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METAL-ACCUMULATING CAPACITY AND ANTIOXIDANT ACTIVITY OF *PYLAISIA POLYANTHA* (HEDW.) SCHIMP. MOSS IN URBAN AREAS

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Background. Bryophytes, including mosses, are widely used in biomonitoring of atmospheric pollution due to their ability to accumulate metals from atmospheric air. However, the effects of metal accumulation on metabolic processes in bryophyte cells have not been thoroughly studied. The aim of this work was to analyse the accumulation of heavy metals, indices of lipid peroxidation (LPO), and antioxidant status in gametophytes of the epiphytic moss *Pylaisia polyantha* (Hedw.) Schimp. collected from urban areas with different levels of technogenic load.

Materials and Methods. The study was conducted in the city of Lviv (western part of Ukraine). Within the city, 15 sampling sites were selected and grouped as follows: the green zone (A) conditionally used as the control, zone influenced by transport activities (B) and the industrial zone (C). In gametophyte shoots of *P. polyantha*, concentrations of heavy metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) were analysed using the method of atomic absorption spectrophotometry; the content of LPO products (lipid hydroperoxides, thiobarbituric acid reactive substances (TBARS)) and the activities of antioxidant system enzymes (superoxide dismutase, catalase, glutathione S-transferase) were analysed using standard methods. The results were processed using standard statistical methods.

Results. Concentrations of heavy metals in *P. polyantha* gametophytes collected from the study area can be arranged in descending order as follows: Fe> Mn> Zn> Pb> Cu> Ni> Cr> Co> Cd. The content of individual metals in moss material varied depending on the sampling site. Moss shoots collected from zone B accumulated significantly higher levels of Cd, Co, Cu, Fe, Mn, Pb and Zn, and shoots from zone C had higher levels of Cr and Zn compared to those from the green zone. Moss gametophytes collected from sites in zone B had higher concentrations of LPO products and increased levels of antioxidant enzymes activity compared to the control.

Conclusions. Elevated concentrations of heavy metals in moss material from sites exposed to traffic and industrial activities reflect atmospheric heavy metal pollution in urban areas. Intensive accumulation of heavy metals in gametophytes of *P. polyantha* that grows in the areas of transport activities is accompanied by increased lipid peroxidation processes and activation of enzymes of the antioxidant system in moss cells. Activation of antioxidant enzymes may play an important role in the adaptation of the moss *P. polyantha* to urban environments contaminated with heavy metals as a result of anthropogenic activities.

Keywords: bryophytes, mosses, *Pylaisia polyantha*, heavy metals, antioxidant system, urban ecosystems, biomonitoring

INTRODUCTION

Ecological conditions in urban ecosystems are strongly influenced by anthropogenic impacts, which affect all components of the abiotic environment, primarily the atmospheric air. In industrial cities, the main sources of air pollution are enterprises operating in various industries, coal-fired power plants, inappropriate waste management and high traffic loads. Among environmental pollutants, heavy metals and metalloids belong to the most dangerous substances (Bjørklund *et al*., 2020, 2022a; Fry *et al*., 2020; Ren *et al*., 2021; Mishra *et al*., 2022). Along with other pollutants, heavy metals are often contained in industrial emissions and fuel combustion products. In the atmosphere, heavy metals are associated with airborne particulate matter, which can be transferred by air currents over long distances (Chen *et al*., 2021; Guo *et al*., 2021; Ren *et al*., 2021).

A number of elements referred to as heavy metals, as well as several metalloids are known to be needed in certain quantities by all living systems for metabolic processes (Snityns'kyĭ & Antoniak, 1994; Snitynskyi *et al*., 1999; Antonyak *et al*., 2018; Bjørklund *et al*., 2022b; Narayanan & Ma, 2023). However, the presence of these substances in the atmosphere poses a significant threat to human health, since many of the heavy metals are highly toxic, mutagenic and carcinogenic (Balali-Mood *et al*., 2021; Guo *et al*., 2021; Ren *et al*., 2021; Bjørklund *et al*., 2020, 2022a).

Among various vegetation groups, bryophytes, including mosses, are widely used as bioindicators and biomonitors to assess atmospheric heavy metal deposition, especially in urban ecosystems (Mahapatra *et al*., 2019; Ștefănuț *et al*., 2019; Trujillo-González *et al*., 2020). It is accepted that mosses can reflect changes in atmospheric metal content more reliably than vascular plants (Jiang *et al*., 2018). Bryophytes can resist the toxicity of heavy metals and accumulate significant amounts of these substances in their cells. The metal-accumulating property is inherent to both terrestrial and aquatic bryophytes (Macedo-Miranda *et al*. 2016; Polishchuk & Antonyak, 2019, 2021; Lesiv *et al*., 2020; Maresca *et al*., 2022). The ability of mosses to tolerate high concentrations of metals and metalloids and to resist their toxicity is of considerable interest. As it is known, heavy metals can induce oxidative stress in plant cells mediated by the formation of reactive oxygen species (ROS), including free radicals (Emamverdian *et al*., 2015; Gill *et al*., 2022; Ghuge *et al*., 2023). The main feature of ROS is their high reactivity; ROS are capable of interacting with various cellular biomolecules, which is accompanied by a damaging effect on plant cells. Therefore, the functioning of the antioxidant system is an important part of the protective mechanisms in bryophyte cells exposed to heavy metals (Polishchuk & Antonyak, 2021; Kyyak, 2022; Maresca *et al*., 2022; Smolińska-Kondla *et al*., 2022).

The relationship between metal accumulation and metabolic status in bryophyte cells has not been extensively studied. In particular, this concerns *Pylaisia polyantha* (Hedw.) Schimp. – a moss distributed in both natural and urban ecosystems (Boiko, 2014; Plášek *et al*., 2014; Stebel & Vončina, 2017; Polishchuk *et al*., 2020). Current data suggest that *P*. *polyantha* moss is resistant to environmental pollution and can be classified as an urbanophilous bryophyte species (Mamchur, 2010). In urban ecosystems, *P*. *polyantha* moss can be found on the bark of trees that grow in both green and industrial areas, along busy roads, etc. (Plášek *et al*., 2014; Polishchuk et al., 2020).

The aim of this study was to analyse the levels of accumulation of heavy metals, indices of lipid peroxidation (LPO) and antioxidant status in gametophyte shoots of *P. polyantha* collected in urban areas with different levels of technogenic load.

MATERIAL AND METHODS

Study area. The study was conducted in the city of Lviv (49°49′48″N 24°00′51″E), one of the largest industrial centres in the western part of Ukraine. Lviv is a densely populated city with an area of about 182 km^2, the centre of the Lviv urban agglomeration, with developed industry and transport infrastructure. The city has interregional and interstate road, rail and air communications. The central part of Lviv is constantly exposed to heavy traffic loads (Polishchuk *et al.*, 2020).

Within the territory of Lviv, fifteen sites were selected for sampling *P. polyantha* gametophytes. Sampling sites were grouped as follows: the green zone (A), which included sites S1–S4 located in city parks; zone influenced by transport activities (B), which included sites S5–S12 in various parts of the city; the industrial zone (C) including sites S13–S15 in areas influenced by industrial activity (**Table 1**).

The potentially uncontaminated green area (zone A) was conditionally considered as the control one, since the sampling sites located there were not exposed to obvious sources of environmental pollution. During the collection of moss material from zones B and C, factors such as the nature of the territory and the availability of *P. polyantha* for sampling were taken into account. Plant samples were taken in triplicate.

Analysis of moss material. Moss material was collected using standard methods (Vanderpoorten *et al*., 2010). In the laboratory, moss material was cleaned of impurities and debris, air dried, and analysed using a stereoscopic microscope XS 6220 (Ukraine) to identify *P. polyantha* species.

The content of heavy metals, namely cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb) and zinc (Zn) in *P. polyantha* gametophytes was determined by the method of atomic absorption spectrophotometry using an atomic absorption spectrometer C-115PK Selmi (Ukraine). Before analysis, moss material was prepared using conventional methods (Ogunkunle *et al*. 2016). The concentrations of metals were expressed in milligrams per 1 kg of dry mass of moss material.

Table 1. **Sampling sites of *Pylaisia polyantha* in the study area**

Site	Location of a sampling site	Sampling site description
S1	49°49′24.0″N 24°01′30.0″E	Stryisky Park
S2	49°49′24.0″N 24°04′00.0″E	Pohulyanka Forest Park
S3	49°48′50.3″N 23°58′16.3″E	Sknyliv Park
S4	49°50′19.0″N 24°01′11.0″E	Ivan Franko Park
S5	49°46′38.5″N 24°00′54.0″E	area adjacent to the European route E471
S6	49°48′13.0″N 24°01′03.5″E	area adjacent to the European route E471
S7	49°49′38.5″N 24°01′52.0″E	area adjacent to the European route E471
S8	49°50′08.0″N 24°04′02.5″E	area adjacent to Lychakivska Street
S9	49°46′51.5″N 23°57′57.0″E	area adjacent to the intersection of the European route E40 and the road T1416
S10	49°47′59.3″N 23°58′42.8″E	area adjacent to the road T1416 and airport
S11	49°49′58.0″N 23°54′17.0″E	area adjacent to the European route E40 and railway
S12	49°50′08.3″N 23°57′58.4″E	area adjacent to the railway
S13	49°51′55.0″N 24°02′34.0″E	area adjacent to the tannery
S14	49°48′42.0″N 24°01′44.0″E	area adjacent to the heat power plant
S15	49°50′17.5″N 23°58′40.5″E	Levandivka microdistrict with local industry

Plant extracts were prepared as described elsewhere (Sun *et al*., 2009). To prepare the extract, a sample of moss material (200 mg) was homogenized using a mortar and pestle with 4 ml of cooled extraction medium containing 100 mM phosphate buffer (pH 7.0) and 0.1 mM EDTA. The homogenate was centrifuged at 10,000 g for 15 min at 4 °C. The supernatant was used as a crude extract to analyse the activities of superoxide dismutase and catalase, as well as the concentration of LPO products.

Concentration of thiobarbituric acid reactive substances (TBARS) in plant material was determined using the method developed by R. L. Heath and L. Packer (1968). During the assay procedure, an aliquot of the crude extract was mixed with an equal volume of a 0.5 % solution of thiobarbituric acid in 20 % trichloroacetic acid. The reaction mixture was heated at 95 °C for 25 min and then chilled in an ice water bath. Subsequently, the mixture was centrifuged at 3000 g for 5 min and the absorbance of the supernatant was monitored at 532 and 600 nm using ULAB102 spectrophotometer (China). Nonspecific absorbance at 600 nm was subtracted. TBARS content was calculated using an extinction coefficient of 155 mM^{-1} cm^{-1} (Heath & Packer, 1968). Concentration of lipid hydroperoxides in plant material was analysed using a method based on spectrophotometric measurement (λ = 480 nm) of products formed in plant extracts in the presence of ammonium ferrous sulfate hexahydrate, hydrochloric acid, and ammonium thiocyanate (Mironchik, 1984).

Superoxide dismutase (SOD, EC 1.15.1.1) activity was analysed using a method based on reduction of nitro-blue tetrazolium in the presence of NADH and phenazine methosulfate (Nishikimi *et al*., 1972; Kakkar *et al*., 1984). The assay mixture contained

1.2 mL of 0.052 M sodium pyrophosphate buffer (pH 7.8), 0.3 mL of 300 µM nitroblue tetrazolium, 0.1 mL of 186 µM phenazine methosulfate, 0.2 mL of 800 µM NADH, 0.1 mL of plant extract, and water (a total volume of 3 ml). Absorbance was measured at 560 nm. One unit (U) of SOD activity was defined as the enzyme amount required to inhibit chromogen production by 50 % within 1 minute of the assay (Kakkar *et al*., 1984).

Catalase (EC 1.11.1.6) activity was determined by a spectrophotometric assay recording the decrease in optical density at 240 nm during the decomposition of H_2O_2 (Aebi, 1984). The reaction mixture contained 2 mL of 0.05 M phosphate buffer (pH 7.0), 0.5 mL of 30 mM H_2O_2, 0.1 mL of plant extract and water to a final volume of 3 mL. Absorbance was measured using a Specord 210 Plus spectrophotometer.

Glutathione *S*-transferase (GST, EC 2.5.1.18) activity was analysed using the reduced glutathione (GSH) and 1-chloro-2,4-dinitrobenzene (CDNB) (Li *et al*., 1995; Dixit *et al*., 2001). To determine GST activity, a sample of plant material (500 mg) was homogenized in an extraction medium containing 50 mM phosphate buffer (pH 7.5), 1 mM EDTA, and 1 mM DTT. The homogenate was centrifuged at 10,000 g for 10 min at 4 °C and the supernatant was used to measure enzyme activity. The reaction mixture contained 50 mM phosphate buffer (pH 7.5), 1 mM CDNB, and 0.1 mL of plant extract. The reaction was started by adding 1 mM GSH. The formation of glutathione-CDNB conjugate (*S*-(2,4-dinitrophenyl)glutathione)) was monitored as the increase in absorbance at 334 nm in order to calculate the activity of GST (Li *et al*., 1995; Dixit *et al*., 2001).

The protein concentration was measured using the method developed by O. H. Lowry *et al*. (Lowry *et al*., 1951).

Statistical processing of results. When processing the results, we used standard statistical methods (Welham *et al*., 2015) to calculate the values of the arithmetic mean, standard deviation (S.D.), geometric mean, median, and coefficient of variation (CV). To compare groups of data, the reliability of the results was assessed using Student's *t*-test; differences were considered significant at $p<0.05$ (Welham *et al*., 2015).

RESULTS

Table 2 shows the levels of metal accumulation in the gametophytes of *P*. *polyantha* collected from all sampling sites within the study territory. During the study, the highest levels of accumulation in the gametophytes of *P. polyantha* were recorded for Fe, while the lowest level was found for Cd, a toxic heavy metal. According to the results of the study, the concentrations of the analysed metals in *P. polyantha* moss can be arranged in a descending order as follows: Fe> Mn> Zn> Pb> Cu> Ni> Cr> Co> Cd. The pattern of heavy metal deposition in gametophytes of *P. polyantha* generally corresponds to the distribution of metallic elements recorded in other moss species collected from the city of Lviv and from different locations in Europe (Marinova *et al*., 2010; Harmens *et al*., 2013; Qarri *et al*. 2014; Polishchuk & Antonyak, 2019, 2021).

Among the metals analysed in this study, Fe, Co, Mn and Ni are siderophile elements, Cr is a lithophile element (although it also exhibits siderophile properties), and Cd, Cu, Pb and Zn are chalcophile elements, according to the classification by V. Goldschmidt (1937). It has been shown that airborne chalcophile elements contained in particulate matter (PM) originate primarily from anthropogenic emission sources (Fukai *et al*., 2007). These elements are found predominantly in fine particles ($PM_{2.5}$), which pose a particular health hazard when inhaled by humans (Fukai *et al*., 2007; Zieliński *et al*., 2018). Siderophile and lithophile elements make up about 50 % of the fraction of airborne coarse particles ($PM_{10-2.5}$); these elements are predominantly of natural origin, but can also be released into the air from industrial sources as a result of coal and biomass combustion and the activities of various modes of transport (Fukai *et al*., 2007; Khan *et al*., 2010; Guéguen *et al*., 2011).

Table 2. **Means (arithmetic and geometric), median, minimum and maximum values, coefficient of variation and standard deviation of heavy metal concentrations in the gametophytes of *Pylaisia polyantha***

Studied metal	Mean, mg/kg	S.D.	Minimum value, mg/kg	Maximum value, mg/kg	CV, %	Median, mg/kg	GeoMean mg/kg
Cd	0.511	0.046	0.210	1.134	9.0	0.493	0.468
Co	2.11	0.13	1.12	3.90	6.16	2.10	2.03
Cr	5.42	1.05	2.12	14.61	19.37	4.24	4.42
Cu	14.66	1.08	7.28	23.98	7.39	13.10	13.73
Fe	1867	176	920	4145	9.43	1653	1681
Mn	134.3	17.10	23.92	262.3	12.70	108.0	111.0
Ni	6.34	0.64	2.64	11.48	10.11	6.84	5.89
Pb	16.75	2.48	1.05	34.54	14.81	14.71	11.90
Zn	50.15	3.48	19.9	77.4	6.81	50.66	48.67

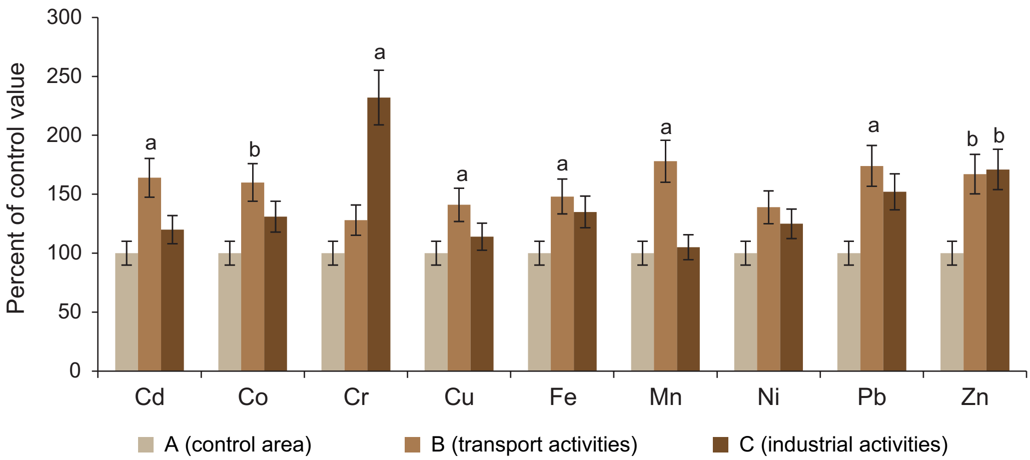
Note: S.D. – standard deviation; CV – coefficient of variation; GeoMean – geometric mean

According to the obtained results (Table 2), among the siderophile and lithophile elements accumulated in the moss *P. polyantha*, iron was the most abundant one, followed by manganese with mean concentrations of 1867 and 134.3 mg/kg, respectively. In contrast to these metals, the concentrations of Ni, Cr and Co in *P. polyantha* moss were low, with mean values of 6.34, 5.42 and 2.11 mg/kg, respectively. The concentration of Cr in moss material showed the highest coefficient of variation (19.37 %) among the analysed elements, which indicates a highly uneven distribution of this metal in the environment within the study area.

Among the chalcophile elements, the highest level of accumulation in the moss material was observed for zinc (50.15 mg/kg), and the lowest for cadmium (0.511 mg/kg). The coefficient of variation of Zn concentration turned out to be the lowest among the chalcophile metals (6.81 %), indicating the homogeneity of the distribution of Zn in moss gametophytes collected from different sampling sites. With regard to the level of Pb accumulation, the mean concentration of this metal in *P. polyantha* reached 16.75 mg/kg, and the CV value was 14.81 %. The variability of Pb content in the moss material indicates heterogeneity of the distribution of lead in the environment, which may be associated with air pollution from anthropogenic sources in different parts of the city.

Various modes of transport and industrial activities are known to be the major sources of environmental pollution and the main contributors to the overall level of heavy metals in the atmosphere of urban areas. To assess the relationship between the level of metal accumulation in *P. polyantha* and anthropogenic activities within the city, we compared the concentrations of individual metals in moss collected from zone A (control) with those in moss material from zones B and C. The data presented in **Figure** show that the content of most analysed metals tends to increase in moss material from areas subjected to technogenic impact compared to those from the control area. Moss gametophytes sampled at sites in zone B contain significantly higher levels of Cd, Co, Cu, Fe, Mn, Pb and Zn (by 1.5–1.94 times, $p<0.05–0.01$) compared to those sampled in zone A. The results suggest that the release of heavy metals into the atmosphere from transport activities mainly contributes to the increased levels of metal accumulation in *P. polyantha* gametophytes. The average traffic volume at sampling sites S5–S9 was previously shown to be 700–1200 vehicles per hour (Polishchuk *et al*., 2020; Polishchuk & Antonyak, 2022).

Analysis of the moss material sampled at sites in zone C did not reveal statistically reliable differences in the content of most metals compared to the control. However, the concentrations of Cr and Zn showed significantly higher levels (2.32 and 1.71 times, respectively) in the moss material from zone C compared to that from zone A. These results indicate that industrial activities carried out in the city of Lviv constitute a relatively small share of the total level of heavy metal pollution of the atmosphere.



Mean concentrations of heavy metals in the gametophytes of *Pylaisia polyantha* collected from zones A–C within the studied urban territory (for convenience, data are presented as a percentage of the values compared to the control; control values are taken as 100 percent)

Note: letters *a* and *b* indicate the significance levels of differences between the concentrations of individual metals in moss samples in comparison to control (a: $p<0.05$; b: $p<0.01$)

Another aspect of this study regards the metabolic changes in moss gametophytes under conditions of heavy metal accumulation. Oxidative injury to cells is one of the widely known consequences of excess levels of heavy metals in plants. To assess the effect of metal accumulation on the balance of pro-oxidant and antioxidant processes in *P. polyantha* gametophytes, we analyzed the content of LPO products and the activity of the antioxidant system in the moss material collected from the control area (zone A) and from areas subjected to traffic load (zone B). It was found that the levels of lipid hydroperoxides and TBARS in moss material from the area subjected to transport activities were significantly higher (by 1.9 and 2.2 times, respectively) than in the material collected from zone A (**Table 3**). An increase in the content of LPO products was accompanied by an alteration in the activity of antioxidant enzymes in *P. polyantha* cells. Namely, the activity of SOD, catalase and glutathione *S*-transferase in moss gametophytes from zone B was 1.7–2.3 times higher ($p<0.05–0.01$) compared to the control.

Table 3. **Levels of lipid peroxidation products formation and activities of antioxidant enzymes in *Pylaisia polyantha* gametophytes collected from zones A and B within the studied urban territory (Mean ± S.D.)**

Studied parameters	Zone A	Zone B
Lipid hydroperoxides, nmol g^{-1} moss material	11.0±1.4	20.7±3.2*
TBARS, nmol g^{-1} moss material	74.5±8.7	168.0±22.0**
Superoxide dismutase, U/mg protein	0.22±0.02	0.37±0.05*
Catalase, μmol H_2O_2 min^{-1} mg^{-1} protein	1.32±0.15	3.10±0.41**
Glutathione S-transferase, μmol glutathione–CDNB conjugate min^{-1} mg^{-1} protein	0.12±0.01	0.23±0.03*

The activation of antioxidant enzymes observed in *P. polyantha* gametophytes appears to be an adaptive response that protects moss cells from oxidative stress, which can develop due to increased ROS production under conditions of heavy metal loading. Intensification of ROS production and alterations in the antioxidant system were also observed by other authors who studied the effect of heavy metals on various bryophyte species under field and experimental conditions (Baik, 2009; Wu *et al*., 2009; Maresca *et al*., 2022).

CONCLUSIONS

The results of the study show that the epiphytic moss *P. polyantha* growing in the city of Lviv accumulates heavy metals in concentrations close to those recorded in other moss species common in urban areas. However, *P. polyantha* gametophytes from areas subjected to transport and industrial activities tend to accumulate significantly higher amounts of heavy metals than plants from the green zone of the city. This effect reflects the pollution of atmospheric air with heavy metals in urban areas under the influence of technogenic load; transport emissions being the source of the bulk of atmospheric metals deposited in *P. polyantha* gametophytes. An increased accumulation of metals is accompanied by intensive formation of LPO products in moss gametophytes growing in areas subjected to traffic load. Under such conditions, activation of antioxidant enzymes contributes to the resistance of bryophyte cells to metal-induced oxidative stress. This effect may play an important role in the adaptation of *P. polyantha* moss to urban environments contaminated with heavy metals as a result of anthropogenic activities.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Animal Rights: This article does not contain any studies with animal subjects performed by any of the authors.

AUTHOR CONTRIBUTIONS

Conceived and planned the experiments [A. P. & H.A.]; conducted experiments and data collection [A.P. & Y.Z.]; all authors analyzed and discussed the results and contributed to the final manuscript.

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МЕТАЛОАКУМУЛЯЦІЙНА ЗДАТНІСТЬ І АНТИОКСИДАНТНА АКТИВНІСТЬ МОХУ *PYLAISIA POLYANTHA* (HEDW.) SCHIMP. НА МІСЬКИХ ТЕРИТОРІЯХ

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Обґрунтування. Бріофіти, зокрема, мохи, широко використовують у біомоніторингу забруднення атмосфери завдяки їхній здатності до акумуляції металів з атмосферного повітря. Однак вплив накопичення металів на метаболічні процеси у клітинах мохів з'ясований недостатньо. Метою дослідження було проаналізувати накопичення важких металів, показники пероксидного окиснення ліпідів (ПОЛ) і антиоксидантний статус у гаметофіті епіфітного моху *Pylaisia polyantha* (Hedw.) Schimp., зібраного в міських районах із різними рівнями техногенного навантаження.

Матеріали і методи. Дослідження проводили у м. Львові (західна частина України). У межах міста було вибрано 15 ділянок відбору проб, згрупованих у такий спосіб: зелена зона (А), яку умовно використовували як контроль, зона впливу транспортної діяльності (Б) та промислова зона (В). У пагонах *P. polyantha* аналізували концентрацію важких металів (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn) методом атомно-абсорбційної спектрофотометрії; вміст продуктів ПОЛ (гідропероксиди ліпідів і речовини, які реагують з тіобарбітуровою кислотою (ТБК-активні продукти)) й активність ензимів антиоксидантної системи (супероксиддисмутаза, каталаза, глутатіон S-трансфераза) аналізували стандартними методами. Результати опрацьовували методами варіаційної статистики.

Результати. Важкі метали, акумульовані в гаметофіті моху *P. polyantha*, зібраного з досліджуваної території, можна розташувати в такому порядку відповідно до концентрації: Fe> Mn> Zn> Pb> Cu> Ni> Cr> Co> Cd. Вміст окремих металів у рослинному матеріалі був різним, залежно від місця відбору проб. Пагони моху, зібрані на ділянках у зоні Б, містили значно вищу концентрацію Cd, Co, Cu, Fe, Mn, Pb і Zn, а пагони із зони В – вищу концентрацію Cr і Zn, ніж пагони моху, зібрані в зеленій зоні. У гаметофіті моху, зібраного на ділянках у зоні Б, виявлено більшу концентрацію продуктів ПОЛ і підвищену активність антиоксидантних ензимів, порівняно з контролем.

Висновки. Підвищення концентрації важких металів у рослинному матеріалі з ділянок, розташованих у зонах впливу транспортного руху та промислової діяльності, відображає забруднення атмосфери в міських районах важкими металами. Інтенсивне накопичення важких металів у гаметофіті моху *P. polyantha*, що росте у зонах впливу транспортної та промислової діяльності, супроводжується посиленням процесів пероксидного окиснення ліпідів і активацією ензимів антиоксидантної системи в клітинах. Підвищення активності антиоксидантних ензимів може відігравати важливу роль в адаптації моху *P. polyantha* до міського середовища, забрудненого важкими металами внаслідок антропогенної діяльності.

Ключові слова: бріофіти, мохи, *Pylaisia polyantha*, важкі метали, антиоксидантна система, урбоекосистеми, біомоніторинг

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