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Needle-Based Assessment of Urban and Industrial Air Pollution in Aktobe

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ABSTRACT

This study is devoted to assessing the degree of pollution with atmospheric particles and dust in the urbanized and industrial zones of the Aktobe Region, Republic of Kazakhstan, using the needles of the Scots pine (Pinus sylvestris) and the Norway spruce (Picea abies) as bioindicators. These trees are good indicators of the state of the air because their needles may collect pollutants like dust, soot, heavy metals, and sulphur dioxide. The study used a variety of techniques, such as quantitative measurement of needle damage and desiccation, biotesting for radioactive contamination, the Hertel turbidity test, and ocular evaluation of needle quality. The study was conducted in 13 districts of the city of Aktobe with different levels of anthropogenic load. The results showed significant differences in the degree of contamination, with particularly high levels of harmful substances in Objects 8, 9, 10, and 13. Object 9 was identified as the most polluted, reaching pollution class VI by the condition of needles and an independent atmosphere assessment. The study confirms the high efficiency of using conifers for rapid assessment of the state of the atmosphere, proving that needle-based bioindication is an affordable and reliable method of environmental monitoring under anthropogenic load.

Keywords: *Bioindication, Dendrological monitoring, Ecological biocontrol, Needles, Norway spruce (Picea abies), Scots pine (Pinus sylvestris)*

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INTRODUCTION

Urban air quality is a major environmental problem affecting human health, flora, and fauna (Sirotiuk, 2016; Aydin *et al*., 2024; Malaj & Xhulaj, 2024; Mahajan & Prakash, 2025). With the increasing level of urbanization and industrial production, air pollution increases significantly (Ilyushin & Martirosyan, 2024; Kazankapova *et al*., 2024), resulting in diseases and reduced life expectancy (Mohammed & Çinar, 2021; Guissou *et al*., 2022; Anwar *et al*., 2025). One of the most effective methods of monitoring the environmental situation is the use of bioindicators—living organisms that can reflect the level of pollution due to their sensitivity to environmental changes (Korotun & Goncharov, 2024; Rarassari *et al*., 2024; Latha & Mahaboob Basha, 2025). Plants are often used as such indicators, since they directly interact with atmospheric air and quickly react to changes in environmental quality (Asylbekova, 2010; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2011; Salgueiro *et al*., 2024; Semenikhin *et al*., 2024).

Conifers are often referred to as "evergreens" because their needles are renewed gradually, unlike deciduous trees, whose leaves fall off in one season. The needles of conifers are characterized by a long life span: for example, in the Scots pine, they live for 2–3 years. During this period, the conifers accumulate a significant amount of toxic substances that can negatively affect the functioning of the photosynthetic apparatus and lead to changes in the normal dynamics of woody plants transitioning into the dormant state and returning from it, which serves as an additional indicator of pollution (Angalt & Zhamurina, 2014). Contrary to expectations, the degree of pine needle damage does not relate linearly to the concentration of a specific pollutant. There are correlations but no direct or indirect relations since pine needles are passive indicators of both organic and inorganic pollutants. In the early research on this topic, it was reported that decreased needle longevity was closely related to increased heavy metal concentrations.

Stomatal chlorosis and tip discolorations were closely related to high concentrations of Ca, Fe, Si, and Cl. Anatomical and morphological changes were also associated with increased concentrations of aluminum (Kalugina *et al*., 2023; Logachev & Korotun, 2023).

Among the most accessible and informative objects for air quality monitoring are coniferous trees such as Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) (Savira *et al*., 2024). These species of conifers are widespread in natural ecosystems and are often used in urban plantations, making them convenient targets for environmental assessment in urbanized areas (Hameed Abd *et al*., 2025). The needles of these trees are susceptible to pollutants such as sulfur dioxide, nitrogen oxides, heavy metals, and radiation, which allows their condition to be used as an indicator of air pollution (Alekseev, 1987; Shubert, 1988; Sobchak *et al*., 2001; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2011; Bekezhanov *et al*., 2018; Legkova & Bulyka, 2022).

The air pollution indicator must meet certain criteria (Chernenkova & Bochkarev, 2013, Zeibert *et al*., 2022), some of the main ones including:

- being characteristic of the ecosystem being monitored and actively functioning in it (Põldma *et al*., 2023);
- being abundant in the ecosystem to provide a representative picture of the ecological situation as a whole (Mikia *et al*., 2024);
- to track changes in pollution, the indicator must remain in the ecosystem for several years;
- being easily accessible for the necessary research and analysis;
- the indicator should allow samples to be analyzed without complicated pre-treatment;
- the state of the indicator should directly reflect the level of environmental pollution (Savira *et al*., 2024);
- it needs to be used in its natural ecosystem to avoid distortion of results due to artificial conditions (Ghisi *et al*., 2023).

In addition, biological indicators can be classified according to the type of response to pollutant exposure. There are two main types of indicators: sensitive and cumulative.

The use of coniferous trees such as pine and spruce makes it possible to observe both sensitive and cumulative responses to pollution. Needle damage (chlorosis, necrosis) is a clear indicator of pollution, while accumulation of toxic substances can serve as an indicator of long-term exposure to pollutants (Dos Santos *et al*., 2023). This research will contribute to a deeper understanding of the effects of pollutants on vegetation and offer important data for practical applications in urban environmental monitoring, which may be useful for other cities with similar pollution problems (Shcherbatiuk, 2013; Davydova, 2021; Talbi *et al*., 2024).

A crucial aspect of our study is investigating the effects of pollutants on plants and determining the sensitivity of coniferous species to different types of pollutants. Particular attention was paid to studying the impact of sulphur dioxide, a major air pollutant in urban areas, on the needles of pine and spruce trees. The uniqueness of this study lies in the local industries in Aktobe, Kazakhstan, which are primarily mining and metallurgy, energy, and chemical industries (Ulman *et al*., 2025). The climatic conditions in Aktobe also contribute to the prevalence of air pollution, as Moldayazova *et al*. (2023) reported that extreme winter and summer temperatures, high humidity, and a predominantly windless climatic nature contributed to year-round pollution. Recently, the air pollution conditions in Aktobe have improved, and as reported by Mukanov and Berdenov (2022), data from regular atmospheric air monitoring indicates a decline in pollution levels.

This study aimed to conduct a rapid and efficient assessment of air quality in the city of Aktobe using pine and spruce needles as bioindicators (Belfiore *et al.,* 2024; Figueroa-Valverde *et al*., 2024; Karatas, 2024; Kęska & Suchy, 2024; Lee & Ferreira, 2024; Negreiros & Ory, 2024; Noor *et al*., 2024; Wolderslund *et al*., 2024; Abdullah *et al*., 2025; Jagsi *et al*., 2025; Schneider & Krüger, 2025; Wong *et al*., 2025; Yu *et al*., 2025).

MATERIALS AND METHODS

Study location

Aktobe is a large industrial and cultural center of Kazakhstan. The city has a high level of air pollution due to the operation of industrial enterprises such as Aktobe Chemical Compounds Plant (ACCP) and Aktobe Ferroalloy Plant (AFP), as well as transport emissions and other anthropogenic factors. The condition of needles in different areas of the city can serve as an important indicator of the degree of atmospheric pollution and, therefore, can be used for environmental monitoring and for planning environmental protection measures.

To analyze the air condition in different districts of Aktobe, the following zones were selected, which will be further titled as Object$_n$: Object 1 — industrial district, Object 2 — HMP district, Object 3 — SAPAR bus interchange district, Object 4 — EXPRESS bus interchange district, Object 5 — "Kolkhoznyi rynok" district, Object 6 — Airport, Object 7 — Aviagorodok district, Object 8 — Zhilyanka district, Object 9 — Zhiogorogok district, Object 10 — railway station, Object 11 — Akzhar 1, Object 12 — Akzhar 2, Object 13 — Yasny district.

Methods

The desiccation and damage of the needles of Scots pine and Norway spruce were examined with a set of techniques aimed at determining the level of environmental radiation pollution and the condition of tree needles. This study was conducted for the rapid assessment of air quality in particular areas with a high risk of pollution.

To achieve the set research objectives, the following methods were employed: 1. Test-analysis and biotesting for radioactive contamination (to assess the impact of radiation on vegetation); 2. Visual assessment of the condition of needles (examination of needles to identify signs of damage and desiccation); 3. Hertel's turbidity test (to additionally examine the condition of needles) (Alekseev, 1987; Sobchak *et al*., 2001; Neverova & Eremeeva, 2006; Sukhareva, 2013; Legkova & Bulyka, 2022).

Materials and equipment

A magnifying glass stands with samples of needles with different degrees of damage, test tubes, and distilled water.

Research stages

The study consisted of several stages:

1. Selecting pines and spruces with a height of 1-1.5 m and 8-15 lateral shoots in open areas;
2. Examining the previous year's shoots of each coniferous tree;
3. Assessing needle damage (chlorotic spots, necrotic spots, etc.);
4. Determining needle longevity;
5. Recording data on needle damage **(Figures 1 and 2)** and desiccation **(Figures 3 and 4);**
6. Assessing air pollution by the degree of needle damage on two-year-old shoots **(Table 1);**
7. Estimating air pollution using pine and spruce trees **(Figures 5 and 6);**
8. Hertel turbidity test: boiling needles in distilled water to determine the concentration of sulfur dioxide gas, which depends on the thickness of the wax layer on the needles.

Next, we established the classifications of needle *damage* and *desiccation*: 1. Needle damage — *no spots, small spots, large spots*; 2. Needle desiccation — *no dry patches, 2-5 mm dried tip, one-third of needles dried, complete desiccation of needles*. In assessing the condition of the needles, we examined the central part of the body of the needles located at the second level from the shoot apex. Special attention was paid to analyzing damage and desiccation. Importantly, the thorn at the end of the needle did not affect our assessment, as it was always lighter in color (Ghiga *et al.*, 2024; Kounatidis *et al.*, 2024; Musa *et al.*, 2025; Njoroge & Odhiambo, 2025; Petronis *et al.*, 2025; Raza *et al.*, 2025).

All needle samples were divided into three groups:

1. Whole, undamaged needles; 2. Needles with small spots; 3. Needles with signs of desiccation.

These data allowed us to get a complete picture of the degree of air pollution in the city by analyzing the condition of needles.

RESULTS AND DISCUSSION

The data on the level of needle damage in the studied objects is presented in **Figure 1**.

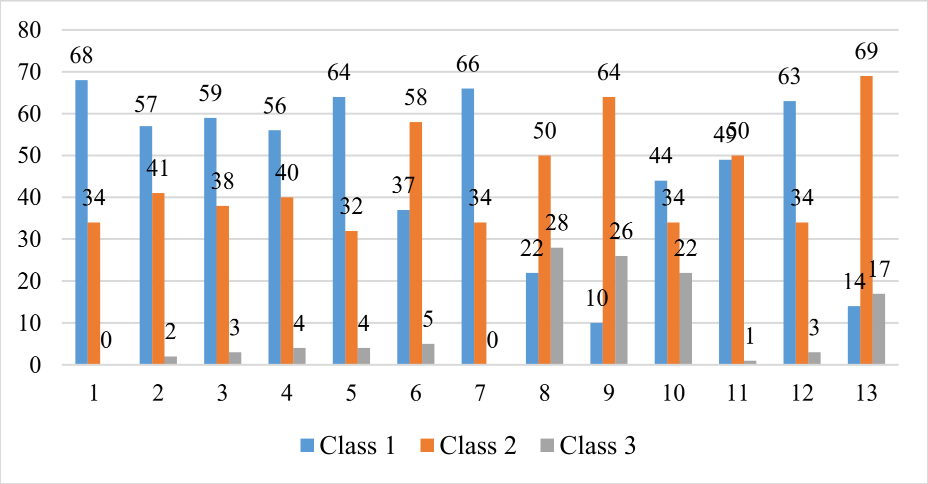

Figure 1. Data on the level of damage to the needles of pine objects (%)

Based on the condition of Scots pine needles, class III damage (chlorotic spots, necrotic spots, etc.) was recorded in the areas of Objects 1-5 and 8-13. Objects 8-10 and 13 had a rather high rate of class III damage, reaching a little less than or above 20%.

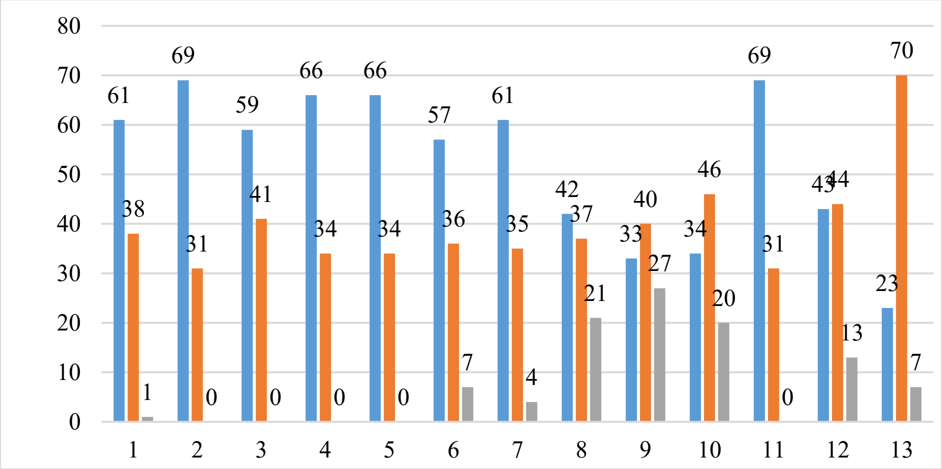

Figure 2. Data on the level of damage to the needles of spruce objects (%)

According to data on the damage of Norway spruce needles, class III damage is observed in Objects 1 and 6-13. On the other hand, Objects 2-5 and 11 do not demonstrate this class of damage.

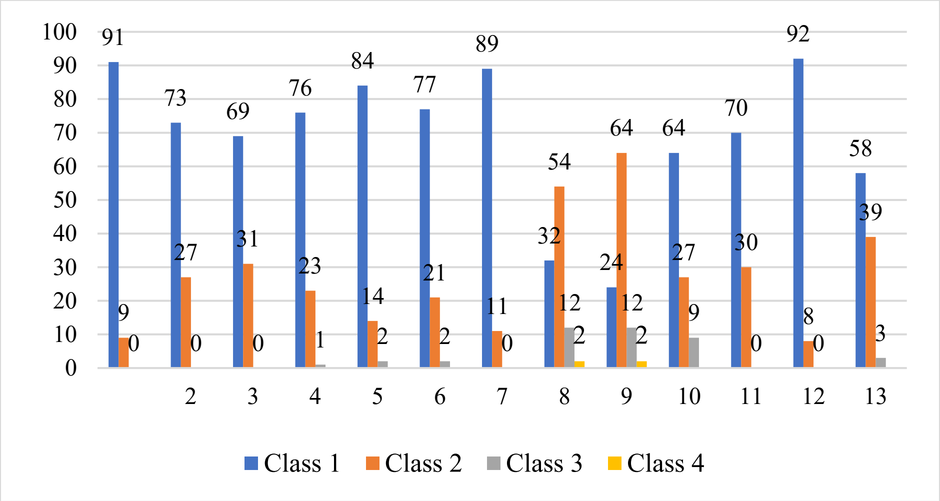

Figure 3. Data on the level of desiccation of the needles of pine objects (%)

The assessment of the desiccation of Scots pine needles reveals that damage of hazard class III is present in Objects 4-10 and 13. Furthermore, Objects 8 and 9 demonstrate damage of hazard class IV.

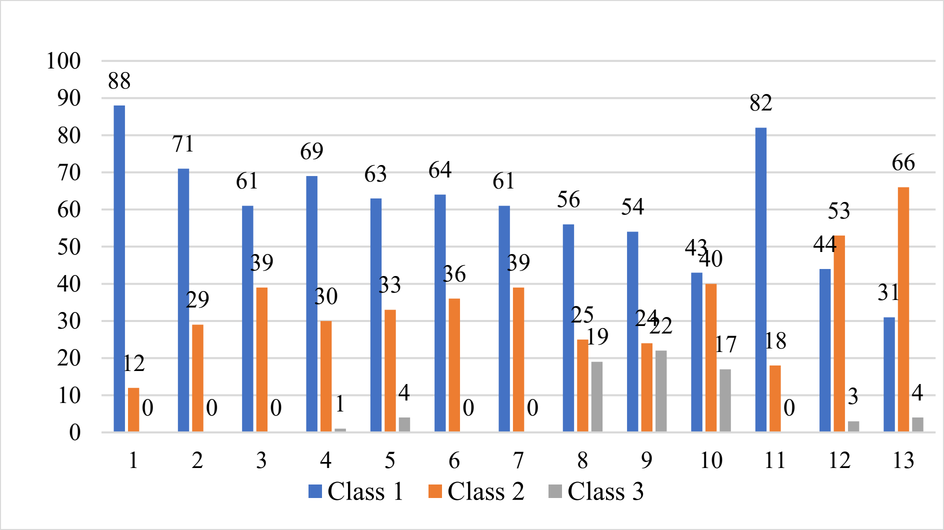

Figure 4. Data on the level of desiccation of the needles of spruce objects (%)

Finally, the assessment of desiccation of Norway spruce needles reveals that most districts demonstrate class III desiccation, specifically Objects 4, 5, and 8-10. Objects 8-10 have a particularly high percentage of desiccation. Fortunately, the desiccation of hazard class IV was not oserved.

Following this, the objects in Aktobe were analyzed using rapid air pollution assessment (based on the condition of needles in terms of damage and desiccation).

The rapid assessment of air pollution based on needle damage used the following scale:

- Level I — perfectly clean air: Pollution does not exceed 3%. In this case, the air quality is the best, and the needles are not significantly damaged. These are ideal conditions for plant growth.
- Level II — clean: Pollution is within 3-10%. This is also considered a good air quality level, where slight damage to the needles may occur, but it has little effect on plant health.
- Level III — relatively clean ("norm"): Pollution ranges from 10% to 20%. This is a normal level of pollution for many industrial and rural areas. Damage to needles becomes more visible but is not critical to the ecosystem.
- Level IV — polluted ("alarm"): Pollution varies from 20 to 35%. This is an alarming signal, as pollution begins to have a negative impact on plants and the ecosystem. Conifers

start to become damaged, which can indicate a deterioration in air quality.

- Level V — dirty ("danger"): Pollution from 35 to 45%. The air becomes hazardous to the health of both human beings and plants. Damage to needles is noticeable and severe, which can lead to reduced viability of trees and other plant species.
- Level VI — very dirty ("harmful"): Pollution from 45 to 65%. This is a very high level of pollution that significantly affects the ecosystem. Damage to needles becomes critical, and the air is dangerous for the long-term health of plants and people.
- Level IC — Impossible combinations: Pollution exceeds 65%. These conditions can lead to ecosystem disasters: severe damage to needles, mass mortality of vegetation, and serious threats to human health. This is a critical level of pollution that requires immediate measures to improve air quality.

Table 1. Rapid assessment of air pollution in Aktobe

Pine sample	Mean damage and desiccation (%)	Danger level	Spruce sample	Mean damage and desiccation (%)	Danger level
1	-	I — perfectly clean air	1	1	I — perfectly clean air
2	2	I — perfectly clean air	2	-	I — perfectly clean air
3	3	I — perfectly clean air	3	-	I — perfectly clean air
4	5	II — clean	4	1	I — perfectly clean air
5	6	II — clean	5	2	I — perfectly clean air
6	8	II — clean	6	7	II — clean
7	-	I — perfectly clean air	7	4	II — clean
8	42	**V — dirty ("danger")**	8	40	**V — dirty ("danger")**
9	40	**V — dirty ("danger")**	9	49	**VI — very dirty ("harmful")**
10	31	**IV — polluted ("alarm")**	10	37	**V — dirty ("danger")**
11	1	I — perfectly clean air	11	-	I — perfectly clean air
12	3	I — perfectly clean air	12	16	III — relatively clean ("norm")
13	20	**IV — polluted ("alarm")**	13	11	III — relatively clean ("norm")

Table 1 shows that based on the indicators of needle damage and desiccation, air pollution in Objects 8-10 corresponds to class V — dirty ("danger"), and Object 9 even reaches class VI — very dirty ("harmful"). Objects 10 and 13 correspond to class IV — polluted ("alarm"). The most hazardous is Object 9.

Next, the Hertel test was performed to determine the degree of obfuscation in the study objects data by categories: 1. No turbidity, 2. Mild turbidity, 3. Severe turbidity. Once again, severe turbidity was observed in Objects 8-10 and 13. However, Object 12 also showed severe turbidity in terms of desiccation (Zabrocki *et al*., 2022, Csep *et al*., 2024; Jin *et al*., 2024; Osluf *et al*., 2024; Rypel *et al*., 2024; Clark & Foster, 2025; Joungtrakul & Smith, 2025; Kebe *et al*., 2025).

The integrated rapid assessment of air pollution based on pine and spruce needle damage and desiccation is presented in **Figure 5**. The figure summarizes the spatial distribution of pollution classes across the studied objects and confirms the highest pollution levels in Objects 8–10, with Object 9 identified as the most hazardous site.

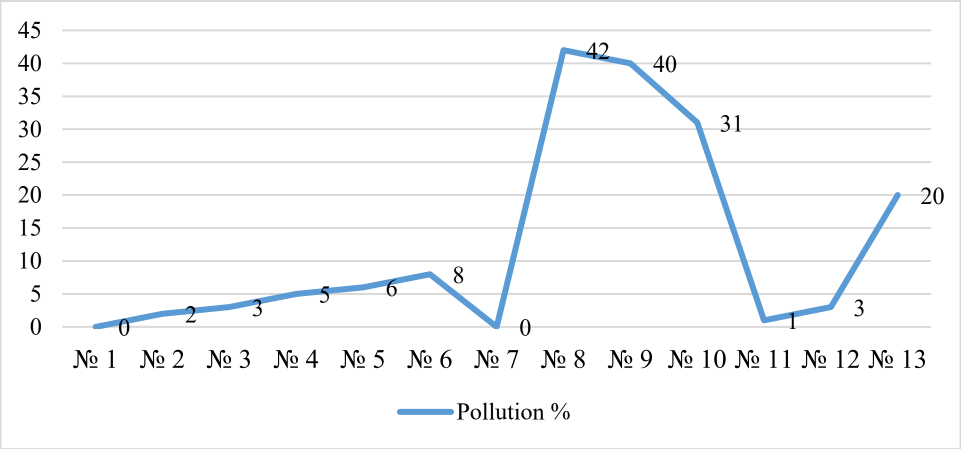

Figure 5. Rapid assessment of air pollution based on pine and spruce

Thus, our study on the use of coniferous tree needles to assess pollution by atmospheric particles in urbanized and industrial zones of the Aktobe Region proves that needles are an effective bioindicator of the environment. The key conclusion of the research is that the needles of Scots pine and Norway spruce can be used as a reliable indicator of atmospheric pollution by various pollutants such as soot, dust, heavy metals, and sulphur dioxide (Prasad, 2004; Aidosova & Sagyndyk, 2007; Atalikova, 2009; Opekunova *et al*., 2018).

The results show that in areas with high concentrations of pollutants, such as industrial areas of Aktobe, the level of damage and desiccation of needles increases significantly. Particularly high pollution levels are observed in Objects 8-10 and 13, where the condition of pine and spruce needles shows signs of severe pollution, corresponding to classes V and VI on the pollution scale. These areas are particularly environmentally hazardous, as the extent of air pollution there is detrimental to vegetation and public health. The results in Aktobe align with pollution patterns in other heavily industrial and emission-dominated cities in Kazakhstan. According to Faurat *et al*. (2024, 2025), monitoring in Pavlodar, a major oil refining and metallurgy city, shows elevated heavy metals in the analyzed environmental media. Similar results are also documented in Assanov *et al*. (2022) study, which showed that Ust-Kamenogorsk is one of the most important industrial centers of Kazakhstan, where non-ferrous metals are produced and there is an active consumption of coal. The average concentrations of SO_2 and NO_2 for the entire study period exceeded the standards of the WHO and Kazakhstan within the whole city all year round. In Almaty, although heavy industry is limited, heavy traffic yields measurable Zn, Cu, and Pb in urban foliage. The results show a high percentage of desiccation for both Scots pine needles and Norway spruce needles in object 10, which is ironically the railway station. These results align with the studies of Yertas *et al*. (2024) and Sadykanova *et al*. (2025), who highlighted the impact of railway stations on air and soil pollution.

Yertas *et al*. (2024) reported that in their study in Kokshetau city, the copper content in the railway station exceeded the maximum permissible level, and Sadykanova *et al*. (2025) went further to correlate an increase in atmospheric air pollution involving nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), along with fine particulate matter (PM2.5), with an increase in carcinogenic risk. The spatial distribution plays a critical role in the influence of pollution in the area. Although the cardinal locations of the study were not explicitly indicated, studies such as Tatarintsev *et al*. (2022) support the notion. Tatarintsev *et al*. (2022) reported in their study that the concentrations of air pollution from the primary constituents of forest-steppe pine woods diminished with increasing distance from pine stands to the city, aligning with the prevailing winds from west to east. Zabrocki *et al*. (2022) also maintained in their study that by studying wind patterns, air pollution can be controlled. This calls for policies that stipulate that industries dealing with emission-related byproducts conduct extensive studies on wind direction to control air pollution. Conifers react strongly to air pollutants physiologically. Mesophyll cells are disrupted when sulfur dioxide enters needle stomata and internally forms bisulfite/bisulfate. Chlorosis and early needle drop result from stomatal malfunction and needle suffocation brought on by high SO_2 exposures. Combined stressors are responsible for the most severe necrosis (>75% brown needles): While metals like Zn, Pb, and Cu build up in cell walls and plastids, displacing Mg in chlorophyll and stopping photosynthesis, SO_2 may seal stomata, impeding gas exchange. Even in the absence of drought conditions, the outcome is water-deficit symptoms (needle desiccation).

There are a number of limitations to the study. Pollutant types were inferred indirectly due to the needle health being assessed visually without the use of tissue chemical assays. Seasonal variation was not recorded, and no simultaneous measurements of the soil or air were taken. This study is limited by the lack of high-resolution meteorological data, real-time wind and emission measurements, and significant correlation between source emissions and damage, which makes it impossible to quantify SO_2 concentrations or heavy metal contents per site.

Multi-season biomonitoring using needle sample chemical analysis should be a component of future research. Plots for long-term monitoring should also be considered since they may show informative trends. Lastly, the suggested stress mechanisms would be confirmed by molecular or physiological tests, such as antioxidant enzyme levels and chlorophyll content.

CONCLUSION

The method of utilizing needles as a bioindicator proved effective. The assessment of needle damage, such as chlorotic and necrotic spots, and desiccation correlates with the level of atmospheric pollution. Visual assessment, as well as the Hertel test, which analyzes the turbidity of water after boiling the needles, provides valuable information about the concentration of atmospheric pollutants.

The rapid assessment of air pollution based on needle damage demonstrated that in some areas, pollution reaches hazardous levels (classes V and VI), which requires urgent measures to improve air quality. Object 9 was identified as the most polluted site requiring special attention from environmental agencies. Moreover, the results confirm the importance of continuing to use needles as bioindicators for continuous monitoring of atmospheric air conditions in urbanized and industrial areas.

Our findings will contribute to a better understanding of the impact of pollutants on vegetation and can be used for further environmental research, as well as for practical application in environmental monitoring of urban areas and other cities with similar pollution problems.

The studies of the morphological characteristics of Scots pine and Norway spruce needles revealed that the level of chlorosis and necrosis in the needles is proportional to distance from the sources of pollution. This damage becomes more severe with proximity to polluted areas and can therefore serve as a direct indicator of the degree of pollution. Importantly, over time, these changes may also depend on the life cycle of needles, as well as their mass, which increases with distance from the source of pollution, potentially indicating the accumulation of harmful substances in plant tissues.

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