

Lichen Biomonitoring of Air Quality Using API, AQI, HII and Environmental Impact in Djelfa, a Semi-Arid Region

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Abstract Air quality in steppe environments can be assessed using lichen biodiversity and environmental variables, which are excellent bioindicators. This study uses biomonitoring techniques to assess and map air pollution levels in the province of Djelfa, while identifying species sensitive to air contamination. The analysis focused on epiphytic corticolous lichens in 36 communes of the province of Djelfa, with samples taken at 121 stations distributed between forests, urban areas and main roads, reflecting different levels of exposure to pollutants. Three indices were used to quantify pollution: the Atmospheric Purity Index (API), the Air Quality Index (AQI) and the Human Impact Index (HII). Twenty-two (22) species of corticolous lichens were identified, mainly foliaceous and crustaceous thalli. The values obtained for the API ranged from (0-44.965), the AQI from (0-27.533) and the HII from (2-28), revealing strong spatial variability, with pollution levels significantly higher in urban and road areas than in forested areas. The results of the statistic analysis (PCA, RDA, Monte Carlo test) demonstrate the influence of environmental factors and arid to semi-arid climatic conditions on lichen diversity, confirming their usefulness as bioindicators, and indicate a marked deterioration in air quality as one moves away from forests. This study contributes to a better understanding of the impact of

human activity on ecosystems in arid environments.

Keywords Air Quality, Biomonitoring, Djelfa, API, AQI, RDA, Lichens

1. Introduction

Air quality has become a major environmental issue [1] due to industrial and road traffic activities; the contamination of ecosystems has harmful impacts on the health of living beings by disrupting the natural balance and compromising our quality of life [2]. To assess these impacts, biomonitoring techniques are implemented [3]. These techniques use living organisms, called bioindicators, to evaluate environmental quality [4]. Lichens, widely distributed across the world [5,6], colonize various substrates [7], particularly tree bark. Each lichen species has specific requirements for ecological and environmental variables [8]. They are sensitive indicators of environmental variations, such as air quality, water availability, and the presence of pollutants [2, 3, 4, 8, 9, 10]. Their sensitive surfaces react quickly to environmental or climatic changes [10-16], making their study relevant for

providing insights into air quality and other environmental parameters [17].

Lichens monitoring thus emerges as an innovative and sensitive strategy for tracking atmospheric pollution [8, 18], using quantitative methods such as the Index of Atmospheric Purity (API) [19], the Air Quality Index (AQI) [20], the Human Impact Index (HII), and environmental variables [17, 21, 22]. The use of these methods has yielded impressive results in recent years in various parts of the world, particularly in humid and subhumid climates, as evidenced by numerous studies [23-28]. Arid and semi-arid regions are characterized by low rainfall, high temperatures, and nutrient-poor soils, which limit biodiversity to species adapted to these extreme conditions [25, 29, 30, 31]. We explored all 36 municipalities of the Djelfa, a study unprecedented at this scale, although similar research had previously been conducted in a single municipality (the city of Djelfa) [32]. This region hosts a steppe ecosystem where lichen biodiversity remains largely understudied, despite its potential significant role in environmental conservation and ecosystem health.

This study focuses on the lichen biodiversity of the Djelfa province and proposes a statistical analysis of the spatial distribution of lichens, as well as their ecological requirements based on the region's environmental factors. The aim is to deepen knowledge and the use of lichens as bioindicators in biomonitoring by calculating the API, AQI, and HII indices, to assess environmental quality in arid and semi-arid zones, and to establish the interaction between atmospheric pollution and ecosystem functions [33].

2. Materials and Methods

2.1. Study Area

The Djelfa province covers an area of 32,256.35 km² and currently consists of 36 municipalities grouped into 12 districts (Figure 1). The altitudes range from the highest point at 1,613 meters to the lowest point at 150 meters. It has a population of 1,508,535 inhabitants [30]. The climate varies from one municipality to another, generally ranging from arid to lower semi-arid, characterized by cold, frost, and snow in winter, and heat and aridity in summer [29].

2.2. Sampling Procedure

The study area was divided into 53 stations, with each station subdivided into 3 sampling points (approximately 0.5–1 km² apart) and 10 trees analyzed per point. This setup allows for the evaluation of 30 trees per station (3 points × 10 trees). In total, all sampled points cover 121 stations across all municipalities of the province (Figure 1). These stations are distributed across various natural habitats, including forests and wooded areas. This methodological

approach helped ensure a representative coverage of lichen biodiversity and allowed us to improve the accuracy of the results obtained. All species were collected between December 2022 and March 2023, using a knife or simply by hand. The collected lichen species were sorted, packed in envelopes, and identified in the laboratory of the DIFAR Department (Dipartimento di Farmacia) at the University of Genoa, Italy. Identification was carried out by observing the morphological characteristics of the thallus under a microscope, as well as the size and color of the spores, and by using identification keys: the site (Italic 8.0) and other works by lichenologists [20, 28, 32, 34-42].

2.3. Index Calculations

A statistical approach was adopted to identify the interactions between lichens and their environment, using three (03) specific indices: API, AQI, and HII.

2.4. Calculation of API

The Atmospheric Purity Index (API) was calculated using the method of LeBlanc & De Sloover [19], taking into account pollution levels (see Table 1). It was determined as follows [28, 43, 44, 45]:

$$API = (1/10) \sum Qi * Fi$$

- Fi: Abundance of each species
- Qi: Ecological index of each species
- ni: Number of species

To calculate the ecological index (Qi) for each species, it is necessary to determine its accompanying species (co-occurring species) and the species total presence (PT). The formula for Qi is as follows:

$$Qi = \frac{\sum (\text{accompanying species})}{PT (\text{total presence of the species})}$$

Where:

Accompanying species: refers to all species found in the same plots as the target species.

Total presence (PT): the number of occurrences or plots where the species is present.

2.5. Calculation of AQI (Air Quality Index)

The Air Quality Index (AQI) was calculated as follows:

$$AQI = \frac{\sum \text{the average frequencies of each species}}{\sum \text{the number of trees}}$$

To classify the results based on the degree of atmospheric pollution, the air pollution scale developed by Kirschbaum and Wirth was used [20], as outlined in (Table 2). This scale is divided into six (06) categories, ranging from 0 to over 50. Here, air pollution is inversely proportional to the AQI value: the higher the AQI value, the lower the atmospheric pollution.

2.6. Calculation of the Human Impact Index (HII)

This index, also called the rating index, was proposed by Gombert [22] to characterize environmental variables. The data on environmental variables were collected from field observations. We used the following environmental variables: vegetation cover, urbanization, number and

distance of roads, and highways; described by Ghennam [47], this index is defined as follows:

$$\text{Rating Index} = I (E + M + O)$$

Where: I: Influence criterion, E: Exposure criterion, M: Environment criterion, O: Openness criterion

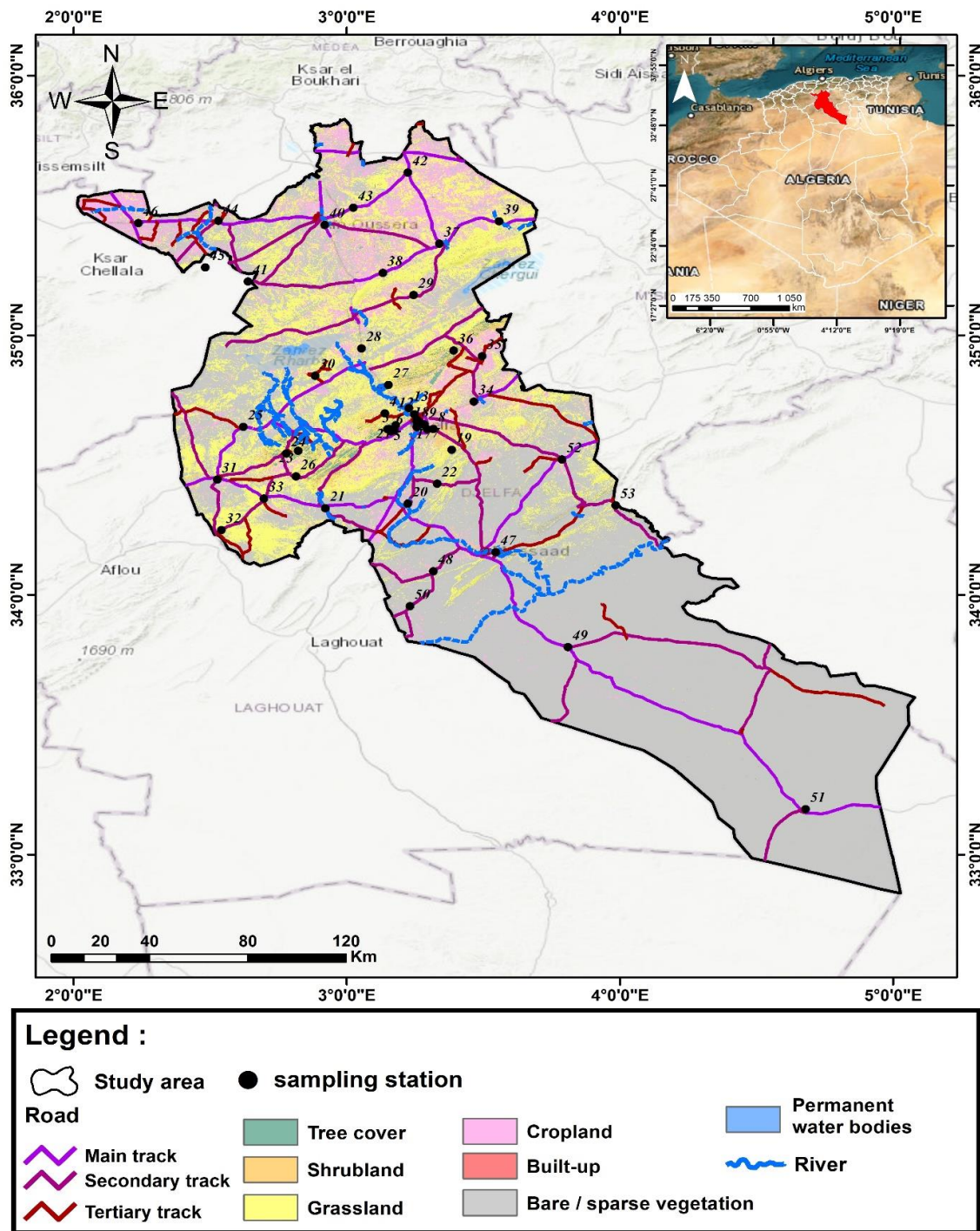


Figure 1. Sampling Points in the Study Area

Table 1. Air Quality Levels According to API [46]

Level A	$0 \leq \text{API} \leq 12,5$	Very high level of pollution
Level B	$12,5 < \text{API} \leq 25$	High level of pollution
Level C	$25 < \text{API} \leq 37,5$	Moderate level of pollution
Level D	$37,5 < \text{API} \leq 50$	Low level of pollution
Level E	$\text{API} > 50$	Very low level of pollution

Table 2. Atmospheric Pollution Scale [20]

AQI Values	0	0-12.5	12.5-25	25-37.5	37.5-50	>50
Atmospheric Pollution	Extremely High	Very High	High	Moderate	Low	Very Low

Table 3. Coding of Environmental Variables [47]

Criterion	Variable	Modalities			
I	Influence criterion	Rural (D = 1,2) 1	Suburban (D = 3,4) 4	Urban (D = 5,6) 4	
E	Exposure criterion	Distance from a traffic route (F = 1,2) 0		Proximity to a traffic route (F = 3,4,5,6) 1	
M	Environment criterion	Field 1	Large park 2	Square – subdivision 3	Roadside parking 4
O	Openness criterion	Isolated trees (C=1) 1	Aligned trees (C=2) 1	Grouped trees (C=3,4,5,6) 2	

2.7. Statistical Analysis Methods

• **Principal Component Analysis (PCA)**

PCA is a statistical method that simplifies multivariate data by transforming it into uncorrelated principal components, thereby reducing its complexity. This enables the identification of hidden patterns within the data [48]. PCA was performed on the rearranged data matrix to reveal the underlying structure of the dataset [49]. In this study, it was used to assess air quality using indices (API, AQI, HII) and environmental factors (CO, CE, CI, CM) (Table 3) and to identify homogeneous groups of sites.

• **Redundancy Analysis (RDA)**

RDA predicts a set of dependent variables (Y) from factors extracted from independent variables (X) [51]. Redundancy analysis is an asymmetric method that links a response matrix (Y) to an explanatory matrix (X). It combines linear regression ($\hat{Y} = X[X'X]^{-1} X'Y$) followed by

a PCA to project sites, response variables, and explanatory variables onto the same graph, simplifying interpretation. The significance of the axes and predictors is assessed using permutation tests [51, 52].

In our study, RDA was used to test, quantify, and visualize the influence of explanatory environmental variables (CE, CI, CM, CO), indices (API, AQI, HII), and atmospheric pollution on the response variable lichen biodiversity (Y).

• **Monte Carlo Permutation Test**

The Monte Carlo permutation test is commonly used in RDA. It involves permutation-based testing (e.g., 999 permutations) to assess the significance of the relationships between explanatory variables (X) and response variables (Y) [53].

In this study, we applied this test to validate the robustness of the RDA by confirming that the relationships between the explanatory variables and the response variable were statistically significant ($P < 0.05$).

3. Results and Discussion

3.1. Lichen Diversity

The sampling of lichens from 121 stations in the Djelfa region allowed us to identify a total of 22 species of corticolous epiphytic lichens (Table 4, Figure 2). It is noted that the dominant species are: *Xpa*, *Rfu*, *Pai*, *Hsc*, *Cal*, *Lar*, and *Lch*. The species *Pte* and *Had* are considered rare.

3.2. Results of Calculated Indices

We can distinguish the state of the air of the communes according to the variations of the values of the indices which is between min-max as follows (e.g., Table 5): HII (2-28); API (0-44.96); AQI (0-27.53). According to this variation, we note that the API values vary between the first 4 levels of air quality (level A, B, C, D) (Table 1), and the

same thing for the air quality index varies between the first 4 classes: from extremely high pollution to average pollution (Table 2). We observe a positive relationship between the air quality indices (API and AQI) as shown in (Table 6). The municipalities with the highest API and AQI values, considered less polluted, are Dj, Mdj, and Chrf, with values of 44, 37, and 32 for API, and 27, 22, and 15 for AQI, respectively. The lower index values are observed in the following municipalities: ACHD, AMR, ANFK, DLDL, DOS, GRN, HFDL, HLCH, MLLH, SIDLAJ, SLMN, and ZCR (Figures 3, 4, 5).

The distribution of API and AQI in Figure 4 and Figure 5 shows that the higher values of both indices are generally found in areas near forests and far from urban centers and roads. We observe that the further we move away from environmental factors (such as urbanization and traffic), the better the air quality becomes.

Table 4. Ecological Index and Total Presence of Species, Djelfa 2023-2024

Scientific Name of the Species	Abbreviations	Qi	Pt	P (%)	Class
<i>Xanthoria parientina</i>	<i>Xpa</i>	6,81	54	12,30	1
<i>Rinodina cf.furfuracea</i>	<i>Rfu</i>	7,61	46	10,48	1
<i>Physcia aipolioides</i>	<i>Pai</i>	7,80	41	9,34	1
<i>Hypocenomyce scalaris</i>	<i>Hsc</i>	7,82	38	8,66	1
<i>Lecanora allophana</i>	<i>Cal</i>	7,82	38	8,66	1
<i>Lecanora argentata</i>	<i>Lar</i>	8,68	37	8,43	1
<i>Lecanora chlorotera,sbsp:meridionalis</i>	<i>Lch</i>	8,38	37	8,43	1
<i>Pertusaria leioplaca</i>	<i>Ple</i>	9,83	18	4,10	2
<i>Buellia griseovirens</i>	<i>Bgr</i>	3,11	18	4,10	2
<i>Lecanora allophana</i>	<i>Lal</i>	9,88	16	3,64	2
<i>Tephromela atra</i>	<i>Tat</i>	4,50	14	3,19	2
<i>Lecanora,sp</i>	<i>Lec</i>	9,08	12	2,73	2
<i>Caloplaca sp</i>	<i>Cla</i>	10,91	11	2,51	2
<i>Pertusaria cf.leioplaca</i>	<i>Pfle</i>	10,27	11	2,51	2
<i>Pertusaria hymenea</i>	<i>Phy</i>	11,10	10	2,28	2
<i>Acrocordia gemmata</i>	<i>Age</i>	10,38	8	1,82	2
<i>Caloplaca cerina</i>	<i>Cce</i>	3,71	7	1,59	2
<i>Polyozosia hagenii</i>	<i>Pha</i>	4,29	7	1,59	2
<i>Rinodina sp</i>	<i>Rin</i>	9,40	5	1,14	2
<i>Dentographa decolorans</i>	<i>Dde</i>	4,60	5	1,14	2
<i>Physcia tenella</i>	<i>Pte</i>	11,00	3	0,68	2
<i>Hyperphyscia adglutinata</i>	<i>Had</i>	11,00	3	0,68	2
Shapiro-Wilk normality test		p-value<5%			
Kruskal-Wallis rank sum test		p-value = 0.4589			

Qi: This is the ecological index for each species, calculated as the ratio of the sum of accompanying species present in all studied sites to the total presence of the species calculated [28].

Pt: It represents the total presence of the species across all stations.

p-value: Probability index; if p-value ≤ 0.05, it indicates that the studied effect is statistically significant.

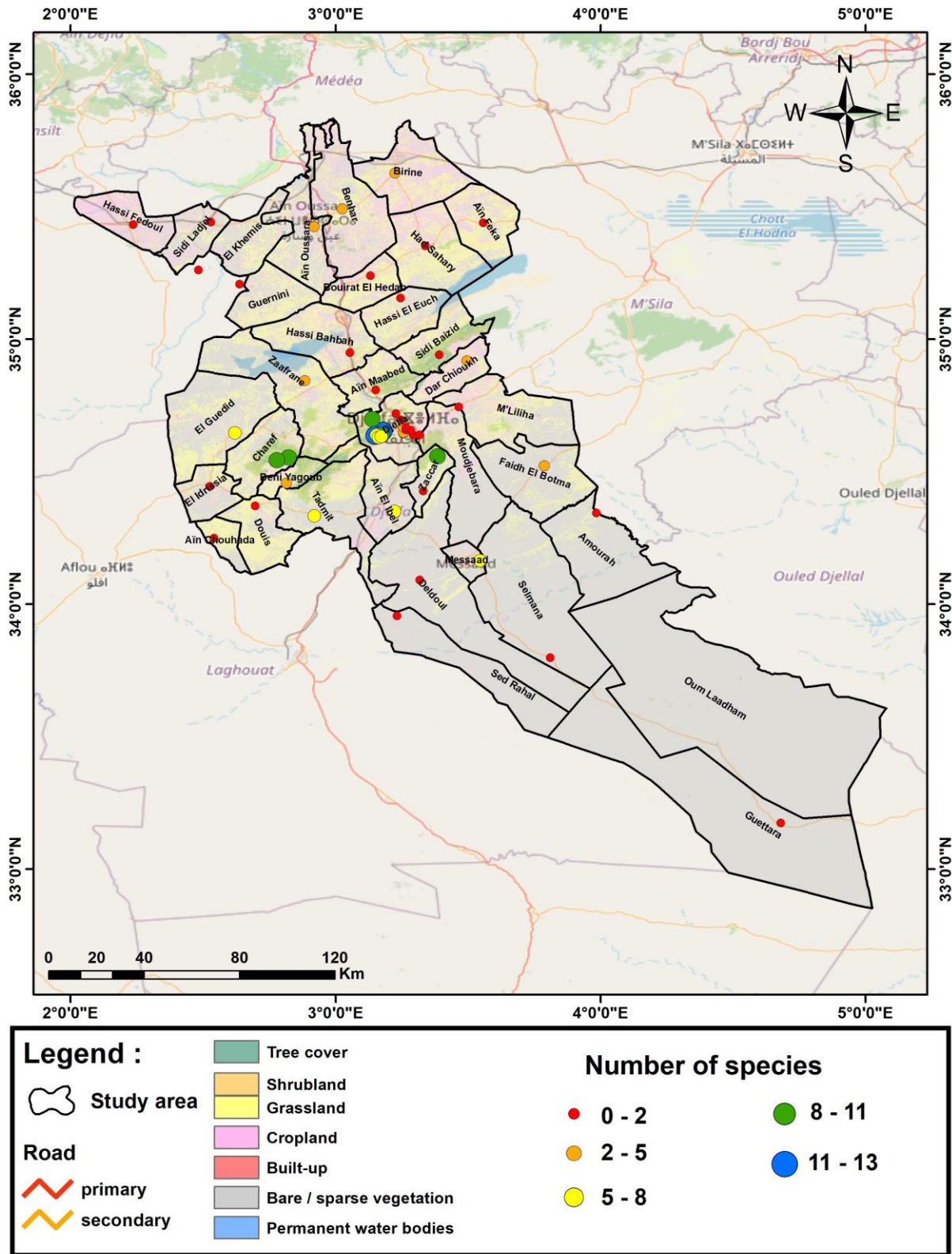


Figure 2. Map of Lichen Species Richness for Each Station

Table 5. Statistical Summary of the indices

Index	Min	Max	Mean
HII	2.000	28.000	9.821
API	0.000	44.965	9.364
AQI	0.000	27.533	5.042

Table 6. Statistical summary of indices by municipality

Municipality	Abbreviation	API			AQI		
		API min	API max	API mean	AQI min	AQI max	AQI mean
Ain ellbel	ABEL	2.28	17.99	9.36	0.70	6.20	2.70
Ain chouhada	ACHD	0.00	0.00	0.00	0.00	0.00	0.00
Amourah	AMR	0.00	0.00	0.00	0.00	0.00	0.00
Ain feka	ANFK	0.00	0.00	0.00	0.00	0.00	0.00
Ain maabed	ANMD	2.82	7.31	5.29	1.70	8.10	4.70
Ain ouessara	ANOUS	0.00	6.78	3.18	0.00	5.10	2.00
Birine	BIRN	0.00	10.86	4.66	0.00	6.40	2.40
Benhar	BNHR	0.00	9.75	3.81	0.00	3.70	1.33
Ben yagoub	BNY	1.56	11.22	6.10	0.20	3.80	1.87
Bouira lahdab	BRLAH	0.00	2.59	1.33	0.00	2.40	1.00
Charef	CHRF	21.21	32.32	28.33	12.83	22.47	16.74
Djelfa	DJ	0.00	44.96	15.20	0.00	27.53	8.68
Deldoul	DLDL	0.00	0.00	0.00	0.00	0.00	0.00
Doius	DOS	0.00	0.00	0.00	0.00	0.00	0.00
Dar chioukh	DRCH	0.00	5.05	1.68	0.00	2.00	0.67
Idrissia	DRIS	0.00	1.83	0.61	0.00	1.40	0.47
Faid elbotma	FDBTM	0.00	6.19	3.91	0.00	3.40	1.97
Guernini	GRN	0.00	0.00	0.00	0.00	0.00	0.00
Gatara	GTRA	0.00	3.04	1.46	0.00	3.50	1.43
Guedid	GUD	0.00	17.04	6.20	0.00	8.40	3.07
Hassi bahbah	HBB	0.00	4.38	1.46	0.00	1.20	0.40
Hassi fdoul	HFDL	0.00	0.00	0.00	0.00	0.00	0.00
Hassi eleuch	HLCH	0.00	0.00	0.00	0.00	0.00	0.00
Had ssahari	HSAH	0.00	0.93	0.31	0.00	1.50	0.50
Elkhmiss	KHMS	0.00	3.22	1.28	0.00	2.50	0.97
Moudjbara	MDJ	28.17	37.46	33.15	11.10	15.40	13.12
Mliliha	MLLH	0.00	0.00	0.00	0.00	0.00	0.00
Messaad	MSSD	0.00	16.97	9.24	0.00	8.00	3.80
Sed rahal	SDRHL	0.00	0.00	0.00	0.00	0.00	0.00
Sidi baizid	SIDBAZ	1.36	4.97	3.54	0.40	3.20	1.90
Sid laadjel	SIDLAJ	0.00	0.00	0.00	0.00	0.00	0.00
Salmana	SLMN	0.00	0.00	0.00	0.00	0.00	0.00
Taadmit	TDM	5.53	14.82	9.46	0.80	4.90	2.57
Zaafra	ZAFR	0.00	4.54	2.13	0.00	4.00	1.53
Zacar	ZCR	0.00	0.00	0.00	0.00	0.00	0.00

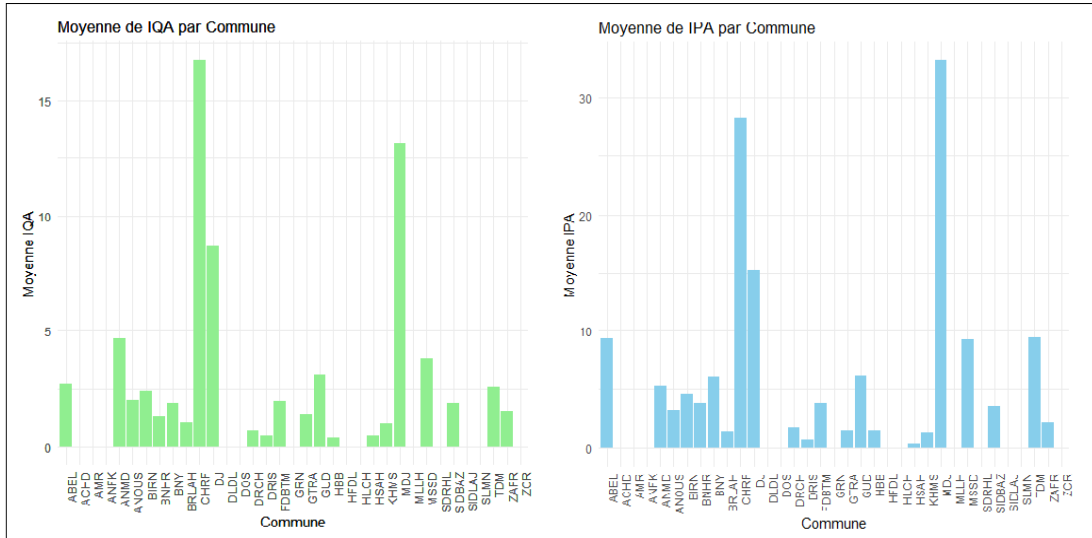


Figure 3. Mean of API and AQI by municipality

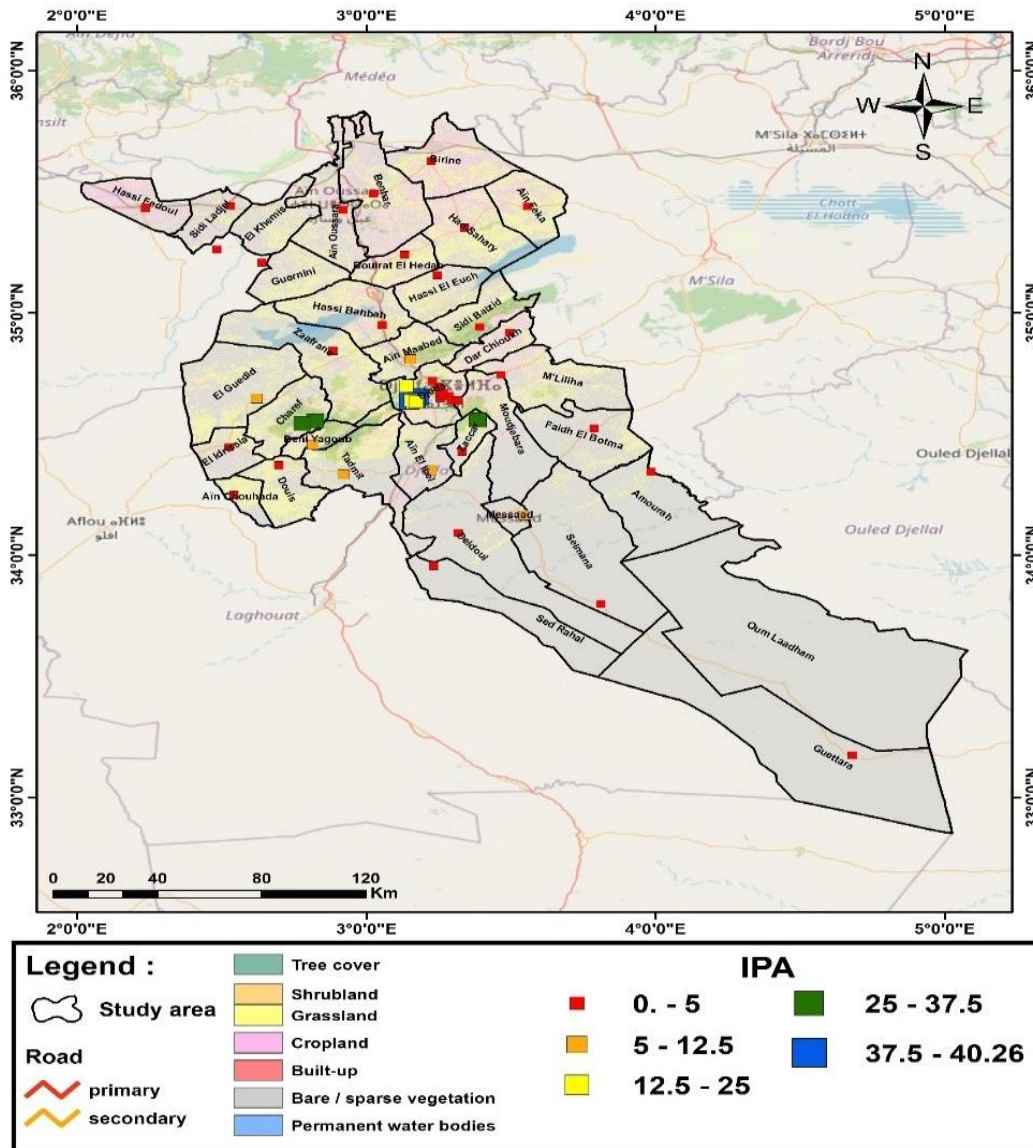


Figure 4. Air quality map calculated using the API index by station

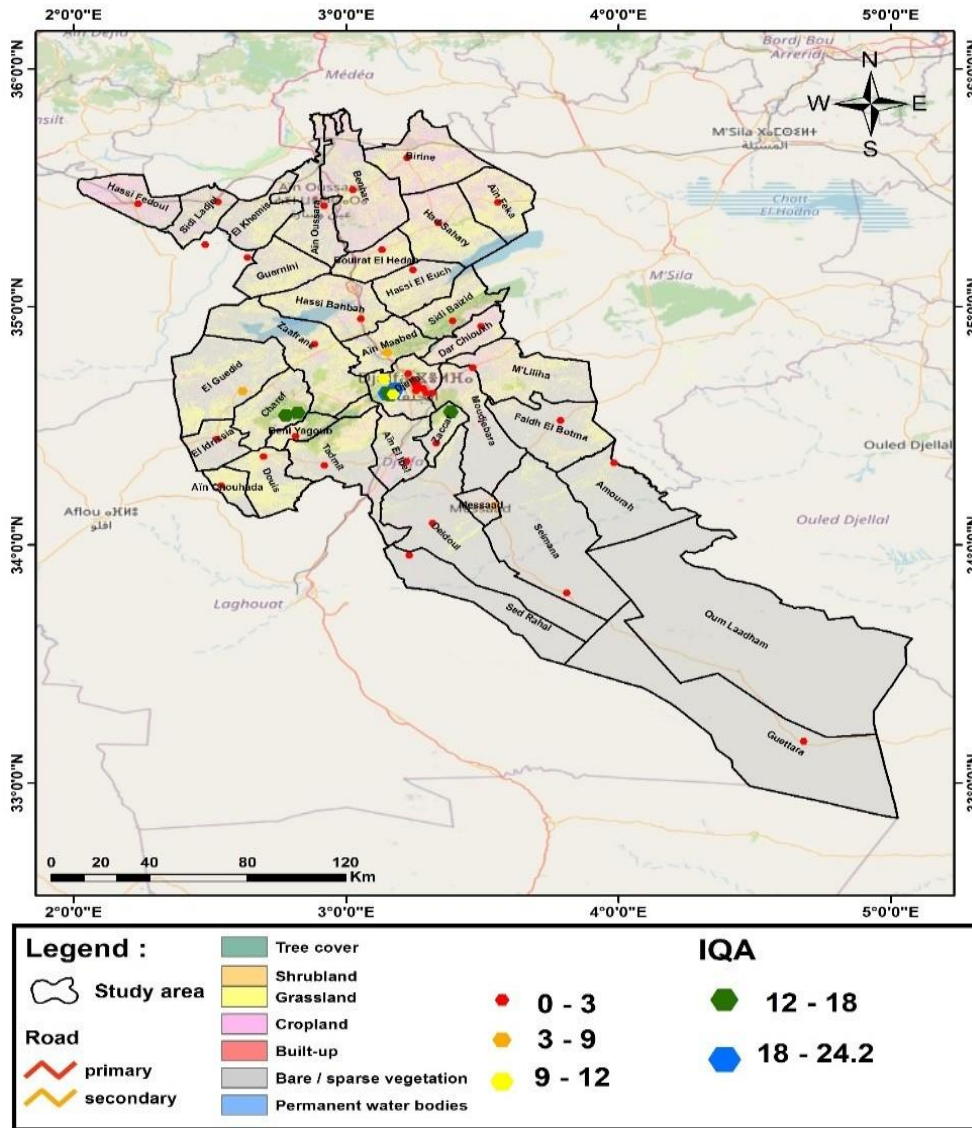


Figure 5. Air quality map calculated using the AQI method by station

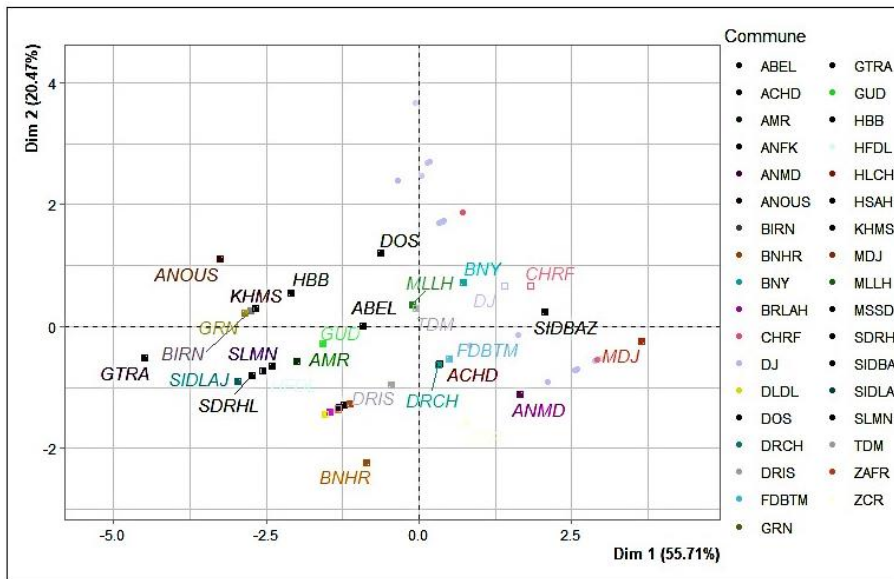
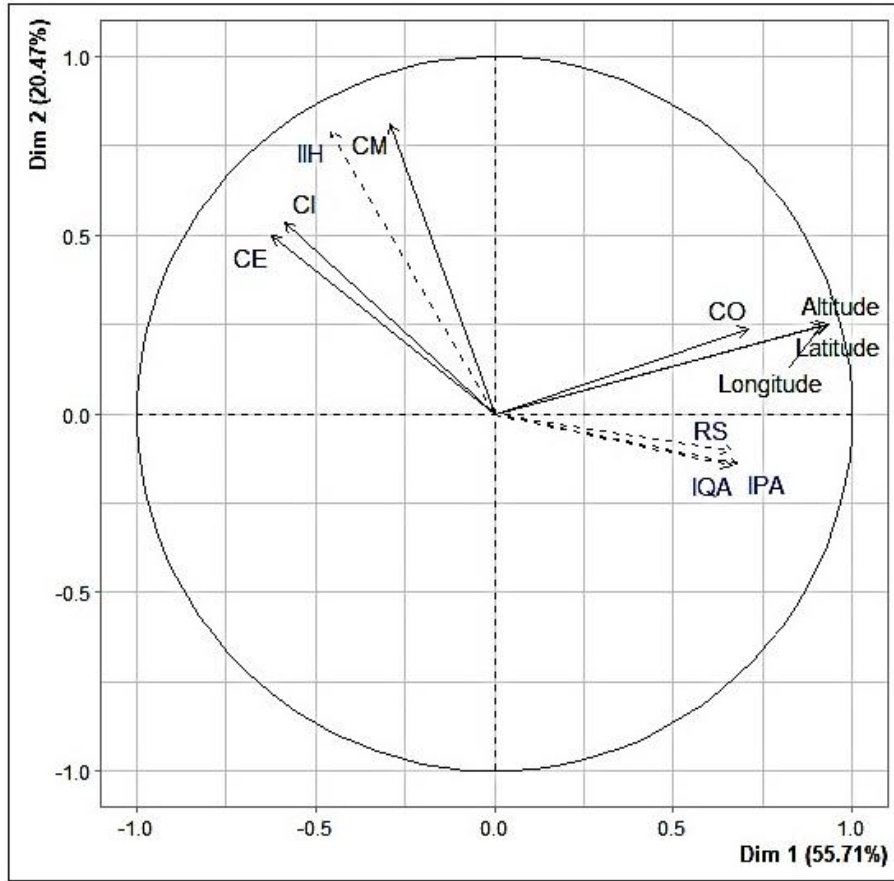
3.3. Study of the Relationship between API, AQI, and HII Indices, Species Richness, and Environmental Factors by Different Analyses PCA, RDA, The Monte Carlo Test

Principal Component Analysis

To determine the different levels of air quality in the Djelfa province region and to identify groups of homogeneous sites, a Principal Component Analysis (PCA) was conducted on 121 sites based on the coupling of bioindication indices and environmental factors (Fig 6 (a)). The inertia rate is (76.18%), which means the total explanation of the PCA informations; according to axis Dim1 (55.71%), there is a strong positive correlation between the API, AQI indices and species richness, as well as the same positive relationship between altitude, latitude, longitude, and vegetation cover (CO). On the other hand, the human impact index (HII) and environmental factors

(CE, CI, CM), already explained in (Table 3), show a negative correlation with API, AQI and species richness (RS). Axis Dim2 (20.47%) shows a positive relationship between the HII and the factors CE, CI, and CM. The second graph explains the influence of bioindication indices and environmental factors on 36 municipalities. It reveals that the municipalities (MDJ, ANMD, DRCH, ACHD, FDBTM, SIDBZ, CHRf, DJ, TDM, BNY) have significant species richness and high API and AQI values. In contrast, the municipalities (HBB, DOS, ANOUS, ABEL, AMR, GTRA, SDRHL, SIDLAJ, BNHR, and others) have low API and AQI values and reduced species richness (RS) (Fig 6 (b)).

The correlation matrix explains one more time the PCA by detailing the coupling between the indices, such as: a strong positive correlation between (HII, CI) and (HII, CM), as well as between (API, AQI) and (RS, API, AQI) (Fig 6 (c)). A negative correlation is observed between (API, AQI, RS with CE) and (API, AQI, RS with HII).



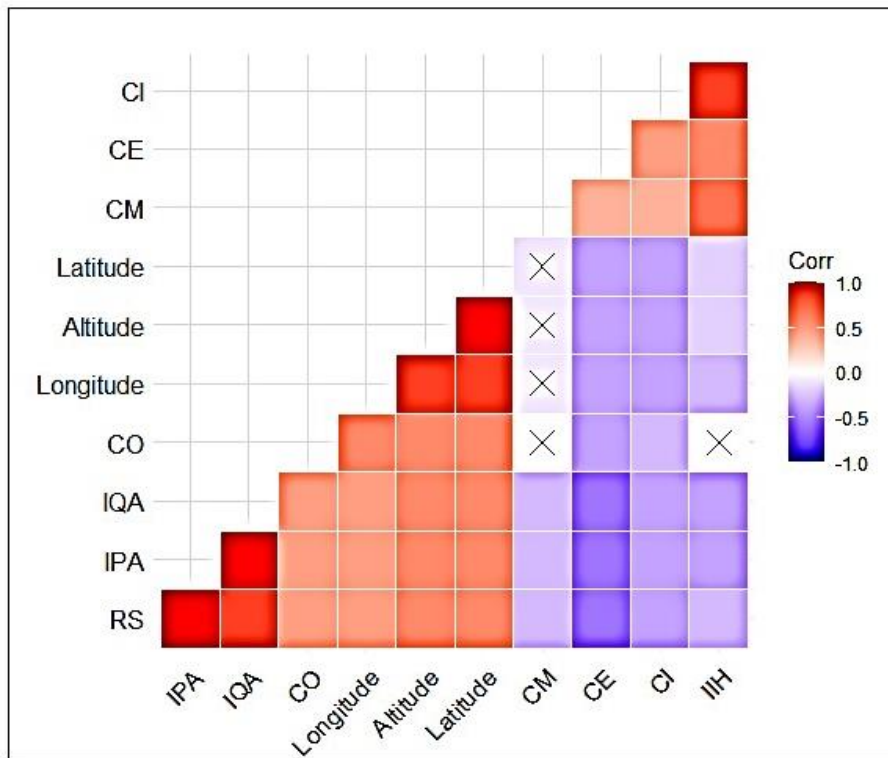


Figure 6. (a) PCA (Principal Component Analysis), (b) HCA (Hierarchical Cluster Analysis), (c) Correlation matrix

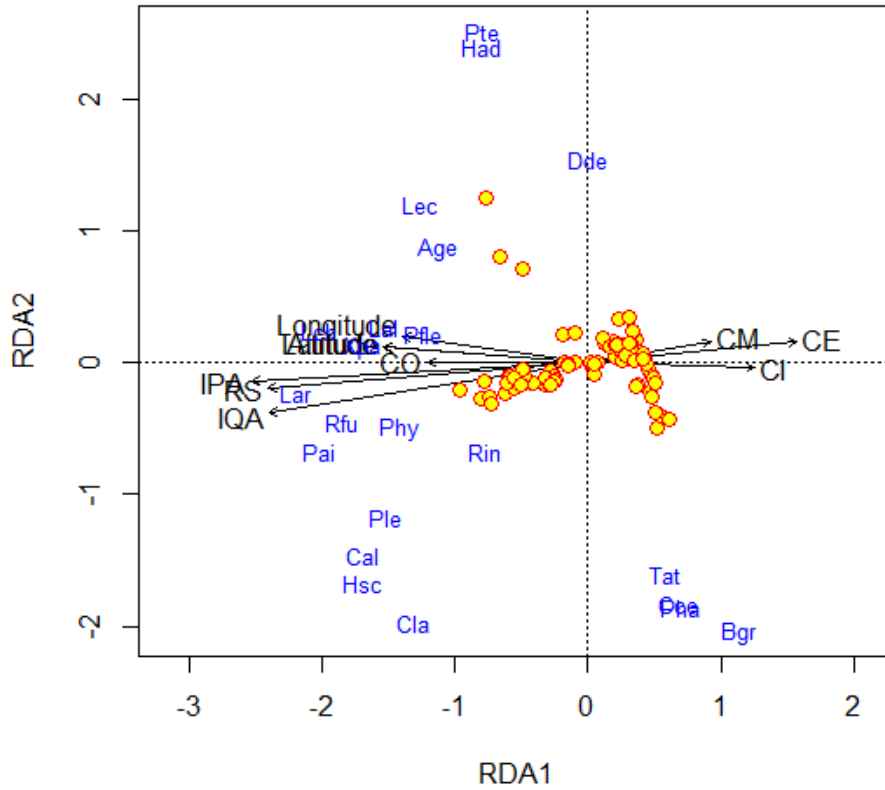


Figure 7. Redundancy Analysis (RDA)

- **Redundancy Analysis (RDA) of the effect of indices and environmental factors on lichen species**

According to the redundancy analysis (Figure 7), it can be observed that species richness, API, and AQI are positively linked with the following species: *Lar, Rfu, Phy, Pai, Ple, Cal, Cla, Pfle, Rin, Hsc, Age*, and others. Conversely, they are negatively correlated with the species *Tat, Bgr, Pha*, and *Cce*. These latter species show a positive relationship with environmental factors (CM, CE, CI).

- **The Monte Carlo test**

The API and AQI values play a crucial role in explaining the variability of the data. These two variables have the highest values, 76.01 for API (Table 7) and 69.01 for AQI, indicating a high observed variability in our data. Additionally, the AIC values are relatively low, suggesting that our model is well-fitted. However, certain variables such as CM, although statistically significant (p-value = 0.005), have significantly lower F-statistic values (6.36), suggesting that they contribute less to explaining the fluctuations in the data. This indicates that their influence is less significant compared to API and AQI. In summary, although all variables in the study are significant, API and AQI stand out due to their strong explanatory power. Other variables, despite their relevance, have a less substantial impact.

Table 7. Monte Carlo test

	Df	AIC	F	Pr(>F)
IPA	1	246.11	76.0111	0.005
AQI	1	249.85	69.0121	0.005
RS	1	252.62	64.0315	0.005
CE	1	279.06	24.2037	0.005
Altitude	1	283.37	18.8476	0.005
Latitude	1	283.53	18.6607	0.005
Longitude	1	286.54	15.0927	0.005
CI	1	288.11	13.2854	0.005
CO	1	289.52	11.6962	0.005
CM	1	294.42	6.3697	0.005

With: Df (Degrees of freedom): These degrees represent the number of explanatory variables tested to explain the response variable, or the number of independent constraints influencing a statistical estimate.

AIC (Akaike Information Criterion): This criterion measures model quality – the lower its value, the better the model, and vice versa.

F (Fisher test): This F-test value indicates how much a variable explains the response variable's variance - the higher the value, the greater the explanatory power.

Pr (p-value): This p-value indicates that the observed effects are highly significant.

4. Discussion

Arid and semi-arid regions in Algeria are poorly studied in terms of lichen flora, as evidenced by this research:

Tiaret [54]; Setif [55, 56]; Bourj bou arerij [57]; Djelfa [32]. A corticolous lichen list has been established for the second time in the Djelfa region, where 22 corticolous epiphytic lichen species were recorded (Table 4). This follows the work of [32], which documented 13 corticolous species among 44 saxicolous and terricolous species.

Studies on lichen flora in urban areas in Algeria are limited and primarily focus on natural environments, such as forests and parks. In this study, we worked not only in natural environments but also, and especially, in urban and agricultural areas, as well as along roads. The results obtained are similar to those found in France [58, 59]; Portugal [60]; Italy [11, 61] and also in India [62].

A rich epiphytic diversity, with high species diversity, is found particularly in forested stations far from pollution sources. Similar observations have been reported by [13, 62]. A decrease in species diversity is observed in other municipalities due to high levels of urbanization, agricultural and industrial activities, as well as road traffic density, which contribute to this decline [22, 62, 63, 64].

On the other hand, wind-borne pollution may be another source affecting stations in the region, limiting the spread of epiphytic species and reducing their abundance and diversity values [57, 65].

The highest values of API and AQI were recorded in the commune of Djelfa reaching 44.96, 27.53 respectively, located exactly at Senelba forest with 13 corticolous species. This forest station is separated from the rest of the stations studied, with a rich diversity and a moderately pure air quality, followed by the stations of Charef, Moudjbara, which are characterized by a rather moderate air quality (average). The stations of Ain elbel, Messaad, Guedid have a high level pollution, with a low diversity of lichens. The PCA coupling results revealed a strong positive correlation between API, AQI and species richness.

Among the 29 other municipalities, most exhibit high pollution levels according to the standard of API (Table 1) and the standard of AQI (Table 2). These areas also show a low lichen diversity, indicated by positive correlations between the HII and environmental factors and negative correlations with species richness, API and AQI. This pattern is likely due to harsh climatic conditions (altitude, dominant winds) [32], proximity to urban areas, anthropogenic activities, and roads. These environmental factors contribute to a maximum HII value of 28 (Table 5), reflecting significant human pressure.

Redundancy Analysis (RDA) substantially simplifies data interpretation and improves the understanding of relationships between explanatory variables (including API, AQI, and environmental factors) and the response variable (lichen biodiversity). The results confirm both the accuracy and reliability of the Principal Component Analysis (PCA) outcomes.

The application of the Monte Carlo permutation test to the complete dataset enables assessment of the statistical significance of explanatory and response variables through calculated indices (AIC, F-statistic, and p-values).

To our knowledge, no prior study in lichenology has combined RDA with Monte Carlo testing before our research.

The results of the API obtained in our analysis are similar to those described in the literature, particularly in Algeria within the same bioclimatic zone [32, 56, 57], and in humid Mediterranean climates [23, 42], and in various parts of the world [59, 62, 66, 67].

Studies on the rating index or HII (Human Impact Index) remain limited in Algeria. This index is a tool used to assess the influence of human activities on the environment, taking into account environmental factors (CO, CI, CE, CM). It also allows for the analysis of air quality and its impact on public health. The study by [17, 42] conducted in Algiers (Algeria), despite climatic differences, shows results similar to ours.

5. Conclusions

In this study 22 corticolous species of epiphytic lichens were identified, among which foliose and crustose lichens were the most common in the region. The pollution indicator indices (API and AQI) showed a clear correlation with each other and a significant difference between the environmental variables of the HII, urban areas, agricultural zones and roadside stations, which exhibited very high levels of air pollution. The use of epiphytic lichens as bioindicators plays an important role in determining air quality across all municipalities of Djelfa. Through this bio-monitoring, we demonstrated that the majority of the municipalities belong to zone 5 (red), where air pollution is very high.

REFERENCES

- [1] World Health Organization (WHO), "Review of Evidence on Health Aspects of Air Pollution e REVIHAAP Project. Technical Report", Regional Office for Europe, Copenhagen, Denmark, 2013, pp. 1-163. http://www.euro.who.int/__data/assets/pdf_file/0004/193108.
- [2] Abas A, "A systematic review on biomonitoring using lichen as the biological indicator: A decade of practices, progress and challenges". *Ecological Indicators, Ecological Indicators*, vol. 121, p. 107197, 2021. DOI: 10.1016/j.ecolind.2020.107197.
- [3] Agnan Y, "Lichens: witnesses to atmospheric pollution". *Futura Sciences*. France, no. 1900, pp 1-10, 2021. <https://www.futura-sciences.com/planete/dossiers/environnement-lichens-temoins-pollution-atmospherique>
- [4] Van Haluwyn C., Asta J., Gaveriaux J., "Guide to lichens in France: tree lichens". Ed Belin, Paris., France, 2013. pp. 1-239.
- [5] Gilbert O, "Lichens". *Harper collins publisher*, New York, USA, 1998. pp. 1-46.
- [6] Lücking R, "Predicting species richness in tropical lichenized fungi with 'modular' combinations of character states". *Biodiversity and Conservation*, vol. 21, pp. 2341-2360, 2012. DOI: 10.1007/s10531-011-0217-7
- [7] Stephenson S L, "The kingdom fungi". *Timber Press, Inc.* Second Avenue, Suite 450 Portland, Oregon, 2010, pp. 1-3527.
- [8] Counouy H, "Bioindication of air quality by lichens in Louvain-la-Neuve Biodiversity inventory and participatory science approach", UCLouvain Faculty of Bioscience Engineering, Belgique, 2022, pp. 1-73.
- [9] Van Haluwyn C, Lerond M, "Guide of lichens". Ed Lechevalier, Paris, France, 1993. pp. 1-178.
- [10] Nash T H I. (Éd.), "Lichen biology". *The Lichenologist*, vol. 41, no. 6, pp. 1-50, 2009. DOI: 10.1017/S0024282909009219.
- [11] Giordani P, "Is the diversity of epiphytic lichens a reliable indicator of air pollution? A case study from Italy". *Environ Pollut*, vol. 146, pp. 317-323, 2007. DOI: 10.1016/j.envpol.2006.03.030.
- [12] Loppi S, "Lichens as sentinels for air pollution at remote alpine areas (Italy)". *Environ Sci Pollut Res*, vol. 21, pp. 2563-2571, 2014. DOI: 10.1007/s11356-013-2181-0.
- [13] Agnan Y, Probst A, Ségalon-Delmas N., "Evaluation of lichen species resistance to atmospheric metal pollution by coupling diversity and bioaccumulation approaches: A new bioindication scale for French forested areas", *EcolIndicat*, vol. 72, pp. 99-110, 2017. DOI: 10.1016/j.ecolind.2016.08.006.
- [14] Loppi S., "May the diversity of epiphytic lichens be used in environmental forensics". *Diversity*, vol. 11, no. 36, pp. 1-13. 2019. DOI: 10.3390/d11030036.
- [15] Nelsen M P, Lücking R, Boyce C K et al, "No support for the emergence of lichens prior to the evolution of vascular plants". *Geobiology*, vol. 18, no. 1, pp. 3-13, 2019, DOI: 10.1111/gbi.12369.
- [16] Nimis P. L, Martellos S, "The Information System on Italian Lichens". Version 6.0. University of Trieste, Dept. of Biology, 2020, pp. 272-281. <http://dryades.units.it/italic>.
- [17] Ghennam K, Attou F, Abdoun F, "Impact of atmospheric pollution on asthma and bronchitis based on lichen biomonitoring using IAP, IHI and GIS in Algiers Bay (Algeria)". *Environ Monit Assess*, vol. 193, article number 198, 2021. DOI: 10.1007/s10661-021-08965-8.
- [18] Dalquier C, "Changes in atmospheric exposure in the Aix-Marseille-Provence metropolitan area using lichen biomonitoring. French Environment and Energy Management Agency". *Institut Pyth à s.*, University Aix-Marseille, 2022. pp. 1-54.
- [19] Le Blanc S. F, De Sloover J. D, "Relation between industrialization and the distribution and growth of epiphytic lichens and mosses in Montreal". *Canadian Journal of Botany*, vol. 48, pp. 1485-1496, 1970. DOI: 10.1139/b70-224.
- [20] Kirschbaum U, Wirth V, "Lichen bio-indicators, Recognising them, assessing air quality". Ed. *Eugen Ulmer*,

- Paris, 1997, pp. 1-128.
- [21] Rahali M., "Study of lead pollution and global pollution in the Algiers region, using lichens as biological indicators". National Institut of Agronomy, Algiers, Algeria, 2003. pp. 1-202.
- [22] Gombert S, Astra J, Seawaed M R D, "Assessment of lichen diversity by index of atmospheric purity (IAP), index of human impact (IHI) and other environmental factors in an urban area (Grenoble, Southeast France)". *Science of the Total Environment*, vol. 324, pp. 183-199, 2004. DOI: 10.1016/j.scitotenv.2003.10.036.
- [23] Yahia N, Marniche F, "Inventory of lichen species and estimation of air quality in the Chré forest massif". *BioRessources.*, vol. 9, no. 1, pp. 38-50, 2019. DOI: 123456789/21152/1/B090105.
- [24] Berrayah M, Maatoug M, Azzaoui M et al, "Biomonitoring of air quality in an urban environment using mosses and lichens: the case of the town of Tlemcen (Algeria)". *European Scientific Journal*, vol. 12, no. 9, pp. 151-163, 2016. DOI: 10.19044/esj.2016.v12n9p151.
- [25] Omar Y, Maatoug M, Ayad N et al, "Bioaccumulation of lead pollution from roads using a moss (*bryum argenteum*) in the town of Tiaret (Algeria): pollution classes and mapping". *European Scientific Journal*, vol. 11, no. 8, pp. 105-121, 2015. <https://eujournal.org/index.php/esj/article/view/5258>
- [26] Ouali alami F-Z, Elabidi A, Mouhir L et al, "Use of lichens as bioindicators of atmospheric pollution by lead, cadmium and zinc in the Rabat-Sale-Zemmour-Zaër region (Morocco)". *Afrique Science*, vol. 10, no. 3, pp. 89-106, 2014.
- [27] Adjiri F, Ramdani M, Lograda T et al, "Bio-Monitoring of metal trace elements by epiphytic lichen in the Bordj Bou Arreridj area, east of Algeria". *Scholars Academic Journal of Biosciences (SAJB)*, vol. 6, no. 2, pp. 199-208, 2018. DOI: 10.21276/sajb.2018.6.2.12.
- [28] Ghennam K, Abdoun F, "GIS biomonitoring of air quality in a Mediterranean city (Algiers), lichen diversity, atmospheric purity index (A.P.I.) and human impact index (H.I.I.)". *Revue d'Écologie*, vol. 72, no. 2, pp. 134-146, 2017. <https://hal.science/hal-03532716v1>.
- [29] Forest Conservation, "Presentation of the forestry sector in the wilaya of Djelfa". *Edition of forest conservation he province of Djelfa*, Algeria., 2015. pp. 1-22.
- [30] Directorate of Programming and Budget Monitoring, "Monograph of the Province of Djelfa. Djelfa", 2018. pp. 1-51.
- [31] Adjiri F, Ramdani M, Lograda T, "Relationship between lichen diversity and air quality in urban region in Bourdj Bou Arriridj, Algeria". *Biodiversitas Journal of Biological Diversity*, vol. 20, no. 8, pp. 2329-2339, 2019. DOI: 10.13057/biodiv/d200831
- [32] Boumakhleb A, "Inventory and Lichenic Diversity of the Djelfa Region - Algeria"; Higher Normal School - Kouba., Algeria, 2021, pp. 1-155.
- [33] Giordani P, "Lichen Diversity and Biomonitoring: A Special Issue". *Diversity*, vol. 11, no. 9, pp. 167-171, 2019. DOI: 10.3390/d11090171.
- [34] Clauzade G, Roux C, "Lichens of Western Europe. Illustrated Identification Guide", Botanical Society of Western France, Royan, no. 7, pp. 1-894, 1985.
- [35] Ozenda P, Clauzade G, "Lichens: Biological Study and Illustrated Flora". Ed. Masson et Cie. Paris. France., vol. 24, no. 4, pp. 633-634, 1970. DOI: https://www.persee.fr/doc/ravec_0040-3865_1970_num_24_4_4821_t1_0633_0000_2
- [36] Emmanuel S, Diederich P, Lambion J, "The Macrolichens of Belgium, Luxembourg, and Northern France: Identification Keys". Ed. MNHN Luxembourg., 2004. pp. 1-188.
- [37] Van Haluwyn C, "What Role and Future Prospects for Plant Biomonitoring in Air Quality Studies in France?". *Air Pur.*, vol. 77, pp. 5-10, 2009.
- [38] Maizi N, Alioua A, Tahar A et al, "The use of inferior plants as bioindicators of automobile lead pollution in the area of Annaba (Algeria) (Utilisation des végétaux inférieurs comme bio indicateurs de la pollution plombique d'origine automobile dans la région de Annaba (Algérie))". *J. Mater. Environ. Sci.*, vol. 1, no. 4, pp. 251-266, 2010.
- [39] Rebbas K, Boutabia L, Touazi Y et al, "Inventory of lichens in Gouraya National Park (Béjaïa, Algeria)". *Phytothérapie*, vol. 9, no. 4, pp. 225-233, 2011. DOI: 10.1007/s10298-011-0628-3
- [40] Ait Hammou M, Maatoug M, Hadjadj Aoul S, "Taxonomic aspects of lichens on Aleppo pine (*Pinus halepensis*) and cypress (*Cupressus sempervirens*) in Guezoul Forest (Tiaret)". *Rev. Ecol. et Environnement.*, vol. 7, pp. 15-26, 2011. <http://dspace.univ-tiaret.dz:80/handle/123456789/8972>
- [41] Roux C, "Checklist of Lichens and Lichenicolous Fungi of France". Bulletin of the Linnean Society of Provence, Spec. Iss. 16, pp. 229, 2012.
- [42] Amrani S, Seaward M, Sipman H et al, "Lichenological exploration of Algeria II: checklist of lichenized, lichenicolous and allied fungi". *Herzogia.*, vol. 31, no. 2, pp. 817-892, 2018. DOI: 10.13158/hea.31.2.2018.817
- [43] Krick R, Loppi S, "The IAP approach. In: Nimis PL, Scheidegger Ch, Wolseley PA (eds). Monitoring with lichens-Monitoring Lichens". *Kluwer Academic Publishers.*, Dordrecht, Netherland., 2002, pp. 21-37.
- [44] Guillaume E, "Comparative study between chemical air analysis and lichen mapping as atmospheric bioindicators in Entre-Sambre-et-Meuse, Belgium". Royal Botanical Society of Belgium, vol. 136, no. 2, pp. 139-144, 2003. DOI: 10.2307/20794525
- [45] Djekic, T., Jaksic, T., Aleksic, G et al, "Epiphytic lichens as indicators of the air quality in the urban part of Pirot city (Southeastern Serbia) 2002-2014". *Oxidation Communications.*, vol. 40, no. 4, pp. 1429-1442, 2017.
- [46] CONTI, M.E. & CECCHETTI, G, "Biological monitoring: lichens as bioindicators of air pollution assessment". *Environ. Pollut.*, vol. 114, pp. 471-492, 2001.
- [47] Ghennam K, "Lichens in the Algiers Region: Study of Their Biodiversity and GIS-Based Biomonitoring of Air Quality". USTHB. University Algiers, Algeria. 2011, pp. 1-148.
- [48] Shaw, P. J. A, "Multivariate Statistics for the Environmental Sciences". Hodder-Arnold, UK. 2003, pp. 233.

- [49] Liu, C.W., Lin, K.H., Kuo, Y.M., "Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan". *Sci. Total Environ.*, vol. 313, no. 1-3, pp. 77-89, 2003. DOI: 10.1016/S0048-9697(02)00683-6.
- [50] Lazraq A, Cleroux R, "Analyse de la redondance robuste [Robust Redundancy Analysis]" *Revue de statistique appliquée*, vol. 53, no. 2, pp. 43-65, 2005.
- [51] Legendre, P, Legendre, L, "Numerical Ecology", Third English, edition, Elsevier, *Developments in Environmental Modelling*, vol. 24, 2012, ISBN: 9780444538680
- [52] Ter Braak, C. J. F, "Canonical Correspondance Analysis: A New Eigenvector Technique for Multivariate Direct Gradient Analysis", *Ecology*, vol. 67, no. 5, pp. 1167-1179, 1986. DOI: 10.2307/1938672.
- [53] Finch W. H, Davenport, T, "Performance of Monte Carlo permutation and approximate tests for multivariate means comparisons with small sample sizes when parametric assumptions are violated". *Methodology: European Journal of Research Methods for the Behavioral and Social Sciences*, vol. 5, no. 2, pp. 60-70, 2009. DOI: 10.1027/1614-2241.5.2.60.
- [54] Ait Hammou M, Miara M.D, Rebbas Kh. et al, "Update of the lichen inventory of Algeria", *Ecology-Environment*, vol. 10, 2014. pp. 75-103.
- [55] Lograda T, Adel K, Boucif L, Ramdani M, "Inventory of lichens of the mountainous massif of Megress (Setif, Algeria)". *Journal of Environmental and Applied Bioresearch*, vol. 3, no. 4, pp. 199-204, 2015.
- [56] Belguidoum A, "Lichen Biodiversity and Environmental Biomonitoring in the Sâïf Region, Algeria". University Setif, Algeria., 2024, pp. 1-184.
- [57] Adjiri F, "Valorization of the Lichen Flora in the BBA Region and Its Application as a Bioindicator of Atmospheric Pollution". University Setif., Algeria, 2020. pp. 1-235.
- [58] Coubes L, "The lichen flora of Toulouse according to the works of J.P". *Vincent., Isatis*, vol. 31, no. 8, pp. 178-184, 2008.
- [59] Dron J, Austruy A, Agnan Y et al, "Use of lichen biomonitoring in the Fos-sur-Mer industrial-port area: Review of three years of monitoring at an inter-municipal scale". *Atmospheric Pollution*, vol. 228, pp. 1-14, 2016. DOI: 10.4267/pollution-atmospherique.5392.
- [60] Pinho P, Augusto S, Branquinho C et al, "Mapping lichen diversity as a first step for air quality assessment", *Journal of Atmospheric Chemistry*, vol. 49, pp. 377-389, 2004. DOI: 10.1007/s10874-004-1253-4.
- [61] Skert N. and Grahonja R, "Biomonitoring of phytotoxic gas pollution in the Friuli Venezia Giulia region using lichens as bioindicators". *ARPA FVG – Gestione Attività centralizzate*, 2013, pp. 1-37.
- [62] Das P, Joshi S, Rout J et al, "Lichen diversity for environmental stress study: Application of index of atmospheric purity (IAP) and mapping around a paper mill in Barak Valley, Assam, northeast India". *Tropical Ecology*, vol. 54, no. 3, pp. 355-364, 2013.
- [63] Khastini R.O, Sari I.J, Herysca Y.H, Sulasanah S, "Lichen diversity as indicators for monitoring ecosystem health in Rawa Danau Nature Reserve, Banten, Indonesia". *BIODIVERSITAS*, vol. 20, no. 2, pp. 489-496, 2019. DOI: 10.13057/biodiv/d200227.
- [64] Kar S, Samal A.C, Maity J.P et al, "Diversity of epiphytic lichens and their role in sequestration of atmospheric metals". *Int. J. Environ. Sci. Technol.*, vol. 11, pp. 899-908, 2014. DOI: 10.1007/s13762-013-0270-8.
- [65] De Sloover J, "Atmospheric Pollution and Species-Specific Tolerance in Lichens". *Soc. bot. Fr., Colloque sur les Lichens*, vol. 115, no. 2, pp. 205-217, 1967.
- [66] Stamenković S, Aranjelović M, "Lichens as Bioindicators of Air Quality in Dimitry grad (South-Eastern- Serbia)". *Arch Biol Sci Belgrade*, vol. 62, no. 3, pp. 643-648, 2010. DOI: 10.2298/ABS1003643S.
- [67] Jayalal U, Oh SO, Park JS, Sung JH et al, "Evaluation of air quality using lichens in three different types of forest in Korea". *For Sci Technol*, vol. 12, no. 1, pp. 1-8, 2015. DOI: 10.1080/21580103.2014.1003983