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RESEARCH

Assessing Tunisia's urban air quality using combined lichens and Sentinel-5 satellite integration

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Abstract In Tunisia, urban air pollution is becoming a bigger problem. This study used a combined strategy of biomonitoring with lichens and satellite mapping with Sentinel-5 satellite data processed in Google Earth Engine (GEE) to assess the air quality over metropolitan Tunis. Lichen diversity was surveyed across the green spaces of the Faculty of Science of Tunisia sites, revealing 15 species with a predominance of pollution-tolerant genera. The Index of Atmospheric Purity (IAP) calculated from the lichen data indicated poor air quality. Spatial patterns of pollutants sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and aerosol index across Greater Tunis were analyzed from Sentinel-5 datasets on the GEE platform. The higher values of these indices in the research area indicate that it may be impacted by industrial activity and highlight the considerable role that vehicle traffic plays in air pollution. The results of the IAP, IBL, and the combined ground-based biomonitoring and satellite mapping techniques confirm poor air quality and an environment affected by atmospheric pollutants which will enable proactive air quality management strategies to be put in place in Tunisia's rapidly expanding cities.

Keywords Air quality · Atmospheric pollutants · Biodiversity · GEE · Lichens · Sentinel-5 satellite

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Introduction

Air pollution must be detected and measured to preserve air quality. However, the use of expensive measuring equipment limits coverage of the entire area (Estrabou et al., 2011). Lichens are effective indicators of air quality in this situation, as they directly assess the effects of pollutants on the environment (Chahloul et al., 2022, 2023; Estrabou et al., 2011; Seed et al., 2013). According to Li et al. (2010), the ideal bioindicator should be simple to identify, even for non-specialists, broad or cosmopolitan, and well-known: plentiful, suitable for lab experiments, highly sensitive to environmental pollution, allowing a positive correlation with atmospheric pollutant concentrations, and less sensitive to environmental stress, such as lichens. Therefore, a mycobiont and a photobiont form a mutualistic interaction that results in lichens. Classification is incorporated into the fungal system as the morphology of lichens is determined by the fungus partner (Grimm et al., 2021). The substrate type is important for the colonization of each lichen, as it is its main colonizer in the terrestrial habitat. Substrate types are classified as corticolous (on tree bark), saxicolous (on rocks), terricolous (on soil), and follicolous (on leaf surfaces). Lichens can adapt to extreme conditions (Boustie & Grube, 2005). Lichens have a wide ecological spread due to their ability to stop their metabolism when it is dry and resume it when water conditions are favorable. Lichens are dual and have a variety of traits. They settle in regions with harsh climatic circumstances that go beyond what most other terrestrial plants can tolerate physiologically (Coste, 2011). They can be used as assessment tools to help us understand air quality more comprehensively and cost-effectively, helping to protect the environment (Estrabou et al., 2011). Their sensitivity to pollutants and their ability to accumulate contaminants have meant that lichens have emerged as effective indicators of air pollution in the field of air quality biomonitoring. Several studies have shown that the diversity of lichens in urban areas is significantly correlated with levels of atmospheric pollution (Cernat Popa & Rusănescu, 2023; Contardo et al., 2020; Dörter et al., 2020).

Studies on air quality using bioindicators are not very well developed in Tunisia. The worldwide use of lichens in several fields notwithstanding, a very limited number of studies have been carried out in Tunisia. Most have focused on assessing the distribution and diversity of lichens and the possible effect of some lichens as bioindicators of air pollutants in rural areas (Chahloul et al., 2022, 2023; Mendili et al., 2023). This is why our interest was focused on urban areas. However, urban air pollution poses a major environmental health risk, especially in developing nations (Manisalidis et al., 2020). In addition, advances in satellite remote sensing technology have opened new prospects for large-scale monitoring of atmospheric pollution. The use of satellite data, such as that provided by the Sentinel-5 system, enables a global assessment of atmospheric pollution and the identification of pollution sources (Duncan et al., 2014; Holloway et al., 2021; Zhang et al., 2021). In this context, environmental monitoring using bioindicators such as lichens is an interesting way of assessing the actual exposure of urban ecosystems to atmospheric pollutants.

There are no permanent measurements of atmospheric pollutants in the urban area of Tunisia. To develop an air quality biomonitoring system using lichens, we carried out systematic sampling. In Tunisia, rapid urbanization and industrialization have degraded air quality in cities like Tunis. However, monitoring air pollution can be challenging without extensive ground-level sensor networks. Now, new satellite technologies offer advanced ways to track pollutants and identify problem areas across wide regions (Shami et al., 2021; Tabunschik et al., 2023).

The present research uses a multi-approach that combines lichen biomonitoring and Sentinel-5 satellite data processed by Google Earth Engine (GEE) to provide a thorough assessment of the air quality in Greater Tunis. Lichens provide a unique viewpoint on localized air quality because of their susceptibility to atmospheric pollutants, while satellite imaging offers a broad perspective on pollution distribution. We want to present a detailed picture of the distribution of important pollutants, such as sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and aerosols, in metropolitan regions by merging these two techniques.

This work is a continuation of our previous research on lichens as indicators of air pollution and accumulators of heavy metals (Chahloul et al., 2022, 2023; Mendili et al., 2023). This new phase of our research focuses on assessing air pollution in urban areas. Therefore, the main aims of this study are to identify the lichen species present in urban areas of Tunisia while using Sentinel-5 satellite imagery to monitor and assess air quality over vast areas of Greater Tunis, thereby providing a better understanding of the environmental environment. Through this work, we seek to increase awareness of the value of good air quality and the effects of our actions on the environment among the university community. We will be able to contribute to campaigns to conserve the atmosphere and implement steps to lessen our ecological imprint by having a better understanding of lichens as bioindicators.

Materials and methods

Study area

The study area is in an urban environment in a large Tunisian city. The governorate of Tunisia is in the north of Tunisia and is characterized by a mixture of road traffic urban and industrial environments, making it a region prone to pollutant emissions from various human activities.

The Mediterranean climate is dominant in the Tunisian capital, where it is mild and rainy in winter and hot and dry in summer. While average temperatures are between 28 and 44 in summer, they drop to 10–25 in winter.

Therefore, we can conclude from the application used "Plume Lab's (neither the European Commission nor ECMWF is responsible for the use of the data used by Plume Labs)" to monitor air quality that Tunis is contaminated during the collection period (24 and 31 March 2023). It has high concentrations of PM2.5, PM10, NO_2, and O_3 (Table 1). According to Table 1, the AQI (air quality index) varies from poor to unhealthy.

Lichen sampling is carried out over the entire surface area of the Faculty of Science in Tunis (2 km^2). For the data on the frequency of lichens on trees, we selected six trees spread throughout the study area. However, the study of atmospheric pollution using Google Earth Engine and ArcGIS was carried out throughout the area of Greater Tunis (2600 km^2). In addition, the resolution up to 7* km × 3.5 km.

Study of air pollution using lichen

Lichen sampling

Lichen samples were collected from the green spaces of the Faculty of Science of Tunisia. (37°07′43″N: 9°39′50″E) region of Tunisia (Fig. 1). Every sample was collected on 24 and 31 March 2023. With the use of a stainless-steel knife, the lichen was gathered, and then transported back to the lab, where it was preserved in glass vials. Voucher specimens have been deposited in the lichenological herbarium of the Department of Biology, Faculty of Sciences, Tunisia.

Table 1 Live air quality reports and air quality forecasts for Tunis during collection dates using the Plume Lab application

Date	AQI	PM2.5 (µg/m^3)	PM10 (µg/m^3)	NO_2 (µg/m^3)	O_3 (µg/m^3)
24 March 2023	105	33	47	16	48
31 March 2023	55	16	32	8	66

Lichen identification

Leprous, crustaceous, squamous, foliose, fruticose, composite, or gelatinous thallus types, colors (yellow, orange, green, blue-green, brown), orientation of the tips, and habitat are just a few examples of the general morphological characteristics that can be used to identify different species of lichens. On the other hand, lichen is identified using chemical testing using certain chemicals that, when in contact with the thallus, produce colorations.

The main reagents used are as follows:

- K test: 10% KOH solution in water.
- C test: NaOCl, an aqueous calcium hypochlorite solution.
- KC test: K and C solutions were applied one after the other.
- P test: 1% 1-phenylenediamine in a 10% aqueous sodium thiosulfate solution.

For the addition of each reagent, a + followed by the observed color is noted if the reaction is positive, and a − is indicated if no color has appeared (a negative reaction).

All lichens are identified and classified in Tables 2, 3, and 4.

Van-Haluwyn (1986) method

Lichen diversity alone can constitute a method for assessing the air quality of a given ecosystem. The most widely used method is Van Haluwyn (1986), which is based on lichen association, and allows us to classify lichens according to their degree of resistance to pollution (Gavériaux, 1999).

Bioindication of lichens

Sampling techniques were carried out according to the methods described by Khairuddin et al. (2017); Rosli and Zulkifly (2022), with modifications. The study was carried out in the green spaces of the Faculty of Science in Tunis, before the locations, which consist of homogeneous and healthy host trees and meet the criteria required for the bio-indication methods used.

The garden of the faculty of sciences is very rich in several types of trees, namely *Cupressus*, *Pinus*,

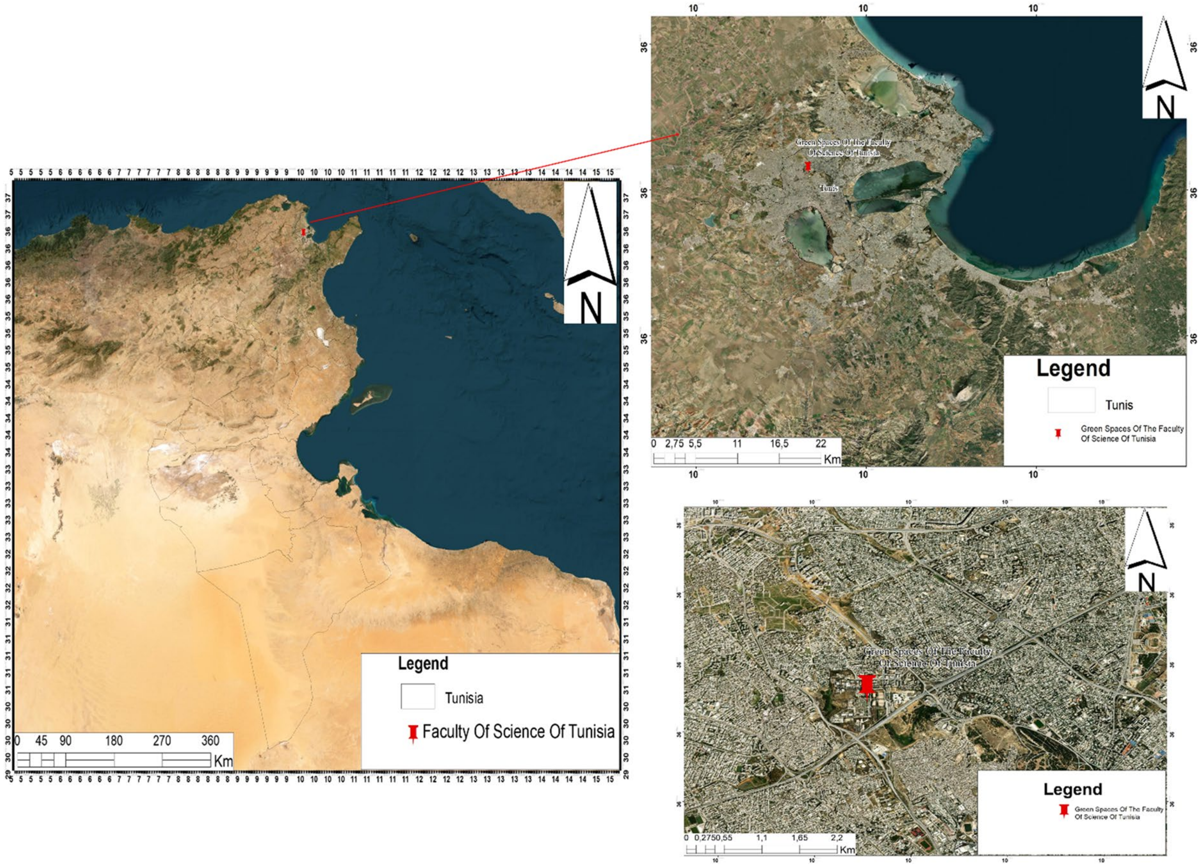


Fig. 1 Location maps of the prospecting stations, Green Spaces of Tunisian Science Faculty

Eucalyptus, and *Olea europaea*. We select *Cupressus*, to determine the quality level of the Index of Atmospheric Purity (IAP) and the Lichen Biodiversity Index (LBI).

The grids were determined based on Rosli and Zulkifly (2022). The four cardinal points of the tree trunk were sampled using a grid of five 10 cm × 10 cm vertical squares to cover the entire surface of the station. The grids were placed at least 1 m above the ground to avoid any influence from the soil (Fig. 2). The total frequency of each species per tree was calculated (Table 4).

Quality level of the index of atmospheric purity (IAP)

The "Index of Atmospheric Purity" (IAP) is an index widely used to determine the air quality in surrounding areas based on the richness and abundance of lichens. This method assesses the frequency of lichens (Table 5). The IAP method aims to infer the purity or level of atmospheric pollution of the surrounding areas by studying the presence and characteristics of these lichens (Conti & Cecchetti, 2001). The IAP method is calculated according to the following Eq. 1:

$$IAP = \sum_{i=1}^{i=n} (fi) \quad (1)$$

F is the frequency. This was determined and the quality level of the table created by Conti and Cecchetti (2001), the Atmospheric Purity Index (API), was compared (Table 6) (Kirschbaum et Wirth, 1997).

Lichen biodiversity index (LBI)

The Lichen Biodiversity Index (LBI) is a tool for measuring air pollution, according to Abas et al.,

Table 2 Morphological characteristics of lichens

Family	Species	Thallus Types	Ecology Color	Substrate
Teloschistaceae	*Xanthoria parietina*	Foliose	Greenish yellow	Corticolus
	Xanthoria polycarpa	Foliose	Yellow orange	Corticolus
	Lecanora argentata	Crustose	Silver	Corticolus
	Lecanora albesense	Crustose	Whitish	Saxicolus
Lecanoraceae	*Lecanora carpinea*	Crustose	Whitish color with yellow apothecia	Corticolus
	Lecanora cenisia	Crustose	Grey to greenish grey	Saxicolus
	Lecanora laxa	Crustose	Grey to greenish grey	Saxicolus
	Lecanora muralis	Crustose	Yellowish green	Saxicolus
	Caloplaca cerina	Crustose	Whitish grey	Corticolus
	Caloplaca citrina	Crustose	Lemon yellow	Saxicolus
Teloschistaceae	*Caloplaca teicholyta*	Crustose	In a greyish white rosette	Saxicolus
	Caloplaca flavescens	Crustose	Yellow orange to white	Saxicolus
	Caloplaca marina	Crustose	Yellow orange to orange	Saxicolus
Collemataceae	*Collema tenax*	Gelatinous	Black when dry Olive green to brown when wet	Terricolus
Physciaceae	*Physcia adscendens*	Foliose	Greenish grey	Corticolus

Table 3 Results of chemical reactions with the lichen thall's

Lichens	K-test	C-test	KC-test	P-test
Xanthoria polycarpa	+ red purple	-	-	-
Xanthoria parietina	+ red purple	-	-	-
Physia adscendens	+ yellow	-	-	-
Lecanora muralis	-	-	-	+ yellow
Lecanora laxa	-	-	-	-
Lecanora cenisia	+ yellow	-	-	+ yellow
Lecanora argentata	+ yellow	-	-	-
Lecanora albesense	-	-	-	-
Collema tenax	-	-	-	-
Caloplaca teicholyta	-	-	-	-
Caloplaca marina	+ red	-	-	-
Caloplaca flavescens	+ purple	-	-	-
Caloplaca citrina	+ red purple	-	-	-
Caloplaca cerina	+ red purple	-	-	-

(2022a, 2022b). The LBI assesses the quantity and frequency of lichen species in a certain environment and converts the data into a condition (Table 7).

Calculate the lichen biodiversity index (LBI) using the following Eq. 2:

$$LBI = (S - 1)/\ln(N) \quad (2)$$

where S is the total number of lichen species in the study area and N is the total number of lichen individuals in the study area.

The LBI recorded at each station was interpreted in terms of deviations from natural conditions, as shown in Table 7.

Study of air pollution using google earth engine and ArcGIS

Sentinel-5P carries the TROPO spheric Monitoring Instrument (TROPOMI) to detect gases and aerosols in the troposphere that affect air quality and climate. TROPOMI can measure wavelengths in the ultraviolet and visible (270–500 nm), near infrared (675–775 nm), and short-wave infrared (2305–2385 nm). This enables it to monitor various pollutants. It is also used for climate, ozone, and surface UV applications with a scan width of 2600 km and a resolution of 7 km × 3.5 km.

The distribution map of sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and aerosol index in the area studied. They were estimated from satellite images using algorithms

Table 4 Systematic classification of collected lichens

Classification	***Photos***
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Teloschistaceae* **Genus** : *Xanthoria* **Species** : *Xanthoria parietina*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Teloschistaceae* **Genus** : *Xanthoria* **Species** : *Xanthoria polycarpa*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : *Lecanoraceae* **Genus** : *Lecanora* **Species** : *Lecanora argentata*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : *Lecanoraceae* **Genus** : *Lecanora* **Species** : *Lecanora albesens*	
Division : *Ascomycota* **Subdivision** : Pezizomycotina **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : *Lecanoraceae* **Genus** : *Lecanora* **Species** : *Lecanora cenisia*	

Table 4 (continued)

Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : Lecanoraceae **Genus** : *Lecanora* **Species** : Lecanora laxa	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : *Lecanoraceae* **Genus** : *Lecanora* **Species** : *Lecanora muralis*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Teloschistaceae* **Genus** : *Caloplaca* **Species** : *Caloplaca cerina*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Teloschistaceae* **Genus** : *Caloplaca* **Species** : *Caloplaca flavescens*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Teloschistaceae* **Genus** : *Caloplaca* **Species** : *Caloplaca marina*	

Table 4 (continued)

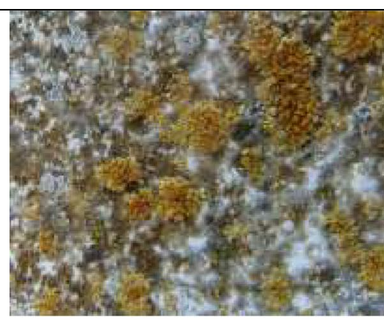
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Peltigeromycetidae* **Order** : *Peltigerales* **Family** : *Collemataceae* **Genus** : *Collema* **Species** : *Collema tenax*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Teloschistales* **Family** : *Physciaceae* **Genus** : *Physcia* **Species** : *Physcia adscendens*	
Division : *Ascomycota* **Subdivision** : *Pezizomycotina* **Class** : *Lecanoromycetes* **Sub-Class** : *Lecanoromycetidae* **Order** : *Lecanorales* **Family** : *Lecanoraceae* **Genus** : *Lecanora* **Species** : *Lecanora carpinea*	
Division : *Ascomycota* **Subdivision :** *Pezizomycotina* **Class :** *Lecanoromycetes* **Sub-Class :** Lecanoromycetidae **Order :** *Teloschistales* **Family :** *Teloschistaceae* **Genus :** *Caloplaca* **Species :** *Caloplaca citrina*	
Division : *Ascomycota* **Subdivision :** *Pezizomycotina* **Class :** *Lecanoromycetes* **Sub-Class :** *Lecanoromycetidae* **Order :** *Teloschistales* **Family :** *Teloschistaceae* **Genus :** *Caloplaca* **Species :** *Caloplaca teicholyta*	

Fig. 2 Sampling grid on the face of the sampled tree *Cupressus*

Table 5 Lichen frequency data on tree

Lichens	Number of lichen in trees of *Cupressus*						Frequency mean (f_i)
	1	2	3	4	5	6	
Caloplaca teicholyta	0	0	0	0	0	0	0
Caloplaca marina	0	0	0	0	0	0	0
Caloplaca flavescens	0	0	0	0	0	0	0
Caloplaca citrina	0	0	0	0	0	0	0
Caloplaca cerina	1	0	0	0	0	0	0.166
Collema tenax	0	0	0	0	0	0	0
Lecanora carpinea	1	0	0	0	2	0	0.5
Lecanora muralis	0	0	0	0	0	0	0
Lecanora laxa	0	0	0	0	0	0	0
Lecanora cenisia	0	0	0	0	0	0	0
Lecanora argentata	8	2	0	1	0	0	1.83
Lecanora albesense	0	0	0	0	0	0	0
Physia adscendens	1	2	0	0	0	0	0.5
Xanthoria polycarpa	2	0	0	0	0	0	0.33
Xanthoria parietina	9	2	3	0	5	0	3.16

Table 6 Index of Atmospheric Purity (IAP)

0	**0 – 12.5**	**12.5 - 25**	**25 – 37.5**	**37.5 - 50**	**50**
Extremely high	Very high	High	medium	low	Very low

Table 7 Lichen Biodiversity Index (LBI)

Color	LBI	Condition
	0	Very High Alteration
	1 – 10	High Alteration
	11 – 20	Moderately High Alteration
	21 – 30	Low Alteration
	31 – 40	Moderately High Naturality
	41 – 50	High Naturality
	51 and above	Very High Naturality

available in the cloud computing platform Google Earth Engine (GEE) and ArcGIS 10.8 software.

Methodology for obtaining sentinel-5 data from the google earth engine (GEE) platform

The methodology for extracting Sentinel-5 data from the GEE platform involves four main steps. Firstly, the region of interest (Greater Tunis) is defined by drawing a polygon with the geographical coordinates of the study area, in this case, the El Manar campus in Tunisia. Secondly, the collection of Sentinel-5P images containing the ozone column density data is loaded and then filtered by a spectral band of interest, period, and by geographical area corresponding to the region of interest. Thirdly, the resulting image from the previous processing (mean Image) is exported to a specified Google Drive folder, with the description, spatial resolution, and maximum number of pixels parameters defined. Finally, in step four, the exported data is integrated and formatted in ArcGIS 10.8 GIS software to produce the final maps ready for interpretation and analysis (Fig. 3).

Study of air pollution using google earth engine and ArcGIS

This study used Google Earth Engine (GEE) to process and analyze Sentinel-5P satellite data on air pollution in Greater Tunis. GEE enables large volumes of Earth observation data to be processed efficiently. Sentinel-5P data were converted using the harp convert tool in GEE. Spatial and temporal filters were applied to the data. Sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and the aerosol index were generated for the study area. The use of GEE and Sentinel-5P data has thus enabled an in-depth analysis of air pollution over the whole of the Greater Tunis area (Fig. 3).

The data obtained was then downloaded and processed in ArcGIS to generate maps of average annual concentrations per pollutant. The temporal evolution of pollution levels was also analyzed by urban area.

Data analysis

Using Microsoft Excel (Office 365), regression analysis was done on the link between emissions in cities based on the examination of satellite pictures by the Google Earth Engine platform (GEE), the Sentinel 5P satellite imagery, and monitoring data using the cloud computing platform and ArcGIS 10.8 software.

Results

Inventory of lichens

Because of our limited knowledge of Tunisian lichen flora, we had to carry out chemical tests and macroscopic observations. We had to use chemical tests and macroscopic observations. The Faculty of Science in Tunis is home to a wide variety of lichens. We therefore had to do chemical tests using various reagents that, when they met the thallus, produced specific colorations. These tests enabled us to identify the lichens in the green spaces of the Faculty of Science in Tunis (Tables 2 and 3).

The taxonomic identification of lichens was carried out using the three Guides of French lichens by Asta et al. (2016).

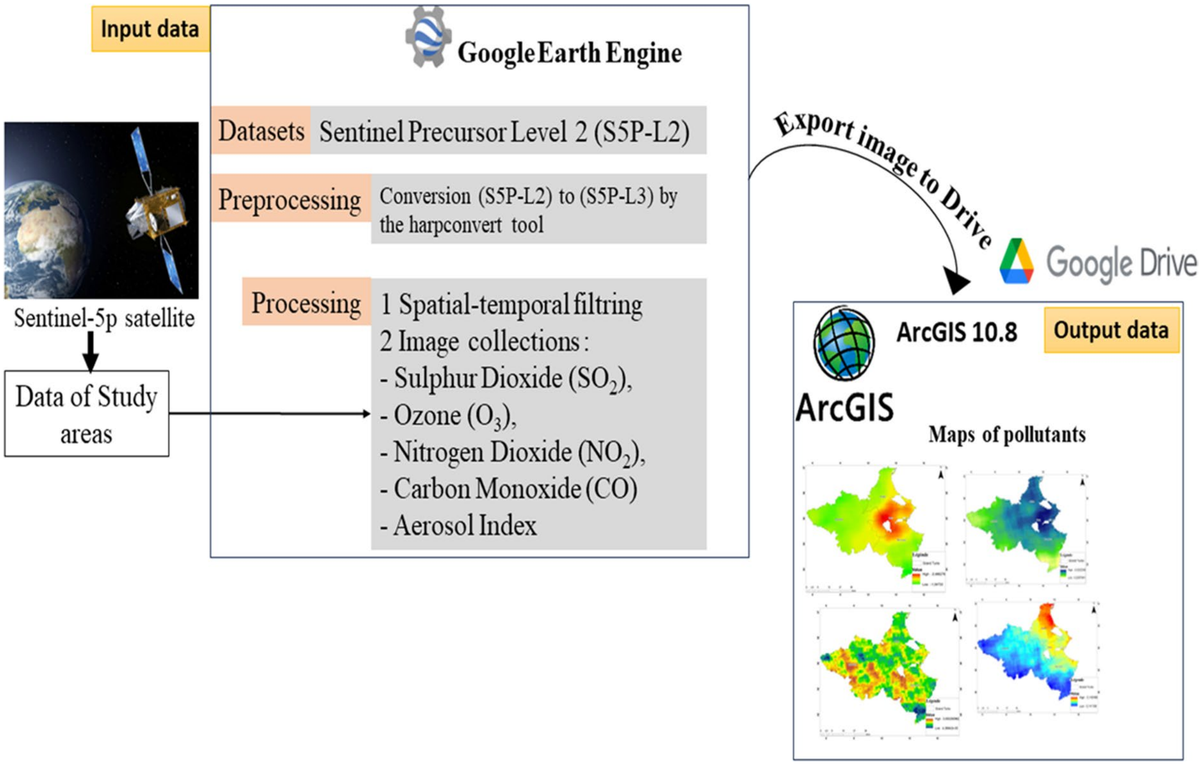
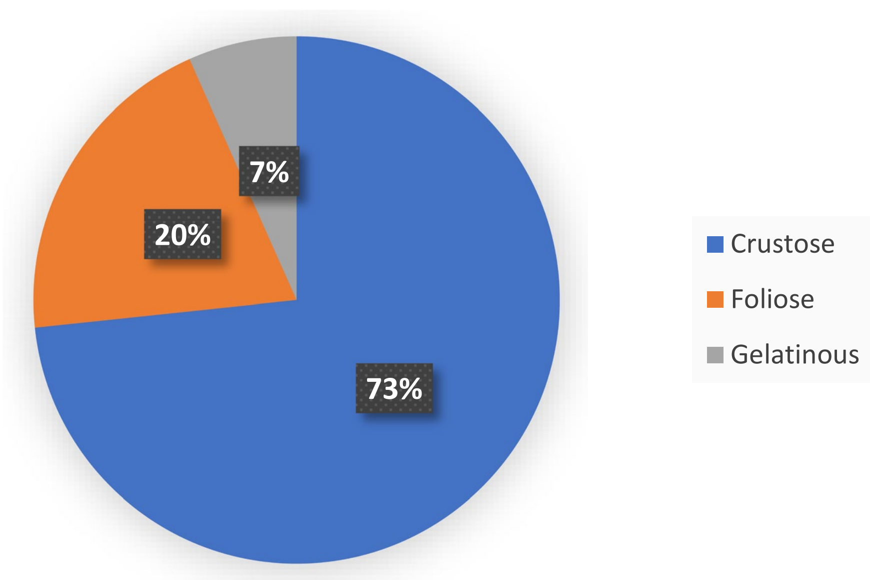


Fig. 3 The process of map generation using Google Earth Engine and ArcGIS

Fig. 4 Distribution of lichens recorded according to thallus type



Fifteen lichens were identified from the samples taken at the Tunis Faculty of Science, divided into six corticolous species, eight saxicolous species, and one terricolous species (Fig. 4). The systematic classification of all the lichens identified is shown in Table 4.

*Lichens and air quality index: Van-*Haluwyn (1986) *method*

According to Van Haluwyn (1986), during our study, we identified three categories of lichen: 12 of them proved to be resistant to atmospheric pollution, while two lichens showed sensitivity to pollution. One lichen was particularly sensitive (Fig. 5, Table 8).

Lichens are recognized as bioindicators of air quality because of their sensitivity or tolerance to pollution. These results suggest that the Faculty of Sciences in Tunis, where the lichens were identified, may have some form of air pollution. The presence of pollution-tolerant lichens confirms the presence of polluting factors.

However, the predominance of tolerant lichens suggests that some parts of the area may be exposed to high levels of pollutants. In addition, most of the species identified are crustaceans. Crustose lichens, such as *Lecanora* and *Caloplaca* (Fig. 6), are often used as indicators of air pollution because of their rapid reactivity to pollutants. They show visible signs of deterioration such as discoloration, tissue necrosis, and reduced species diversity in areas exposed to high levels of pollution. These lichens can accumulate heavy metals and toxic compounds from ambient air, making them valuable indicators of air quality. The Faculty of Sciences in Tunis is exposed to high levels of pollution in various areas, but there are also areas with low to moderate levels of pollution, allowing lichens to adapt.

Table 8 Degree of resistance of lichens to pollution (Van Haluwyn and Lerond, 1986)

Lichens	Degree of resistance to pollution
Caloplaca teicholyta	Tolerant to pollution
Caloplaca marina	Tolerant to pollution
Caloplaca flavescens	Tolerant to pollution
Caloplaca citrina	Tolerant to pollution
Caloplaca cerina	Tolerant to pollution
Collema tenax	Tolerant to pollution
Lecanora carpinea	Tolerant to pollution
Lecanora muralis	Tolerant to pollution
Lecanora laxa	Tolerant to pollution
Lecanora cenisia	Highly sensitive to pollution
Lecanora argentata	Tolerant to pollution
Lecanora albesense	Sensitive to pollution
Physia adscendens	Tolerant to pollution
Xanthoria polycarpa	Sensitive to pollution
Xanthoria parietina	Tolerant to pollution

Quality level of the index of atmospheric purity (IAP)

The IAP values and pollution levels are shown in Table 9. The IAP is equal to 6, which means that the

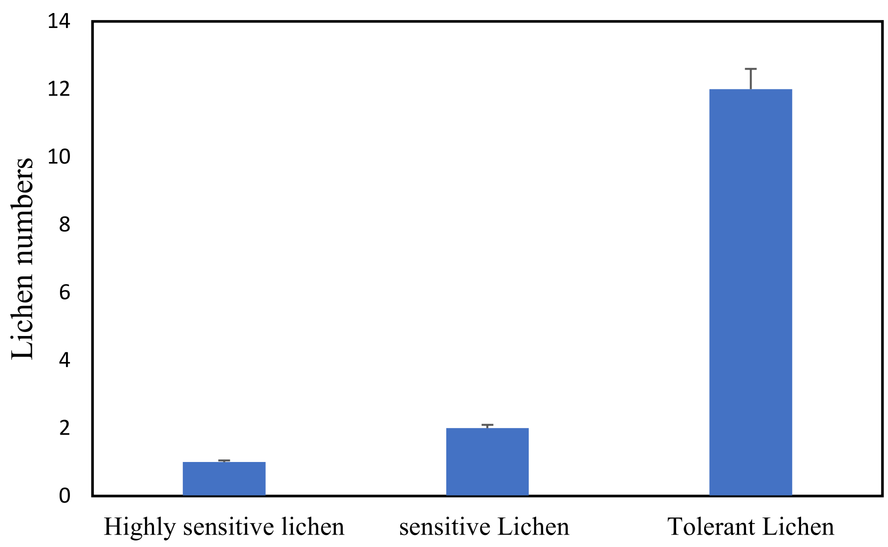


Fig. 5 Numeric distribution of the degree of resistance of lichens to pollution

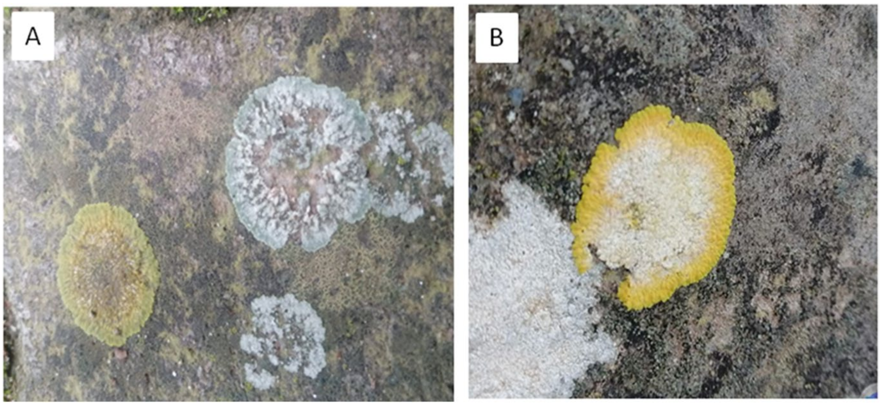


Fig. 6 **A** *Lecanora murais*. **B** *Caloplaca marina*

Table 9 The IAP and LBI values

LBI	IPA
3.82	6.5

air quality in the area studied is very poor according to the IAP quality levels ($0 \leq IAP \leq 12.5$), a very high level of air pollution.

Lichen biodiversity index (LBI)

The LBI (3.82) indicates a low biodiversity of lichens in the garden of the Faculty of Sciences of Tunis (Table 9). According to Table 9, this corresponds to a high alteration.

This low biodiversity may result from several factors, such as atmospheric pollution, changes in habitats and environmental conditions, and disturbances due to human activities. This suggests that the environment assessed shows significant signs of pollution.

Study of air pollution using google earth engine and ArcGIS

The analysis used data collected from the Google Earth Engine (GEE) platform and the Sentinel 5P satellite. The distribution map of sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and the aerosol index in Greater Tunis in 2023 provides the following maximum values for each pollutant in these areas. The spatial distribution map of the substances considered in the atmosphere from January to December 2023 in Greater Tunis is illustrated in Figs. 7, 8, 9, 10, and 11.

For all pollutants, the maximum values are obtained in the Tunis area. We can therefore conclude that the most polluted zone of all is the Tunis zone. It has the highest concentrations of SO_2, O_3, NO_2, CO, and aerosol index.

According to the distribution map of SO_2, O_3, NO_2, CO, and aerosol indices, the maximum values for all pollutants are obtained in the study area Greater Tunis including all urban area. Hence, we can conclude that the Faculty of Science in Tunis is among the most polluted. It has the highest concentrations of SO_2, O_3, NO_2, CO, and aerosol index (Figs. 7, 8, 9, 10, and 11).

Although the Sentinel-5 data provide a valuable overview of spatial pollution trends on a regional scale, their relatively coarse resolution presents a challenge for direct comparison with point observations of lichens in the field. Indeed, each Sentinel-5 pixel integrates the conditions over an area of around 1 km^2, while the lichen sampling provides specific information. To better link these two complementary datasets at different spatial scales, advanced techniques such as sub-pixel extraction or high-resolution pollutant dispersion modeling could be explored in future studies.

The higher values of these indices in the study area suggest that this area is potentially affected by industrial activities and reveal the significant contribution of motor traffic to air pollution.

Discussion

The atmospheric pollution brought on by geothermal power plants and forest disturbance is measured using lichens (Abas et al., 2022a, 2022b). As cities

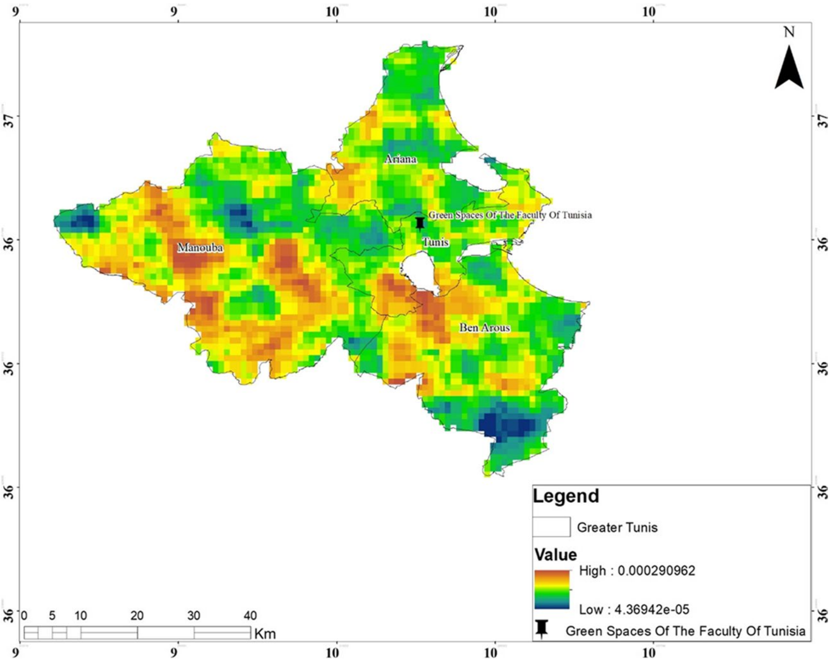


Fig. 7 Distribution of sulfur dioxide (SO_2)

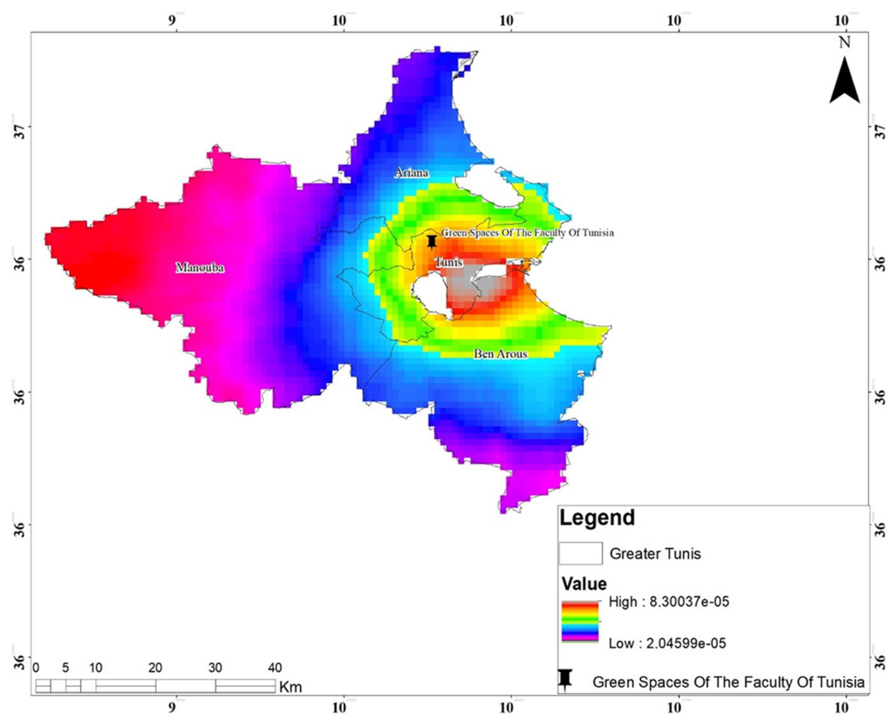


Fig. 8 Distribution of nitrogen dioxide (NO_2)

grow and become more industrialized, air pollution becomes a greater hazard to public health, particularly in developing countries (Mannucci & Franchini, 2017). In Tunisia, growing traffic, industrial emissions, and other pollution sources have all lowered the quality of the air in metropolitan areas. Due to the lack of ground-level monitoring infrastructure, however, comprehensively monitoring and managing

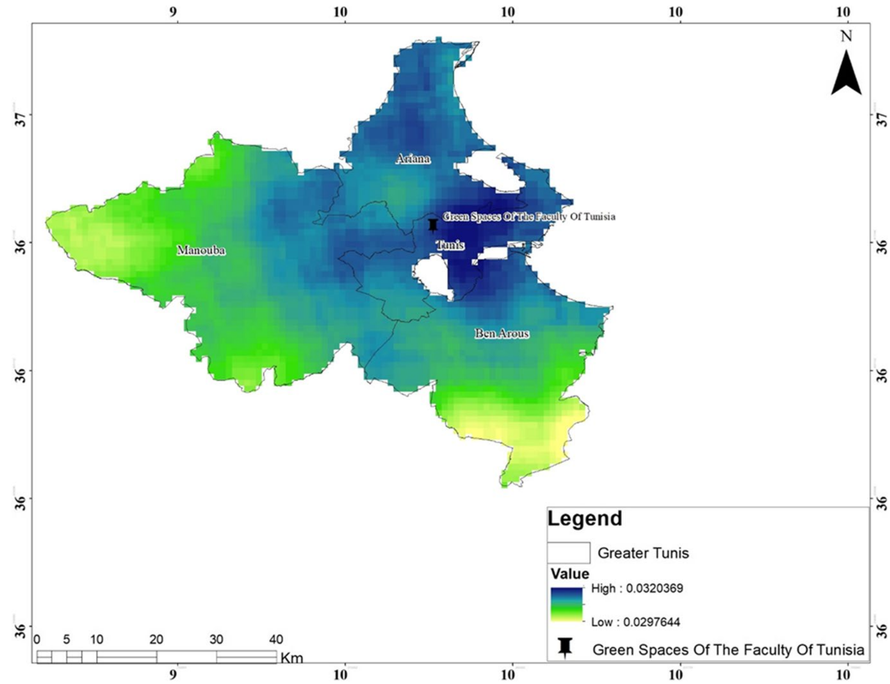


Fig. 9 Distribution of carbon monoxide (CO)

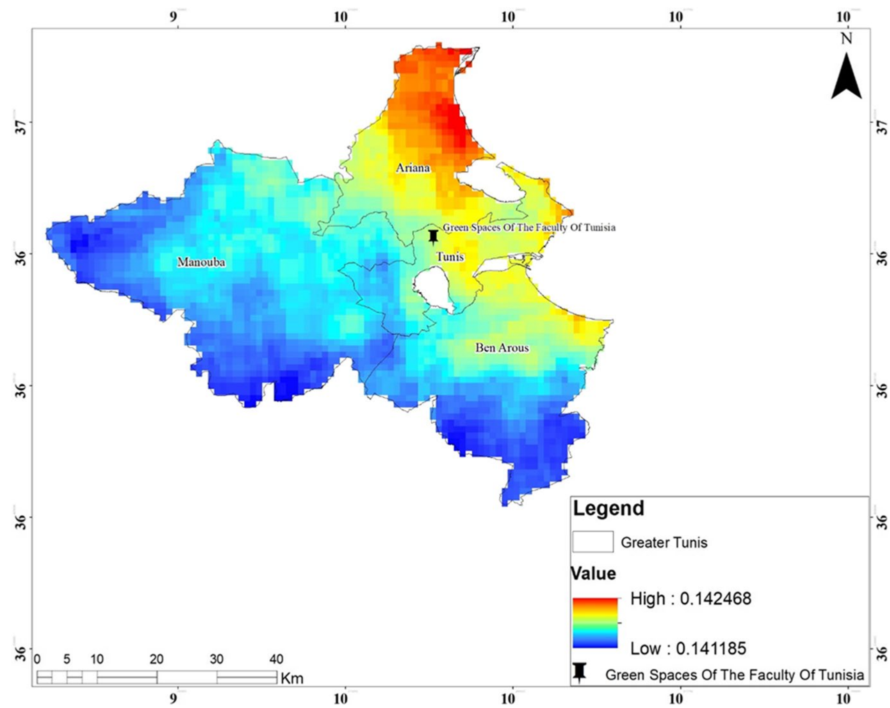


Fig. 10 Distribution of carbon monoxide (O_3)

urban air pollution creates difficulties. This work highlights the utility of combining lichen biomonitoring with satellite data analysis to evaluate urban air quality. Lichen research has been used to assess species diversity and pollution tolerance.

Lichens are useful as bioindicators of ecological continuity, climatic change, and environmental contamination (Abas et al., 2022b; AL-Alam et al., 2019). Because they may respond to atmospheric contaminants year-round and are easy to employ to

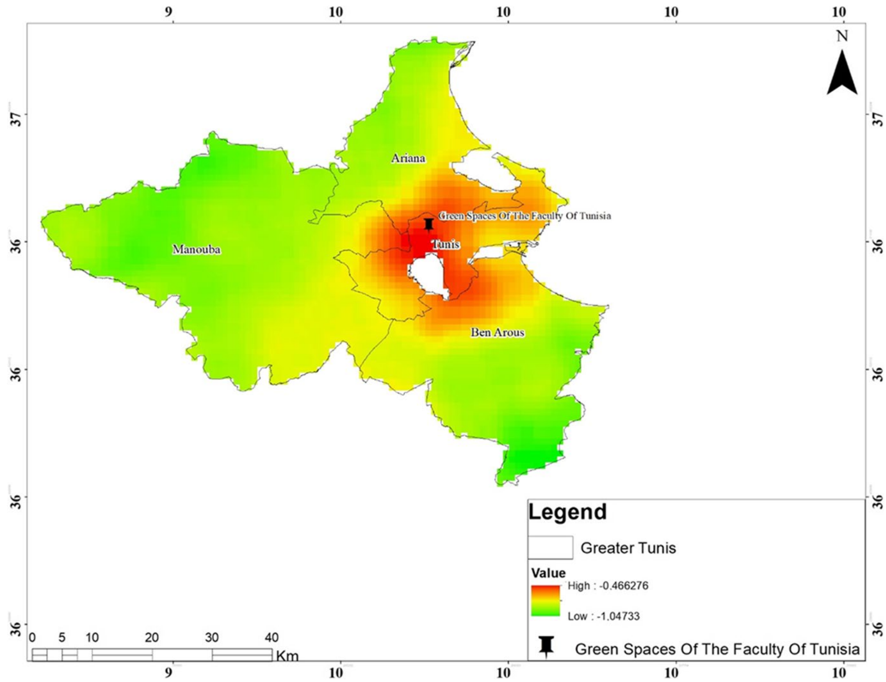


Fig. 11 Distribution of aerosol in the atmosphere

measure air pollution, lichens are beneficial bioindicators of air pollution (Abas et al., 2022b). Lichens are ideal bio-indicators of air pollution because they can react to atmospheric pollutants throughout the year and are inexpensive to use to assess air pollution (Khairuddin et al., 2017). Therefore, they breathe over their entire surface, which makes them sensitive to air pollution. They absorb pollutants and concentrate heavy metals, which scientists can extract and analyze to determine the content of the local atmosphere. Lichens are sensitive to sulfur dioxide, nitrogen, mercury, lead, and other acidic pollutant gases (Nascimbene et al., 2019).

Lichens are extremely sensitive to atmospheric pollutants such as nitrogen, heavy metals, photo-oxidants, and other acidic pollutant gases since they get all their nutrients and water from the atmosphere (Estrabou et al., 2011).

Through examining the biodiversity of lichens, our study evaluated the air quality at the Green Spaces of the Faculty of Science of Tunisia. Since they are sensitive to contaminants, lichens are well-known bioindicators of atmospheric pollution. The findings indicate that the area under study has a low diversity of lichens, with only 15 species identified, the majority of which are tolerant to pollution. Poor air quality and a changed environment due to atmospheric pollution are confirmed by the IAP and LBI calculations (Abas et al., 2022a; Gombert et al., 2004). The IAP and LBI are widely used to estimate air quality in terms of atmospheric pollutants (Abas et al., 2022b; Gombert et al., 2004).

Our results show that the area has a very high concentration of air pollutants that can affect human health and the environment. Air pollutants can come from sources such as industrial emissions, vehicles, forest fires, and power station emissions. Several studies have explored the effectiveness of lichens in air biomonitoring in developing countries and urban area and the impact of environmental conditions on their diversity (Cernat Popa & Rusănescu, 2023; Contardo et al., 2020; Dörter et al., 2020).

Several reasons can be used to explain these findings. First off, numerous contaminants are released into the atmosphere because of human activity, particularly road traffic, and due to vehicle traffic, which may contribute to the observed bad air quality (Gombert et al., 2004). Additionally, the region's industrialization may cause the discharge of toxins into the atmosphere, aggravating already existing air pollution.

Lichens living in urban areas are affected by a complex interaction between factors such as pollution and temperature (Lättman et al., 2014). Crustose lichens are the most tolerant of air pollution. They can survive in much-polluted air (Hauck et al., 2008). Several studies (Calvelo et al., 2009; Larsen et al., 2007) have shown that the variety of lichens declines steadily as atmospheric pollution rises. Our findings concur with those of Abas et al. (2022b), who indicate that lichen diversity is frequently lower in urban settings than it is in rural regions. As a result, the variety of lichen species that can grow there is highly constrained due to the challenging environment in urban environments. Our results are a further confirmation of what other studies carried out in cities around the world like Teleorman County, Setif, Algeria, and Nigeria have revealed that lichen are effective bioindicators of urban air pollution (Belguidoum et al., 2022; Cernat Popa & Rusănescu, 2023; Lawal et al., 2023).

The use of lichen bioindicators and Sentinel-5 satellite mapping in a multimodal approach has been particularly beneficial. While lichens provide point-source data on environmental effects, satellite imagery makes it possible to visualize the spatial patterns of different pollutants on a regional scale. However, the Sentinel-5 system, which provides an overall assessment of atmospheric pollution and identifies its sources (Mejía et al., 2023; Shami et al., 2021; Tabunschik et al., 2023).

As a complement to the lichen data, satellite mapping of the atmospheric pollutants sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and aerosol using Sentinel-5 and Google Earth Engine has made it possible to visualize the spatial patterns of pollution in the Tunis metropolitan area. The satellite data revealed hotspots located near industrial facilities and high-traffic areas that correspond to the results of the bioindicators. The study highlights the benefits of using GEE to monitor air quality while utilizing satellite data. Various research uses the Sentinel-5P satellite and the Google Earth Engine (GEE) platform to evaluate air pollution (Shami et al., 2021; Tabunschik et al., 2023).

However, the maximum values for each pollutant in each of the zones are provided. The Tunis zone yields the highest readings for all contaminants. Considering this, we can say that the "Green Spaces of the Faculty of Science of Tunisia" study area is one of the most polluted. The concentrations of SO_2, O_3, NO_2, CO, and aerosols are the highest there. The higher values of these indices in the research area indicate that it may be impacted by industrial activity and highlight the considerable role that vehicle traffic plays in air pollution. In addition, residents' health is in danger, especially for vulnerable communities, when high levels of NO_2, CO, and particulate matter are prevalent near major thoroughfares. High ozone concentrations might aggravate pre-existing medical illnesses and lead to respiratory issues. These results agree with those of Mannucci and Franchini (2017). Similarly, studies carried out in other regions of the Mediterranean basin have revealed high levels of various pollutants in major urban centers such as Guayaquil (Ecuador), Arak city (Iran), and The Republic of Croatia (Kazemi Garajeh et al., 2023; Mamić et al., 2023; Tabunschik et al., 2023).

This combination of techniques provides a clearer picture of air quality problems in Tunis than either of these approaches in isolation. The study shows how lichen diversity is a bioindicator of widespread pollution levels in green spaces of the Faculty of Science of Tunisia, while satellite mapping provides spatial detail on concentrations of specific pollutants. The use of both methods enables areas of high pollution and likely sources to be identified in a targeted manner.

In comparison to employing either method separately, the combined strategies provided increased capability to detect air pollution. The study establishes this framework as a reliable technique for determining air quality, with wider applications for cities around the world that are increasingly urbanizing. Adopting these techniques will give authorities crucial information they need to implement science-based public health policies and initiatives as Tunisia continues to urbanize.

Nevertheless, it is important to highlight certain limitations of our study. Although tried and tested, focusing on lichens as the sole bioindicators does not allow us to characterize the response of urban ecosystems. Integrating other bio-accumulating organisms such as mosses would provide a more complete picture. Furthermore, the limited spatial and temporal resolution of current satellite data means that hyper-local and daily variations in pollutants cannot be accurately captured.

Action must be taken right away to enhance air quality and lower environmental and human health concerns. This can be accomplished by reducing emissions from polluting sources like industry and transportation, expanding the area of green spaces that can absorb pollutants, and implementing routine air quality monitoring to manage its evolution. These recommendations are corroborated by several studies on urban air pollution, which suggest these actions reduce its effects (Bikis, 2023; Riggs et al., 2021).

Conclusion

This work illustrates an efficient integrated system for evaluating urban air quality utilizing satellite remote sensing and lichen biomonitoring. Based on species variety and pollution tolerance indices, the research on lichens offered crucial biological evidence of Tunisia's poor air quality. Additionally, it is now possible to visualize spatial pollution trends and locate specific pollution hotspots thanks to satellite mapping of air pollutants. To lessen this pollution's negative impacts on the environment and public health, real action must be taken. As part of future projects, we have proposed a solution to reduce air pollution in urban areas by transplanting lichens.

Author contribution The authors confirm their contribution to the paper: Ayda Khadhri and Mohamed Mendili conceived and designed the experiments, performed the experiments, analyzed and interpreted the data, and wrote and edited the article. Zahra Sellami and Rania Somai performed the experiments and analyzed and interpreted the data. All authors reviewed the results and approved the final version of the manuscript.

Data availability Not applicable.

Declarations

Ethical statement Not applicable.

Competing interests The authors declare no competing interests.

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