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# CHARACTERISTICS OF THE ASSIMILATION APPARATUS OF SPECIES FROM THE GENUS *Picea* A. DIETR. IN THE CONDITIONS OF DIFFERENT POLLUTION LEVELS

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Abstract

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In the course of our investigations, we have found a suppressed state of assimilation organs in the trees of *Picea abies* and *P. pungens* from plantations with moderate and high pollution levels. It causes a decrease of morphometric characteristics (needle length, width, thickness, cross-section perimeter, surface area, and shoot length) and anatomical parameters [thickness of the epidermis, hypodermis, endoderm, diameter of central conducting cylinder (CCC), resin duct numbers, and their diameter] in both species. However, regarding the endoderm thickness and central conductor cylinder indices in *P. pungens* in conditions of urban technogenic environments, we observed an increase of these parameters in contrast to *P. abies,* which can be explained as the adaptive response spruce species to technogenic stress. It is shown that the higher pollution levels in both species cause 1.6-fold decrease in shoot length and 1.4 times shorter needle lifespan, respectively, along with worsening of tree ornamental traits. At the same time, a 1.3-fold increase in the needle number per shoot was observed as compared to the control being probably an adaptive response to adverse environmental conditions. Our investigations have shown that emissions from industry and transport suppress anatomical and morphometric indices of two-year-old needles and shoots of second order in *P. abies* and *P. pungens*, but the latter species demonstrates anatomical changes of adaptive nature.

*Key words:* coniferous plants, assimilation apparatus, needles, air pollutants, anatomic and morphologic parameters.

## Introduction

The total amount of toxic emissions in the air in Kryvyi Rih – one of the ten cities of Ukraine with the highest levels of air pollution – was 224.248 thousand tons as for 2020 (Regional Report..., 2022). The main sources of air pollutants in the city are emissions from industry and transport (Savosko et al., 2022).

Tree plantations play an important role in the system of environmental improvement measures (Zibtseva, 2022; Yorkina et al., 2022). Plantations located closely to industrial sites and along highways clean the air and enrich it with oxygen, reduce the wind and noise, improve the air quality, and moderate the radiation and temperature regimes (Shupranova et al., 2022; Wang et al., 2022; Linden et al., 2023; Valderrama-Martín et al., 2023). Among biodiversity of the urban dendroflora, the species of the *Pinaceae* family are most often recommended as year-round bioindicators of air technogenic pollution (Azzazy, 2020; Ayan et al., 2021; Maria et al., 2022; Wrońska-Pilarek et al., 2023). Some authors claim that coniferous plants are more sensitive to man-induced pollution than that of deciduous ones (Zhang et al., 2020; Guo et al., 2022; Pleijel et al., 2022). Due to their complex structure with rough, sticky, or waxy surfaces, needles have been reported to retain and accumulate toxic substances more effectively than leaves (Chen et al., 2022; Guo et al., 2022). It has been proven that the assimilation apparatus of conifers was a potentially reliable biomarker of plant response to stress (Zhu et al., 2022; Živanović, Jokanović, 2023) and technogenic influence (Chen et al., 2022; Azzazy, 2020; Pleijel et al., 2022).

The assimilation organs of conifers perform important functions: in the process of plant growth and development, their anatomical and morphometric characteristics indicate the potential of stands, especially in urban environments (Zítková et al., 2021; Chen et al., 2022; Świercz et al., 2022). At first, plant injuries occur at physiological and biochemical levels (Fedorchak, 2020), and then, they become noticeable at the anatomical level, that is, manifested in the indicators of the thickness of epidermis, hypodermis, endoderm, the size of mesophyll and central conducting cylinder (CCC), the number of resin ducts, and their diameter (Yusypiva, 2018; Popovic et al., 2022; Živanović, Jokanović, 2023). Furthermore, visual manifestations of plant damage are observed, namely, chloroses and necroses of needle tissues, their premature fall, reduction of needle length, and growth of lateral shoots (Moskalyk, Kostyshyn, 2008; Gebauer et al., 2019; Bessonova, Ponomarova, 2017). Therefore, a well-developed assimilation apparatus not only plays an important role in the plant decorativeness but is also one of the main indicators of the resistance to adverse technogenic factors.

There still have been no comprehensive studies on the anatomical and morphological parameters of needles in species of the genus *Picea*, namely *Picea abies* (L.) Karst. and *P. pungens*

**Table 1.** Detailed characteristics of monitoring sites in the city of Kryvyi Rih.

| Abbreviation | Monitoring sites | GPS latitude, longitude |
|---|---|---|
| Ms1 | Kryvyi Rih Botanical Garden of the NAS of Ukraine (northern part of the city, insignificantly polluted area) | 48°09‘06“N 33°34‘41“E (height above sea level is 115 m) |
| Ms2 | Shakhtarskyi Park (central part of the city, remote from highways and industrial enterprises) | 48°01‘34“N 33°28‘35“E (height above sea level is 81 m) |
| Ms3 | Heroiv ATO Park (southern part of the city, remote from highways and industrial enterprises) | 47°54‘21“N 33°23‘22“E (height above sea level is 90 m) |
| Ms4 | Cherkasova Street (northern part of the city, with two-way traffic) | 48°09‘17“N 33°33‘11“E (height above sea level is 122 m) |
| Ms5 | Vatutina Street (central part of the city, with two-way traffic, and two times greater number of cars per hour than that in the Cherkasova Street) | 48°01‘00“N 33°28‘30“E (height above sea level is 72 m) |
| Ms6 | Metallurhiv Avenue (southern part of the city, with intensive two-way traffic, and three and two times greater number of cars per hour than that in the Cherkasova Street and Vatutina Street, respectively) | 47°53‘46“N 33°23‘42“E (height above sea level is 94 m) |
| Ms7 | Private JSC “North Ore Dressing Combine” (northern part of the city, with emissions of 12.7 thousand tons per year) | 48°10‘41“N 33°32‘21“E (height above sea level is 117 m) |
| Ms8 | PJSC “ArcelorMittal Kryvyi Rih” (southern part of the city, with emissions of pollutants 15 times greater than at Private JSC “North Ore Dressing Combine”) | 47°52‘58“N 33°23‘12“E (height above sea level is 100 m) |

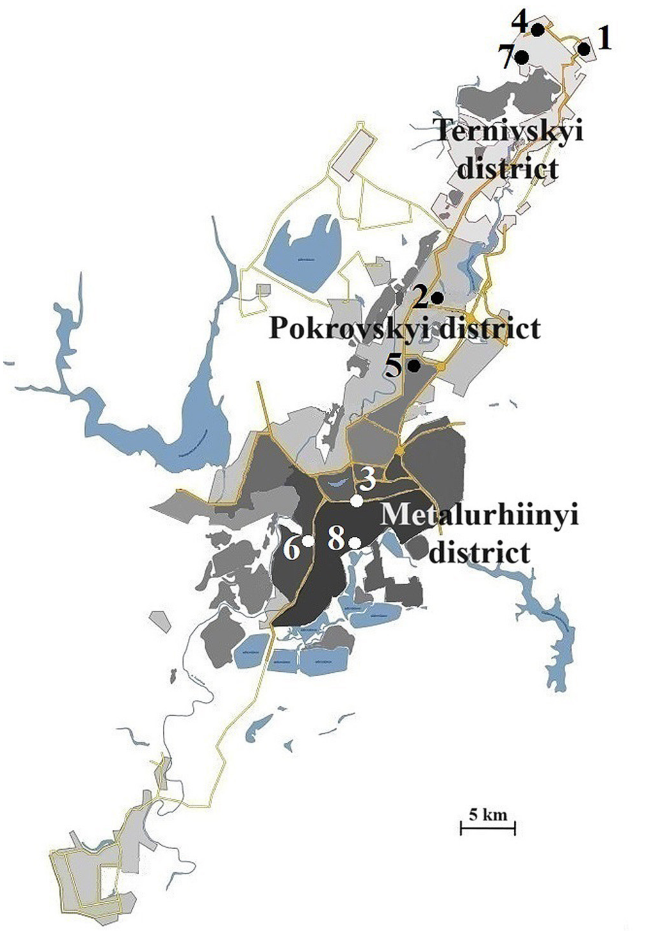


**Fig. 1.** Map of monitoring sites within the territory of Kryvyi Rih city (Ukraine).

Beissn., both species being common in the plantations of Kryvyi Rih, although it is known that the development and functional states of assimilation organs is an important indicator of plant viability. Features of their development determine photosynthesis and transpiration processes (Wang et al., 2022). In this regard, research on the anatomical and morphological structures of needles in species of the genus *Picea* is quite relevant, and the data obtained by us initiate monitoring observations of the assimilation organs of *P. abies* and *P. pungens* in the plantations of large industrial city of Kryvyi Rih.

The aim of this work is to identify the specific state of the assimilative organs of *P. abies* (L.) Karst. and *P. pungens* Beissn. in conditions of different pollution levels in the city of Kryvyi Rih.

## Material and methods

### *Study site*

For a representative coverage of the city of Kryvyi Rih, the monitoring sites were located from the northeast to the southwest along the length of the city with different levels of air technogenic influence (Fig. 1, Table 1). Among these, two plantations are exposed to heavy emissions of industry: monitoring site No. 8 – PJSC “ArcelorMittal Kryvyi Rih” and monitoring site No. 7 – PJSC “Northern Mining and Processing Plant”; the following three are roadside plantings exposed to a moderate pollution due to intensive traffic: monitoring site No. 6 – Metalurgiv Avenue, monitoring site No. 5 – along Vatutina Street, and monitoring site No. 4 – along Cherkasova Street; and the last three ones are exposed to an insignificant pollution level: monitoring site No. 3 – Heroiv ATO Park, monitoring site No. 2 – Shakhtarskyi Park, and monitoring site No. 1 – the Arboretum of the Kryvyi Rih Botanical Garden of the National Academy of Sciences of Ukraine (KBG). Plantings of both species of spruce in the Kryvyi Rih Botanical Garden's Arboretum were considered as conditional control.

### *Data and methods*

The research materials were 2-year-old needles and second-order shoots of 30 to 40-year-old trees of *P. abies* and *P. pungens* investigated during 2020. The form with blue-green needles (*P. pungens* "Glauca") was studied, which is extremely popular in landscaping both in Kryvyi Rih and in other cities of Ukraine (Moskalyk, Kostyshyn, 2008). A total of one hundred needles were sampled from trees of both species at a height of 2 m from the earth in each of 8 sites, and the lengths of the second-order shoots were also measured without cutting. The width and thickness were determined on sections in the needle central part using a BIOMED-4 binocular microscope with 4×7 magnification. Sections were made using a manual microtome MS-2. The peculiar features of the anatomical structure of two-year-old needles were studied on temporary preparations made according to generally accepted methods (Panyuta, 2019). Investigation of the absolutely dry mass of needles was carried out in a drying cabinet at 105 $^{0}$C for 24 hours.

The presence of necroses and chloroses in needles was determined according to the classification of E.J. Jäger (Jäger, 1980).

The perimeter of the needle cross-section was calculated according to Thiren's formula (Vyshniakova, Atkina, 2011):

$$\Pi = 2 \sqrt{a^2 + b^2} \quad (1)$$

where P is the perimeter of the cross-section, a is the thickness, b is the width of the needle.

The needle surface area was determined according to the formula of L.A. Ivanov (Feklistov, 2002):

$$S=2l \sqrt{a^2 + b^2} \quad (2)$$

where S is the surface area, l is the needle length, a and b are the width and thickness of the needle.

### *Statistical analysis*

The results were statistically analyzed using a descriptive statistics. To compare two independent samples, we used Student's *t*-criterion ($P < 0.05$). Statistical analysis was performed using Microsoft Office Excel 2003.

## Results

In the course of investigation, it has been established that in the site No. 8 with a high pollution level, the needle length of 30 to 40-year-old *P. abies* and *P. pungens* trees decreases, reaching minimum values of 12.27 mm and 18.56 mm, respectively, that is on average 30.4 and 23.9% smaller than needle length in the control plantation (Table 2). Insignificantly smaller differences were found in the needles of *P. abies* and P. *pungens* trees exposed to moderate pollution, and these were on average 13.7 and 13.4% lower compared to that of the control.

The parameters of needle width and thickness decreased in both plant species exposed to technogenic influence (Table 2). So, in *P. abies*, these indicators are 12.0 and 16.2% lower in the sites with high pollution levels than that in the control plants; in needles of *P. pungens*, those are 9.7 and 7.1% lower, respectively. Comparing the perimeter of needle cross-section in both species of spruce trees affected by various pollution types, its decrease is noticeable in *P. abies* and *P. pungens*, growing in conditions of a heavy pollution (12.5 and 9.2% lower than that in the control).

The surface area of needles is an important indicator of tree condition. The lowest values of this parameter in trees of *P. abies* and *P. pungens* were registered in areas with moderate and high levels of load and were 20.6, 15.5, and 39.5, 26.9% smaller than those of control trees in the monitoring site No.1. In the course of our research, the needle surface area in both species of spruce was smaller in plants affected by exhaust gases and industry emissions. A change in the morphometric characteristics of a needle leads to a change in its general assimilating surface; as a result, it affects the productivity and tree condition in later years.

Heavy pollution levels negatively affect the shoot growth; as a result, bundles of conifers are located closer to each other (Fig. 2). So, in the sites with a high level of pollution, shoot length indicators in *P. abies* and *P. pungens* are on average 34.6 and 27.5% lower compared to that in control. Somewhat smaller differences were found in *P. abies* and *P. pungens* trees growing in plantations with a moderate level of pressure, and on average, they were 24.9 and 23.0% lower than in that in the control trees.

The maximum sizes of shoots with two-year needles were recorded at the monitoring site No.1: in *P. pungens*, they were 8.54 cm and 7.25 cm in *P. abies*; and the minimum ones were found at the monitoring site No. 8: 5.18 cm and 4.52 cm, respectively; that is 1.6 times smaller than that in the control. Regarding the indicator of the shoot length, we should emphasize that one of the manifestations of the toxic substances action is a decrease in the linear dimensions of this parameter. Deterioration of the shoot condition gradually leads to a lower level of tree decorativeness of both species in urban and technogenic conditions.

It was noted that in the plants of *P. abies* and *P. pungens* exposed to high pollution levels the needle numbers on the second-order shoots are 34.3 and 26.2% higher than that in the control plantations. In conditions of moderate pollution, this indicator was 21.1 and 13.6% greater, respectively. That is, along with an increase in technogenic impacts, the number of needles per shoot also increases, which can be explained by the adaptive response of plants to stress. When comparing the numbers of the second-order needles between *P. abies* and *P. pungens*, it was found that the proportion is almost 1.3 times smaller in the trees of the latter species in all research areas.

The density of the needle placement on the shoots and its life span characterizes the species adaptability, mostly depending on the growing conditions. Our study has shown that the needle life span in plants exposed to heavy pollution decreases by 1.4 times compared to trees in monitoring sites with insignificant levels of load (Fig. 3), and the presence of needle chloroses and necroses, on the contrary, increases 2.5-fold (Table 2). At high concentrations of toxic substances, characteristic damage is observed in conifers, namely necrosis and chlorosis. The needle life span at different levels of pollution in the city of Kryvyi Rih varied within 3–5 years for trees of both species, reaching a maximum in the monitoring areas under conditions of insignificant level of air technogenic pressure. Such a research result demonstrates that the long needle life span is indicative of environment purity.

**Table 2.** Morphometric parameters and assessment of the needle condition in *Picea abies* and *Picea pungens* under conditions of different pollution levels.

| Site No. | Length, mm | Width, mm | Thickness, mm | Perimeter, mm | Needle surface area, mm² | Shoot length, cm | Needle number on second-order shoot | Necrosis (score) | Chlorosis (score) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Picea abies* | | | | |
| 1 | 18.45±0.44 | 1.17±0.02 | 0.71±0.02 | 2.76±0.04 | 50.59±1.37 | 7.25±0.38 | 144.6±2.41 | 1.07±0.03 | 1.16±0.04 |
| 2 | 17.19±0.57 | 1.12±0.03 | 0.68±0.01 | 2.64±0.05 | 46.38±1.88 | 6.39±0.49 | 150.8±3.32 | 1.15±0.04 | 1.32±0.05* |
| 3 | 17.23±0.56 | 1.14±0.02 | 0.67±0.01 | 2.68±0.03 | 46.53±1.55 | 6.65±0.43 | 152.5±2.16* | 1.56±0.07* | 1.51±0.07* |
| 4 | 16.58±0.42* | 1.07±0.03* | 0.65±0.01* | 2.52±0.03* | 41.71±1.41* | 5.43±0.36* | 160.7±4.03* | 2.14±0.07* | 2.36±0.10* |
| 5 | 15.85±0.44* | 1.08±0.03* | 0.66±0.02* | 2.56±0.04* | 40.67±1.37* | 5.78±0.42* | 176.2±3.12* | 2.09±0.08* | 2.52±0.12* |
| 6 | 15.31±0.47* | 1.05±0.02* | 0.64±0.02* | 2.47±0.03* | 38.08±1.35* | 5.12±0.46* | 188.6±2.58* | 2.33±0.09* | 2.61±0.14* |
| 7 | 13.43±0.51* | 1.04±0.03* | 0.60±0.02* | 2.45±0.05* | 32.61±1.30* | 4.97±0.53* | 194.1±2.96* | 2.56±0.08* | 2.78±0.13* |
| 8 | 12.27±0.48* | 1.02±0.02* | 0.59±0.02* | 2.38±0.03* | 28.64±1.01* | 4.52±0.45* | 194.4±2.34* | 2.64±0.08* | 2.83±0.12* |
| | | | | | *Picea pungens* | | | | |
| 1 | 24.52±0.63 | 1.44±0.04 | 1.26±0.02 | 3.87±0.08 | 80.29±2.06 | 8.54±0.57 | 127.6±2.06 | 1.05±0.02 | 1.14±0.04 |
| 2 | 23.77±0.76 | 1.40±0.03 | 1.24±0.04 | 3.79±0.07 | 76.95±2.44 | 7.36±0.76 | 133.8±2.46 | 1.21±0.04 | 1.29±0.07 |
| 3 | 23.13±0.81 | 1.41±0.02 | 1.25±0.03 | 3.80±0.06 | 75.85±2.86 | 7.29±0.64 | 138.1±3.93* | 1.44±0.07* | 1.65±0.10* |
| 4 | 21.67±0.65* | 1.38±0.03 | 1.22±0.04 | 3.75±0.07 | 69.66±2.21* | 6.87±0.69 | 141.6±3.56* | 1.96±0.09* | 1.61±0.12* |
| 5 | 22.82±0.73* | 1.33±0.02* | 1.23±0.03 | 3.67±0.04* | 72.93±2.33* | 6.93±0.58* | 147.4±3.18* | 2.02±0.08* | 2.05±0.10* |
| 6 | 19.21±0.67* | 1.35±0.03* | 1.20±0.03* | 3.65±0.05* | 60.88±2.02* | 5.92±0.55* | 145.7±3.86* | 2.31±0.08* | 2.39±0.09* |
| 7 | 18.74±0.70* | 1.31±0.02* | 1.18±0.02* | 3.54±0.04* | 59.12±2.19* | 5.64±0.62* | 154.2±2.85* | 2.55±0.07* | 2.54±0.08* |
| 8 | 18.56±0.61* | 1.29±0.03* | 1.16±0.02* | 3.49±0.05* | 58.22±1.97* | 5.18±0.59* | 167.9±3.51* | 2.59±0.07* | 2.75±0.13* |

Note: Differences are significant according to Student's *t*-test $*P < 0.05$. M ± m is the average value with an error.


**Fig. 2.** Sizes of two-year-old shoots in *Picea abies* (I) and *Picea pungens* (II) growing: a – at the monitoring site No. 1 (conditional control); b – at the monitoring site No. 8 (area of high pollution level).

Anatomical studies make it possible to understand the mechanisms of penetration of air pollutants into the internal tissues of assimilation organs, the degree and details of their impact. The dimensions of the epidermis, hypodermis, endoderm, mesophyll, central conducting cylinder (CCC), the number of resin ducts, and their diameter are used as structural indicators of atmospheric pollution.

The epidermis covers needles with a continuous layer and regulates gas exchange and transpiration. The maximum indicators of the thickness of epidermis (8.31 and 9.27 μm) were recorded in *P. abies* and *P. pungens* from the monitoring site No.1, and the minimum ones (6.62 and 7.87 μm respectively) were registered under conditions of high pollution levels (Table 3), which is on average 18.6 and 14.8% lower compared to that of the control plants (Fig. 4).

Somewhat smaller differences in anatomical indicators were found in plants of both species from the sites with moderate pollution levels, which is on average 13.1 and 10.8% lower than that in trees from control plantations.

The hypodermis is located beneath the epidermis, and due to it, the needles have a usually hard external skeleton, which gives it a characteristic rigidity. The lowest dimensions of the hypodermis thickness were detected in *P. abies* and *P. pungens* from plantations with excessive pollution levels (those being on average by 15.5 and 14.2% smaller compared to the control). A decrease in the thickness of epidermis and hypodermis as a result of the negative impact of airborne technogenic emissions obviously leads to a violation of gas exchange regulation and cell transpiration.

The endoderm surrounds the needle central conductive cylinder and regulates the supply of substances to the conductive tissues. Thickness of the endoderm in all stands of *P. abies* ranges between 10.42 and 13.91 μm; in the stands of *P. pungens*, it varies between 12.62 and 15.37 μm. Endoderm thickness indicators were 23.5 and 17.9% lower depending on the distance from *P. abies* trees to sources of strong and moderate pollution as compared that of to control. In the trees of *P. pungens*, on the

**Table 3.** Anatomical parameters of needles in *Picea abies* and *Picea pungens* from plantations in Kryvyi Rih.

| Site No. | Thickness (on cross-section) | | | CCC diameter, mcm | Resin duct number on cross-section, pcs. | Resin duct diameter, mcm |
|---|---|---|---|---|---|---|
| | of epidermis, mcm | of hypodermis, mcm | of endoderm, mcm | | | |
| *Picea abies* | | | | | | |
| 1 | 8.31±0.45 | 11.93±0.54 | 13.91±0.63 | 123.65±2.73 | 0.87±0.15 | 42.85±0.91 |
| 2 | 7.73±0.48 | 11.78±0.56 | 12.83±0.68 | 120.22±3.12 | 0.73±0.14 | 40.03±1.14 |
| 3 | 7.95±0.51 | 11.54±0.55 | 12.27±0.62 | 119.32±3.33 | 0.67±0.13 | 41.26±1.31 |
| 4 | 7.48±0.38 | 10.31±0.58* | 11.35±0.51* | 115.38±2.71* | 0.57±0.13 | 37.91±1.50* |
| 5 | 7.12±0.34* | 11.37±0.51 | 12.08±0.56* | 112.75±2.86* | 0.63±0.14 | 39.17±1.38* |
| 6 | 6.96±0.45* | 10.09±0.63* | 10.81±0.56* | 109.37±2.67* | 0.47±0.12* | 35.62±1.42* |
| 7 | 6.84±0.39* | 10.24±0.56* | 10.67±0.67* | 103.09±2.45* | 0.23±0.12* | 36.29±1.24* |
| 8 | 6.62±0.42* | 9.92±0.62* | 10.42±0.65* | 98.62±2.14* | 0.17±0.10* | 34.87±1.11* |
| *Picea pungens* | | | | | | |
| 1 | 9.27±0.53 | 13.29±0.64 | 12.62±0.67 | 164.58±3.09 | 1.37±0.13 | 54.21±1.16 |
| 2 | 8.72±0.50 | 13.18±0.67 | 12.74±0.63 | 165.37±2.75 | 1.13±0.14 | 51.68±1.43 |
| 3 | 9.06±0.48 | 12.93±0.75 | 13.01±0.53 | 167.83±3.86 | 1.20±0.15 | 52.32±1.29 |
| 4 | 8.54±0.54 | 12.75±0.68 | 12.75±0.68 | 173.64±2.70* | 0.97±0.15 | 46.84±1.21* |
| 5 | 8.25±0.49 | 11.52±0.59* | 13.64±0.74* | 169.17±3.71* | 0.83±0.16* | 49.67±1.39* |
| 6 | 8.01±0.32* | 12.24±0.61 | 13.89±0.63* | 178.76±3.06* | 0.67±0.16* | 47.53±1.48* |
| 7 | 7.92±0.40* | 11.47±0.62* | 14.05±0.52* | 176.84±3.46* | 0.53±0.15* | 44.34±1.59* |
| 8 | 7.87±0.44* | 11.34±0.65* | 15.37±0.57* | 187.11±3.51* | 0.60±0.14* | 43.84±1.41* |

Note: Differences are significant according to Student's *t*-test. *$P < 0.05$. M ± m is the average value with an error.

contrary, they were 17.5 and 14.6% greater, respectively, when compared to that of control. In the latter case, such a reaction of plants to pollution is associated with changes of an adaptive nature.

An important feature of the anatomical structure of needles is the structure of the central conducting cylinder, which is located in the center of the needle and consist of conducting bundles with sclerenchyma cell between them. The index of the central conducting cylinder diameter in the needles of *P. abies* exposed to a high pollution level decreased by an average of 18.4% compared to that of the control. In *P. pungens* plants, on the contrary, it increased by 10.6% compared to that of the control. We believe that the accumulation of dust on the needle surface leads to a disturbance of the water state of the needles and a condition similar to water stress. An increase in the diameter of the central conducting cylinder contributes to the strengthening of the transpiration process. Obviously, this reaction of *P. pungens* trees characterizes them as more resistant to the action of air pollutants.

An integral part of the needle anatomy is the presence of resin ducts passing through the mesophyll, and some of them are attached to the abaxial hypodermis. In the needles of *P. abies* and *P. pungens* trees growing under conditions of high pollution levels, we noted a decrease in the number of resin canals by 5.1 and 2.6 times compared to that of the control, as well as a decrease in their diameter by 16.9 and 18.7% respectively. Similar indicators of the number of resin ducts and their diameter were registered in both species of spruce under conditions of a moderate level of pollution. In our case, the excessive concentration of toxic substances causes a decrease in the number of resin canals or leads to their complete absence.

The process of accumulation of needle mass reacts very sensitively to technogenic influence. Thus, the lowest values of absolute dry mass of needles were recorded in *P. abies* and *P. pungens* trees in the areas with an excessive level of pollution, which is 38.5 and 37.6% smaller compared to the control (Fig. 5).

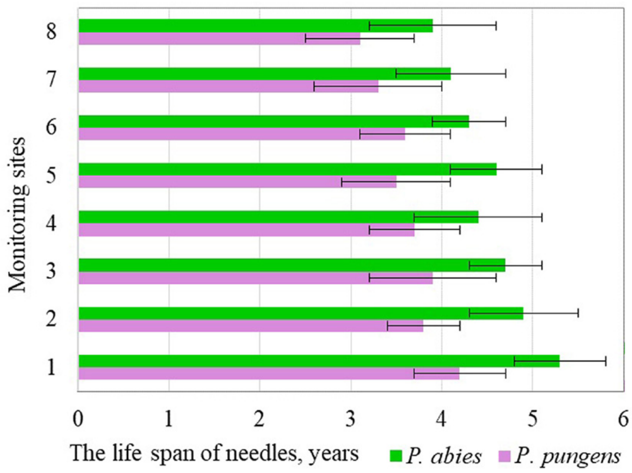


**Fig. 3.** The life span of needles in *Picea abies* and *Picea pungens* depending on the growth conditions.

Under conditions of moderate pollution, this indicator was lower by 25.7 and 28.3%, respectively, than that of the control. This fact is indicative of the negative effect of air pollutants on the growth and development of needles and the content of substances necessary for the main life processes (transpiration, photosynthesis).

The analysis of the research shows that in both species of spruce, anatomical indicators reflect the impact of air pollutants

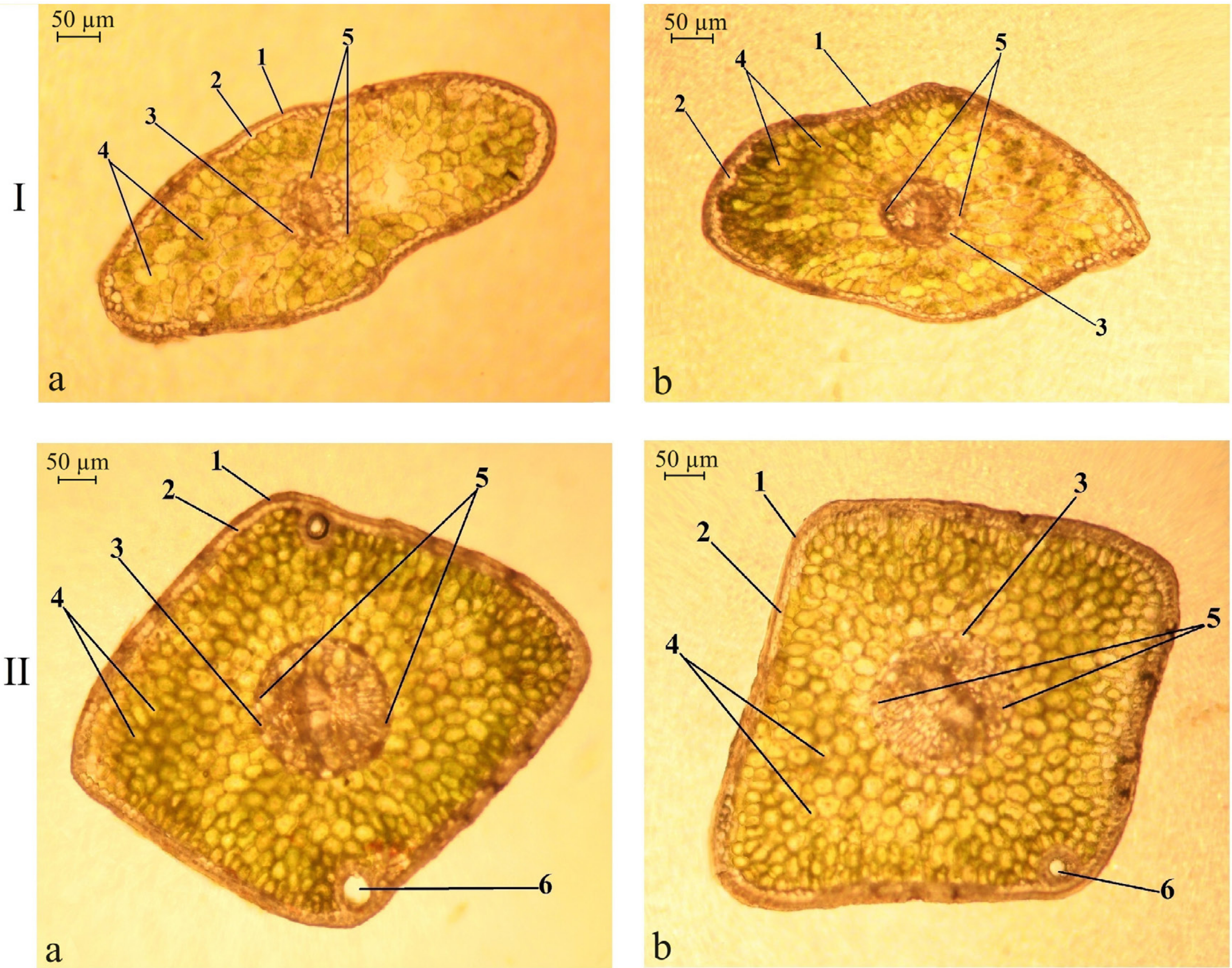


**Fig. 4.** Cross-sections of needles in *Picea abies* (I) and *Picea pungens* (II) growing: a – in the Arboretum of the Kryvyi Rih Botanical Garden of the National Academy of Sciences of Ukraine; b – near ArcelorMittal Kryvyi Rih; 1 – epidermis, 2 – hypodermis, 3 – endodermis, 4 – folded mesophyll, 5 – central conducting cylinder (CCC), 6 – resin ducts.

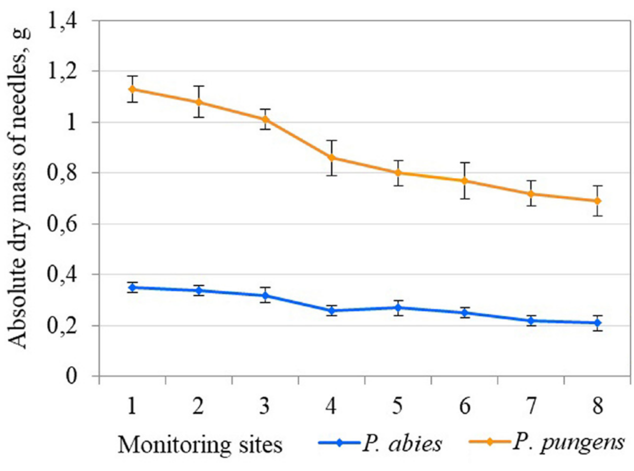


**Fig. 5.** Absolute dry mass of needles *Picea abies* and *Picea pungens* depending on growth conditions.

on plants earlier than that of morphological ones. The registered significant decreases, less often increases, of anatomical and morphological parameters in plantations exposed to moderate and high levels of pollution confirm the fact of a notable effect of toxic substances on the needle structure in *P. abies* and *P. pungens*.

## Discussion

Among the informative diagnostic indicators of the assimilation apparatus condition, the length of the needles is of particular importance. A number of authors (Moskalyk, Kostyshyn, 2008; Yusypiva, 2018; Nikolić et al., 2019; Gebauer et al., 2019) argue that this indicator decreases in trees of *P. abies* and *P. pungens* along with an increase in the pollution levels. In this regard, our research findings agree with the results of other researchers.

The analysis of published investigations shows both an increase and a decrease in the values of the width and thickness of needles in *P. abies* and *P. pungens* in urban environments compared to that of insignificantly polluted areas (Bessonova, Ponomarova, 2017; Yusypiva, 2018; Nikolić et al., 2019). Even the maximum similarity of environmental conditions does not guarantee the complete identity of morphological features of needles (Wang et al., 2022, Zhu et al., 2022). In our case, these indicators in both species decreased depending on the distance to the sources of technogenic emissions. The same trend was observed when comparing the needle cross-sectional perimeter and surface areas in trees of both species of spruce.

It was noted that in trees of *P. abies* and *P. pungens* growing near industrial enterprises the number of needles per shoot increases by 1.3 times compared to that of control plantations. The results of the author's studies agree in general with previous publications (Moskalyk, Kostyshyn, 2008), reporting that needle numbers on the shoots of *P. abies* and *P. pungens* were 173.9 and 198 pcs., while on a relatively "clean" area, they were 134.5 and 142 pcs., respectively. In other words, with the increase of technogenic influence, the number of needles on the shoots also increases. Our data also agree with previously formulated statements (Moskalyk, Kostyshyn, 2008; Gheorghe, Barbu, 2011; Khrutba et al., 2020) about an increase in the number of necrotic spots and chloroses in conifers from urbanized areas.

To study anatomical changes in spruce needles, indicators of the thickness of the epidermis, hypodermis, endoderm, dimensions of the central conducting cylinder (CCC), the number of resin ducts, and their diameter (sensitive to stress) are most often used (Kivimäenpää et al., 2003; Yusypiva, 2018; Gebauer et al., 2019; Matějka, Krpeš, 2022; Popovic, 2022).

Under the influence of the highest level of air technogenic pollution, there is a decrease in the thickness of epidermis and hypodermis in both species of fir trees. To the author's viewpoint (Yusypiva, 2018), the decrease in sizes of the epidermis and hypodermis in needles of *P. pungens* is equivalent to the level of anthropogenic load. The indicators of endoderm size cells significantly decrease relatively to the closeness of *P. abies* trees to industrial plants and highways compared to an insignificantly polluted area. In *P. pungens* trees, on the contrary, they increase when compared to the control. In the latter case, such a reaction of plants to pollution is associated with changes of an adaptive nature. A similar thickening of the endoderm was observed in *P. pungens* in technogenic conditions of another region (Yusypiva, 2018) as a result of strengthening barrier functions aimed at limiting the flow of toxic substances into conducting tissues.

There is a number of works that show that under excessive exposure to air pollutants, the size of the central conducting cylinder diameter in sensitive coniferous species usually decreases (Lin et al., 2001; Legoshchina et al., 2013), and in resistant species it increases (Kivimäenpää et al., 2003); Yusypiva, 2018). In our case, this indicator decreases in *P. abies* growing closer to the sources of pollution, and it changescinversely in *P. pungens*. It is obvious that such a reaction of *P. pungens* trees characterizes it as a more stress-tolerant species to the influence of the urban technogenic environments of Kryvyi Rih.

From some publications (Moskalyk, Kostyshyn, 2008; Marin et al., 2009), it is known that pollutants reduce the number of resin canals or lead to their complete absence, but other researchers (Yusypiva, 2018; Perreca et al., 2022), on the contrary, emphasize their increased or unchanged number in conifers under unfavorable growth conditions. In our case, the first option is confirmed, and with the increase in the level of pollution of the urban environment, the number of gum ducts decreases more noticeably.

## Conclusion

Our comprehensive study of the assimilation organ condition in *P. abies* and *P. pungens* trees in the plantations of Kryvyi Rih has shown that both species are significantly affected by exhaust gases and emissions from industrial enterprises, which is reflected in most cases in a decrease in anatomical and morphometric parameters within the range of 7.1–43.4%, and especially in the length of needles and shoots, the surface area of needles, absolutely dry weight of needles, and indicators of the thickness of the epidermis, hypodermis, the number of resin canals, and their diameter. It was found that when plantings grow near mining and metallurgical plants, the number of resin ducts in the needles of *P. abies* and *P. pungens* decreases by 5.1 and 2.6 times compared to that of the plants of the Botanical Garden, and their diameter also decreases. In conditions of severe suppression, both types of fir trees experience a 1.4-fold reduction in the life span of needles compared to those of KBG. Due to excessive exposure to air pollutants from highways and industrial enterprises, the degree of damage and drying of needles (necroses, chloroses) in *P. abies* and *P. pungens* increases by 2.5 and 2.4, times respectively, compared to that of plants in insignificantly polluted areas, and this eventually lead to a deterioration of the condition and decorativeness of fir trees. However, the thickening of the endoderm and the increase in CCC indicators in *P. pungens*, in contrast to *P. abies*, indicate a better adaptability and tolerance of the *P. pungens* species to technogenic influence. Therefore, based on the degree of development of needles and the state of its anatomical and morphometric characteristics, it is possible to draw conclusions about the further development of plantations and determine their potential in the conditions of the urban environment, as well as recommend these plant species as bioindicators.

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