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Corticolous Lichen Communities and Their Bioindication Potential in an Urban and Peri-Urban Ecosystem in the Central Region of Colombia

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Abstract: The richness, composition, abundance, and correlation with the atmospheric oxide concentrations of the community of corticolous lichens in the urban and peri-urban areas of the city of Ibagué (Colombia) were evaluated, selecting 25 individuals of the four most abundant phorophyte species. Twenty-nine lichen taxa grouped in 13 families and 17 genera were recorded, with a higher lichen coverage and taxa richness in the urban area. A non-metric multidimensional scaling (NMDS) analysis showed the conformation of two lichen communities associated with the urban and peri-urban areas of the city, and variation in composition among the phorophyte species. Exclusive and indicator taxa were found for both zones, as well as associations between variables through the application of a general linear model. Higher concentrations of atmospheric gases CO, SO_2, NO_2, and O_3 were found in the urban zone, and positive/negative relationships with some lichen taxa. There is high variability in the response of the lichen assemblage of urban and peri-urban ecosystems to environmental effects, with substantial or minimal changes in the variables of richness, coverage, and phorophyte association, and according to their interaction with atmospheric oxides, the patterns of potential tolerant and/or sensitive species are formed for their implementation in bioindication studies.

Keywords: lichenized fungi; cover; diversity; phorophyte; area; oxide concentrations

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1. Introduction

Lichens or lichenized fungi are a symbiotic association of holobionts that constitute an ecological unit by the integration of a fungus (mycobiont), a photosynthetic organism that can be a eukaryotic alga (phycobiont) and/or a cyanobacterium (cyanobiont), together with an accompanying microbiome [1–4]. These adaptations have given them a cosmopolitan presence and they can develop in all the environments of the planet (deserts, jungles, moorlands, aquatic systems, and polar zones, among others) [5]. According to their growth form or biotype, the structure of their thallus can be foliaceous, gelatinous, crustaceous, fruticose, squamulose, and some other composite types, and can be found on different substrates such as wood, rock, soil, or other solid materials [6]. Currently, lichens represent a biological model for the study of environmental quality, given their strict dependence on atmospheric conditions that determine their growth, diversity, dominance, and permanence in the habitat [7]; likewise, they possess a high richness of the bioactive compounds of pharmacological interest, derived from multiple biosynthetic pathways with a particular genetic fingerprint [8].

Together with bryophytes, lichens constitute one of the least-studied groups in tropical areas due to the lack of taxonomic knowledge despite the high richness of species they comprise and the diverse plant formations they colonize [9,10]; however, their potential use as the bioindicators of environmental quality has encouraged the characterization studies of lichen communities at the international level, with the development of protocols for the evaluation of their diversity and the subsequent estimation of indices for atmospheric monitoring [11,12].

The calculation of bioindication indices fundamentally requires the knowledge of lichen diversity at a regional or local scale [13] so that the distribution and abundance patterns of the species are known and their sensitivity or tolerance to different factors, or the correlation with some environmental parameters is identified [14]. In this way, the characterization of lichen communities allows the estimation and analysis of atmospheric quality and purity indexes [15], which have been implemented in environmental monitoring in Europe and North America [16,17]; however, in Latin American countries these methodologies have not yet been explored [18–20].

The scientific validation of the bioindicator potential of lichens for the influence of atmospheric oxides, heavy metals, eutrophication, and acid rain has been explored since the mid-20th century [21], and their use in tropical areas, northern Europe, and northern Asian cities constitutes a user-friendly tool for the analysis of air pollution-generating sources with the diversity and distribution of local lichen communities [22–24].

In Colombia, the literature on the diversity and composition of lichen communities is growing. Some studies compiled information on lichen communities at the biogeographic or ecosystem scale that has allowed the estimation of species richness for the country [25–40], as well as assemblages and relationship with environmental variables [41–43], which is complemented by nomenclatural and taxonomic updates to the Lichen Catalog of the country [44]. In the department of Tolima, studies dating back to those conducted by Sipman [9] and Restrepo and Esquivel [45], together with the contributions of Esquivel and Nieto [46], Rivera and Sierra [47], Zarate et al. [48], and Barreto and Esquivel [49] in the last two decades, contribute to knowledge about lichen diversity patterns; however, there are information gaps between areas with different degrees of disturbance and studies in the gradients of intervention especially below 1500 masl.

In this context, the objective of this study was to determine the richness, composition, abundance, and correlation with atmospheric oxide concentrations of the community of corticolous lichens in the urban and peri-urban areas of the city of Ibagué.

2. Materials and Methods

2.1. Study Area

The municipality of Ibagué is located on the eastern flank of Colombia's central mountain range, in the center of the department of Tolima (4°15′ to 4°40′ N and 74°00′ to 75°30′ W) (Figure 1). The city extends from the tropical dry forest life zone to the transition to Premontane Moist Forest, at altitudes between 800 masl and 1200 masl [50]. The average annual temperature is 23 °C and the average precipitation is 1993 mm, distributed in a bimodal regime, with peak rainfall in April and October.

The urban area of the city covers approximately 43 km^2 and is divided into 13 communes, with residential, commercial, and industrial zones and small patches of vegetation in green areas. The rural zone is divided into 17 corregimientos and 140 veredas [51].

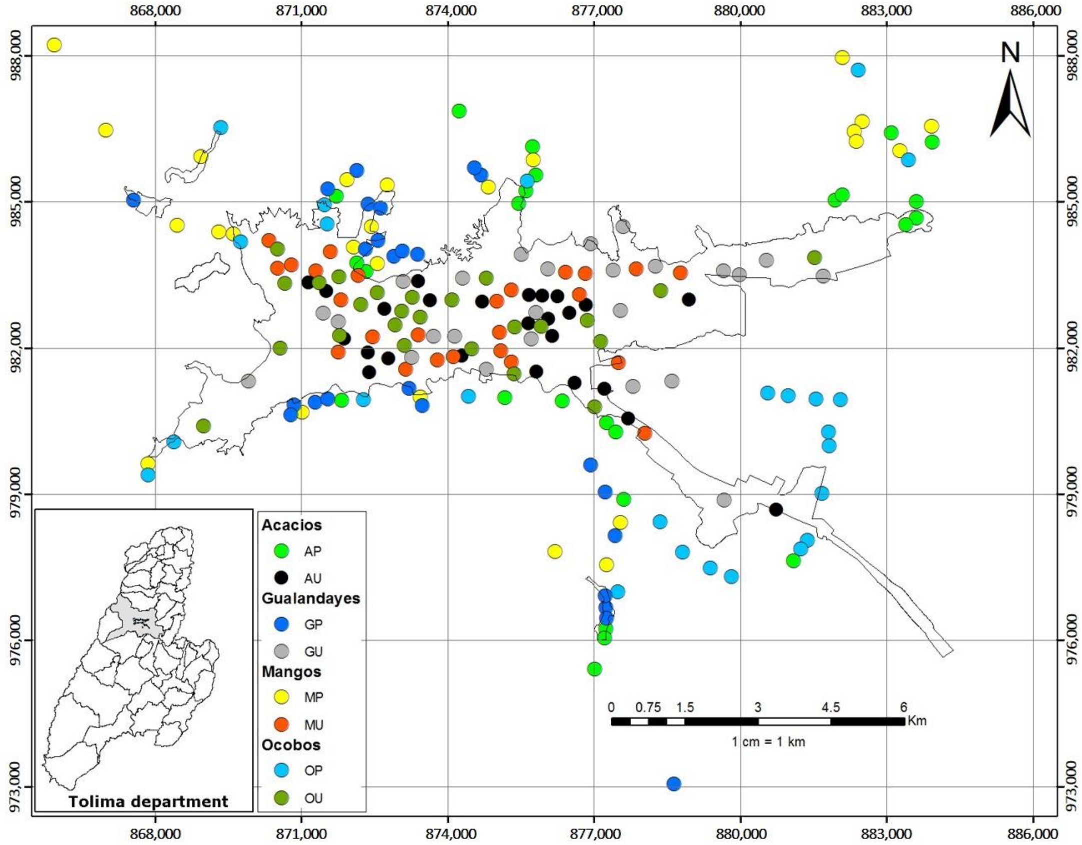

Figure 1. Location of the 200 phorophytes distributed in the urban (U) and peri-urban (P) areas of the city of Ibagué (Colombia), corresponding to 50 trees of each selected species: *Senna spectabilis* (acacios), *Jacaranda caucana* (gualandayes), *Mangifera indica* (mangos), and *Tabebuia rosea* (ocobos).

2.2. Sampling

The city of Ibagué was divided into urban and peri-urban zones, the latter being considered as that zone located between 0.5–4 km after the end of the urban area of the city (paved roads) and presenting less vehicular traffic. In each zone, 25 individuals of each of the four most abundant phorophyte species in the city were located: *Tabebuia rosea* (pink ocobo), *Mangifera indica* (mango), *Jacaranda caucana* (gualanday), and *Senna spectabilis* (yellow acacia) (Figure 1), for a total of 200 georeferenced phorophytes. The trees with DBH $\geq$ 20 cm, separated by a minimum distance of 200 m, with optimal physical and phytosanitary conditions were chosen.

Lichen sampling was carried out in each phorophyte using a 100 cm^2 acetate grid, located 1.3 m from the ground in the four flanks of each tree [52], for a total of 400 cm^2 evaluated per phorophyte. In this way, the lichen taxa were identified, and the cover of each taxa was calculated by counting the number of 1 cm^2 squares. The trees were georeferenced, and DBH, total height, and elevation were measured to be used as covariates.

For atmospheric oxide sampling, NO_2, SO_2, CO, and O_3 measurements were taken at 50 points, 25 in the urban area and 25 in the peri-urban area of the city of Ibagué, using the Aeroqual S500 equipment with interchangeable sensors previously calibrated. The value recorded for each gas was the arithmetic average of 60 measurements/hour and measurements were taken daily from Monday to Sunday for two months.

2.3. Taxonomy Determination

The lichens were collected in paper bags, dried at room temperature, and identified to the lowest possible taxonomic level using the guides and keys of Chaparro and Aguirre [6], Esquivel and Nieto [46], Sipman [53], Campos et al. [54], Moberg [55], Käffer et al. [56], Soto et al. [57], Soto et al. [58], and the collection of the Herbarium of the Universidad Distrital Francisco José de Caldas of Bogotá (Colombia), with the collaboration of Professor Alejandra Suárez Corredor.

2.4. Statistical Analysis

To evaluate the representativeness of the sampling at the scale of the areas (urban and peri-urban), species accumulation curves were developed using the phorophytes as the sampling unit. Jack 1, Jack 2, and Bootstrap estimators were calculated with the program EstimateS 9.0 [59] to compare the number of observed and estimated species with presence–absence data.

To evaluate the richness alpha diversity, the Margalef, Shannon, and Simpson's dominance indices were calculated. Likewise, a *t*-test was performed to establish the significance of the difference in the Shannon diversity and dominance between the zones. To examine the difference in the taxa composition and turnover between the zones, Bray–Curtis (quantitative Sørensen) similarity indices were used. To represent the difference in the lichen community composition between the zones, non-metric multidimensional scaling (NMDS) was performed using the total cover of the lichen taxa in the four phorophyte species, and the Bray–Curtis index as a measure of distance. The significance of differences in the community composition was assessed through a two-way (phorophyte and zone) Permanova analysis using the Bray–Curtis index.

To assess phorophyte specificity, an indicator taxa analysis was performed using a Monte Carlo simulation in PC-ORD 5.0 [60], in which all the p-values for simulated IVI less than 0.05 were considered as the indicator taxa. To evaluate the effect of the area and substrate (phorophyte species) on abundance (total cover in cm^2) and specific richness, the family of General Linear and Mixed Models, incorporated in the Infostat v2016p program [61], was used using the Poisson distribution and the logit link. As fixed effect factors, the area (urban and peri-urban) (Z_i) and the four phorophyte species (F_j) were used, including the interaction effect between the factors (ZF_{ij}). To decrease the error caused by individual tree variation, this factor was incorporated as a random effect (I_{ij}). Finally, the effect of the covariates, phorophyte height (A), DBH (D), and elevation (E), was included. The model was defined as follows:

$$Y_{ij} = \mu + Z_i + F_j + ZF_{ij} + I_{ij} + A + D + E + Er_{ij}$$

The average concentration (ppm) of each gas in the urban and peri-urban zone was analyzed through boxplot plots with their respective averages. The degree of association between the concentration of the atmospheric oxides and the diversity of the lichen taxa was determined through Spearman's correlation test (data without normal distribution) and principal component analysis (PCA).

According to the protocol described, the work uses a classical approach to the study of beta diversity and the evaluation of similarity between zones through a variance decomposition test as the statistical evidence of change in community composition. This analysis was also complemented with a linear model that sought to explore the effect of the zones on the traditional variables such as richness and abundance, but analyzed here in a crude manner, also controlling the effects of the covariates.

3. Results

A total of 50,380 cm^2 of lichen cover distributed in 13 families, 17 genera, and 29 taxa of lichens was recorded (Table 1). The families Physciaceae (32,662 cm^2), Candelariaceae (10,090 cm^2), and Parmeliaceae (5646 cm^2) accounted for 96% of the cover; the other families had less than 2% cover (Table 2). On the other hand, the richest family was Physciaceae (10 spp.), followed by Lecanoraceae (3 spp.), and the other families included one or two taxa (Figure 2).

Table 1. Taxa of the corticolous lichens recorded in the four species of phorophytes in the urban (U) and peri-urban (P) areas of the city of Ibagué (Colombia).

Family	Taxa	Zone			
		P (cm²)	**%**	**U (cm²)**	**%**
Arthoniaceae	*Crypthotecia* sp.	6	0.02	41	0.16
	Herpothallon sp.	29	0.12	0	0
Candelariaceae	*Candelaria concolor* (Dicks.) Stein	973	3.97	4704	18.19
	Candelaria sp.	1545	6.30	2868	11.09
Chrysothricaceae	*Chrysothrix chlorina* (Ach.) J.R. Laundon	0	0	90	0.35
	Chrysothrix sp.	67	0.27	0	0
Collemataceae	*Leptogium isidiosellum* (Riddle) Sierk	127	0.52	85	0.33
	Leptogium sp.	34	0.14	304	1.18
Graphidaceae	*Fissurina* sp.	16	0.07	0	0
Haematommataceae	*Haematomma leprarioides* (Vain.) Vain.	0	0	100	0.39
Lecanoraceae	*Lecanora alba* Lumbsch	40	0.16	47	0.18
	Lecanora helva Stizenb.	400	1.63	6	0.02
	Lecanora tropica Zahlbr.	4	0.02	1	<0.01
Parmeliaceae	*Parmotrema* sp.	4	0.02	0	0
	Canoparmelia sp.	4273	17.42	1369	5.30
Pertusariaceae	*Pertusaria* sp.	176	0.72	49	0.19
Physciaceae	*Phaeophyscia pusilloides* (Zahlbr.) Essl.	0	0	6	0.02
	Physcia alba (Fée) Müll.Arg.	410	1.67	40	0.15
	Physcia krogiae Moberg	0	0	11	0.04
	Physcia lacinulata Müll.Arg.	5184	21.14	13,227	51.16
	Physcia manuelii Moberg	15	0.06	220	0.85
	Physcia sp.1	0	0	3	0.01
	Physcia sp.2	0	0	112	0.43
	Pyxine cocoes (Sw.) Nyl.	382	1.56	191	0.74
	Pyxine pyxinoides (Müll.Arg.) Kalb	10,030	40.90	1792	6.93
	Pyxine sp.	530	2.16	509	1.97
Porinaceae	*Porina* sp.	144	0.59	76	0.29
Ramalinaceae	*Ramalina celastri* (Spreng.) Krog & Swinscow	136	0.55	3	0.01
Thelotremataceae	*Chapsa albida* (Nyl.) Lücking & Sipman	1	<0.01	0	0
Total		24,526	100	25,854	100

Table 2. Absolute and relative coverage of the corticolous lichen families registered in the city of Ibagué (Colombia).

Family	Coverage (cm^2)	Relative Coverage (%)
Physciaceae	32,662	64.8
Candelariaceae	10,090	20.0
Parmeliaceae	5646	11.2
Collemataceae	550	1.1
Lecanoraceae	498	1.0
Pertusariaceae	225	0.4
Porinaceae	220	0.4
Chrysothricaceae	157	0.3
Ramalinaceae	139	0.3
Haematommataceae	100	0.2
Arthoniaceae	76	0.2
Graphidaceae	16	<0.1
Thelotremataceae	1	<0.1
Total	50,380	100

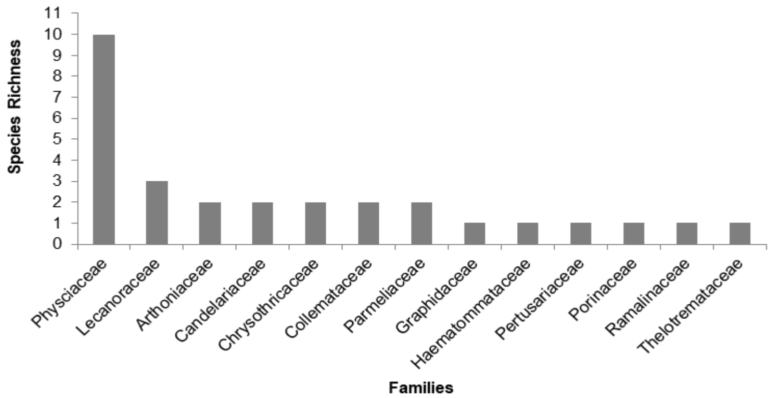

Figure 2. Lichen taxa richness in the families registered in the city of Ibagué (Colombia).

According to the sampling performed, the most abundant lichen in the study area was *Physcia lacinulata* (18,411 cm^2), followed by *Pyxine pyxinoides* (11,822 cm^2), *Candelaria concolor* (5677 cm^2), *Canoparmelia* sp. (5642 cm^2), and *Candelaria* sp. (4413 cm^2) (Figures 3 and 4), which together account for 91% of the recorded cover; the other taxa had less than 3% relative cover (Table 1).

Figure 3. Lichen sampling activities: flank location, DBH confirmation, and sampling grid.

(**A**)

(**B**)

(**C**)

(**D**)

Figure 4. Most abundant taxa registered in the city of Ibagué (Colombia). (**A**) *Physcia lacinulata*, (**B**) *Pyxine pyxinoides*, (**C**) *Candelaria concolor*, and (**D**) *Canoparmelia* sp.

Lichen coverage and taxa richness were higher in the urban area (25,854 cm^2, 24 spp.) in contrast to the peri-urban area of the city of Ibagué (24,526 cm^2, 23 spp.). According to the Jack 1, Jack 2, and Bootstrap estimators, the representativeness of the sampling was between 63–86% for the urban zone, and 66–87% for the peri-urban zone (Figure 5). The coverage was higher in *T. rosea* phorophytes and lower in *J. caucana*. The richness was similar between *J. caucana*, *M. indica*, and *T. rosea*, and *S. spectabilis* presented the lowest richness. Similarly, the diversity was higher in *J. caucana* and *M. indica*, and lower in *T. rosea* and *S. spectabilis* (Table 3).

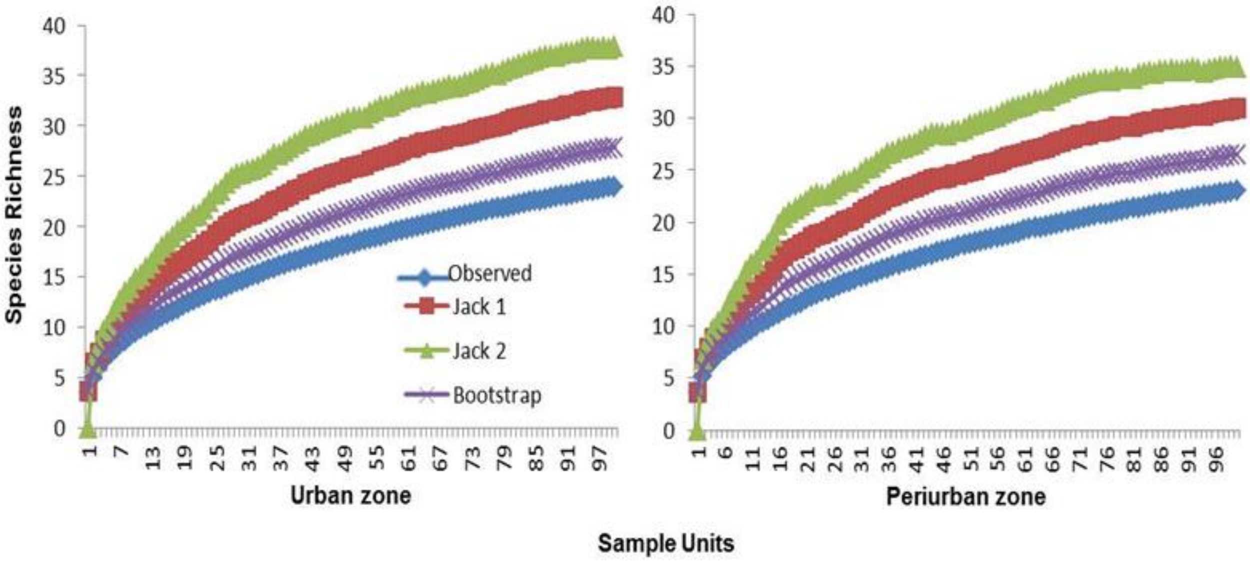

Figure 5. Species accumulation curves for the lichen sampling in the urban and peri-urban areas of the city of Ibagué (Colombia).

Table 3. Ecological parameters in the four species of phorophytes.

Parameter	*Jacaranda caucana*	*Mangifera indica*	*Senna spectabilis*	*Tabebuia rosea*
Richness	18	17	12	17
Coverage	10886	11,451	12,768	15,275
Dominance_D	0.187	0.199	0.293	0.301
Simpson_1-D	0.813	0.801	0.707	0.699
Shannon_H	1.894	1.96	1.558	1.545
Evenness_e^H/S	0.369	0.418	0.396	0.276

The Margalef index was higher in the urban zone (D = 2.26) than in the peri-urban zone (D = 2.18), while the Shannon index was significantly higher in the peri-urban zone ($H' = 1.76$, t = 15.67, $p < 0.0001$) compared to the urban zone ($H' = 1.60$). On the other hand, Simpson's dominance index was significantly higher in the urban zone (D = 0.32, $p < 0.0001$) than in the peri-urban zone (D = 0.25).

The NMDS allowed us to observe the conformation of two lichenic communities associated with the urban and peri-urban zones of the city, although there was overlap (Figure 6). These communities were significantly different (Permanova, $p < 0.05$), showing that the zone factor exerts an important effect on the composition and structure of the assemblages. The composition also varied among the phorophyte species, although *J. caucana* with *M. indica* and *S. spectabilis* with *T. rosea* showed no significant differences (Table 4). Variation in the composition was strongly associated with the total cover, mean, and SD (r = 0.5).

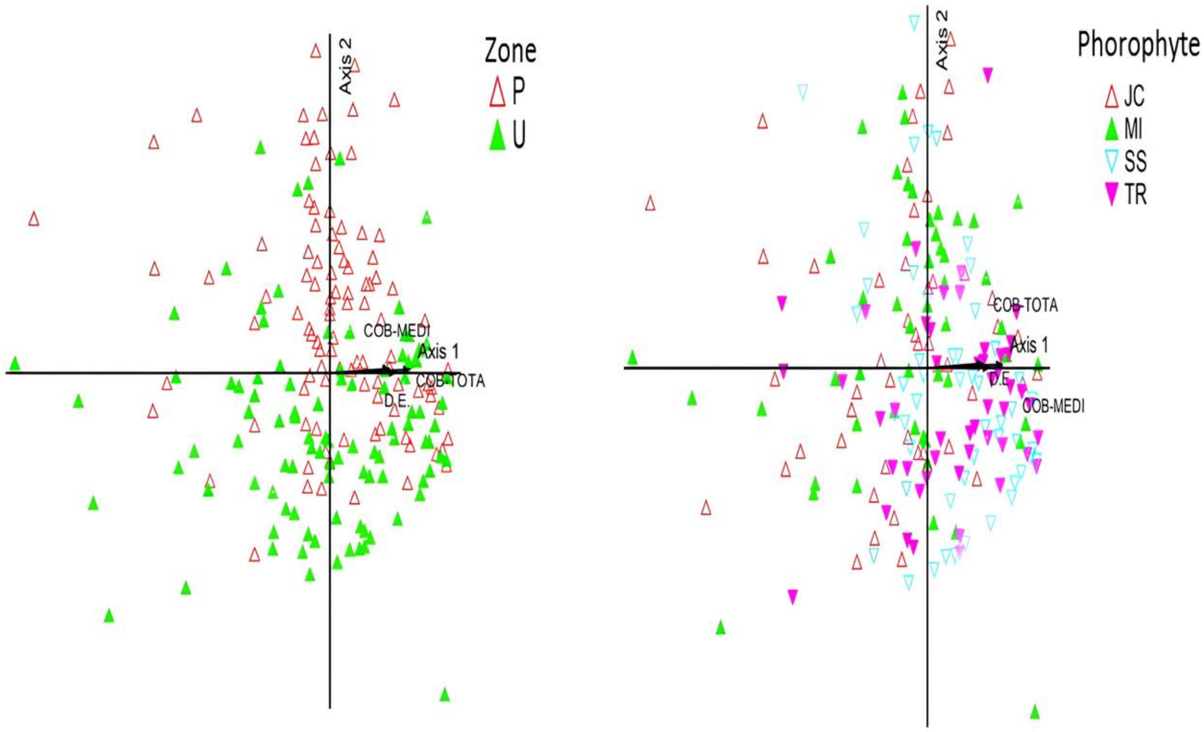

Figure 6. Non-metric multidimensional scaling (NMDS) for zone and phorophyte. Urban (U) and peri-urban (P) zone. *Jacaranda caucana* (JC), *Mangifera indica* (MI), *Senna spectabilis* (SS), *and Tabebuia rosea* (TR).

Table 4. Permanova two-way analysis for zone and phorophyte.

Source	Observed F	Mean F	SD	P
Phorophyte	7.31	1.00	0.00	0.00 *
Zone	48.67	1.01	0.00	0.00 *
Interaction	2.11	1.00	0.01	0.02
	Comparison		t	P
JC	vs.	MI	15,866.00	0.02
JC	vs.	SS	18,651.00	0.01 *
JC	vs.	TR	27,707.00	0.00 *
MI	vs.	SS	26,917.00	0.00 *
MI	vs.	TR	35,092.00	0.00 *
TR	vs.	SS	14,432.00	0.08

Note: *Jacaranda caucana* (JC), *Mangifera indica* (MI), *Tabebuia rosea* (TR), and *Senna spectabilis* (SS). * Significant differences ($p < 0.05$).

The taxa *Chrysothrix chlorina*, *Haematomma leprarioides*, *Phaeophyscia pusilloides*, *Physcia krogiae,* and *Physcia* sp.1 were found exclusively in the urban zone, while *Herpothallon* sp., *Chrysothrix* sp., *Fissurina* sp., *Parmotrema* sp., and *Chapsa albida* were recorded only in the peri-urban zone. The indicator taxa analysis suggests that five taxa were indicators and four marginal indicators for the phorophytes. Seven were indicator taxa for the zones, with three being characteristic of the peri-urban zone (*Canoparmelia* sp., *Pyxine pyxinoides,* and *Ramalina celastri*) and four for the urban zone (*Physcia lacinulata*, *Candelaria concolor*, *Physcia manuelii*, and *Parmotrema* sp.) (Table 5).

Table 5. Analysis of indicator taxa by phorophyte species and zone.

Taxa	Group	(IV) Observed Indicator	Mean from Randomized Groups	*p*	Concept
Physcia lacinulata	*Tabebuia rosea*	35.1	21.4	0.0002	Indicator
Physcia manuelii	*Mangifera indica*	11.9	3.6	0.0006	Indicator
Parmotrema sp.	*Tabebuia rosea*	33.1	18.8	0.001	Indicator
Pyxine pyxinoides	*Mangifera indica*	24.7	18.3	0.018	Indicator
Canoparmelia sp.	*Mangifera indica*	24.9	19.3	0.0364	Indicator
Leptogium sp.	*Mangifera indica*	6.8	3.4	0.0562	Marginally indicative
Lecanora helva	*Senna spectabilis*	6	2.8	0.0586	Marginally indicative
Candelaria concolor	*Tabebuia rosea*	28.5	23.1	0.064	Marginally indicative
Physcia alba	*Jacaranda caucana*	6.8	3.8	0.0732	Marginally indicative
Canoparmelia sp.	Peri-urban	60.6	32.4	0.0002	Indicator
Pyxine pyxinoides	Peri-urban	70.4	30.9	0.0002	Indicator
Ramalina celastri	Peri-urban	7.8	3.8	0.0094	Indicator
Physcia lacinulata	Urban	66.1	37	0.0002	Indicator
Candelaria concolor	Urban	67.9	38.4	0.0002	Indicator
Physcia manuelii	Urban	7.5	3.7	0.0136	Indicator
Parmotrema sp.	Urban	39	30.7	0.018	Indicator

The proposed linear model did not detect a significant effect of the zone on the total cover ($p = 0.2352$), as well as no significant contribution of the covariate elevation on the variability of the observations ($p = 0.6828$), nor a significant interaction of the variables zone x phorophyte ($p = 0.3298$). However, the model showed highly significant differences of total cover between the phorophyte species ($p < 0.0001$), where *T. rosea* was the phorophyte with the significantly higher lichenic cover (*T. rosea*: $\bar{x} = 293.83$, EE = 26.49; *S. spectabilis*:

x̄ = 228.05, EE = 20.23; *J. caucana*: x̄ = 187.19, EE = 17.14; *M. indica*: x̄ = 148.18, EE = 14.33). Likewise, it was observed that the covariates DBH ($p = 0.0073$) and height ($p < 0.0001$) showed a significant contribution to the explanation of the variability in the data.

On the other hand, the model revealed a contribution of each phorophyte to the variability of the observations, such that the use of the covariate individual analyzed as a random effect strongly decreased the Akaike Information Criterion (AIC) values (AIC without random effect = 15,820.9; AIC with random effect = 2544.7), showing furthermore, that not incorporating the random effect of the phorophyte individuals can easily be reflected in the apparent significant effects of the zone on the total lichen cover. Finally, when using richness as a response variable in the model, no significant effects of zone ($p = 0.9139$), phorophyte ($p = 0.2452$), zone x phorophyte interaction ($p = 0.1302$), nor the significant contributions of the covariates DBH ($p = 0.5764$), height ($p = 0.8168$) or elevation ($p = 0.1970$) were found.

Regarding the behavior of the four atmospheric gases evaluated, it was found that the average concentrations were significantly higher in the urban area CO (x̄ = 1.16; n = 25), NO_2 (x̄ = 0.05; n = 25), SO_2 (x̄ = 0.20; n = 25), and O_3 (x̄ = 0.04; n = 25) versus the peri-urban zone CO (x̄ = 0.61; n = 25), NO_2 (x̄ = 0.03; n = 25), SO_2 (x̄ = 0.11; n = 25), and O_3 (x̄ = 0.03; n = 25) (Figure 7).

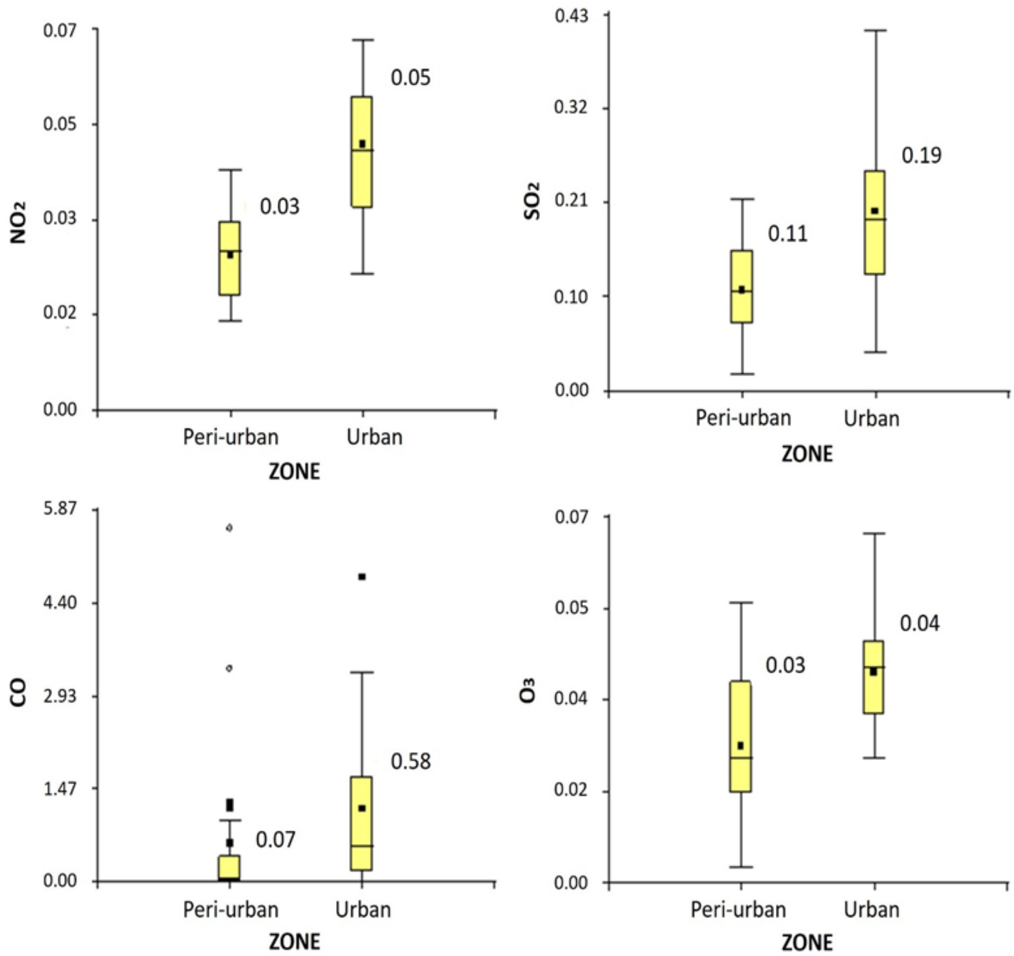

Figure 7. Boxplot of the atmospheric oxide concentrations in the urban and peri-urban areas of the study area. The values represent the average in parts per million (ppm).

With the correlation tests, four taxa presented a significance effect as follows: *Candelaria concolor* correlated positively with NO_2 concentrations (rs = 0.32; p = 0.0247); *Physcia lacinulata* presented a positive correlation with NO_2 (rs = 0.49; $p = 0.0003$), CO (rs = 0.29; $p = 0.0397$), and O_3 (rs = 0. 39; p = 0.0047); *Canoparmelia* sp. showed a negative relationship with NO_2 (rs = −0.46; p = 0.0009) and O_3 (rs = −0.43; p = 0.0020); and *Pyxine pyxinoides* presented a negative relationship with NO_2 (rs = −0.52; p = 0.0001) and O_3 (rs = −0.43; p = 0.0019). Figure 8 shows the differential response of these lichen taxa to the concentrations of the four atmospheric oxides through the PCA, which explained 43% of the total variation in the data in the first three components.

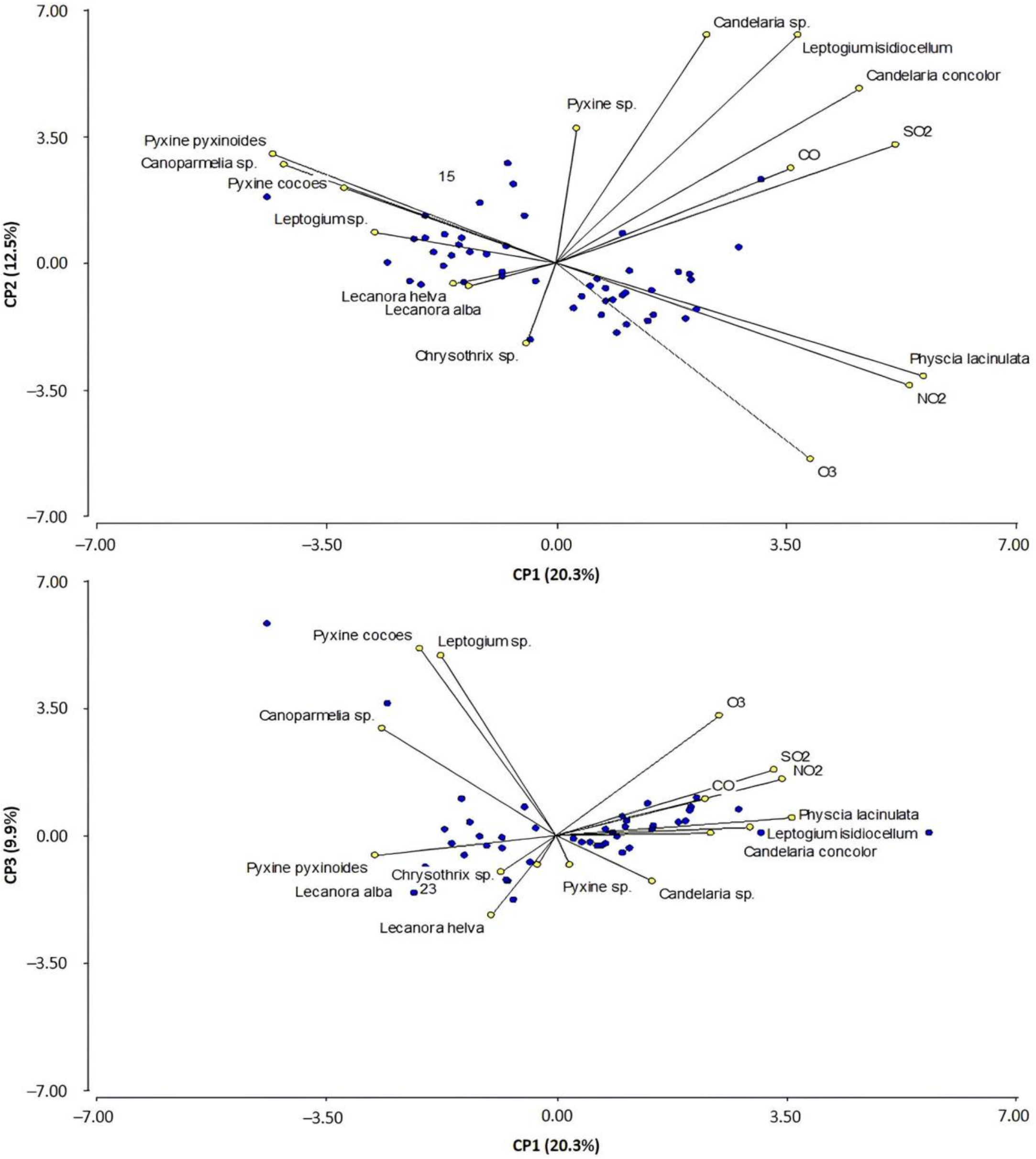

Figure 8. Principal component analysis of the relationship between the atmospheric oxides and lichen taxa.

4. Discussion

The families found in the study area represent 15% of those recorded in the Colombian Cordillera system, 25% of those reported for the Central Cordillera, and 23% of the families known for the sub-Andean region [25]. The Physciaceae family registered the highest richness and coverage, similar to that documented by Aguirre [25], who mentions that the Parmeliaceae, Physciaceae, and Thelotremataceae families present the highest abundance in the Colombian Andean region; in addition, the Physciaceae family is also reported as the most frequent in urban ecosystems such as the metropolitan area of Bucaramanga (Santander, Colombia) [62].

The most abundant species found in this study, *Physcia lacinulata* and *Pyxine pyxinoides*, have scarce records in Colombia according to the review of the information deposited in the Colombian National Herbarium and the Catalog of Plants and Lichens of Colombia [63]. On the other hand, *Candelaria concolor* is a species with a wide distribution and abundance in the Andean region, and like *Canoparmelia* sp., has several records in the other areas of the country [7]. These taxa are generally associated with lowland ecosystems, while in localities above 2500 masl, the genera *Candelariella*, *Cladia*, *Cladina*, *Cladonia*, *Flavoparmelia*, *Flavopunctelia*, *Rimelia*, *Usnea*, and *Xanthoparmelia* predominate [64], and species such as *Parmotrema commensuratum*, *Hypotrachyna meridensis*, and *Phyllopsora confusa* in forest environments [43].

The representativeness of the study suggests that the number of trees sampled was adequate for the evaluation of the corticolous lichen community; however, the incidence-based index yielded values close to 60%, indicating a low frequency of species recording in the sampling units. This result is to be expected considering that lichens are not distributed homogeneously among trees, and show microsite (substrate) preferences, which may affect richness estimates [48,65,66].

The Margalef richness was higher for the urban zone due to the presence of one more taxa inside the city. However, the Shannon index showed higher diversity in the peri-urban zone, a result associated with higher equitability, which translates into similar values of the lichen taxa covered in this zone. On the other hand, the dominance index was significantly higher in the urban zone, which suggests that there are taxa within the city that have greater coverage than the others. For example, in the urban zone, *Candelaria concolor* increased its coverage by 79%, while *Physcia lacinulata* by 61% and *Candelaria* sp. 46%, compared to the peri-urban zone. Ten other taxa *Leptogium* sp., *Physcia manuelii*, *Physcia* sp.2, *Haematomma leprarioides*, *Chrysothrix chlorina*, *Lecanora alba*, *Crypthotecia* sp, *Physcia krogiae*, *Phaeophyscia pusilloides*, and *Physcia* sp.1 also increased their cover within the city.

The two zones presented a high similarity (47–62%) by sharing a high number of taxa; however, the 23% turnover suggests that, despite the proximity between the zones, some conditions such as the concentration of atmospheric oxides, ambient temperature or relative humidity may be favoring a change in the structure of the corky lichen assemblage between the city of Ibagué and its periphery [12]. This is visible not only when evidencing the loss of some taxa within the city, but also when observing the increase in the abundance of taxa, mainly from the Physciaceae family.

The linear models did not detect a significant difference in the total cover or richness of the lichen community between the urban and peri-urban areas of the city of Ibagué. The non-existence of this effect may be related to two aspects: first, likely, the atmospheric conditions in the urban area of the city are not as marked as may occur in larger cities or with greater industry; for example, Atanayaka and Wijeyaratne [23], who conducted the study of lichens in the city of Colombo, Sri Lanka (a city of more than 750 thousand inhabitants), evaluated the lichen community through transects from the city towards the periphery, finding that diversity and coverage increased as they moved away from the urban center. Second, the negative effect that atmospheric components may have on the abundance of some sensitive species could reduce interspecific competition, allowing tolerant species to cover a larger area [67]. This would lead to the effect of the zone being associated with a change in cover at the species level, rather than at the level of total community cover, an approach that is supported by the greater dominance recorded within the city, suggesting the presence of toxitolerant taxa. Similarly, the failure to detect a significant difference in richness suggests that the number of species is not a good indication of the possible effect of the change in conditions between the city of Ibagué and its periphery, probably a consequence of low atmospheric stress, which does not yet generate a decrease in the number of taxa within the city.

Although the linear models failed to detect significant impacts on the averages of the total cover and lichen richness variables, this does not mean that there is no effect on the community. The composition and structure of the lichen assemblages presented a difference greater than that expected by chance, thus proving that despite the size of the city and its low industrialization, the lichen community is different compared to that present in the periphery of the city, with a dissimilarity associated mainly to the change in the abundances of at least three lichen species. *P. lacinulata* and *C. concolor* increased their coverage by more than 50% inside the city, being considered toxilolerant species; on the contrary, *P. pyxinoides* showed a high sensitivity to the urban area, decreasing by 82% in this zone. These data are rightly related to several reported studies that confirm the correlation of the structure of the lichen species assemblage with the concentrations of atmospheric gases, especially NO_2 and SO_2, and highlight the sensitivity and resilience of these symbiont organisms, and their importance as the sensors of global change [68–73].

On the other hand, the phorophyte species significantly influenced the total cover, confirming what was mentioned in the literature about the effect of the substrate on the development of the lichenic cover [74]. Barreno and Pérez [75] mentioned that the chemical and physical characteristics of the bark represent a discriminating factor for lichen species; for example, texture could act as a limiting factor for the composition of lichens, since a smooth bark has less water retention, which can be reflected in low diversity and abundance.

T. rosea presented the development of a higher cover of associated lichen taxa, which can be explained by a higher light input, and given that lichen has been reported as photophilic organisms [75], the foliage cover of *T. rosea* may influence the increase in lichenic cover [41,66]; in contrast, the other phorophytes have denser foliage, which decreases light entry and disfavors lichen settlement.

In the general context, the theory posits that lichen assemblages can function as ideal bioindicators of atmospheric quality [76]; however, there is high variability in the way different taxa respond to the effects of environmental variables, which is why total richness or cover may not show significant changes between zones with apparently differential characteristics.

5. Conclusions

This study represents the first report on the corticolous lichen community assemblage and its relationship with the concentration of atmospheric oxides in the department of Tolima in central Colombia. In this work, it is demonstrated that it is the community structure itself that can be altered, allowing the preliminary identification of tolerant and sensitive taxa. Likewise, the general idea about the phorophyte effect is corroborated, which entails the requirement to adequately control this variable, especially in studies that intend to conclude or compare the atmospheric quality of a site [77]. Likewise, the need to include the random factor of phorophytes in statistical models is emphasized, since the high individual variation can influence the detection of false positives and increase the probability of committing type I errors.

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