Regulatory Mechanisms
in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.

Impact of lead on *Catalpa bignonioides* and *Paulownia tomentosa* and its phytoremediation ability

N. V. Nuzhyna*, N. V, Henzerska*, H. O. Rudic*, S. P. Kovalova**, O. V. Dmytrenko***

**Taras Shevchenko National University of Kyiv, Kyiv, Ukraine*
***Polissya Institute of Agriculture NAAS, Zhytomyr, Ukraine*
****State Institution 'Soils Protection Institute of Ukraine', Chabany, Ukraine*

Article info

Received 10.05.2025
Received in revised form 15.06.2025
Accepted 21.07.2025

Educational and Scientific Centre "Institute of Biology and Medicine" Taras Shevchenko National University of Kyiv, Symona Petlyury st., 1, Kyiv, 01032, Ukraine. Tel.: +38-067-339-97-73. E-mail: nuzhynan@gmail.com

Polissya Institute of Agriculture NAAS, Kyivske Highway, 131, Zhytomyr, 10007, Ukraine. E-mail: svitlanakovalova2@gmail.com

State Institution 'Soils Protection Institute of Ukraine', Mashinobudivnykyv st., 2b, Chabany Village, 08162, Kyiv-Svyatoshyn District, Kyiv Region, Ukraine. Tel.: +38-067-442-80-22. E-mail: ecolab23071964@ukr.net

Nuzhyna, N. V., Henzerska, N. V., Rudic, H. O., Kovalova, S. P., & Dmytrenko, O. V. (2025). Impact of lead on Catalpa bignonioides and Paulownia tomentosa and its phytoremediation ability. Regulatory Mechanisms in Biosystems, 16(3), e25146. doi:10.15421/0225146

Environmental pollution by heavy metals resulting from anthropogenic activities is an extremely important issue in the world. This problem is especially exacerbated during wars, which generate long-term ecological consequences that can affect human health and the environment for decades. Combat operations, destruction of industrial facilities, use of explosives and ammunition – all this leads to the release of significant amounts of toxic elements into the environment. One of the most dangerous of these is lead. Developing effective strategies to remediate soils from heavy metal contamination is critical to protecting public health and ensuring a sustainable future. The aim of our research was to analyse paulownia and catalpa for their resistance to lead and their phytoremediation ability. The plants *Catalpa bignonioides* and *Paulownia tomentosa* were watered with a solution of lead acetate at the rate of 100 or 300 mg/kg soil. The state of the photosynthetic system (chlorophyll fluorescence measured using a fluorometer and the content of chlorophylls and carotenoids); and malondialdehyde as a stress index and peroxidase activity as an antioxidant enzyme were determined by spectrophotometric method; growth and lead content in plants were also measured. The photosynthetic system of paulownia was resistant to the action of lead: the activity of peroxidase, the efficiency of the dark phase of photosynthesis and the content of chlorophyll b increased, and the stimulation of plant growth was observed. Llead had a negative effect on catalpa: a decrease in the content of chlorophyll a and carotenoids, and in the efficiency of the light phase of photosynthesis and plant growth. *Paulownia* has shown the ability to phytoremediation, accumulating lead in the stem and root. *Catalpa* did not show any resistance to lead and phytoremediation capabilities.

Keywords: pollution; resistance; antioxidant system; chlorophyll fluorescence; carotenoids; malondialdehyde.

Introduction

Anthropogenic impact on the environment has caused significant contamination of soil, water and atmosphere with lead. The most common anthropogenic sources of pollution are: car batteries, mining and metallurgy, oil refineries (Zhang et al., 2023), sulphide deposits, lead additives in petrol, use of lead pipes for water, addition of Pb to paints (Singh & Kalamdhad, 2011; Neeti & Prakash, 2013), landfills, electroplating, Au-Ag-Pb-Zn mining, etc. In addition to such anthropogenic impacts, environmental pollution with metals is caused by military operations and armed conflicts. Military activities lead to the release of metals in the form of gunshot residues such as lead (Pb), copper (Cu), cadmium (Cd), antimony (Sb), chromium (Cr), nickel (Ni) and zinc (Zn) into the environment (Shukla et al., 2023). Military activities, such as live-fire, training, waste disposal and maintenance of military infrastructure, have caused enormous damage to soil, water and air (Gorecki et al., 2017). Heavy metal contamination of shooting ranges is a widespread environmental problem of concern worldwide. The accumulation of contaminants in the soil of a shooting range can pose potential environmental and human health risks. In military training areas in Australia, Korea and Spain, the highest contamination was observed for Pb, with much lower concentrations for Sb, As, Cu and Zn (Sanderson et al., 2012; Islam et al., 2016; Rodriguez-Seijo et al., 2016). Among all the contaminants, lead has been shown to be present in doses that are hazardous to human health (Liu et al., 2014; Bai & Zhao, 2020). The amount of Pb measured at the sites of firing ranges was up to 5000 ppm (5000 mg/kg) (Urrutia-Goyes et al., 2017).

Environmental pollution, including heavy metals, is particularly intense during armed conflicts and wars, including the large-scale war in Ukraine. Constant bombardment and destruction of infrastructure, including industrial facilities, lead to large-scale air, soil and water pollution. Particularly dangerous are the emissions of heavy metals, chemicals and combustion products released into the environment as a result of explosions and fires. Military attacks on cities with missiles and drones cause large-scale fires, including in old buildings, civilian vehicles and military equipment painted with lead-based paints (Singh & Kalamdhad, 2011). Studies of heavy metal content in the soils of military landscapes, which are also in the areas of influence of industrial facilities, show a significant excess of regional background lead values (to 14,000 mg/kg) (Golubtsov et al., 2023).

Among the numerous potentially toxic elements in areas of military impact, Pb seems to be particularly problematic due to its high toxicity, prevalence, and persistence (Broomandi et al., 2020). Risks to human health are primarily associated with the consumption of food of plant and animal origin produced in the contaminated area. Lead is one of the most toxic heavy metals for humans: it damages the nervous, cardiovascular, reproductive systems, kidneys, and bone tissue (Sun et al., 2018; Collin et al., 2022). People living near the affected areas also experience respiratory and visual disorders, as well as haematopoiesis.

Remediation of heavy metal contaminated land is carried out using a variety of strategies. Most studies focus on remediation by removing lead (Laporte-Saumure et al., 2010, Thangavadivel et al., 2018; Black et al., 2021) or immobilising contaminants by adding components to the soil (Sanderson et al., 2014; Kamari et al., 2015). Phytoremediation is a promising approach to clean up contaminated soil and the environment (Conesa et al., 2012; Rodríguez-Seijo et al., 2016; Zhang et al., 2024). The main advantages of phytoremediation are cost-effectiveness, environmental friendliness and practicality compared to other technologies. Phytoremediation most often uses fast-growing commercial plants to remove pollutants from the environment (hemp, kenaf, jute and flax) (Cleophas et al., 2023). However, it would also be advisable to use tree plantations to clean up heavy metal contaminated urban areas. The root system of woody plants is much more powerful, which helps to clean up a deep contamination across large areas and reduce soil erosion, can accumulate heavy metals for a much longer time than herbaceous plants without the need for utilization. Restoring and expanding green space in cities will also reduce the effects of urban heat islands in summer, as well as improve the comfort and health of local communities (Branas et al., 2018; Zhao et al., 2018). In addition to the ability to phytoremediation, plants should also be resistant to high doses of pollutants, and preferably drought-resistant, which makes their cultivation more economically viable (Lanza & Stone, 2016; Kannenberg et al., 2019).

In this regard, the aim of the study was to identify woody plant species resistant to growth on lead-contaminated soils and to establish the potential of these plants for phytoremediation.

Material and methods

The study of resistance to heavy metals, in particular to lead, was conducted on plants of two species native to temperate and continental climates: *Catalpa bignonioides* Walter and *Paulownia tomentosa* Steud. These plants have shown high drought tolerance and photosynthetic efficiency (Nuzhyna & Ivanova, 2023; Nuzhyna et al., 2023), which makes their cultivation easy and cost-effective. In addition, paulownia is characterised by very fast growth, which is important for phytoremediation work and rapid greening of urban areas destroyed by military operations. Catalpa is also a well-known valuable ornamental plant with high-quality woody that is widely cultivated due to its excellent quality, resistance to decay, and attractive shape (Meng et al., 2022). For the experiment, two-year-old plants were taken, growing in separate pots, soil pH 6.2. At the end of May, the seedlings were watered once with a solution of lead acetate at the rate of 100 mg/kg soil or 300 mg/kg soil, and the plants of the control group were watered with water (three pots of each species in each group). Two measurements of each parameter were taken from each plant ($n = 6$). Three times (one week, one month and two months after watering with lead solution) the state of the photosynthetic system was measured using a fluorometer. The content of chlorophylls and carotenoids, malondialdehyde (MDA) and peroxidase (POX) was determined twice (one week and one month after watering with lead solution) by spectrophotometric method. The length of shoots was also measured at the beginning of the experiment, one month and two months after the treatment of plants with lead solutions.

The content of substances was determined using spectrophotometer SF-2000: chlorophylls and carotenoids were extracted with 80% acetone and determined at $\lambda = 663$, 646 and 470 nm (Lichtenthaller, 1987), the content of MDA was determined by reaction with thiobarbituric acid, at $\lambda = 533$ nm (Kumar, 1997), POX activity was determined by the rate of benzidine oxidation reaction in the presence of H_2O_2, at $\lambda = 590$ nm (Sharifi, 2010).

Diagnostics of the photosynthetic apparatus was carried out using a fluorometer ‘Floratest’ (Ukraine). Leaves for measurement were taken from the upper tier of all plants; dark adaptation before measurement was 10 min; the time of each measurement was 240 s.

The analysis was based on the chlorophyll fluorescence induction curve, such indicators were calculated using the formulae of Strasser et al. (2004), Stirbet & Govindjee (2011):

K_1 – is an indicator of the efficiency of the light phase of photochemical reactions;

K_2 – efficiency coefficient of dark photosynthetic processes;

K_3 – is a viability indicator sensitive to exogenous factors; a decrease in K_3 values indicates a decrease in the potential activity of the photosynthetic apparatus of plants;

K_{pl} – is an indicator of the probable presence of the disease, the lower this indicator, the more resistant the plant;

F_v – an indicator of photochemical redox processes, characterises the activity of the initial stages of photosynthesis; decreases as the environmental conditions deviate from the temperature optimum.

The content of mobile lead compounds in the vegetative organs of plants was determined using an atomic absorption spectrophotometer (AAS Kvant – 2AT). The content of mobile lead compounds in the upper and lower tier of leaves, in the stem and in the roots was studied.

Plant samples for determining the content of Pb were prepared using the dry mineralization method. The method involves the complete decomposition of organic matter by burning in an electric furnace. The charring of the crushed sample was carried out on an electric stove. Then the samples were burned in a muffle furnace, gradually raising the temperature to 500 ºC. Mineralization continued until grey ash was formed. The cooled ash was wetted with concentrated nitric acid, evaporated, then placed in a muffle furnace and burned to form white ash. The ash content was transferred to a measuring flask, washed off with distilled water, and after filtering, the lead content was measured using an atomic absorption spectrophotometer (Estefan et al., 2013).

The reliability of the results was determined by multivariate ANOVA analysis with Bonferroni adjustment.

Results

Resistance of Paulownia tomentosa plants to high doses of lead and their ability to phytoremediation. The study of the pigment content of the photosynthetic system of paulownia did not reveal any significant changes in the first week after lead treatment. However, it showed that ultra-high doses of lead in the soil (300 mg/kg of soil) tend to have a destructive effect on pigments. Thus, a week after watering the plants with a solution containing a heavy metal, a decrease in the amount of chlorophyll *a*, chlorophyll *b* and carotenoids was observed (Fig. 1). At the same time, treatment with a solution with a slightly lower concentration of lead probably stimulated adaptive defense functions in the leaves. As can be seen in the groups with a lead concentration of 100 mg/kg soil, there was a tendency to increase the content of chlorophyll a and carotenoids one week after treatment. One month after the treatment with lead solutions, the plants adapted better, and the pigment content either did not differ from the control (in the case of chlorophyll *a* and carotenoids) or was slightly higher than the control (in the case of chlorophyll *b*, Fig. 1). Such an increase in chlorophyll *b* affected the chlorophyll *a*/chlorophyll *b* ratio, reducing this ratio in plants that had been growing on the contaminated soil for a month.

One week after the treatment with lead at a dose of 100 mg/kg soil, no significant changes in the efficiency of photosynthetic processes were observed. Treatment with lead at a dose of 300 mg/kg soil tended to have a negative effect on the light phase of photosynthesis (K_1) in the first week and sharply increased the vulnerability to disease (K_{pl}, Fig. 2).

A month after the treatment with the heavy metal solution, the plants turned on adaptive defense mechanisms, which manifested as an increase in the efficiency of light and especially dark stages of photosynthesis (K_1 and K_2), a tendency to increase viability and resistance to growing conditions (K_3 and F_v) and a tendency to reduce the incidence of disease (K_{pl}), in particular, it was observed that plants growing on lead-contaminated soils were less affected by whitefly than control plants. Moreover, higher lead concentrations involved more powerful defense mechanisms (Fig. 2). Two months after treatment, the group with a lead dosage of 100 mg/kg of soil did not differ from the control group. While the addition of lead at 300 mg/kg soil showed a tendency to reduce viability (K_3), it also reduced pest damage (K_{pl}). The latter probably contributed to a better response to growing conditions and a slightly higher activity of the initial stages of photosynthesis (F_v).

The biochemical analysis showed an increase in malondialdehyde (MDA) content in the group with a dose of 100 mg/kg of soil a week after treatment with a heavy metal solution, while the activity of peroxidase (POX) in all groups was similar (Fig. 3). Indicators such as MDA and peroxidase respond quickly to a large number of factors, which makes it difficult to interpret the results. In particular, a decrease in MDA levels in the control and experimental groups in early July, compared to early June, may indicate more favorable weather conditions. A month later, we observed the activation of adaptive mechanisms at the biochemical level.

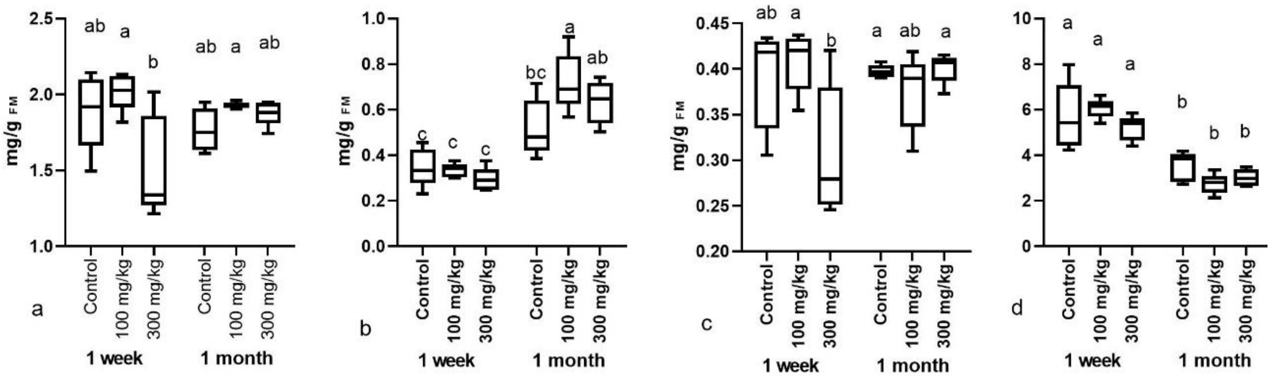

Fig. 1. Effect of high doses of lead on the content of photosynthetic pigments in the leaves of *Paulownia tomentosa*: chlorophyll *a* (*a*), chlorophyll *b* (*b*), carotenoids (*c*), chlorophyll *a*/chlorophyll *b* (*d*); x ± SD, n = 6; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

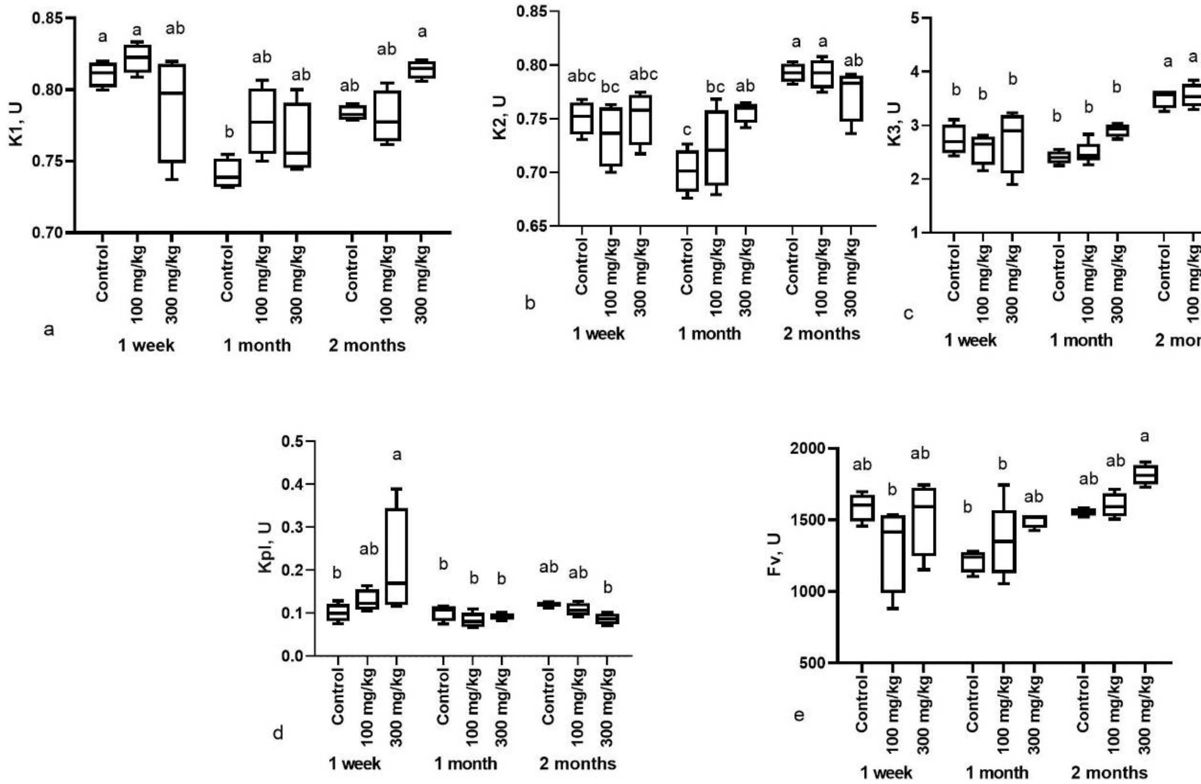

Fig. 2. Effect of high doses of lead on the efficiency of the photosynthetic system in *Paulownia tomentosa* leaves: x ± SD, n = 6; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

The content of MDA in the experimental groups no longer differs from the control group, and the activity of POX, which is an important antioxidant, increases with higher concentrations of heavy metal (Fig. 3). In the first month after treatment with heavy metals, the intensity of plant growth slightly increased both after the addition of lead at a dose of 100 mg/kg soil and at a dose of 300 mg/kg soil, compared to the control group. The sharp increase in growth in the second month in all groups compared to the first month of the study is explained by the increase in average daily temperatures in July, which is more optimal for growing *P. tomentosa*. At the same time, it can be seen that the addition of lead at a dose of 100 mg/kg soil did not affect growth in the second month of cultivation, while the dose of lead at 300 mg/kg soil still stimulated growth (Table 1).

The analysis of the uptake of mobile lead compounds by various vegetative organs of *P. tomentosa* showed that contamination with 100 mg/kg of soil did not cause active uptake and the lead content in these plants did not differ significantly from the control group (Table 2).

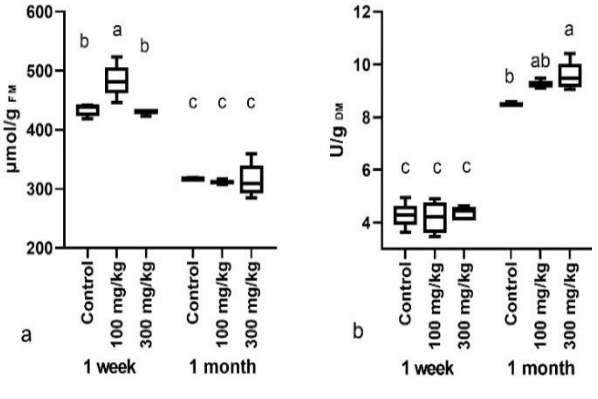

Fig. 3. Malondialdehyde (MDA) content (*a*) and peroxidase (POX) activity (*b*) in *Paulownia tomentosa* leaves at high lead doses: x ± SD, n = 6; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

Table 1
Shoot length increase of *Paulownia tomentosa* at high lead doses (cm, x ± SD, n = 3)

Groups	1 month	2 months
Control (without Pb)	3.33 ± 0.58^{c}	14.13 ± 1.63^{b}
100 mg/kg (Pb)	5.17 ± 1.44^{c}	16.07 ± 2.06^{ab}
300 mg/kg (Pb)	5.53 ± 0.45^{c}	18.63 ± 2.37^{a}

Note: different letters indicate significant differences between all groups ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment.

Table 2
Content of mobile lead compounds in different vegetative organs of *Paulownia tomentosa* (mg/kg, x ± SD, n = 3)

Groups	Upper leaves	Lower leaves	Stem	Root
Control (without Pb)	1.29 ± 0.28^{d}	$6.76 \pm 0{,}35^{dc}$	7.15 ± 0.29^{dc}	2.83 ± 0.52^{d}
100 mg/kg (Pb)	1.65 ± 0.22^{d}	7.09 ± 0.56^{dc}	12.03 ± 1.51^{c}	2.79 ± 0.55^{d}
300 mg/kg (Pb)	4.19 ± 0.57^{dc}	9.56 ± 0.47^{c}	42.25 ± 5.91^{a}	34.27 ± 4.82^{b}

Note: see Table 1.

At the same time, when contaminated with the heavy metal at a dose of 300 mg/kg of soil, paulownia increased lead uptake. The lead content increased 12 times in the roots and 6 times in the stem over three months. The amount of mobile lead compounds also increased in the leaves at a lead concentration of 300 mg/kg soil, however, the leaves accumulated heavy metals the least (the highest lead content was in the leaves of the lower tier under the 300 mg/kg soil treatment – 9.56 mg/kg).

Resistance of Catalpa bignonioides plants to high doses of lead and their ability to phytoremediation. Studies of the resistance of catalpa to lead have shown that a week after the treatment of catalpa plants with heavy metal solutions, a negative effect on the photosynthetic system is observed, namely a decrease in the amount of chlorophyll *a* and carotenoids at a dose of lead of 100 mg/kg soil. The chlorophyll *a*/chlorophyll *b* ratio decreased due to the destructive effect on chlorophyll *a* (Fig. 4 and 5). After a month of growth on the contaminated soil, there is a tendency for lead to have a destructive effect on chlorophyll *a*, but, as in paulownia, a protective reaction is included – a tendency to increase chlorophyll *b*. Carotenoids are intensively destroyed even after a month of cultivation on lead-treated soil at a dose of 300 mg/kg.

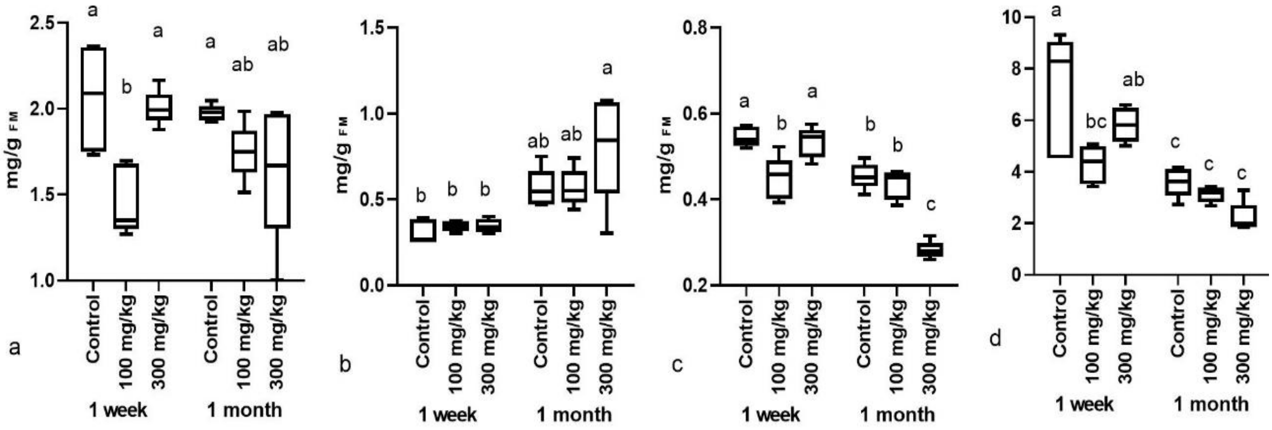

Fig. 4. Effect of high doses of lead on the content of pigments of the photosynthetic system in leaves of *Catalpa bignonioides*: chlorophyll *a* (*a*), chlorophyll *b* (*b*), carotenoids (*c*), chlorophyll *a*/chlorophyll *b* (*d*); x ± SD, n = 6; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

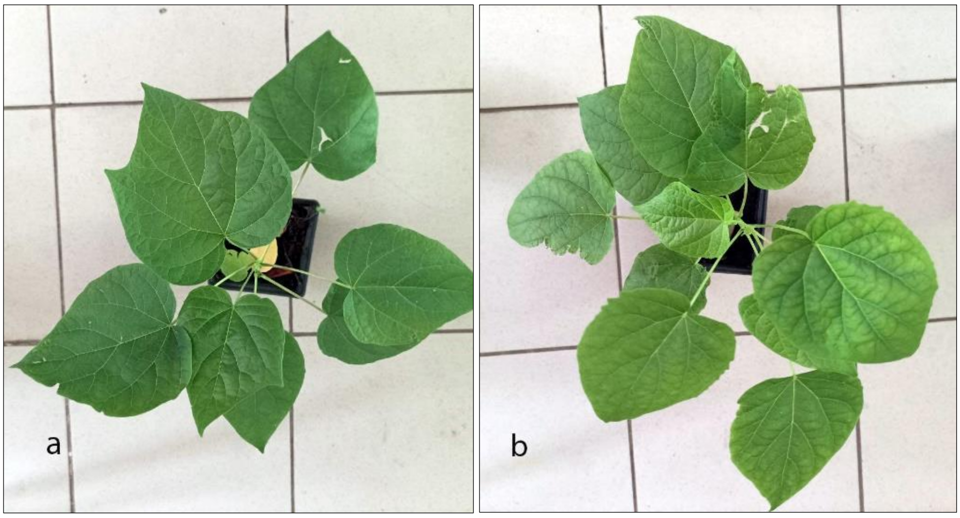

Fig. 5. Chlorosis on *Catalpa bignoniodes* leaves one week after treatment with lead at a dose of 100 mg/kg (*b*), compared to the control plant (*a*)

Treatment of catalpa with lead (100 mg/kg soil) had almost no effect on the dark phase of photosynthesis, but suppressed the light response of photosynthesis, especially in the first week of the experiment, which contributed to the tendency to reduce the activity of the initial stages of photosynthesis (Fv) at this dose of treatment during both months (Fig. 6). The indicator of viability (K*3*) did not differ significantly in different experimental groups, although there was a tendency to decrease in this indicator (especially when treated with lead at a dose of 100 mg/kg soil) in the first week after treatment and a slight increase in viability in a month after treatment and a slight decrease in this indicator after two months of exposure to lead, especially in a higher dose (Fig. 6). When treated with a lower dose of lead, there was a tendency for the Kpl coefficient to increase, especially in the first week after treatment with a heavy metal solution. When treated with a lead solution at a dose of 300 mg/kg, all measured parameters did not differ from those of the control group (Fig. 6).

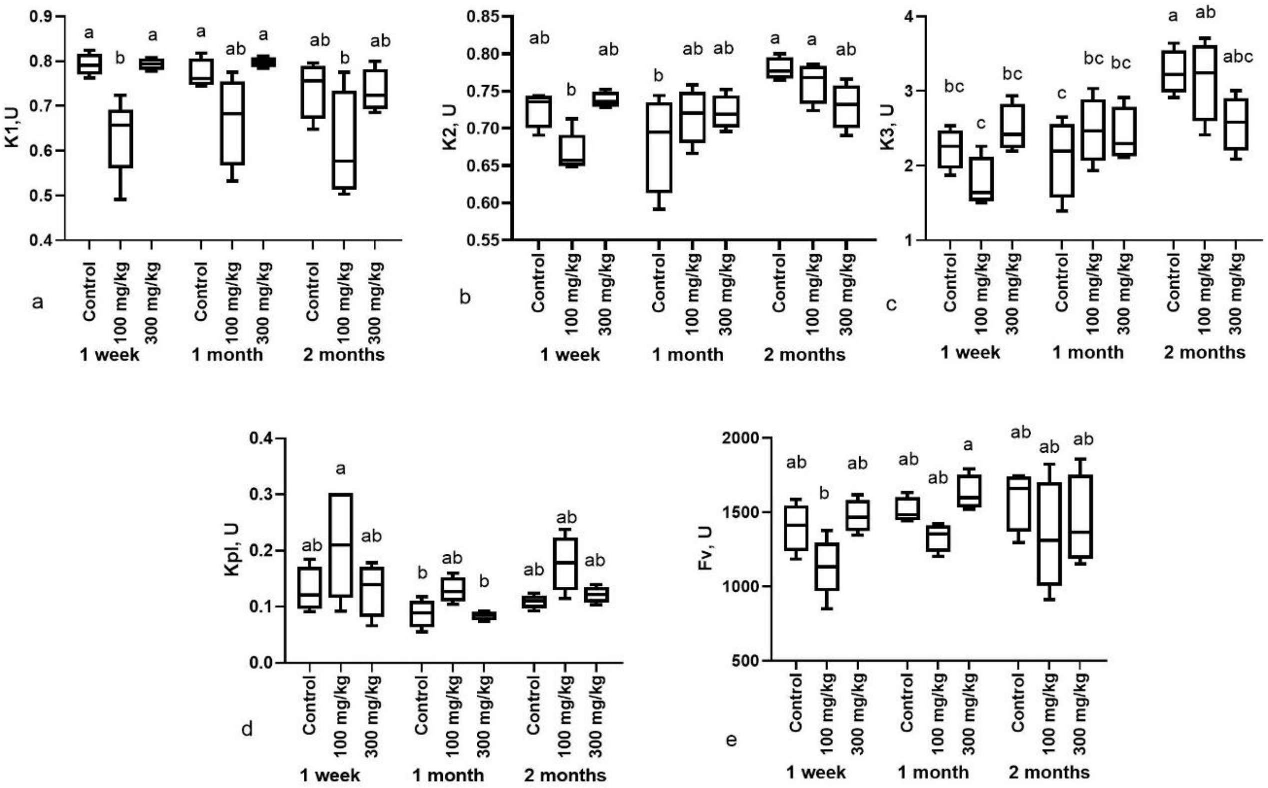

Fig. 6. Effect of high doses of lead on the efficiency of the photosynthetic system in *Catalpa bignonioides* leaves: x ± SD, n = 6; different letters indicate significant differences inside the parameter (P < 0.05) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

The MDA content and peroxidase activity in *C. bignonioides* leaves in the lead-treated groups did not differ from those in the control groups. After a month of cultivation with lead doses of 300 mg/kg, even a decrease in the stress index was observed, which may be due to the more intensive inclusion of protective adaptive reactions at those links that were not studied in this work (Fig. 7). The decrease in MDA content in early July compared to early June is probably also due to less favorable growth conditions in early June, namely lower temperatures and less light (as cloudy, rainy weather prevails during this period).

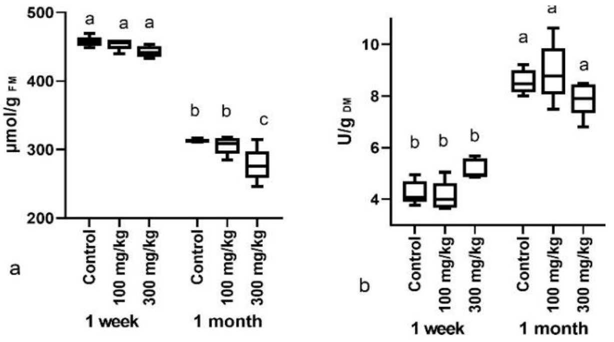

Fig. 7. Malondialdehyde (MDA) content (*a*) and peroxidase (POX) activity (*b*) in leaves of *Catalpa bignonioides* at high lead doses: x ± SD, n = 6; different letters indicate significant differences inside the parameter (P < 0.05) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

The treatment of *C. bignonioides* with lead did not significantly affect plant growth, although after one month of growth on lead-contaminated soil in both concentrations there was a tendency to inhibit plant growth, and after two months, growth was tendency to reduce only in the group with a higher concentration of lead (Table 3).

Atomic absorption spectrophotometry showed that catalpa leaves almost do not accumulate lead, but, similar to paulownia, the lower tier of leaves contains a greater amount of lead mobile forms compared to the upper tier. The small amount of lead in the upper tier after treatment with a higher dose of heavy metal can be explained by the fact that, getting into the leaves of the lower tier, lead negatively affects the photosynthetic system, the leaves of catalpa quickly turn yellow and fall off already at a low dose of heavy metal. The stem did not show the ability to accumulate lead; in three months, at a very high dose, the lead content was only 3.63 mg/kg. In the root, a slight increase in lead was found from 5.66 in the control to 9.85 mg/kg (Table 4).

Table 3
Shoot length increase of *Catalpa bignonioides*
at high lead doses (cm, x ± SD, n = 3)

Groups	1 month	2 months
Control (without Pb)	4.83 ± 1.04^b	8.97 ± 1.95^a
100 mg/kg (Pb)	3.07 ± 0.74^b	9.77 ± 0.67^a
300 mg/kg (Pb)	3.67 ± 0.58^b	7.17 ± 0.76^a

Note: see Table 1.

Table 4
Content of mobile lead compounds in different vegetative organs
of *Catalpa bignonioides* (mg/kg, x ± SD, n = 3)

Groups	Upper leaves	Lower leaves	Stem	Root
Control (without Pb)	3.23 ± 0.44^d	3.78 ± 0.52^d	4.46 ± 0.26^{cd}	5.66 ± 0.65^c
100 mg/kg (Pb)	3.64 ± 0.42^d	5.82 ± 0.83^c	2.99 ± 0.60^d	4.23 ± 0.16^{cd}
300 mg/kg (Pb)	1.68 ± 0.35^d	7.56 ± 0.83^b	3.63 ± 0.74^d	9.85 ± 0.45^a

Note: see Table 1.

The content of mobile lead compounds in upper leaves and stem of *C. bignonioides* did not show significant differences between the control and experimental groups. The entire vegetative mass of a two-year-old plant accumulated rather low values Pb of about 20 mg/kg in a few months.

Discussion

The photosynthetic system of paulownia proved to be more resistant to lead than that of catalpa. During the initial phase (a week), an increase in the amount of MDA could be seen in paulownia, indicating the presence of some stress due to the influence of heavy metal. However, within the first month after growing on contaminated soil, paulownia activated adaptation mechanisms. In particular, at a dose of Pb 300 mg/kg of soil, the POX activity, as one of the important enzymes of the antioxidant system, increased, as well as the efficiency of the dark phase of photosynthesis. At a dose of Pb 100 mg/kg of soil, the content of chlorophyll *b* increased. Chlorophyll *b* is characterized by a protective function during photosynthesis, and an adaptive increase in this pigment was also found under the influence of other stress factors, including high temperature (Nuzhyna et al., 2017; Nuzhyna et al., 2020). Thus, lead in a high dose (300 mg/kg) did not have a negative effect on the photosynthetic system of paulownia and stimulated defense mechanisms. And the increase in the efficiency of the dark phase of photosynthesis within a month after exposure contributed to more intensive plant growth.

On the contrary, the lead solution had a sharply negative effect on catalpa, in particular, after a week at a dose of 100 mg/kg, a decrease in the content of chlorophyll *a* and carotenoids and, accordingly, a decrease in the efficiency of the light phase of photosynthesis were observed. Such a negative effect of lead on the catalpa photosynthetic system led to a sharp decrease in plant growth. According to the literature, lead reduces the rate of plant photosynthesis by distorting the ultrastructure of chloroplasts, reduces chlorophyll synthesis, interferes with electron transport, and inhibits the activity of Calvin cycle enzymes (Souahi et al., 2017; Souahi et al., 2021). Heavy metals are the factors that cause damage to mesophyll cells and disruption of plant functioning (Cristaldi et al., 2017; Li et al., 2018). At the same time, the effect of Pb on different plants is quite different depending on the anatomical and biochemical characteristics of the species, which generally determines the status of sensitivity or tolerance of plants to the effects of heavy metals. According to the literature, studies on agricultural herbaceous crops have also shown a multidirectional effect of lead on the pigments of the photosynthetic system, including a decrease in the content of chlorophyll *a* and chlorophyll *b* in *Hordeum vulgare*, an increase in their amount in *Avena sativa*, and no changes in the content of these pigments in *Triticum durum* and *T. aestivum* (Souahi, 2021).

The tendency to increase in the Kpl coefficient in catalpa with a lower dose of lead may be due to the fact that a dose of lead of 100 mg/kg soil had a suppressive effect on the photosynthetic system and the plants were more vulnerable to damage by various pests. Treatment with a higher dose of lead (300 mg/kg soil) led to premature shedding of the lower tier leaves in these groups, and lead reached the upper tiers (where photosynthesis was studied) to a small extent. Probably, therefore, in these groups, less damage was detected in both the efficiency of the photosystem and the content of chlorophyll throughout the experiment. On the other hand, it is possible that such leaf fall included protective mechanisms at more intense stress and stimulated photosynthesis in the leaves of the upper layer.

Herbaceous plants have been studied for phytoremediation, which mainly requires the annual collection and disposal of plants, and can be a complex and expensive process (Conesa et al., 2012; Rodríguez-Seijo et al., 2016a; Li et al., 2018; Cleophas et al., 2023). Failure to comply with biomass management technologies can lead to secondary environmental pollution. Compliance with phytoremediation technologies is particularly difficult in urban environments (man-made polluted cities or cities affected by military operations), where contaminated areas are usually relatively small and scattered over a large area in separate groups. In such conditions, the use of effective woody plants that accumulate heavy metals in the stem and/or root will allow for a long period of soil clean-up without planting new plants and their disposal. This would additionally avoid some of the problematic issues, in particular: the use of ornamental trees allows soil cleanup in conditions of deep contamination, which is one of the obstacles to the use of herbaceous phytoremediation plants (Suman et al., 2018), and is especially important in the case of contamination due to military shelling, as soils are contaminated many metres deep. It takes more time to achieve effective results because it is a slow process (Shah & Daverey, 2020) – woody plants can grow, accumulate phytomass and thus accumulate toxins for a much longer time than herbaceous plants, without the need for disposal. The root system is much more powerful, which makes it suitable for large contaminated areas and helps to reduce the likelihood of soil erosion (Favas et al., 2014). Treatment with certain substances, such as $Ca(OH)_2$, organic and mineral fertilizers (Conesa et al., 2012; Litvinova et al., 2020), can significantly accelerate lead uptake. At the same time, the negative impacts of urban heat islands will be reduced: carbon dioxide absorption will increase, urban temperatures will decrease, soil erosion will be reduced, etc. Over time, the wood that has accumulated heavy metals can be used for other purposes, such as cogeneration and biofuel production.

According to our research, the low rates of lead accumulation in the vegetative organs of catalpa and its low resistance to the effects of heavy metal indicate that this plant is not suitable as a phytoremediant for soil clean-up. Meanwhile, paulownia accumulates lead 11.5 times more in the stem and 3.5 times more in the root compared to catalpa. In addition, paulownia is characterized by the resistance of the photosynthetic system to the effects of heavy metal. These properties allow us to recommend paulownia as a phytoremediant plant. At the same time, the general characteristics of heavy metal accumulation for both species are similar. Thus, in both species, the leaves of the lower tier accumulated more heavy metals than the upper tier. Lead accumulated most in the roots of both plant species compared to the aerial parts. This trend is typical for most plants (Sengar et al., 2008; Rodríguez-Seijo et al., 2016a). The accumulation of Pb in the roots demonstrated the phytostabilisation properties of paulownia. The lead content in shoots and roots correlated with the total Pb concentration in the soil for both species, and the dependence of the uptake rate on the increase in soil lead content also was shown by other researchers (Chandra et al., 2009; Conesa et al., 2012).

Conclusion

Thus, it can be said that *P. tomentosa* is resistant to cultivation in areas contaminated with high doses of lead. Paulownia showed the ability for phytoextraction and phytoremediation. Lead accumulation is intensive in the stem and roots and low in the leaves, which contributes to soil clean-up and long-term accumulation of heavy metals in one place and reduces the migration of mobile forms of lead in the soil. Its resistance, ability to accumulate lead and rapid growth make it suitable for cultivation in cities where active military operations have taken place and in industrial areas for phytoremediation of soils. *Catalpa bignonioides* did not show any resistance to lead and phytoremediation capabilities.

The study was funded by the Ministry of Education and Science of Ukraine as part of a scientific project "Biology and Health Care" No. 0121U112939, 2021–2025.

The authors declare no conflict of interest.

References

Bai, J., & Zhao, X. (2020). Ecological and human health risks of heavy metals in shooting range soils: A meta assessment from China. Toxics, 8(2), 32.

Black, O., Smith, S. C., & Roper, C. (2021). Advances and limitations in the determination and assessment of gunshot residue in the environment. Ecotoxicology and Environmental Safety, 208, 111689.

Branas, C. C., South, E., Kondo, M. C., Hohl, B., Bourgois, Ph., Wiebe, D. J., & MacDonald, J. M. (2018). Citywide cluster randomized trial to restore blighted vacant land and its effects on violence, crime, and fear. Proceedings of the National Academy of Sciences USA, 115(12), 2946–2951.

Broomandi, P., Guney, M., Kim, J. R., & Karaca, F. (2020). Soil contamination in areas impacted by military activities: A critical review. Sustainability, 12(21), 9002.

Chandra, R., Bharagava, R. N., Yadav, S., & Mohan, D. (2009). Accumulation and distribution of toxic metals in wheat (*Triticum aestivum* L.) and Indian mustard (*Brassica campestris* L.) irrigated with distillery and tannery effluents. Journal of Hazardous Materials, 162, 1514–1521.

Cleophas, F. N., Zahari, N. Z., Murugayah, P., Rahim, S. A., & Mohd Yatim, A. N. (2023). Phytoremediation: A novel approach of bast fiber plants (Hemp, Kenaf, Jute and Flax) for heavy metals decontamination in soil – review. Toxics, 11, 5.

Collin, M. S., Venkatraman, S. K., Vijayakumar, N., Kanimozhi, V., Arbaaz, S. M., Stacey, R. G. S., Anusha, J., Choudhary, R., Lvov, V., Tovar, G. I., Senatov, F., Koppala, S., & Swamiappan, S. (2022). Bioaccumulation of lead (Pb) and its effects on human: A review. Journal of Hazardous Materials Advances, 7, 100094.

Conesa, H. M., Wieser, M., Studer, B., González-Alcaraz, M. N., & Schulin, R. (2012). A critical assessment of soil amendments (slaked lime/acidic fertilizer) for the phytomanagement of moderately contaminated shooting range soils. Journal of Soils and Sediments, 12(4), 565–575.

Cristaldi, A., Conti, G., Eun HeaJho, E., Zuccarello, P., Grasso, A., Copat, C., & Ferrante, M. (2017). Phytoremediation of contaminated soils by heavy metals and PAHs: A brief review. Environmental Technology and Innovation, 8, 309–326.

Estefan, G., Sommer R., & Ryan J. (2013). Methods of soil, plant, and water analysis. A manual for the West Asia and North Africa region. ICARDA, Beirut.

Favas, P. J. C., Pratas, J., Varun, M., D'Souza, R., & Paul, M. S. (2014). Phytoremediation of soils contaminated with metals and metalloids at mining areas: Potential of native flora. Environmental Risk Assessment of Soil Contamination, 3, 485–516.

Gorecki, S., Nesslany, F., Hubé, D., Mullot J.-U., Vasseur, P., Marchioni, E., Camel, V., Noël, L., Le Bizec, B., Guérin, T., Feidt, C., Archer, X., Mahe, A., & Rivière, G. (2017). Human health risks related to the consumption of foodstuffs of plant and animal origin produced on a site polluted by chemical munitions of the First World War. Science of the Total Environment, 599–600, 314–323.

Holubtsov, O., Sorokina, L., Splodytel, A., & Chumachenko, S. (2023). Vplyv viyny Rosiyi proty Ukrayiny na stan ukrayins'kykh gruntiv. Rezultaty analizu [Impact of Russia's war against Ukraine on the state of Ukrainian soils. Results of the analysis]. Ekodiia, Kyiv (in Ukrainian).

Islam, M. N., Nguyen, X. P., Jung, H. Y., & Park, J. H. (2016). Chemical speciation and quantitative evaluation of heavy metal pollution hazards in two army shooting range backstop soils. The Bulletin of Environmental Contamination and Toxicology, 96, 179–185.

Kamari, A., Yusoff, S. N. M., Putra, W. P., Ishak, C. F., Hashim, N., Mohamed, A., Isa, I. M., & Bakar, S. A. (2015). The effects of application of agricultural wastes to firing range soil on metal accumulation in *Ipomoea aquatica* and soil metal bioavailability. Chemistry and Ecology, 31(7), 622–635.

Kannenberg, S. A., Maxwell, J. T., Pederson, N., D'Orangeville, L., Ficklin, D. L., & Phillips, R. P. (2019). Drought legacies are dependent on water table depth, wood anatomy and drought timing across the eastern US. Ecology Letters, 22(1), 119–127.

Kumar, G. N. M., & Knowles, N. R. (1993). Changes in lipid peroxidation and lipolitic and free radical scavenging enzyme activities during aging and sprouting of potato (*Solanum tuberosum*) seed-tubers. Plant Physiology, 102, 115–124.

Lanza, K., & Stone, B. (2016). Climate adaptation in cities: What trees are suitable for urban heat management. Landscape and Urban Planning, 153, 74–82.

Laporte-Saumure, M., Martel, R., & Mercier, G. (2010). Evaluation of physic-chemical methods for treatment of Cu, Pb, Sb, and Zn in Canadian small arm firing ranges backstop soils. Water Air and Soil Pollution, 213, 171–189.

Li, J., Zhang, D., Zhou, P., & Liu, Q. (2018). Assessment of heavy metal pollution in soil and its bioaccumulation by dominant plants in a lead-zinc mining area, Nanjing. Huan Jing Ke Xue, 39(8), 3845–3853.

Lichtenthaller, H. K. (1987). Chlorophylls and carotenoids, pigments of photosynthetic biomembranes. Methods in Enzymology, 148, 350–382.

Litvinova, O., Litvinov, D., Degodyuk, S., Romanova, S., & Rasevich, V. (2020). Effect of fertilizers systems on accumulation of heavy metals in gray forest soil. International Journal of Ecosystems and Ecology Science, 10(4), 603–608.

Liu, Y., Fang, Z., Xie, C., & Li, J. (2014). Analysis of existing speciation and evaluation of heavy metals pollution of soil in a shooting range. Nature Environment and Pollution Technology, 13(3), 449–456.

Meng, P., Chen, W., Feng, H., & Zhang, S. (2022). Effect of inoculation with arbuscular mycorrhizal fungi on growth of *Catalpa bungei*. New Zealand Journal of Forestry Science 52, 3.

Neeti, K., & Prakash, T. (2013). Effects of heavy metal poisoning during pregnancy. International Research Journal of Environmental Sciences, 2(1), 88–92.

Nuzhyna, N. V., Gaidarzhy, M. M., & Aviekin, Y. V. (2017). Species-specific response to acute hyperthermal stress of *Haworthia* (Asphodelaceae) plants. Regulatory Mechanisms in Biosystems, 8(4), 506–511.

Nuzhyna, N. V., Gaidarzhy, M. M., & Holubenko, A. V. (2020). Anatomical structure and antioxidant response to temperature stress in plants of the *Crassula* genus. Ukrainian Biochemical Journal, 92(4), 112–124.

Nuzhyna, N. V., Ivanova, I. Y., & Gaidarzhy, M. M. (2023). Introduced plant species in the urban environment of the temperate-continental climate zone under conditions of global warming. Regulatory Mechanisms in Biosystems, 14(4), 539–545.

Nuzhyna, N., & Ivanova, I. (2023). Drought resistance monitoring of introduced tall trees species under changed urban climatic conditions. Bulletin of Taras Shevchenko National University of Kyiv Series Biology, 94(3), 23–27.

Rodriguez-Seijo, A., Alfaya, C. M., Andrade-Couce, M., & Alonso Vega, F. (2016). Copper, chromium, nickel, lead and zinc levels and pollution degree in firing range soils. Land Degradation and Development, 27, 1721–1730.

Rodríguez-Seijo, A., Lago-Vila, M., Andrade, M. L., & Vega, F. A. (2016a). Pb pollution in soils from a trap shooting range and the phytoremediation ability of *Agrostis capillaris* L. Environmental Science and Pollution Research, 23(2), 1312–1323.

Sanderson, P., Naidu, R., & Bolan, N. (2014). Ecotoxicity of chemically stabilised metal(loid)s in shooting range soils. Ecotoxicology and Environmental Safety, 100, 201–208.

Sanderson, P., Naidu, R., Bolan, N., Bowman, M., & Mclure, S. (2012). Effect of soil type on distribution and bioaccessibility of metal contaminants in shooting range soils. Science of the Total Environment, 438, 452–462.

Sengar, R. S., Gautam, M., Sengar, R. S., Garg, S. K., Sengar, K., & Chaudhary, R. (2008). Lead stress effects on physiobiochemical activities of higher plants. Reviews of Environmental Contamination and Toxicology, 196, 73–93.

Shah, V., & Daverey, A. (2020). Phytoremediation: A multidisciplinary approach to clean up heavy metal contaminated soil. Environmental Technology and Innovation, 18, 100774.

Sharifi, G., & Ebrahimzadeh, H. (2010). Changes of antioxidant enzyme activities and isoenzyme profiles during *in vitro* shoot formation in saffron (*Crocus sativus* L.). Acta Biologica Hungarica, 61, 73–89.

Shukla, S., Mbingwa, G., Khanna, S., Dalal, J., Sankhyan, D., Malik, A., & Badhwar, N. (2023). Environment and health hazards due to military metal pollution: A review. Environmental Nanotechnology, Monitoring and Management, 20, 100857.

Singh, J., & Kalamdhad, A. S. (2011). Effects of heavy metals on soil, plants, human health and aquatic life. International Journal of Research in Chemistry and Environment, 1(2), 15–21.

Souahi, H. (2021). Impact of lead on the amount of chlorophyll and carotenoids in the leaves of *Triticum durum* and *T. aestivum*, *Hordeum vulgare* and *Avena sativa*. Biosystems Diversity, 29(3), 207–210.

Souahi, H., Gharbi, A., & Gassarellil, Z. (2017). Growth and physiological responses of cereals species under lead stress. International Journal of Biosciences, 11(1), 266–273.

Stirbet, A., & Govindjee. (2011). On the relation between the Kautsky effect (chlorophyll *a* fluorescence induction) and Photosystem II: Basics and applications of the OJIP fluorescence transient. Journal of Photochemistry and Photobiology B: Biology, 104(1–2), 236–257.

Strasser, R. J., Tsimilli-Michael, M., & Srivastava, A. (2004). Analysis of the chlorophyll fluorescence transient. In: Chlorophyll fluorescence: A signature of photosynthesis, advances in photosynthesis and respiration. Springer, Dordrecht. Vol. 19. Pp. 321–362.

Suman, J., Uhlik, O., Viktorova, J., & Macek, T. (2018). Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? Frontiers in Plant Science, 871, 1476.

Sun, Z., Xie, X., Wang, P., Hu, Y., & Cheng, H. (2018). Heavy metal pollution caused by small-scale metal ore mining activities: A case study from a polymetallic mine in South China. Science of the Total Environment, 639, 217–227.

Thangavadivel, K., Ranganathan, S., Sanderson, P., Chadalavada, S., Naidu, R., & Bowman, M. (2018). Case study of testing heavy-particle concentrator-aided remediation of lead-contaminated rifle shooting range soil. Remediation, 28(3), 67–74.

Urrutia-Goyes, R., Argyraki, A., & Ornelas-Soto, N. (2017). Assessing lead, nickel, and zinc pollution in topsoil from a historic shooting range rehabilitated into a public urban park. International Journal of Public Health, 14(7), 698.

Zhang, L., Zhu, Y., Gu, H., Shiung Lam, S., Chen, X., Sonne, C., & Peng, W. (2024). A review of phytoremediation of environmental lead (pb) contamination. Chemosphere, 362, 142691.

Zhang, Y., Li, T., Guo, Z., Xie, H., Hu, Z., Ran, H., Li, C., & Jiang, Z. (2023). Spatial heterogeneity and source apportionment of soil metal(loid)s in an abandoned lead/zinc smelter. Journal of Environmental Sciences, 127, 519–529.

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., Guan, K., & Liu, X. (2018). Interactions between urban heat islands and heat waves. Environmental Research Letters, 13, 034003.