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Assessing Atmospheric Contamination Zones Through Lichen Bioindicators in a Northwestern Peruvian City

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ABSTRACT

Lichens, which are symbiotic associations between fungi and algae, serve as bioindicators for assessing air quality via the Modified Index of Atmospheric Purity (IAP_M). This research evaluated atmospheric conditions and mapped isocontamination zones in Chachapoyas, Peru. Lichen samples were collected from 36 locations across six urban sectors, while measurements of phorophyte bark pH, ambient temperature, and humidity were also taken. A total of 27 lichen species on 15 phorophyte species were identified. Statistical analysis found no significant correlation between IAP_M scores and environmental factors such as bark pH, phorophyte species, temperature, or humidity. Using the IAP_M data and Kriging interpolation in QGIS, an isocontamination map was created to display spatial air pollution patterns. The map indicated that the central sector of Chachapoyas had the lowest air quality, while peripheral areas showed decreasing pollution levels, illustrating a clear urban pollution gradient.

1. INTRODUCTION

Anthropogenic activities and the productive growth of countries damage the atmosphere (Sinha & Sen 2016). These activities generate stationary sources of pollution, such as factories (Yang et al. 2019), and mobile sources like vehicles (Xue et al. 2020). Air pollution has long been a global concern and continues to pose a serious threat to human health (WHO 2018), damage biodiversity, and cause the displacement of species (Manning & Tiedemann 1995). Lichens, organisms formed by the symbiotic association of a fungus and algae (Bargagli 2016), are among the most sensitive to air contaminants and are therefore widely used as bioindicators (Méndez & Campos 2015, Pescott et al. 2015). In addition to lichens, moss bags have recently emerged as active biomonitors with increasing applications for air quality monitoring (Chaudhuri & Roy 2024).

Atmospheric monitoring using lichens is well established and provides an economical and effective means of assessing environmental quality (Conti & Cecchetti 2001). Two main approaches exist: the active method, which consists of transplanting lichens from clean to polluted sites to assess pollutant accumulation (Capozzi et al. 2020, De Agostini et al. 2020), and the passive method, which examines lichens in situ due to their capacity to accumulate pollutants well above ambient concentrations (Boonpeng et al. 2020). Lichens vary in sensitivity to air pollutants (Agnan et al. 2017); the most sensitive taxa may exhibit reduced cover, reproductive inhibition, and pigment alteration (Bajpai et al. 2010, Gonzales-Vargas

et al. 2016, Pescott et al. 2015), while tolerant species display fewer morphological changes (Estrabou et al. 2004, Lijteroff et al. 2009). These community-level responses make lichens reliable indicators of atmospheric quality (Will-Wolf et al. 2017).

The most common metric used for evaluating lichen communities is the Index of Atmospheric Purity (IAP), which relates lichen abundance and frequency to air quality (LeBlanc & Sloover 1970). IAP values are often used to produce isocontamination maps that delineate areas with similar pollution levels (Bustamante et al. 2013). Although parameters such as humidity and temperature are sometimes measured to refine IAP interpretations, their influence on lichen diversity is often weak (Lubek et al. 2018, Pandey 2019). Other environmental variables, including bark pH, rainfall, and cardinal orientation, can also affect lichen composition (Agnan et al. 2017, Méndez & Campos 2015). For this reason, this study employs the Modified Index of Atmospheric Purity (IAP_M), proposed by Rubiano (1988), which integrates both biological and environmental factors rather than relying solely on abundance.

Furthermore, air contaminants generated by the combustion of fossil fuels, such as sulfur dioxide (SO_2) and carbon monoxide (CO) (Gonzales-Vargas et al. 2016), have significant impacts on living organisms (Mateos & González 2016). According to MINAM (2014), SO_2 and CO concentrations in Chachapoyas exceed Environmental Quality Standards (EQS), and the city has been designated a Priority Attention Zone (PAZ). These issues are primarily linked to the reduction of green areas and the concentration of intense commercial and vehicular activity in the city center (Vivanco et al. 2013). Although lichen biomonitoring has been widely applied in Latin America, most studies have focused on large or coastal urban centers such as Córdoba (Argentina), Cochabamba (Bolivia), or San José (Costa Rica), where industrial and vehicular emissions dominate the pollution profile (Bustamante et al. 2013, Estrabou et al. 2011, Gonzales-Vargas et al. 2016). In contrast, Chachapoyas is a high-Andean intermediate city (2,334 m a.s.l.) characterized by complex topography, limited industrial activity, and seasonal inversion layers that influence the dispersion of pollutants. These distinctive climatic and geographic conditions make it an ideal natural laboratory for evaluating how lichen bioindicators respond to pollution in mountain-city environments, where studies remain scarce.

Therefore, this study applies the Modified Index of Atmospheric Purity (IAP_M) to assess air quality in Chachapoyas city, identifying atmospheric isocontamination zones and analyzing their spatial distribution. By integrating lichen community data with environmental variables and

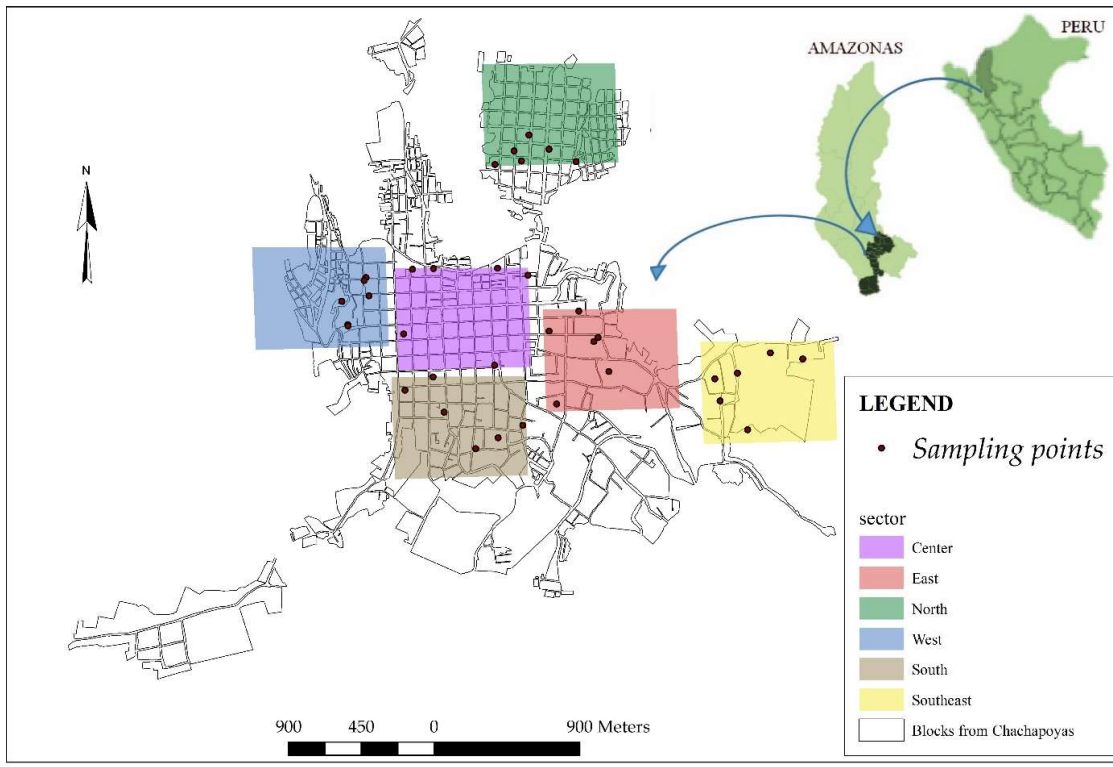

Fig. 1: Locations of study sectors and sampling points.

using geostatistical interpolation techniques, the research aims to provide a precise and cost-effective diagnosis of atmospheric quality.

2. MATERIALS AND METHODS

2.1. Area of Study

The sampling was conducted in Chachapoyas city, located at 2334 m a.s.l. in the northeastern Andes of Peru. The area has an annual temperature range between 13°C (minimum) and 22 °C (maximum) (SENAMHI 2018) and a population of 32,026 inhabitants in 2017 (INEI 2018). The urban area, which covers approximately 802.2 ha, was divided into six sectors: central (C), east (E), north (N), west (W), south (S), and southeast (SE) (Fig. 1). Following the methodology of Lijteroff et al. (2009), the central sector (C) was delimited according to the highest concentration of commercial and vehicular activity, while the remaining five sectors were defined based on the city's geographic distribution and natural boundaries, such as small streams that separate neighborhoods. Within each sector, sampling points were selected according to the presence of phorophytes that met the minimum requirements for lichen colonization and measurement, ensuring adequate spatial coverage and methodological consistency with previous lichen biomonitoring studies (Rindita et al. 2015).

2.2. Phorophyte Selection and Inventory of Lichens

According to the methodology proposed by Asta et al. (2002), a preliminary survey of the study area was conducted to characterize the phorophyte population and ensure adequate representation across all sectors. Phorophytes were selected based on specific criteria to ensure consistency and suitability for lichen sampling: (i) tree species commonly distributed throughout the urban area and present in at least two sectors, (ii) trunk diameter at breast height (DBH) greater than 20 cm, allowing a sufficient and homogeneous substrate for lichen colonization, and (iii) healthy individuals with intact bark, free of wounds, resins, or epiphytes that could interfere with lichen development (Käffer et al. 2011a, Lubek et al. 2018, Matos et al. 2017). Following these criteria, six phorophytes were selected per sector, according to the sampling design described by Lijteroff et al. (2009). To analyze lichen abundance and frequency, four 10 × 10 cm quadrats were constructed and placed vertically on each phorophyte, with the lower edge positioned at least 1 m above the ground (Riquelme-Acevedo 2008). Each quadrat was oriented toward one of the four cardinal directions (north, south, east, and west) to account for potential differences in exposure and microclimatic conditions. The sampling was conducted between December 2017 and January 2018, corresponding to the transition from the dry to the rainy season in the region.

Within each quadrat, all individual lichens were identified and counted by species. The relative abundance of each species was calculated as the percentage of individuals belonging to that species relative to the total number of individuals recorded. Frequency was determined based on the number of sectors (ranging from 1 to 6) in which each species was present, and relative frequency represented the percentage of occurrences of a given species with respect to the total number of occurrences across all sectors.

2.3. Lichen Identification

Lichen keys were used for identification (Etayo 2010, Moreno et al. 2007, Shukla et al. 2014), using a stereo camera (Carl Zeiss Model Stereo Discovery V.12 AxioCam ERc5s) and corroborated using two lichen web databases (http://www.bgbm.fu-berlin.de/sipman/keys/ and http://lichenportal.org/portal/index.php).

2.4. Modified Index of Atmospheric Purity

The air quality in each sector was analyzed using epiphytic lichens and applying the Index of Atmospheric Purity (IAP), proposed by LeBlanc & Sloover 1970 and modified (IAP_M) by Rubiano 1988, which measures the frequency, abundance, the number of phorophytes per station (in this case, a station is a phorophyte), and the resistance factor of each species.

The modified Index of Atmospheric Purity (IAP_M) was calculated based on the following formulas:

$$Qi = \sum_{j}^{n} \frac{Aj}{Ej}$$

Where:

Qi: Resistance factor of species *i* (The Qi expresses the capacity of a species to resist atmospheric pollutants, considering its frequency and relative abundance in the different sampled phorophytes.)

Aj: Number of species in each phorophyte

Ej: Number of the phorophytes where *i* is found

$$IAP_M = \sum_{j}^{n} \frac{(Qi\ x\ Fi)}{n}\ x\ Ci$$

Where:

Ci: Relative abundance of species *i* in phorophyte *j*

Fi: Frequency of species *i* (number of phorophytes in sector *j* where species *i* is found)

n: number of phorophytes registered in sector *j*.

2.5. Map of the Isocontamination Area

To construct the isocontamination map, the ordinary Kriging (linear) interpolation method was applied in QGIS v.3.14.15. This geostatistical technique estimates unknown values at unsampled locations by weighting nearby measured points according to their spatial autocorrelation, minimizing estimation variance (Isaaks & Srivastava 1989). The IAP_M values showed a non-normal distribution; however, ordinary Kriging can be reliably applied to non-normal datasets provided that spatial dependence is properly modeled through the semivariogram (Isaaks & Srivastava 1989, Webster & Oliver 2007). Based on this principle, interpolation was performed assuming intrinsic stationarity of the variable. This approach, also supported by Ribeiro et al. (2016), allows the generation of continuous surfaces representing zones of similar atmospheric pollution derived from IAP_M values. The areas that contain similar lichen communities have similar pollution levels, in accordance with Herzig et al. (2020).

The formula to find areas with similar pollution levels is defined by:

$$Z(so) = \sum_{i=1}^{N} \lambda i Z(si)$$

Where:

Z (si) = the IAP_M value measured in phorophyte *i*

λi = an unknown value for the measured value in phorophyte *i*

so = the location of the prediction

N = the number of measured values

2.6. Measurement of Environmental Parameters

Thirty-six phorophytes belonging to 15 different tree species were sampled. The bark pH was measured following the procedure described by Kricke (2002). A 0.5 g sample of bark surface was taken from each phorophyte and immersed in 50 mL of 0.25 M potassium chloride (KCl) solution. The samples were then placed in an oven at 80°C for one h, cooled to 20°C, and the pH was determined using an analytical pH meter (SI Analytics Handylab 680).

Environmental temperature and relative humidity were also recorded in two randomly selected phorophytes per sector to evaluate the possible influence of these variables on the IAP_M values. Measurements were taken using a portable thermohygrometer (Isolab model) exposed to ambient conditions for eight consecutive hs per day. Due to the relatively stable microclimate around each phorophyte, mean daily values were used in subsequent analyses.

2.7. Data Analysis

The Shannon–Wiener Diversity Index (H) was calculated for all lichen species recorded. Each individual was delineated within the grid, with each closed perimeter representing the contour of a lichen thallus (Correa-Ochoa et al. 2020). Because the sample size was below 50 phorophytes (n = 36), the Shapiro–Wilk test ($p < 0.05$) was used to verify the normality of the data. To assess relationships among variables, the Spearman rank correlation ($p < 0.05$) was applied between environmental parameters (temperature, humidity, and bark pH) and biological variables (lichen diversity), with the final IAP_M values. Differences among sectors were tested using the Kruskal–Wallis non-parametric test ($p < 0.05$). Finally, a Principal Component Analysis (PCA) was performed to identify patterns and groupings among the analyzed variables, providing a multivariate understanding of their combined effects on air quality. At this point, a threshold for the extraction of the components was established at a minimum of 60%, according to Hair et al. (2019). These statistical tests were performed with the R statistical software (R Core Team 2019).

3. RESULTS

The most frequently sampled phorophyte was Eucalyptus globulus (Eucalyptus), representing 13 of the 36 surveyed trees. Environmental humidity ranged from 56% to 65%, while temperature varied between 19°C and 22°C. The lowest bark pH was recorded in E. globulus (4.54), with the highest in Persea americana (7.70).

A total of 27 lichen species across 23 genera were identified. The most abundant species was Candelaria concolor (3,126 individuals), followed by *Flavoparmelia caperata* (2,975) and *Buellia aethalea* (2,795). The least represented species were *Parmotrema latissimum* (15 individuals), *Collema fuscovirens* (13), and *Leptogium phyllocarpum* (2) (see Table 1).

All sectors exhibited low Shannon–Wiener diversity values, with an overall average of 2.32. The northern sector showed the highest diversity, while the southeastern sector recorded the lowest (Fig. 2).

To delineate the contamination zones, the recorded IAP_M values were grouped into six classes based on data dispersion and similarity patterns (Table 2). Each class represents a distinct level of atmospheric pollution, ranging from maximum to minimal.

The highest IAP_M value (16.42) was recorded in the southern sector on the phorophyte *Schinus molle*, corresponding to Zone 6 (minimal contamination). Conversely, the lowest IAP_M value (0.76) was observed

Table 1: Analyzed lichens in the city of Chachapoyas.

Specie	Abundance	Relative Abundance	Frequency	Relative Frequency
Acarospora nodulosa	758	5.45	3	3.23
Arthonia microcarpa	469	3.37	5	5.38
Arthopyrenia excellens	386	2.77	6	6.45
Buellia aethalea	2795	20.09	6	6.45
Candelaria concolor	3126	22.47	6	6.45
Cladia aggregata	137	0.98	4	4.3
Cladonia perforata	26	0.19	3	3.23
Cladoniicola irregularis	71	0.51	1	1.08
Coccocarpia palmicola	375	2.7	4	4.3
Collema sp1	710	5.1	6	6.45
Collema sp2	388	2.79	6	6.45
Collema fuscovirens	13	0.09	1	1.08
Evernia prunastri	112	0.8	5	5.38
Flavoparmelia caperata	2975	21.38	6	6.45
Lecidea versicolor	385	2.77	5	5.38
Leptogium phyllocarpum	2	0.01	1	1.08
Myriotrema glaucophaenum	71	0.51	1	1.08
Myriotrema squamuloides	324	2.33	2	2.15
Parmelia caperata	114	0.82	1	1.08
Parmotrema latissimum	15	0.11	2	2.15
Psoroma hypnorum	45	0.32	2	2.15
Rimelia reticulata	80	0.57	3	3.23
Roccella caribaea	32	0.23	2	2.15
Sticta canariensis	40	0.29	4	4.3
Teloschistes exilis	143	1.03	4	4.3
Teloschistes flavicans	37	0.27	1	1.08
Xanthoria polycarpa	285	2.05	3	3.23
Total	13914	100	93	100

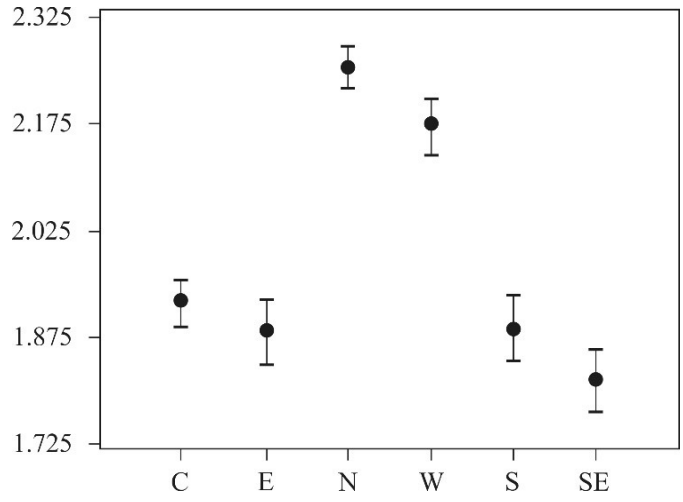

Fig. 2: Lichen diversity (Shannon–Wiener index) across sectors of Chachapoyas.

Table 2: Contamination zone per phorophyte.

IAP_M value	Description	Contamination zone
0-3.38	Maximum contamination	Zone 1
3.38-5.98	Acute contamination	Zone 2
5.98-8.59	Medium contamination	Zone 3
8.59-11.20	Moderate contamination	Zone 4
11.20-13.81	Transition zone	Zone 5
> 13.81	Minimal/Low contamination	Zone 6

in the central sector on *Eucalyptus globulus*, which falls within Zone 1 (maximum contamination) (Table 3). showed a positive and significant correlation with lichen diversity ($r = 0.577$, $p < 0.001$). Bark pH was primarily dependent on the phorophyte species ($r = 0.526$, $p < 0.01$) and, to a lesser extent, on the sector ($r = –0.370$, $p < 0.05$). Temperature and humidity exhibited an inverse relationship ($r = –0.657$, $p < 0.001$), confirming their expected environmental interaction.

The Kruskal–Wallis test indicated that there were no significant differences among sectors for any of the analyzed variables: lichen diversity ($H = 13.19$, $p = 0.511$), bark pH ($H = 22.78$, $p = 0.064$), humidity ($H = 21.13$, $p = 0.098$), temperature ($H = 21.08$, $p = 0.100$), and IAP_M ($H = 11.04$, $p = 0.683$).

According to the Principal Component Analysis (PCA), the first two principal components explained 67.43% of the total variance in the dataset (Table 4). The first component (CP1) accounted for 39.05% of the variance and was mainly associated with temperature (–0.948) and humidity (0.875), indicating an inverse relationship between these variables. The second component (CP2) explained 28.38% of the variance and was dominated by IAP_M (–0.842) and lichen diversity (–0.839), suggesting that these two biological variables covary and are independent of the environmental factors represented in CP1. This separation demonstrates that IAP_M and diversity were not significantly related to temperature, pH, or humidity, highlighting the predominance of anthropogenic over microclimatic influences on lichen distribution (Fig. 3).

The histogram of IAP_M values (Fig. 4) displayed a positively skewed distribution, with most phorophytes concentrated at low IAP_M values and a long tail toward higher ones. This pattern indicates high data dispersion and the presence of a few sites with cleaner air conditions, supporting the subsequent use of non-parametric statistical tests and Kriging interpolation for spatial modeling.

The isocontamination map generated through ordinary Kriging interpolation (Fig. 5) revealed the spatial distribution of air quality across Chachapoyas. Six contamination zones were identified, ranging from maximum contamination (Zone 1) to low contamination (Zone 6). The central sector

Table 3: Classification of IAP_M values per phorophyte and per sector.

Phorophyte	IAP_M for each phorophyte	Air quality zone for each phorophyte
C1	7.07	3
C2	4.64	2
C3	1.86	1
C4	0.85	1
C5	8.49	3
C6	0.77	1
E1	3.10	1
E2	3.01	1
E3	1.24	1
E4	6.15	3
E5	9.14	4
E6	2.46	1
N1	6.14	3
N2	3.31	1
N3	11.16	4
N4	7.50	3
N5	4.85	2
N6	1.94	1
W1	4.29	2
W2	1.23	1
W3	1.52	1
W4	3.02	1
W5	11.34	5
W6	4.62	2
S1	7.23	3
S2	2.24	1
S3	2.27	1
S4	16.42	6
S5	7.92	3
S6	2.35	1
SE1	9.32	4
SE2	6.59	3
SE3	1.05	1
SE4	8.84	4
SE5	2.02	1
SE6	4.80	2

Table 4: Results of the main component analysis of the studied variables.

C	CP1	CP2
Total	1.3974	1.1911
Variance [%]	39.05	28.38
V. accumulated [%]	39.05	67.43
Diversity	0.008	**-0.839**
pH	-0.534	-0.035
Humidity	**0.875**	-0.029
Temperature	**-0.948**	-0.043
IAP_M	0.032	**-0.842**

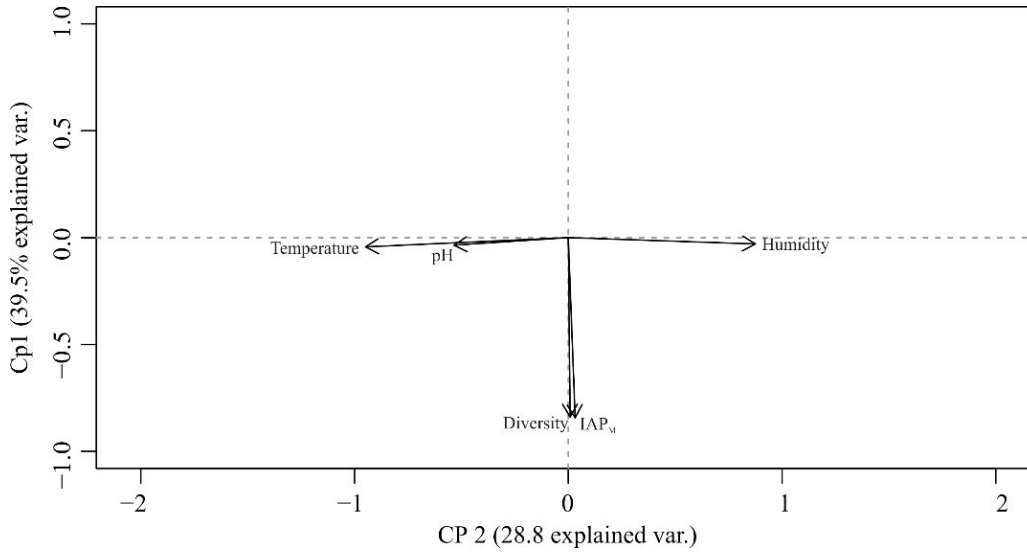

Fig. 3: Grouping of variables according to PCA analysis.

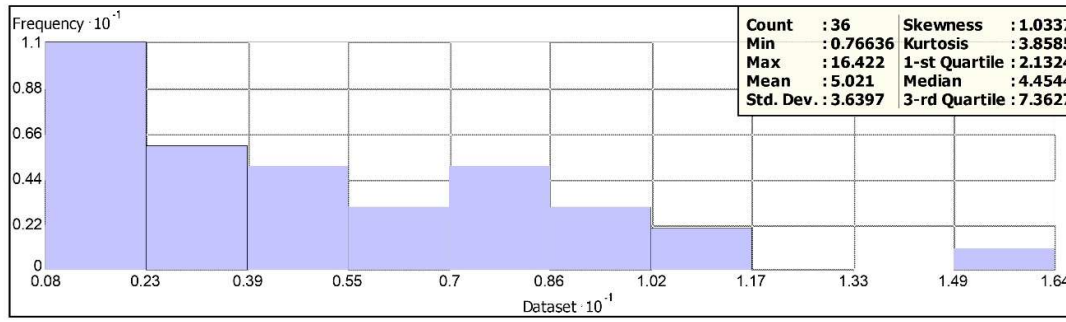

Fig. 4: Histogram of IAP_M values.

exhibited the highest pollution levels, followed by adjacent areas classified as high contamination (Zone 2). These zones coincide with areas of greater commercial activity, higher population density, and limited green cover. Medium (Zone 3) and moderate (Zone 4) contamination zones were mainly located toward the northeast and parts of the southeast, while transition (Zone 5) and low contamination (Zone 6) areas occurred in the southern and southwestern sectors, where urbanization is less intense and vegetation cover is denser. Sampling points, represented by black dots, ensured spatial representativeness across all sectors. Overall, the map revealed a clear pollution gradient from the city center toward the periphery, reflecting the impact of anthropogenic activities on local air quality.

4. DISCUSSION

The most frequent lichens found were *C. concolor*, *F. caperata*, and *B. aethalea*, which are therefore considered resistant to pollution (Gonzales-Vargas et al. 2016). On the other hand, the least found lichen species were *P. latissimum*, *C. fuscovirens*, and *L. phyllocarpum*; these species are suitable to be used as bioindicators, since they are highly sensitive to pollution (Simijaca-Salcedo et al. 2014). Although the northern sector is the most diverse (H = 2.25), it belongs to Zone 1 of contamination, which is the most contaminated according to the IAP_M values. However, the southeastern sector had the lowest value of diversity (H = 1.82) and is also in Zone 1 of contamination. This apparent contradiction reflects that high lichen diversity does not necessarily indicate better air quality, as tolerant species can dominate in moderately polluted environments, maintaining relatively high diversity but low IAP_M values (Conti & Cecchetti 2001, Pinho et al. 2008). Hence, IAP_M not only considers diversity but also incorporates abundance, frequency, and resistance factors, making it a more integrative and reliable index (Zilio et al. 2017). The values of IAPM should be the resistance factor of lichens to pollution; therefore, the most diverse sector will not necessarily exhibit the highest IAPM values, as also reported by Rubiano (1988).

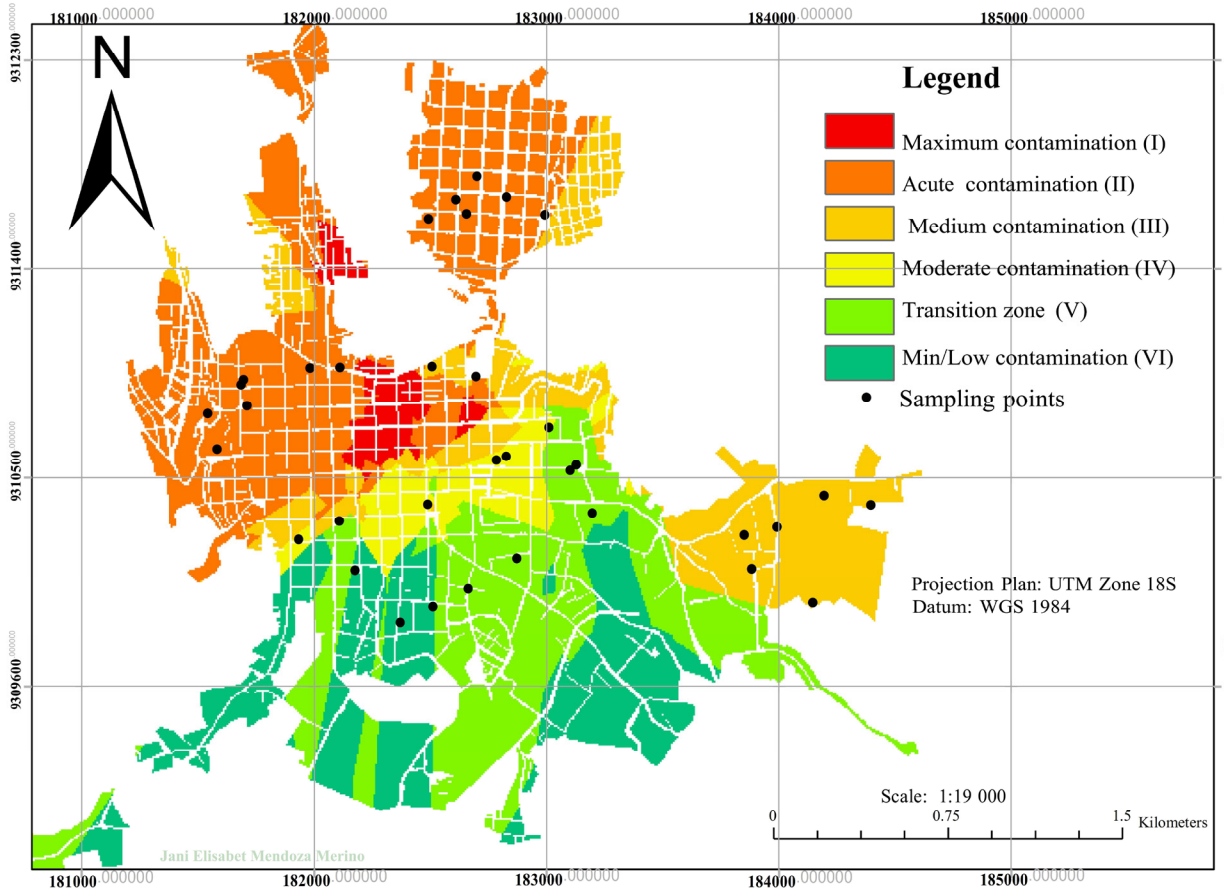

Fig. 5: Spatial distribution of atmospheric contamination zones in Chachapoyas city.

Chachapoyas does not have uniform vegetation, so trees that met the minimum requirements for the IAP_M application were selected. The influence of phorophyte species on the IAP_M value has been previously reported (Matos et al. 2017); however, Spearman's test indicated an insignificant relationship between phorophyte species and IAP_M values in this study, which contrasts with Käffer et al. (2011b). As for the diversity of lichens, one of the most influential variables is the pH of the phorophyte's bark (Agnan et al. 2017). Nonetheless, the correlation between pH and lichen diversity was not significant in this study. Although temperature and humidity were also mentioned as relevant variables for diversity values (Batke et al. 2015), their correlations were considered insignificant. It was observed that bark pH differs among phorophytes but does not influence lichen diversity or IAP_M values, similar to the findings of Pandey (2019).

Although several studies have reported that phorophyte species and bark pH strongly influence lichen colonization and diversity (Agnan et al. 2017, Käffer et al. 2011b, Matos et al. 2017), our results revealed no significant relationship between these variables and IAP_M values. This discrepancy may arise from differences in bark texture, chemical composition, and microclimatic exposure among tree species, which can vary across regions (Lubek et al. 2018). Moreover, while acidic bark pH is generally associated with lower lichen diversity (Pandey 2019), some tolerant taxa may persist even under unfavorable substrate conditions, weakening this pattern in polluted environments (Conti & Cecchetti 2001). These contrasting findings highlight the context-dependence of lichen–phorophyte interactions, suggesting that atmospheric pollution levels in Chachapoyas may exert a stronger selective pressure on lichen communities than substrate characteristics alone. The sectorial differences in all the values of the variables were insignificant, so the study is valid, and a correct selection of phorophytes has been made. According to the Kruskal–Wallis test, this investigation of air quality in Chachapoyas can be summarized in two blocks (Table 4). Furthermore, with regard to environmental and biological variables, similar results were found for epiphytic lichens in the national park of Białowieża, in northeastern Poland (Lubek et al. 2018).

The number of contamination zones identified through IAP_M depends not only on the method applied but also on

factors such as the spatial scale of sampling, local climate, and the degree of urbanization, which determine pollutant dispersion and deposition patterns (Matos et al. 2017, Will-Wolf et al. 2017). To predict air quality in untested areas, Ribeiro et al. (2016) used interpolation along with the Kriging method. Thus, the central sector was observed to be the most polluted, directly corresponding to the most densely populated area (Ku 2020). It is observed that commercial activities, transportation, and the lack of green areas, unpaved streets, and constant dust release of particles (PM = 2.5), which is above permissible limits, contribute to the reduction of air quality and increased pollution in the central area, these are the main causes of the decline in air quality and the decrease of IAP_M (Gonzales-Vargas et al. 2016). However, the generated isocontamination map is an automatic spatial construction, and its reliability should be assessed in future studies. We recommend using separate datasets for model training and validation, as well as comparing the performance of different geostatistical and emerging machine learning approaches such as Random Forest regression or Gaussian Process models, which have recently shown promise for spatial air quality estimation (Li et al. 2022, Liang et al. 2025). On the other hand, the southern sector presents less pollution, where transportation and commercial activities are limited compared to the central sector.

The use of lichens as bioindicators allowed us to analyze the air quality in Chachapoyas, which, according to the IAPM, is classified as polluted and comprises six contamination zones. This classification pattern reflects both methodological and spatial factors and can vary across regions depending on landscape complexity and anthropogenic activity. For instance, in Argentina, four contamination zones were identified using IAP (Estrabou et al. 2011), while in Serbia, three zones were reported (Stamenkovic & Arandjelovic 2010). This research provides the first baseline assessment of atmospheric quality in Chachapoyas using lichen bioindicators and the IAPM. The resulting isocontamination map reveals spatial gradients of air pollution that can inform urban green-space planning, emission control strategies, and environmental education programs in the city. Although the methodological approach follows established biomonitoring frameworks, its application in a high-Andean Peruvian city fills a critical geographic gap in regional air quality monitoring. Therefore, the study contributes applied value by demonstrating the feasibility of low-cost, nature-based monitoring tools for local governments and research institutions in developing urban contexts.

4.1. Limitations

Although this study successfully identified spatial pollution patterns in Chachapoyas, limitations must be acknowledged. The sampling effort (36 phorophytes distributed across six sectors) provides sufficient coverage for exploratory mapping but restricts the robustness of spatial interpolation, particularly in areas with uneven phorophyte distribution. As a result, the accuracy of the Kriging model may be affected by local variability and the limited number of input points. (Isaaks & Srivastava 1989). Additionally, environmental variables such as temperature, humidity, and bark pH were measured during a short timeframe and at a reduced number of points, limiting their capacity to explain variation in lichen diversity and IAP_M values (Pinho et al. 2008, Will-Wolf et al. 2017).

4.2. Future Perspectives

To strengthen future applications of the IAP_M, temporal monitoring programs should be implemented to capture seasonal and multiannual variations in air quality, since single-point assessments may overlook short-term pollution events or climatic fluctuations affecting lichen communities (Pinho et al. 2008, Will-Wolf et al. 2017). In addition, molecular characterization of lichen species through DNA-based techniques is recommended to ensure taxonomic accuracy, complemented by chromatographic and spectrometric analyses to detect and quantify accumulated pollutants. Such long-term and multi-approach monitoring would enhance the precision and reliability of bioindicator-based air quality assessments in Chachapoyas and other Andean urban ecosystems.

5. CONCLUSIONS

This study recorded 27 lichen species belonging to 23 genera, with *Candelaria concolor*, *Flavoparmelia caperata*, and *Buellia aethalea* being the most abundant and resistant to atmospheric pollution, while *Parmotrema latissimum*, *Collema fuscovirens*, and *Leptogium phyllocarpum* were the least abundant and identified as sensitive bioindicators. The isocontamination map derived from IPA_M values effectively classified the urban area of Chachapoyas into six contamination zones, highlighting the central sector as having the poorest air quality, likely due to the lack of green areas, high population density, and intense commercial activity that increase particulate matter (PM2.5) emissions.

Shannon–Wiener diversity values were low across all sectors, and correlations between IAP_M and environmental variables (phorophyte species, bark pH, humidity, and temperature) were statistically insignificant. This indicates that IAP_M performance is influenced by a combination of biological and environmental factors rather than diversity alone.

In summary, this study demonstrates that IAP_M is an effective and low-cost approach for identifying spatial

gradients of air quality in medium-sized Andean cities such as Chachapoyas. The method integrates both biological sensitivity and environmental context, allowing for a reliable classification of urban pollution levels.

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