm established by the EQS for soils, which is similar to the results obtained. This indicates that lichens can accumulate metals at levels higher than those found in soils. For Cu, a concentration of 4.105 ppm was reached, which exceeds the range of 3–14 ppm observed in soils from countries such as Denmark and Poland; this demonstrates the ability of lichens to accumulate copper at concentrations higher than typical soil values. For Pb, they reached 3.995 ppm, well below the EQS limit of 70 ppm, but *Cladonia* accumulated more Pb, which continues to indicate considerable accumulation of this metal in lichens. Conti & Cecchetti (2001) explain that lichens have a high capacity to accumulate air pollutants due to their porous structure and direct exposure to the atmosphere, allowing them to capture heavy metals more efficiently than soils. According to Szczepaniak & Biziuk (2003), lichens are useful as bioindicators due to their capacity to accumulate atmospheric metals through wet and dry deposition, making them particularly effective in urban and industrial areas, where heavy metal levels are higher in the air than in the soil.

In the study by Arroyo Sánchez (2022), concentrations of up to 11.210 ppm of manganese and 15.792 ppm of zinc were found in lichens from urban areas with high industrial activity, reinforcing the capacity of *Usnea* to accumulate metals such as Mn and Zn in contaminated environments. On the other hand, Huamán de la Cruz et al. (2018) reported copper concentrations of 9.6 ppm in lichens from the Andean region, which are lower than our results. This species stands out in industrial environments, where Cu is one of the most common metals. This accumulation capacity of these lichens can be attributed to their morphological and physiological characteristics. According to Conti & Cecchetti (2001), metal accumulation in lichens depends largely on local environmental conditions, such as proximity to emission sources and climatic variability, factors that may explain the differences in metal concentrations observed in various regions of Peru.

The results obtained in this study have important implications for environmental monitoring and air quality management in Peru. The identification of lichens such as *Cladonia*, *Physcia erumpens*, *Flavoparmelia caperata*, and *Usnea* as effective bioindicators of heavy metal accumulation offers an accessible and low-cost alternative to traditional monitoring methods, especially in rural or hard-to-access areas. This capacity of lichens to accumulate heavy metals allows them to be used not only as indicators of pollution, but also as tools for continuous environmental monitoring. This function is crucial in areas where resources for implementing conventional monitoring systems are limited. The finding of high concentrations of metals such as Pb, Cu, and Cd in several species underscores the urgent need to strengthen pollution management in the country. When comparing metal concentrations with international standards, such as the EQS and other standards from Canada, the United States, and South Africa, it is observed that several of the metals evaluated exceed the established limits, highlighting the importance of incorporating lichens into environmental monitoring programs at the national level. Conti & Cecchetti (2001) highlighted that lichens have great potential for monitoring atmospheric pollution due to their capacity to accumulate

heavy metals, especially in urban and industrial areas. In this context, the results of this study not only expand knowledge about the behavior of lichens in response to atmospheric pollution, but also propose a feasible and effective approach to environmental surveillance, contributing to improving the protection of public health and the environment.

One of the main limitations of this study was the scarcity of research on heavy metal bioaccumulation in lichens, especially in several regions of Peru. Most studies focus on specific areas, such as Lima, Junín, and Cusco, which limits geographical coverage and does not allow a comprehensive assessment of the potential of lichens as bioindicators at the national level. In addition, many of the existing studies do not provide sufficient detail on environmental conditions and sampling methods, which makes direct comparison of the results difficult. For future studies, it is crucial to expand research to other regions of Peru, particularly those most affected by mining activity and vehicular traffic. Standardizing analytical and sampling methods would be beneficial, as this would allow better comparison among studies and greater accuracy in the results.

The fact that species such as *Dirinaria cf. applanata* have exceeded the EQS restrictions for chromium and cadmium should not be viewed solely as a quantitative finding, but also as a warning sign for environmental health. In contrast to soils, which have the capacity to store geogenic metals, the study demonstrates that the metals accumulated in lichens originate predominantly from atmospheric sources of anthropogenic origin. Thus, their role as air sentinels in Peruvian urban areas where instrumental monitoring is not conducted is confirmed.

Conclusions

It is concluded that in Peru, lichen species present a distinct hierarchy in terms of bioindicator effectiveness. *Cladonia* is the most effective organism for multielement monitoring (Pb, Zn, Cd, and As), while *Physcia erumpens* is particularly effective for identifying Cu. These results confirm that these organisms can be used as an economical environmental monitoring network, which addresses the limited coverage of traditional instrumental systems in the country and the need for technical alternatives.

The results highlight the potential of lichens as accessible and economical tools for monitoring air quality in regions with limited resources for the use of traditional measurement equipment. Species such as *Cladonia* and *Physcia erumpens* can be used in national environmental monitoring programs to detect heavy metal pollution. These findings contribute to decision-making in environmental management and public health protection, helping to identify areas with a higher pollutant load and to implement policies that promote cleaner air in areas affected by industrial and mining activities.

In the case of iron (Fe), no direct comparison with environmental standards was made because its natural concentration presents high geological and soil-related variability, making it difficult to establish universal reference values for its interpretation in atmospheric bioaccumulation studies.

In practical terms, this review suggests incorporating lichens into environmental monitoring programs at the national level, especially in areas influenced by industrial and mining activities in the Peruvian Andes. To reduce the discrepancies observed among the different studies and facilitate the creation of a reliable and comparable national database of bioindicators, it is advisable to standardize sample-cleaning protocols and exposure periods in future research.

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Conflicts of interest

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