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Micrographic image of air pollutants in Poland

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Abstract: The subject of studies was one-year-old needles of Scots pine (*Pinus sylvestris* L.), collected from various characteristic landscape zones of Poland, reflecting different conditions of air pollutant emission and deposition (Integrated Monitoring of the Natural Environment base stations, industrial centers, and large cities). Analyses were carried out using a Quanta 250 FEI scanning electron microscope equipped with an EDAX Genesis X-ray spectroscopy microanalyzer. The needle surfaces were examined to identify natural structures (e.g., stomata, pollen, fungi) and anthropogenic structures (e.g., particulates with heavy metals) under conditions of diversified anthropopressure. In samples from areas with no significant local pollution sources (Wigry, Borecka Forest, Parsęta, Tuchola Forest), particles of mineral origin (resulting from rock weathering) containing Si, Al, Ca were identified. Needles collected in Roztocze, Łysogóry, Kampinos and Karkonosze, contained round technogenic particles (spherules) containing Fe, Al and Si, which had traveled significant distances. In Katowice, Poznań and Kraków, particles deposited on the bioindicators' surfaces were composed of Ca, Si, Al, Fe, Cu, and other heavy metals. Micrographs obtained from the analysis were used to develop a model for identifying air pollutants using artificial intelligence.

Introduction

Microscopic analyses of particulates commonly present in the air enable to determine the current state and sources of atmospheric pollution (Brostrøm et al. 2020, Kokoulin et al. 2023, Longoria-Rodríguez et al.2021). Particles deposited on the surface of trees, originating from both natural and anthropogenic sources, limit life processes and affect their condition (Kardel et al. 2018, Sahu et al. 2021, Zhang et al. 2022). Their harmfulness depends on their chemical composition, and when absorbed through the respiratory tract, they may be hazardous to human health (Hamdan et al. 2020, Jadoon et al. 2020, Maria et al. 2023,). Particulates being carriers of various elements, including heavy metals, may contribute to cardiovascular diseases (Badeenezhad et al. 2023, Sielski et al. 2021). The presence of toxic metals has been identified in precipitation and air, both in urban areas and outside them, where harmful dust is transported (Adamiec et al. 2023, Michalski & Pecyna-Utylska 2022, Szwed et al. 2023). In monitoring research, analyses of the assimilation organs of trees with wide geographical ranges are commonly used. The confirmed bioindicator properties of pine needles established their extensive use in monitoring the natural environment exposed to multidirectional anthropogenic pressure (Chen et al. 2022, Chung et al. 2021, Sensuła et al. 2023, Szwed et al. 2021, Zsigmond et al. 2021).

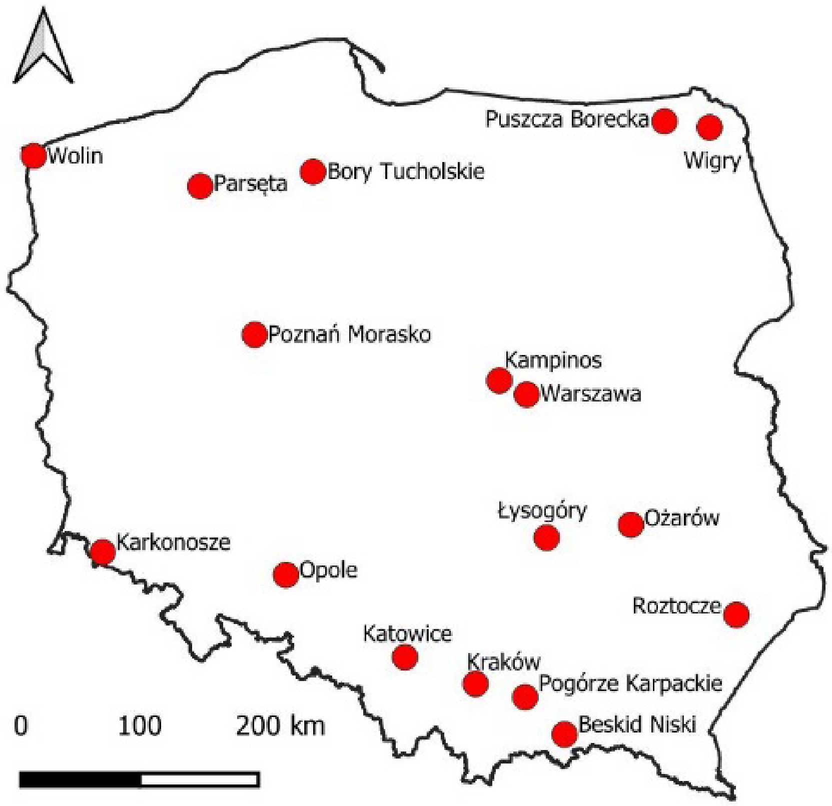
The objective of this study is to conduct a microscopic analysis of one-year-old Scots pine needles collected from areas with different levels of deposition of natural and anthropogenic particulates. To this end, samples were taken from the research catchments of the national network of Integrated Monitoring of the Natural Environment in Tuchola Forest (reference sample), large cities (Kraków, Poznań, Warsaw, Katowice), and cement industry centers significantly affecting the air quality in Ożarów and Opole. Micrographs obtained from the analysis were used to demonstrate the potential of artificial intelligence in identifying air pollutants.

Area of the studies

One-year-old needles of Scots pine (*Pinus sylvestris* L.) were collected in October 2023 from trees located at the Integrated Monitoring of the Natural Environment base stations (Kostrzewski and Majewski 2021). Their location in the territory of the country corresponds to morphogenetic diversity and represents individual landscape zones. In addition, the samples were taken from several large cities, which serve as sources of municipal, transport and industrial pollutants, as well as from selected industrial centers. A reference sample was obtained from forest areas in Tuchola Forest (Fig. 1).

Methods of the studies

The analysis was carried out using a Quanta 250 FEI scanning electron microscope equipped with an EDAX Genesis microanalyzer. Randomly selected samples from each location



Place of sample collection	GPS (Decimal Degrees) latitiude / longitude
1. Beskid Niski	49.63416 / 21.11722
2. Bory Tucholskie	53.66583 / 18.25138
3. Kampinos	52.28777 / 20.44888
4. Karkonosze	50.80861 / 15.61277
5. Katowice	50.26333 / 19.03638
6. Kraków	50.07944 / 20.06888
7. Łysogóry	50.87083 / 21.05500
8. Opole	50.68000 / 17.91611
9. Ożarów	50.92833 / 21.68138
10. Parsęta	53.74777 / 16.55361
11. Pogórze Karpackie	49.96527 / 20.49833
12. Poznań-Morasko	50.46527 / 16.93250
13. Puszcza Borecka	54.11305 / 22.02000
14. Roztocze	50.58972 / 22.99638
15. Warszawa	51.73555 / 21.02916
16. Wigry	54.05944 / 23.01305
17. Wolin	53.94666 / 14.47611

Fig. 1. Location of sampling points of pine needles (*Pinus sylvestris* L.)

were mounted on standard aluminum tables (ø12 mm) using carbon discs and then sputter-coated with 24 carat gold using the Leica EM SC050 system. These prepared samples were subjected to microscopic imaging under high vacuum with an accelerating voltage of 20 kV. The surface of the needles was analyzed using the microanalyzer, providing the weight and atomic percentages of the identified elements. Scanning electron microscopy (SEM) micrographs from all sampling points were used to develop a self-learning algorithm to identify pollutants on the surface of the needles. For data processing and analysis, the Python programming language was employed alongside several external libraries (Chollet 2021, Driscoll 2021). Images were loaded and processed using the PIL (Python Imaging Library) library. The torch.utils.data. Dataset module was used for data management and loading, while the torchvision.transforms library facilitated data transformations. A predictive model based on neural networks was implemented using the torch and torch.nn libraries. The model was trained using the optimizers from the torch.optim module, while loss and activation functions were defined using torch.nn.functional. Data analysis and visualization were carried out using the numpy and matplotlib.pyplot libraries. (Nelli 2018). By integrating these tools, it was possible to develop an effective self-learning algorithm able to identify air pollutants in a precise manner.

Results of the studies

Based on the SEM/EDX analysis, a significant diversification of the imaged structures and chemical composition of needles was observed. Stomata were visible in all the analyzed samples, but their density, in relation to the surface, varied. The analysis of pine needle images from Parsęta, Borecka Forest, Wolin, Roztocze, Wigry and Tuchola Forest did not reveal the presence of harmful particulates. Instead, their surfaces exhibited mineral particles with a predominance of aluminum, silicon and calcium. Natural structures of pollen and fungi were also identified (Fig. 2).

Samples from the Low Beskids, Kampinos, Carpathian Foothills, Łysogóry and Karkonosze were characterized by the presence of finer, round (spherical) particles. These particles were predominantly composed of iron, aluminum, and silicon (Fig. 3).

In the photos from Ożarów, Opole and Poznań, the surfaces of the needles were covered with a layer containing calcium, silicon and magnesium. Additionally, the stomata showed significant impregnation with cement-lime particles (Fig. 4).

In urban samples (Kraków, Warsaw, Katowice), but also those from Kampinos, Karkonosze, and Łysogóry, small, spherical particles (ferruginous-silicate spherules) were commonly observed. Additionally, much larger conglomerates with diverse chemical compositions were also present (Fig. 5).

Discussion

Habitat conditions, including anthropopressure, have a fundamental impact on the life processes of trees (Wrońska-Pilarek et al. 2023). Mineral particles, particulates and pollen deposited on the needle surfaces hinder gas exchange and evapotranspiration. A strong impregnation of assimilation organ surfaces with fine particles can disrupt these life processes by penetrating and blocking the stomata (Torahi et al. 2021). The chemical composition of particulates, especially the presence of heavy metals, can negatively affect the condition of forest stands in highly polluted areas (Osma et al. 2016). Increased heavy metal

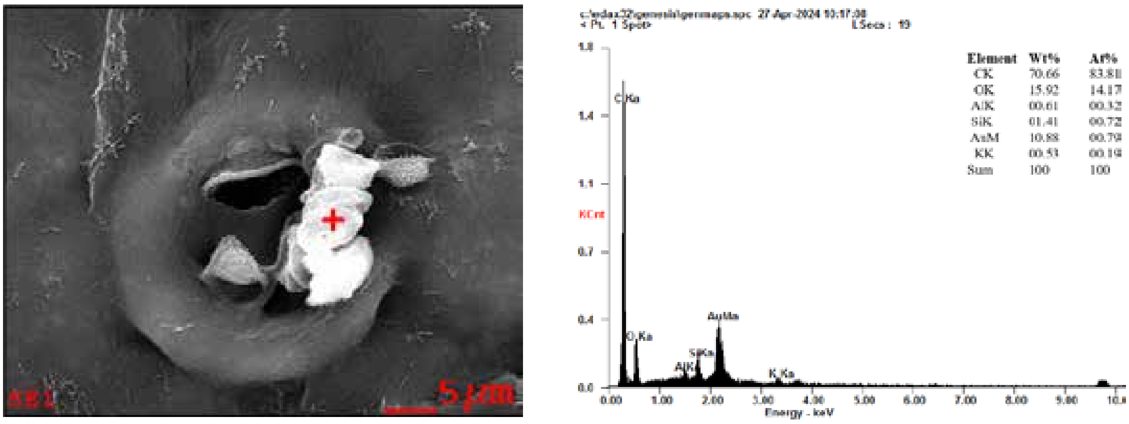


Fig. 2. SEM/EDS analysis of the surface of a needle from the Parsęta IMNE base station.

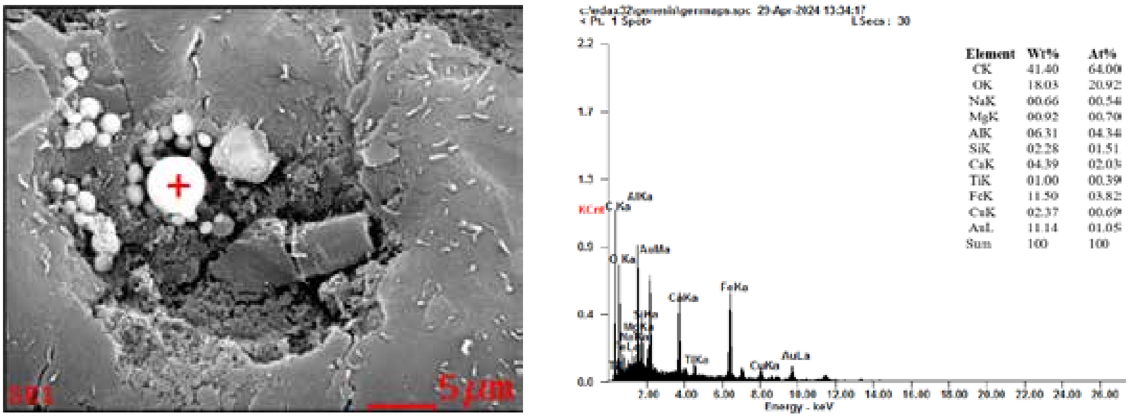


Fig. 3. SEM/EDS analysis of the surface of a needle from the Kampinos IMNE base station.

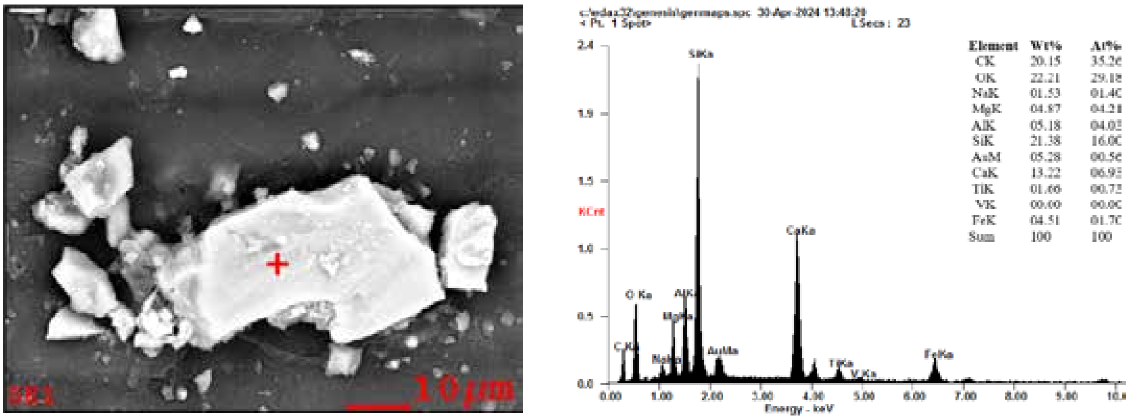


Fig. 4. SEM/EDS analysis of the surface of a needle from the Poznań-Morasko IMNE base station.

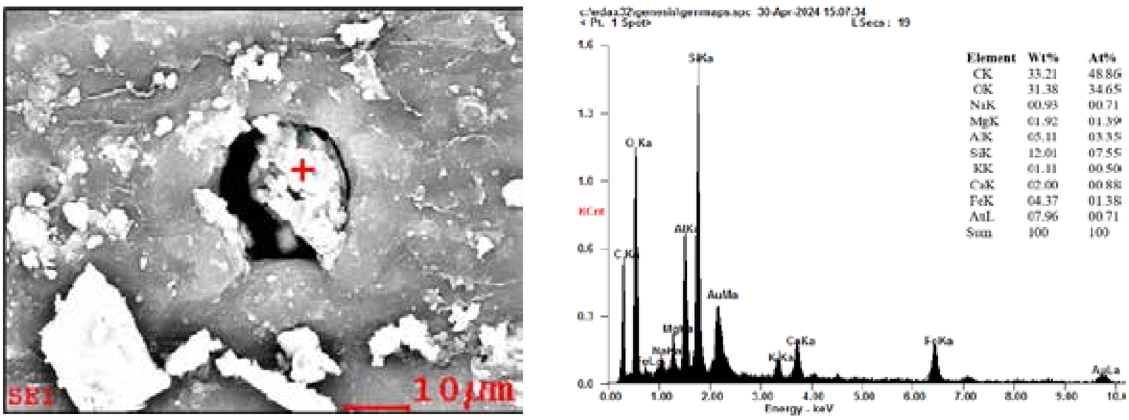


Fig. 5. SEM/EDS analysis of the surface of a needle from Katowice.

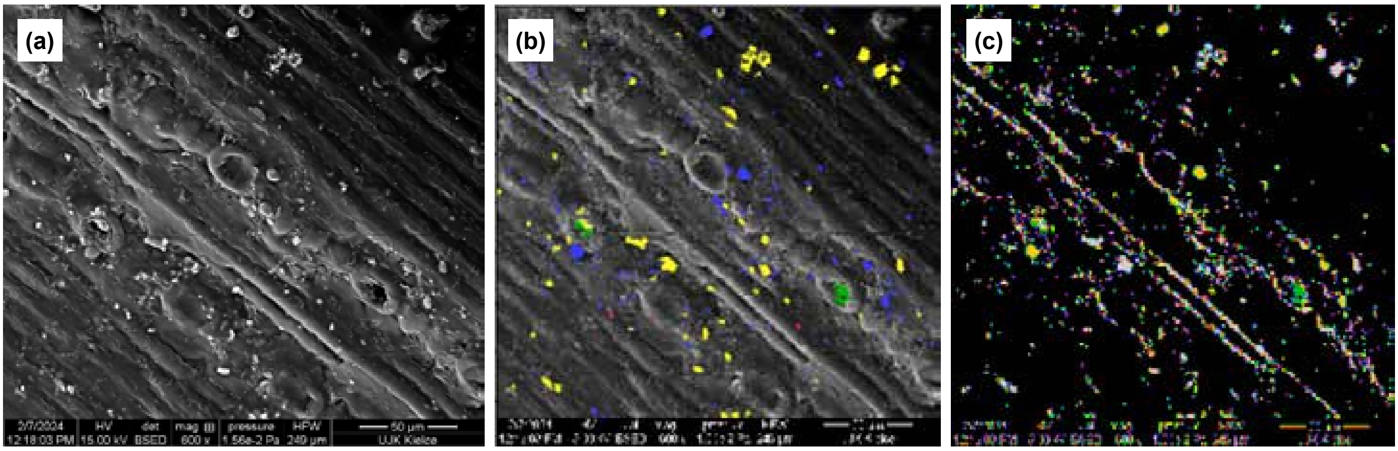


Fig. 6. Results of model operations on SEM images of pine needles; a) orginal, b) preprocessed, c) predicted

concentrations may reduce the number of stomata and impair their metabolic function (Guo et al. 2023). A similar mechanism limiting the number of stomata in pine needles has also been associated with climate change and increased atmospheric carbon dioxide levels (Marek et al. 2021). Fine particles, approximately 5 µm in size, can remain airborne for extended periods, enabling their transport over long distances (Leung 2021). These particles have been detected in locations devoid of local pollution sources (Kampinos, Łysogóry, Karkonosze).

Characteristic features observed on needle surfaces, such as round stomata, fine mineral particles, spherical particulates, and larger cement-lime conglomerates, formed the basis for developing a neural network algorithm. Micrographs were manually processed to ensure that these specific features were assigned consistent colors (attributes) across all images. This preprocessing resulted in input data layers (masks) from all sampling locations. The self-learning algorithm was tasked with identifying these specific features in subsequent images. A color map was used to map each color to a corresponding class of pollutants. The model processed the images by converting the color-coded masks into pollutant class indexes. This dataset was then used to train a U-Net neural network model, which utilized encoding and decoding layers to precisely identify and classify pollutants in the images (Ronneberger et al. 2015).

The training of the model involved cross-entropy loss and the Adam optimizer, which facilitated efficient weight adjustment in the neural network (Sankaran et al. 2017). The model was trained for 10 epochs, during which its parameters were iteratively optimized using the training dataset. After each epoch, predictions were visualized to monitor progress and accuracy in identifying pollutants on needle surfaces. Using this architecture and methodology, the developed self-learning algorithm achieved a high accuracy of 80% in detecting and classifying pollutants (Fig. 6).

Summary

Microscopic analyses of the pine needles from various regions of Poland revealed potential hazard to the assimilation organs of this common coniferous species. Particles observed on the needle surfaces can effectively block stomata, impending gas exchange. The chemical composition of these particulates, particularly the presence of heavy metals, may adversely affect the metabolic processes of needles and overall tree condition. In highly industrialized areas, the particle composition reflected specific types of anthropopressure. For example, calcium, magnesium, and iron were predominant in samples from cement industry centers (Ożarów, Opole). In contrast, fine particles containing iron, aluminum and silicon (technogenic spherules) transported over long distances were visible on the needles from Kampinos, Łysogóry, and Karkonosze. Needles from regions with multidirectional anthropogenic pressures, including traffic, municipal, and industrial sources (Katowice, Poznań, Kraków and Warsaw), exhibited the greatest diversity in particle composition. The presence of heavy metals identified in the analyzed samples may pose a threat to human health, as harmful particulates can enter the body through inhalation of low-quality air. The pollutant identification method employed in this study proved highly effective, achieving an accuracy of 80%. The model successfully processed the images by converting te image masks into corresponding pollutant classes, enabling efficient recognition of characteristic shapes and features on the needle surfaces. This precise mapping and analysis of pollutant distribution provide valuable insights into the impact of anthropopressure on tree health and air quality in various regions of Poland.

Data availability

Data will be made available on request.

Acknowledgement

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Mikrofotograficzny obraz zanieczyszczeń powietrza w Polsce

Streszczenie. Celem pracy jest analiza mikroskopowa jednorocznych igieł sosny zwyczajnej z obszarów o zróżnicowanych warunkach depozycji pyłów naturalnych i antropogenicznych. Wykonane mikrofotografie zostały wykorzystane do prezentacji możliwości sztucznej inteligencji w identyfikacji zanieczyszczeń powietrza. Do budowy samouczącego algorytmu identyfikującego zanieczyszczenia na powierzchni igieł wykorzystano mikrofotografie skaningowej mikroskopii elektronowej (SEM) ze wszystkich punktów poboru próbek. Do przetwarzania i analizy wykorzystano język programowania Python wraz z kilkoma zewnętrznymi bibliotekami. Na podstawie przeprowadzonej analizy SEM/EDX stwierdzono znaczne zróżnicowanie zobrazowanych struktur (naturalnych i antropogenicznych) oraz składu chemicznego igieł. We wszystkich analizowanych próbkach zobrazowano aparaty szparkowe, jednak ich liczba w stosunku do powierzchni była zróżnicowana. Zidentyfikowano także naturalne struktury pyłków i grzybów. W przypadku próbek miejskich (duże miasta), ale także z Łysogór, powszechne są okrągłe, drobne cząstki (sferule żelazowo-krzemianowe) oraz znacznie większe konglomeraty o zróżnicowanym składzie chemicznym. Obecność metali ciężkich zidentyfikowana w badanych próbkach może stanowi zagrożenie dla zdrowia ludzi w wyniku przenikania szkodliwych pyłów do wnętrza organizmu w wyniku oddychania niskiej jakości powietrzem. Zastosowana metoda identyfikacji zanieczyszczeń cechowała się dużą sprawnością. Działanie sieci na poziomie 80% stanowi zadowalający wynik.