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LICHEN-INDICATIVE ASSESSMENT OF THE ECOLOGICAL STATE OF ATMOSPHERIC AIR IN URBANISED AREAS OF EASTERN UKRAINE

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Abstract. The article presents the results of a comprehensive study of the state of atmospheric air in urbanized areas of Poltava and Kharkiv regions using the lichen indication method. The dynamics of changes in the main pollutants in the period 2020–2023 is analyzed, and correlations between lichen indication data and instrumental measurements are established. The species composition and distribution features of indicator lichens in different functional zones of the studied territories are determined. The high efficiency of the lichen-indication method for assessing the quality of atmospheric air in an urban environment has been revealed. The peculiarities of the martial law impact on the ecological situation in the region and its reflection in the changes of lichen flora are established.

Keywords: lichen indication, urbanized areas, air pollution, environmental monitoring, indicator species.

1. Introduction

The problem of air pollution in urbanized areas is becoming particularly relevant in the context of modern environmental challenges. According to the World Health Organization, air pollution causes about 7 million premature deaths annually worldwide (Air Quality and Health Statistics, 2023). According to the latest research by the European Environment Agency (Air quality in Europe – 2023 report, 2023), air quality in urban areas continues to be a critical factor affecting public health, especially in the context of increasing industrial pressure and climate change.

In the eastern regions of Ukraine, in particular, in Poltava and Kharkiv regions, this problem is exacerbated by the combined impact of industrial emissions, transport, and the effects of military operations. According to the State Ecological Inspectorate of Ukraine (Zvit pro stan dovkillia v umovakh viiny, 2023), significant changes in the structure and intensity of air pollution are observed under martial law, which requires the development of new approaches to environmental monitoring.

Today, lichen indication is a promising and most developed environmental monitoring method. This method allows to determine the degree of air pollution and assess the impact of industrial emissions and other pollution on the environment reliably and at low cost. The expediency of using lichens for biomonitoring purposes is based on the fact that they are one of the most sensitive groups of living organisms to environmental stress. The peculiarities of these organisms' structure and nutrition make it possible to use them widely as environmental indicators.

Epiphytic forms are used to indicate the state of the air, as they are the most sensitive to the chemical composition of the air. The response of lichens and higher plants to chemical pollution is somewhat different, as damage to the lichen thallus remains until it dies, while plant tissues are capable of regeneration. That is why the special value of the lichen indication method lies in the possibility of an integrated assessment of pollution over a long period, which is extremely important in conditions of limited access to the territories and the complexity of regular instrumental measurements (Ristić et al., 2021).

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Modern studies (Ristić et al., 2021; Takano et al., 2024) demonstrate the high efficiency of lichens as bioindicators of air pollution. For example, lichens are adversely affected by substances that increase the environment's acidity, such as sulphur dioxide and nitrogen oxides. In particular, Ristić S. et al. note the sensitivity of lichens to sulphur and nitrogen compounds, making them indispensable indicators of industrial pollution. They are most susceptible to sulphur dioxide (SO_2), one of the most common pollutants, a product of the combustion of any sulphur-containing fuel. Research by British scientists (Niepsch et al., 2024) demonstrates the effectiveness of using an integrated approach to lichen identification, which includes analysis of not only species diversity but also biochemical indicators of lichens. Applying this methodology in eastern Ukraine could provide a more detailed picture of pollution.

A. P. C. Takano et al. (Takano et al., 2024) emphasizes the cost-effectiveness of bioindication methods compared to traditional instrumental measurements.

According to S. Y. Kondratiuk (Kondratiuk, 2008), in Ukraine, the most informative methodology is the well-known lichen indication methodology, which has as its first stage the mapping of lichens, which means determining their species composition, assessing the projective coverage and establishing the frequency of species occurrence. Based on the assessment of population vitality, the determination of the field tolerance index and the analysis of morphological changes in the melt, the air purity index (IAP) is calculated. Correlation, factor, and regression analyses are used for statistical data processing.

Biocenotic monitoring takes into account various indicators of species diversity. Bioindication methods are divided into two types: recording bioindication and accumulative bioindication. Recording bioindication allows us to conclude the impact of environmental factors based on the condition of individuals of a species or population. In contrast, accumulative bioindication uses the property of lichens to accumulate certain chemicals. According to these methods, recording and accumulating indicators are distinguished. Registering indicators respond to changes in the environment by changing their numbers, tissue damage, somatic manifestations (including disfigurement), changes in growth rate, and other clearly visible signs. Accumulative indicators concentrate pollutants in their tissues, which are further used to determine the degree of environmental pollution by means of chemical analysis (Kondratiuk, 2008).

The analysis of modern research (Windisch, 2017; Heiner et al., 2023; Niepsch et al., 2024) shows that the effectiveness of lichen indication is significantly increased with the integrated use of various methods and taking into account the regional characteristics of the studied areas.

2. Materials and Methods

The paper uses a comprehensive scientific analysis of literary sources, research and observation, statistical processing, and synthesis of the obtained research and scientific and theoretical data.

The research was conducted in large cities (Kharkiv and Poltava) in 2020–2023. According to regional environmental reports (Ekolohichnyi pasport Kharkivskoi oblasti, 2023; Ekolohichnyi pasport Poltavskoi oblasti, 2023), the study areas are characterized by a diversity of industrial load and transport infrastructure. The study area was divided into functional zones in accordance with the recommendations of the European Environment Agency (Air quality in Europe – 2023 report, 2023):

1) the central part of cities;
2) industrial areas;
3) sleeping areas;
4) park areas and green spaces.

In Kharkiv, 10 monitoring sites were surveyed (expanded from the original 8). In Poltava, the monitoring network covered 8 key sites covering areas with varying degrees of urbanization.

The methodological basis of the study was expanded to take into account modern European protocols and adapted to the specifics of the studied territories. Field studies were carried out according to the modified Braun-Blanquet methodology (Braun-Blanquet, 1964) using European standards for air quality assessment (Directive 2008/50/EC of the European Parliament and of the Council, 2008). Taking into account that lichens can inhabit different species of trees in different ways, we chose the most common trees in both cities: sharp-leaved maple (Acer platanoides L.), heart-leaved linden (Tilia cordata Mill.) and common ash (Fraxinus excelsior L.). According to the methodology, 10 trees were selected in each of the experimental plots, the number of lichens of each type was counted, and the degree of coverage of the pallet area by lichen in the most overgrown part of the tree was measured. Lichens were described at the base of the forophyte (up to 0.5 m) and in the middle part of the trunk (up to 2.0 m from the soil surface). Observations were made twice a year, in April and September, during 2020–2023.

For each type of lichen (crustose, leafy, and fruticose), the average frequency of occurrence and degree of coverage were calculated, and then a conditional score of relative air purity was determined. This indicator was used to conclude the degree of air pollution according to the scale shown in Table 1.

Table 1

Scale for assessing air pollution based on the results of lichen indication

Frequency of occurrence and degree of coverage	Conditional score for the relative air purity	Pollution assessment
0.0–0.20	1	strong ("lichen desert")
0.21–0.40	2	quite strong
0.41–0.60	3	middle
0.61–0.80	4	insignificant
0.81–1.0	5	no pollution is present

Pearson's correlation coefficient was calculated using Google Sheets, Version 2024, Google LLC (Google Sheets [Online Software], 2024).

3. Results and Discussion

In the study area, 35 species of lichens were found in Kharkiv and 49 s pecies in Poltava, which corresponds to the European indicators for urban areas (Air quality in Europe – 2023 report, 2023). It is known that lichens are more demanding on air purity in the order "crustose → foliose→ fruticose". In other words, the hardiest and most tolerant lichens are the crustose lichens. The foliose lichens show medium sensitivity to air pollution, and the fruticose lichens disappear at the first symptoms of pollution (Sujetovienė, 2017). Among the identified genera, Lecanora, Khanthoria, Physcia, and Phaeophyscia were the most resistant to air pollution. The foliose lichens of the genera Parmelia and Hypogymnia are medium-sensitive indicators. The most sensitive indicators are fruticose lichens of the genera Ramalina, Evernia, and Usnea.

The dynamics of changes in lichen indication indicators, namely the average frequency of lichen occurrence and the degree of coverage of sites Q and the conditional score of relative atmospheric purity P during the observation period, are shown in Tables 2, 3.

Table 2

Dynamics of changes in lichen indication indicators in Kharkiv during the observation period

Area of the city	Year of observation							
	2020		2021		2022		2023	
	Q	*P*	*Q*	*P*	*Q*	*P*	*Q*	*P*
central part	0.43	3	0.44	3	0.38	2	0.32	2
industrial areas	0.39	2	0.37	2	0.30	2	0.28	2
sleeping areas	0.48	3	0.46	3	0.39	2	0.36	2
park areas and green spaces	0.64	4	0.63	4	0.59	3	0.56	3

As can be seen from the results of the lichen biomonitoring of the air, the industrial areas of both cities were characterized by quite severe pollution, the central and residential areas by medium pollution, and the green areas by minor pollution. At the same time, the environmental situation in Kharkiv deteriorated significantly during the war (2022–2023), which can be explained by the proximity to the war zone and frequent shelling of all districts of the city without exception.

Table 3

Dynamics of changes in lichen indication indicators in Poltava during the observation period

Area of the city	Year of observation							
	2020		2021		2022		2023	
	Q	*P*	*Q*	*P*	*Q*	*P*	*Q*	*P*
central part	0.39	2	0.44	3	0.43	3	0.37	2
industrial areas	0.35	2	0.37	2	0.34	2	0.33	2
sleeping areas	0.42	3	0.46	3	0.42	3	0.41	3
park areas and green spaces	0.62	4	0.63	4	0.61	4	0.56	4

The data obtained were compared with the air quality indicators provided in the regional reports of the Department of Environmental Protection and Nature Management of the Kharkiv Regional State Administration (since 2022 – Kharkiv Regional Military (State) Administration) (Dopovid pro stan navkolyshnoho pryrodnoho seredovyshcha v K harkivskii oblasti, 2020, 2021, 2022, 2023) and Department of Ecology and Natural Resources of the Poltava Regional State Administration (since 2022 – Poltava Regional Military (State) Administration) (Rehionalna dopovid pro stan navkolyshnoho pryrodnoho seredovyshcha v Poltavskii oblasti, 2020, 2021, 2022, 2023). According to the provided reports, there is a negative trend in the most significant indicators of air pollution in populated cities, namely sulfur dioxide, nitrogen dioxide, and dust (Tables 4, 5).

Table 4

Dynamics of changes in key indicators of air pollution in Kharkiv over the monitoring period

Pollutant	Annual average value of the pollutant, mg/m^3				MAC, mg/m^3
	2020	2021	2022	2023	
Sulfur Dioxide	0.007	0.007	0.011	0.014	0.05
Nitrogen Dioxide	0.03	0.03	0.03	0.028	0.04
Dust	0.09	0.07	0.43	0.43	0.15
Carbon monoxide	1.31	1.4	1.3	1.18	3.0

Table 5

Dynamics of changes in key indicators of air pollution in Poltava over the monitoring period

Pollutant	Annual average value of the pollutant, mg/m^3				MAC, mg/m^3
	2020	2021	2022	2023	
Sulfur Dioxide	0.027	0.003	0.003	0.003	0.05
Nitrogen Dioxide	0.0275	0.037	0.038	0.04	0.04
Dust	0.109	0.141	1.166	1.156	0.15
Carbon monoxide	0.193	1.95	1.975	1.95	3.0

This trend can be explained by the direct correlation between the intensity of military actions and the deterioration of air quality. According to satellite monitoring data (Status report of air quality in Europe for year 2023, 2024), in zones of active combat operations, there is an increase in particulate matter concentration by 200–300 %, increase in SO_2 content by 150–400 %, and increase in NO_x concentration by 180–250 %.

In particular, the current state of atmospheric air pollution in the Kharkiv region is affected by emissions of pollutants from mobile and stationary sources of pollution, as well as daily emissions of pollutants due to explosions and fires resulting from active combat operations in the region. Simultaneously, the forced use of alternative energy sources (solid fuel, diesel generators, etc.) during planned and emergency power outages also deteriorates the quality of atmospheric air (Zvit pro stan dovkillia v umovakh viiny, 2023).

Comparing the results of lichen indication mapping and air pollution observation data in cities, the territories were zoned according to pollution levels (Tables 6, 7).

Table 6

Species composition of lichens in the studied areas of Kharkiv

Area of the city	Number of species	Dominant species	Air Purity Index (IAP)
central part	5–7	Phaeophyscia orbicularis, Xanthoria parietina	0–20
industrial areas	3–5	Lecanora conizaeoides	0–15
sleeping areas	8–12	Parmelia sulcata, Hypogymnia physodes	20–35
park areas and green spaces	15–20	Evernia prunastri, Ramalina farinacea	35–50

Table 7

Species composition of lichens in the studied areas of Poltava

Area of the city	Number of species	Dominant species	Air Purity Index (IAP)
central part	7–9	Xanthoria parietina, Physcia adscendens	15–25
industrial areas	4–6	Lecanora conizaeoides, Scoliciosporum chlorococcum	10–20
sleeping areas	10–14	Parmelia sulcata, Hypogymnia physodes	25–40
park areas and green spaces	18–22	Evernia prunastri, Ramalina farinacea, Usnea hirta	40–55

The study revealed variations in lichen species composition. Overall, the epiphytic complex of cities consists of species resistant to moisture deficiency and air pollution. In industrial zones with the most polluted air, toxicotolerant crustose lichens of the species Lecanora conizaeoides predominate. Medium-sensitive to atmospheric pollution, foliose lichens (Parmelia sulcata, Hypogymnia physodes) dominate in residential areas of both cities.

The lichen complexes in the central districts of both cities are primarily composed of crustose species such as Xanthoria parietina, with Phaeophyscia orbicularis also common in Kharkiv and Physcia adscendens in Poltava. The distribution of these epiphytic lichen species of the genus Physcia indicates the prevalence of species classified as synanthropic, whose distribution is associated with significant dust pollution and reduced competition from other species, which is a characteristic feature of urbanized territories. In the cleanest zones of both cities, fruticose lichens of the genera Evernia and Ramalina are found, and in Poltava's park zones, Usnea as well, which are highly sensitive indicators of acid air pollution and completely disappear in areas with elevated content of pollutants such as sulfur and nitrogen oxides. It should be noted that both in terms of species diversity and coverage degree in the studied areas of Poltava, a better situation is observed, which is confirmed by relatively higher values of the air purity index.

Furthermore, comparative analysis of lichen species composition revealed a 50–70 % decrease in fruticose lichen species in military impact zones and a corresponding 30–50 % increase in “lichen desert” areas, as well as the dominance of pollution-resistant species (predominantly crustose forms).

Comparing the results of lichen species composition analysis, the frequency of occurrence of individual species, and the degree of area coverage with air pollution indicators, a high degree of correlation was established between lichen indication data and instrumental measurement results. According to our data, lichens of the genera Xanthoria and Physcia are appropriate to use as indicator species for sulphur dioxide air pollution (correlation coefficients 0.87 and 0.85, respectively).

4. Conclusions

1. It was found that lichen identification is an effective method for evaluating air quality in urban areas, as shown by a strong correlation (r_{xy} = 0.85–0.87) between lichen monitoring data and instrumental pollution measurements. The most informative indicator species for air quality monitoring in urban environments have been identified, specifically Xanthoria parietina and Physcia adscendens.

2. A significant deterioration in atmospheric air quality has been established in the studied regions during 2020–2023, correlating with the intensity of military actions. A critical reduction in lichen biodiversity (by 40–90 %) has been recorded in areas with increased military impact. The formation of new "lichen deserts" has been identified in areas of industrial facility destruction and intensive military equipment use

3. Based on the conducted research results and the experience of domestic and foreign developments, a series of recommendations have been developed regarding the expansion and effective application of lichen monitoring across various levels of environmental supervision. For local government authorities, it is proposed to implement a system of continuous atmospheric air quality monitoring using lichen indication methods, develop and implement urban greening programs considering lichen indication zoning results, and create interactive air pollution maps based on lichen indication data. For industrial enterprises, we consider it necessary to implement a biomonitoring system as a component of environmental management and develop emission reduction programs considering lichen indication data.

4. For environmental scientific institutions, we consider the expansion of monitoring site networks, implementation of modern lichen indication data analysis methods, and development of regional sensitivity scales for indicator species as promising directions. Considering the ongoing reformation of the state environmental monitoring system under martial law conditions, which provides for systematic observations at all levels – from national to facility-specific, we also propose the implementation of biomonitoring as part of systematic monitoring of territories affected by combat operations, continuation of research on developing methods for assessing the impact of military actions on atmospheric air quality, and creation of a database for post-war environmental monitoring restoration

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