LONG-TERM SPATIAL CHANGES IN AIR QUALITY IN JELGAVA CITY

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Abstract
Air pollution has been identified as a significant environmental issue and a major health threat, particularly in densely populated urban areas. Long-term and spatial variations in air quality across Jelgava City were analyzed using the Air Purity Index (I.A.P.), which is calculated based on the distribution and frequency of sensitive lichen species. Lichens were utilized effectively as biomonitoring tools due to their high sensitivity to air pollutants, their ubiquity, and their cost-effectiveness for detecting pollution trends over extensive spatial scales. Sampling plots were systematically established across various city zones, and comprehensive field data were collected from 1,250 deciduous trees carefully selected for uniformity in age, crown shape, and local growth conditions. The analysis revealed that in 2016, approximately 2.75% of Jelgava's urban area was categorized as high pollution zones, while 44.0% fell into moderate pollution zones, and 53.25% were classified as low pollution zones. Improvements in air quality were predominantly observed in suburban and peripheral areas; conversely, increased pollution was distinctly noted in the city center, correlating strongly with intensified industrial activities, growing vehicular emissions, and traffic congestion. The findings highlight the critical role of urban green infrastructure in mitigating air pollution impacts, particularly in moderate and low-pollution zones, whereas high-pollution hotspots continue to threaten biodiversity, public health, and urban ecosystem sustainability, demanding urgent mitigation efforts.
Keywords: biomonitoring, lichen-based monitoring, Air Purity Index (I.A.P.), urban sustainability.

Introduction

Air pollution has been identified as a pressing global issue, particularly in urban environments where its effects are exacerbated by population density and industrial activities. It is reported by the World Health Organization (WHO) that nearly 90% of the global population is exposed to polluted air, with urban areas being affected most severely due to high levels of vehicular emissions and industrial discharges (Dhimal et al., 2021; Bräuer et al., 2021a). In cities, alarming levels of pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) are observed, leading to significant health risks and environmental degradation (Rohde & Muller, 2015; Jennings et al., 2021).

The profound and multifaceted health impacts of air pollution are well-documented. Premature mortality is reported to be significantly contributed by air pollution, with millions of deaths annually attributed to respiratory and cardiovascular diseases (Burnett et al., 2018; Syuhada et al., 2023). For instance, in India, a substantial burden of disease has been linked to air pollution, with increased morbidity and mortality rates observed due to high exposure levels (Balakrishnan et al., 2019; Kumar, 2023). The economic implications are also highlighted; it has been estimated by the Public Health Agency of Canada that CAD 114 billion is lost annually due to health-related issues caused by air pollution (Syuhada et al., 2023). Similar economic burdens are noted in other countries, where a considerable percentage of GDP loss is attributed to health care costs and lost productivity (Balakrishnan et al., 2019; Syuhada et al., 2023).

Urban environments are regarded as particularly vulnerable to the effects of air pollution due to unique geographical and infrastructural characteristics. Stagnated air flow is commonly experienced in high-density areas, exacerbating pollution levels in street canyons and densely built environments (Yuan et al., 2014). Pollutant dispersion is influenced by the configuration of urban landscapes, resulting in localized hotspots of poor air quality (Baró et al., 2014). Additionally, socio-economic disparities in urban settings are noted to disproportionately expose marginalized communities to the brunt of air pollution, emphasizing the necessity of equitable environmental policies (Bräuer et al., 2021b; Jennings et al., 2021).

Mitigation strategies are considered essential to combat the adverse effects of air pollution in urban areas. Air quality improvements are shown to be achievable through nature-based solutions, such as urban forestry and green infrastructure, which enhance pollutant dispersion and absorption (Baró et al., 2014; Menon & Sharma, 2021). Significant reductions in urban air pollution levels are demonstrated by the implementation of green traffic policies, suggesting that positive outcomes can be achieved through strategic urban planning (Qiu & He, 2017). However, the operationalization of these strategies is recognized as requiring time and investment, with their success contingent upon comprehensive policy frameworks addressing both environmental and public health concerns (Gani, 2023).

The monitoring of air pollution is regarded as critical for understanding its impact on human health and the environment. The assessment of air quality is often conducted using bioindicators, particularly lichens. Lichens, which are symbiotic organisms composed of fungi and algae, are recognized for their high sensitivity to air pollution, making them excellent indicators of atmospheric conditions. The absorption of pollutants directly from the air by lichens allows the levels of various contaminants, including heavy metals and other toxic elements, to be gauged by researchers (Pilecka-Ulcugaceva et al., 2022; Pilecka-Ulcugaceva et al., 2024).

The widespread utilization of lichens in biomonitoring studies has been facilitated by their sensitivity to environmental changes. It has been demonstrated through studies that lichen diversity and vitality are significantly influenced by air pollution, particularly in urban areas. It was highlighted by Biase et al. (2022) that lichens are among the most commonly utilized bioindicators for monitoring atmospheric quality, as many species exhibit particular sensitivity to chemical pollution (Biase et al., 2022). This sensitivity has enabled the assessment of the impact of pollutants on lichen communities, which are reflective of broader environmental health.

The transplantation technique is employed as a common method in lichen biomonitoring. Lichens are collected from unpolluted areas and are then exposed to polluted environments for a specified duration. It has been noted by Klimek et al. that the success of this technique depends on the background concentration of pollutants and the vitality of the transplanted lichens (Klimek et al., 2015). Similarly, it was demonstrated by Abas et al. (2022) that the lichen '*Usnea misaminensis*' can be utilized as a reliable biological indicator for measuring urban air pollution, confirming its effectiveness when compared to traditional monitoring instruments (Abas et al., 2022).

Advancements in lichen research have recently been focused on high-resolution assessments of air quality. Lichen carbon, nitrogen, and sulfur contents, along with stable-isotope-ratio signatures, have been utilized by Niepsch et al. (2023) to evaluate air quality in urban centers. This approach is recognized for providing a nuanced understanding of pollutant deposition and dispersion in complex urban environments, where traditional monitoring methods may fall short.

The diversity of lichen species in a given area has also been identified as a qualitative measure of air quality. It was found by Belguidoum et al. (2022) that changes in lichen diversity were closely linked to air pollution levels, particularly in urban areas with significant anthropogenic impacts (Belguidoum et al., 2022). The correlation between lichen diversity and pollution levels underscores the importance of lichen diversity as a bioindicator, as the cumulative effects of multiple pollutants, including particulate matter and nitrogen oxides, are reflected.

In addition to diversity, lichen functional traits are also regarded as informative. It was emphasized by Pinho et al. that lichen functional diversity is sensitive to atmospheric ammonia levels, indicating that specific lichen species can be utilized to monitor particular pollutants (Pinho et al., 2011). This functional approach is recognized as complementing traditional diversity assessments and enhancing the robustness of lichen-based biomonitoring.

The urban environment of Jelgava, Latvia, is regarded as a unique case study for the monitoring of air pollution using bioindicators such as lichens. This approach is facilitated by the sensitivity of lichens to various atmospheric pollutants, particularly heavy metals and sulfur dioxide, which makes them effective indicators of air quality in urban settings (Pilecka-Ulcugaceva et al., 2021).

One notable methodology utilized in Jelgava involves the transplantation of lichens. Lichen samples are collected from less polluted areas and are exposed to urban environments for a predetermined duration. The physiological responses of the lichens, along with the accumulation of pollutants, are analyzed to assess air quality. For instance, it was demonstrated by Lackovičová et al. (2013) that the lichen '*Evernia prunastri*' exhibited significant changes in physiological parameters in response to urban pollution levels, indicating a decline in heavy metal concentrations following a reduction in emissions in Bratislava. These findings can be extrapolated to similar urban contexts like Jelgava (Lackovičová et al., 2013).

In addition to transplantation studies, the assessment of lichen diversity and vitality is employed to provide valuable insights into air quality. It was highlighted by Matwiejuk in Białystok (2011) that the average concentrations of accumulated elements in lichens were lower than in other Polish cities, suggesting a relatively better air quality in that urban area. This methodology can be applied to Jelgava, where the monitoring of lichen diversity may reveal the impacts of local pollution sources, such as traffic and industrial activities.

Furthermore, the use of lichen bags, as described by Petrova (2015), is implemented to monitor air quality in areas with high traffic and industrial activity. In this technique, lichens are placed in mesh bags at various urban locations, and the accumulation of pollutants over time is assessed (Petrova, 2015). This method is recognized as particularly effective in Jelgava, where specific sites can be targeted for detailed pollution studies.

The physiological responses of lichens to air pollutants have also been extensively documented. For example, it was explored by Yemets et al. (2014) that airborne pollutants affected lichen growth and viability along a rural highway in Norway, demonstrating the correlation between pollutant concentrations and lichen health. Such studies provide a framework for understanding how lichens in Jelgava might respond to local air quality conditions.

Moreover, the integration of lichen monitoring with other environmental assessments is considered beneficial for enhancing the understanding of urban air quality. The research by Guttová et al. (2011) in Bratislava illustrated how lichen responses reflected broader trends in air pollution, particularly in urban areas where emissions have significantly decreased since the 1990s (Guttová et al., 2011). This approach is recognized as adaptable for Jelgava, allowing for a comprehensive assessment of air quality over time.

The aim of this study is to evaluate the Air Purity Index (I.A.P.) in Jelgava City and to identify changes in air quality over time, utilizing bioindicators such as lichens to assess the impacts of urban pollution and environmental dynamics.

Materials and Methods

Research area

The assessment of air quality in Jelgava using lichen bioindication has been conducted in a standardized 10-year cycle since 1996, with full surveys carried out in 1996, 2006, and 2016. This study focuses on the comparative analysis of air quality across these three years. Identical sampling protocols, plot layouts, and indicator species assessments were used during each monitoring cycle to ensure comparability and long-term trend evaluation.

Jelgava, located in the central part of Latvia, is recognized as the fourth-largest city in the country and is considered an important regional hub for education, culture, and industry. The city is situated approximately 40 kilometers southwest of the capital, Riga, along the Lielupe River, which has been historically significant for its development, economic activities, and environmental dynamics. An area of approximately 60 square kilometers is covered by the city, and a population of around 55,000 residents has been recorded in recent demographic data.

Jelgava lies at an elevation of approximately 3 to 5 meters above sea level, making it part of the lowland region of Latvia. This relatively flat terrain is characteristic of the Zemgale Plain, which influences hydrological processes and pollutant dispersion patterns within the city. The city's land use is predominantly characterized by residential, commercial, and industrial zones, interspersed with green spaces and parks. Additionally, agricultural land surrounds the city, with fields and pastures making up a significant portion of the regional landscape. These agricultural areas, while economically significant, are also potential sources of diffuse pollution, such as ammonia and particulate matter.

The climate of Jelgava is classified as humid continental (Köppen climate classification Dfb), with cold winters and mild summers. The average annual temperature is approximately +6 °C, with January being the coldest month (-3.5 °C average) and July the warmest month (+17.5 °C average). Annual precipitation averages around 600-700 mm, with the majority occurring during the summer months. Winters are typically marked by snowfall, which facilitates pollutant deposition, while the warmer months improve air circulation and promote pollutant dispersion.

The urban landscape of Jelgava has been shaped by historical and industrial development. Industrial activities, including food processing, metalworking, and manufacturing, have been historically concentrated in the city. While economic growth has been facilitated by these industries, environmental challenges, particularly regarding air and water quality, have also been posed. Urban traffic and industrial emissions are considered contributing factors to localized air pollution, which is compounded by the flat topography and limited vertical mixing of air masses in certain conditions.

Jelgava's environmental significance is further highlighted by its proximity to the Lielupe River, which acts as an ecological corridor for pollutant transport and serves as an important waterway for the region. The interaction of urban, industrial, and agricultural activities within this landscape underscores the need for integrated environmental management.

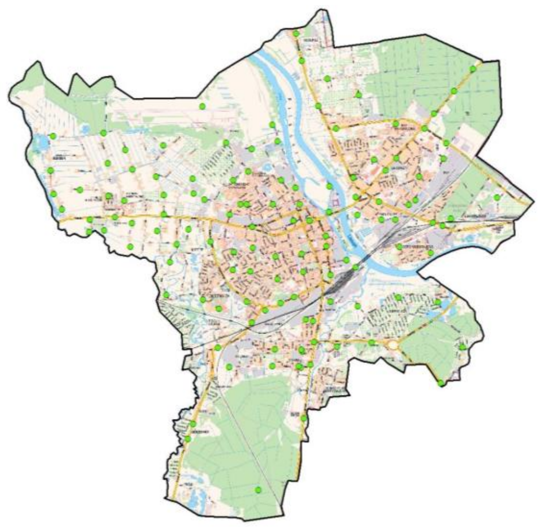
Jelgava is regarded as a unique case study for air quality evaluation, particularly through the use of innovative approaches such as bioindicators like lichens. Such studies are expected to contribute to the development of sustainable urban planning and environmental policies, ensuring long-term well-being for both residents and ecosystems.

Data collection

To conduct lichen indication, the city was divided into 104 sample plots based on building density, the location of industrial enterprises, and transportation corridors. The central district was divided into 52 sample plots, each measuring 500 m x 500 m, while the remaining city area was divided into 52 sample plots measuring 1000 m x 1000 m. This arrangement of sample plots was established based on air quality studies conducted in 1996 and 2006. In 2016, an additional 21 sample plots were added due to urban development and the expansion of built-up areas 'Figure 1'. In total, lichen indication was performed in 125 sample plots in 2016.

In each sample plot, 10 trees were selected for lichen counting. The trees were chosen to ensure similar age, height, and dimensions. On each tree trunk, all lichen species were recorded within the height range of 30 cm to 2 m. On the side of the tree trunk with the highest abundance of lichens, the percentage cover of lichens was evaluated for each species.

Figure 1
Sample plots in Jelgava city in 2016



Data analysis

The Air Purity Index (I.A.P.) is determined for each sample plot and consists of the sum of the products of the toxic tolerance factor Q and the occurrence degree for all lichen species. The index is calculated using Equation 1:

$$I.A.P. = \sum_{i=1}^{n} Q_i \cdot f_i \qquad (1)$$

where:

I.A.P. - Air Purity Index,

n - the number of lichen species in the studied area,

Q - the toxic tolerance factor (constant for each lichen species), calculated using Equation 2:

$$Q = \frac{n_1}{n_2} \qquad (2)$$

where:

n_1 - the total number of sample plots where the species of interest is found,

n_2 - the total number of sample plots containing all lichen species.

The occurrence degree is determined by combining the percentage cover of the lichen species and its frequency in each sample plot. The f-values are assigned as follows:

f=1: Rare species with minimal coverage,

f=2: Rare species or species with 1–5% coverage,

f=3: Occasional species or species with 5–10% coverage,

f=4: Frequent species or species with 10–20% coverage,

f=5: Very frequent species with coverage exceeding 20%.

In the study, 1,250 deciduous trees of various species were selected. Trees were chosen to ensure similar age, crown shape, and exposure, as well as comparable growth conditions. Most of the selected trees were located along streets and roadsides.

The Air Purity Index (I.A.P.) data were utilized to develop Air Purity Index (I.A.P.) maps using Geographic Information Systems (GIS) with the Inverse Distance Weighting (IDW) interpolation method. This approach allowed for the spatial visualization and analysis of air quality distribution across the studied area, providing a detailed representation of variations in air purity.

Results and Discussion

Air quality monitoring conducted in Jelgava in 2016 revealed notable trends in pollution distribution across the city 'Figure 2'. Improvements were observed in various areas, including Satiksmes Street, Dobeles/Lielā Street, Lithuania Highway, and RAF residential zones. However, significant air quality deterioration was noted near the wastewater treatment plant, SIA Larelini, Palīdzības Street, and areas outside the center, such as Langervalde Park, Brīvības Boulevard, and Riga Highway.

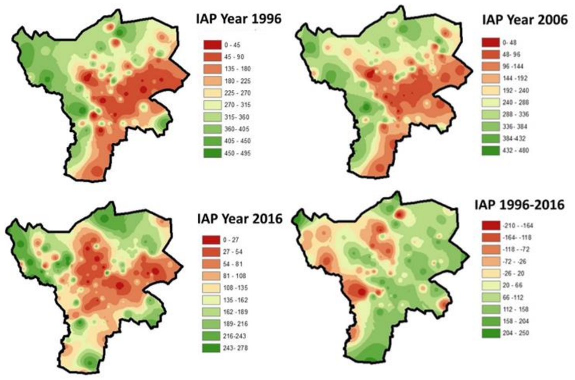
High air pollution zones were found to cover 1.66 km² (2.75%) of the city's area in 2016, representing a reduction from 1996 (4.06%) but a slight increase compared to 2006 (2.49%). These zones were primarily concentrated in the city center and near Langervalde Park. Moderate pollution zones were reported to span 26.54 km² (44.0%), reflecting a decrease from 2006 (48.51%) but an increase in the city center, where they accounted for 71.15%. Outside the center, a decline in moderate pollution zones was noted, dropping to 36.54% since 2006.

Clean air zones were recorded to cover 32.12 km² (53.25%) of Jelgava in 2016, showing an increase compared to 1996 and 2006. While clean air areas outside the center expanded to 61.54%, a significant decline was observed in the city center, where clean zones accounted for only 23.08%.

These findings highlight shifting pollution patterns, with air quality improving outside urban centers and increasing challenges identified in densely populated central areas.

Figure 2

Air quality monitoring results in Jelgava city by applying the Air Purity Index (I.A.P.)



The air quality monitoring conducted in Jelgava in 2016 revealed significant trends in pollution distribution across the city, with both improvements and ongoing challenges being highlighted. It was observed that certain areas, particularly Satiksmes Street, Dobeles/Lielā Street, Lithuania Highway, and the RAF residential zones, experienced notable improvements in air quality. These findings indicate that targeted interventions and policies may have been effective in reducing pollution levels in these regions. However, the deterioration of air quality near the wastewater treatment plant, SIA Larelini, Palīdzības Street, and areas outside the city center, such as Langervalde Park and Riga Highway, has raised concerns about localized pollution sources, which require further investigation and management.

The spatial analysis of pollution zones in Jelgava revealed that high air pollution zones were found to cover 1.66 km² (2.75%) of the city's area in 2016, representing a reduction from 4.06% in 1996 but a slight increase from 2.49% in 2006. This fluctuation suggests that while overall air quality has improved, certain areas have remained vulnerable to pollution, particularly in the city center and near Langervalde

Park. The persistence of high pollution zones in these areas has been attributed to increased traffic, industrial emissions, and possibly the effects of urbanization, which often result in higher concentrations of pollutants in densely populated regions (Kleperis et al., 2016).

Moderate pollution zones were reported to span 26.54 km² (44.0%) of Jelgava, reflecting a decrease from 48.51% in 2006. However, an increase in moderate pollution levels within the city center, where they accounted for 71.15%, has been noted, suggesting that unique challenges are being faced in urban core areas. The concentration of moderate pollution in the city center has been linked to traffic congestion, construction activities, and emissions from nearby industrial facilities, which are common contributors to urban air quality issues (Kleperis et al., 2011). Conversely, a decline in moderate pollution zones outside the center, dropping to 36.54% since 2006, was noted, indicating that efforts to improve air quality in suburban and rural areas may be yielding positive results.

Significant clean air zones were recorded, covering 32.12 km² (53.25%) of Jelgava in 2016. This represents an increase compared to previous years, suggesting that measures aimed at reducing pollution have been effective in expanding areas of clean air. Notably, clean air areas outside the center were observed to have expanded to 61.54%, indicating that residents in these regions are benefiting from improved air quality. However, a significant decline in clean air zones within the city center, where they accounted for only 23.08%, was observed, underscoring the urgent need for targeted interventions to address pollution in urban hotspots.

The shifting pollution patterns observed in Jelgava are indicative of broader trends in urban air quality management. Improvements in air quality outside urban centers suggest that emissions from transportation and industry have been successfully reduced through strategic policies. However, challenges faced in the city center highlight the need for comprehensive urban planning that considers the unique characteristics of densely populated areas. Stricter emissions regulations, enhanced public transportation options, and the promotion of green infrastructure are recommended as measures to mitigate pollution.

Moreover, the correlation between air quality and public health has been well-documented. Studies have shown that exposure to air pollutants is linked to various health issues, including respiratory diseases and cardiovascular conditions (Hart et al., 2012; Adami et al., 2021). The persistence of high pollution levels in certain areas of Jelgava is considered to pose significant health risks to residents, particularly vulnerable populations such as children and the elderly. Therefore, ongoing monitoring and assessment of air quality are deemed essential for informing public health initiatives and ensuring the well-being of the community.

Conclusions

1. The long-term spatial analysis of air quality in Jelgava City provides valuable insights into the dynamics of urban pollution and the effectiveness of biomonitoring techniques.
2. A significant reduction in high-pollution zones was observed, decreasing from 4.06% in 1996 to 2.75% in 2016. While this suggests a possible positive effect of general urban development and environmental management, the lack of data on specific interventions limits definitive conclusions. A slight increase from 2.49% in 2006 to 2.75% in 2016 underscores the persistence of localized pollution hotspots.
3. The expansion of clean air zones to 53.25% of the city's total area in 2016, particularly in suburban regions, reflects positive impacts of urban green infrastructure and reduced emissions. This improvement aligns with efforts to decentralize urban activities and enhance environmental quality outside the urban core.
4. Despite overall progress, the city center experienced a decline in clean air zones, covering only 23.08% of its area in 2016. This trend emphasizes the need for targeted pollution mitigation strategies in densely populated areas, focusing on traffic management, industrial emission controls, and urban planning innovations.
5. The use of lichens as bioindicators has proven to be an effective and cost-efficient method for assessing air quality. The Air Purity Index (I.A.P.) provided a detailed representation of pollution distribution, enabling the identification of trends and problem areas that require attention.
6. To address ongoing challenges, stricter emissions regulations, the promotion of green infrastructure, and enhanced public transportation systems are recommended. Continued investment in biomonitoring programs and GIS-based spatial analyses will support the tracking of air quality trends and the formulation of evidence-based policies.
7. Persistent high-pollution zones in certain areas pose significant risks to public health, particularly for vulnerable populations. Integrating air quality monitoring with public health initiatives is essential for mitigating the adverse effects of urban pollution.

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