



Research Article



Comparative Characteristics of the Effect of Nickel and Lead on *Sorghum bicolor* nothosubsp. *drummondii* f. *nigra* and *Raphanus sativus* convar. *oleifer* Seedlings Formation

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The increasing levels of toxic metals in the environment are of growing concern. This problem has been significantly exacerbated by the Russian military aggression in Ukraine, where military activities have resulted in extensive contamination of terrestrial and aquatic ecosystems. Phytoremediation has attracted increasing attention as an environmentally friendly and cost-effective alternative to chemical methods of soil purification. Our studies were aimed at comparing the characteristics of *Sorghum bicolor* nothosubsp. *drummondii* f. *nigra* (black sorghum) and *Raphanus sativus* convar. *oleifer* (oil radish) seedlings in the early stages of growth in the presence of toxic metals. Seeds were germinated at a temperature of 24 °C during 7 days on a filter paper in Petri dishes with water solutions of Ni(NO₃)₂ (0, 5, and 10 mg·L⁻¹ by Ni²⁺) and Pb(NO₃)₂ (100, 200, and 400 mg·L⁻¹ by Pb²⁺). Shoot and root weight and tolerance indices of seedlings were compared. Shoot tolerance index (TI_{sh}) of plants of the two species grown in the medium with Ni(II) was close to “1” with a slight predominance of TI_{sh} of oil radish, however, the root tolerance indices (TI_r) were quite different. The TI_r of black sorghum in the presence of Ni(II) was only 0.221 ± 0.037 and 0.102 ± 0.015, while TI_r in oil radish was 3–5 times higher. The tolerance index of shoots growing in the medium with Pb(II) was also close to “1” with a slight predominance of TI_{sh} of oil radish (up to 1.190 ± 0.094). The TI_r of black sorghum was equal to 0.682, 0.341 and 0.0, respectively. The TI_r of oil radish was 1.052 ± 0.121; 0.723 ± 0.105 and 0.356 ± 0.079. At the lowest concentration of Pb(II) – 100 mg·L⁻¹ – it was close to “1”, which indicates moderate resistance of plants to this metal. Thus, according to the TI_r index, oil radish plants turned out to be more resistant than black sorghum plants. Due to the fact that oilseed radish demonstrated higher resistance to both nickel and lead, plants of this species can be considered as potential objects for use in phytoremediation of lands contaminated with these metals, especially if they are present in relatively low concentrations.

Keywords: *Sorghum bicolor* nothosubsp. *drummondii* f. *nigra*, *Raphanus sativus* convar. *oleifer*, toxic metals, nickel, lead, tolerance

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Introduction

Heavy metals are persistent environmental pollutants that exert severe phytotoxic effects on plants, leading to growth inhibition, metabolic disturbances, and reduced productivity. When accumulated in soil or water resources, these metals can also enter food chains and pose serious risks to human health (Mitra, 2022). Mercury, chromium, copper, lead, nickel, and cadmium are among the most toxic metals, and their toxicity depends on both their chemical form and concentration in the soil environment (Gaetke et al., 2014; Wani et al., 2015; Buxton et al., 2019; Charkiewicz et al., 2023; Yan et al., 2023; Wu et al., 2024).

The increasing levels of toxic metals in the environment are of growing concern, necessitating the development of effective strategies for soil and water remediation. This problem has been significantly exacerbated by the Russian military aggression in Ukraine, where intensive military activities have resulted in extensive contamination of terrestrial and aquatic ecosystems due to bombings, fires, and the destruction of civil infrastructure. In particular, soil analyses conducted in the Sumy region revealed substantial exceedances of background metal concentrations following air bombardments: lead levels were 5.4-fold higher, zinc 3.9-fold, cadmium 1.4-fold, and copper 4.6-fold, while nickel and iron exceeded background values by 1.2- and 1.1-fold, respectively (Zaitsev et al., 2022).

Given the urgency of this environmental challenge, a variety of remediation approaches are currently under investigation. Modern remediation strategies include biological methods (biodegradation by living organisms), chemical methods (use of chelating agents, chemical immobilization, and oxidation–reduction reactions), and physical methods (electrokinetic remediation, soil washing, stabilization/solidification, thermal desorption, and combustion technologies) (Azhar, 2022). Among these approaches, phytoremediation has attracted increasing attention as an environmentally friendly and cost-effective alternative. Phytoremediation relies on the use of plants to remove, immobilize, or transform contaminants present in soil or water (Wang, 2021).

Phytoremediation can proceed through phytostabilization and/or phytoextraction. Phytostabilization reduces the mobility and bioavailability of metals by their immobilization in the rhizosphere or sequestration within root tissues, often mediated by root exudates (Bakshe, 2023). In contrast, phytoextraction involves the uptake and translocation of metals from soil to above-ground

plant parts, enabling their removal through biomass harvesting (Suman et al., 2018). These approaches offer significant advantages, including low implementation costs, the potential for simultaneous removal of multiple pollutants, minimal disturbance to soil structure, and aesthetic and ecological benefits.

Numerous plant species have demonstrated the ability to accumulate toxic metals from contaminated soils. For example, *Scariola orientalis* (Boiss.) Soják, *Cardaria draba* L., and *Gundelia tournefortii* L. exhibit a strong capacity for lead accumulation, while *Cydonia oblonga* Mill., *Euphorbia cheiradenia* Boiss.&Hohen., and *S. orientalis* are effective in zinc uptake. Cadmium accumulation has been reported in *Biebersteinia multifida* DC and *Marrubium vulgare* L., copper accumulation in *E. cheiradenia* and *Ziziphora tenuior* L., and nickel accumulation in *Euphorbia* spp. and *Salix excelsa* S.G.Gmel. (Chehregani and Malayeri, 2007).

Our studies were aimed at comparing the growth characteristics of seedlings of two species, *Sorghum bicolor* nothosubsp. *drummondii* (Nees ex Steud.) de Wet ex Davidse f. *nigra* (black sorghum) and *Raphanus sativus* convar. *oleifer* Alef. (oil radish), in the early stages of growth (from seed germination) in the presence of toxic metals – nickel and lead – in the medium. Such a study allows us to assess the possibility of using a biological method of soil purification by sowing seeds and short-term cultivation of plants of a particular species, since plants at the beginning of germination, not yet having a developed root system, may be much more sensitive to toxicants than those that are already vegetating and have significant biomass (Marcin et al., 2025).

Although nickel (Ni) is listed as a toxic metal, it is also a trace element and is required in small amounts for normal physiological function of cells. Cells need this metal for the function of enzymes, including urease, hydrogenase, and superoxide dismutase (Küpper, 2007; Kaluarachchi, 2010; Awasthi 2022). However, nickel in higher concentrations causes disruption of plant cell function, which leads to growth inhibition (especially of root growth), chlorosis and other negative effects (Rahman, 2005; Gajewska, 2006; Maheshwari, 2007; Ahmad and Ashraf 2011).

Lead (Pb), unlike nickel, is not an element necessary for cell function. The accumulation of this metal leads to disruption of metabolic processes in cells, initiation of oxidative stress, disruption of enzyme activity. Lead negatively affects the morphological, physiological and biochemical functions of plants. The metal is absorbed by plant roots in an apoplastic way or

through Ca^{2+} -permeable channels. Entering the cells, lead changes the permeability of cell membranes and reacts with the active groups of various enzymes involved in plant metabolism. Its toxic effect is also manifested in the inhibition of ATP synthesis, as well as DNA damage due to excessive production of reactive oxygen species and the initiation of oxidative stress (Małkowski, 2002; Reddy, 2005; Liu, 2008; Meyers, 2008; Romanowska, 2008; Sengar, 2009; Qufei and Fashui, 2009; Pourrut, 2011).

Comparison of the features of the action of Ni(II) and Pb(II) on plants of two species belonging to different classes and families allows us to assess the toxicity of these metals at the early stages of plant formation, as well as to determine the potential for using plants for phytoremediation of soils contaminated with toxic metals.

Material and Methodology

Plant cultivation

To determine the effect of metals on plant growth at the short-term stage of seed germination, studies were conducted under non-sterile conditions. Seeds were placed in Petri dishes with filter paper and water with solutions of nickel nitrate and lead nitrate (Sigma) in the appropriate concentrations: Ni(II) – 5 $\text{mg}\cdot\text{L}^{-1}$ and 10 $\text{mg}\cdot\text{L}^{-1}$; Pb(II) – 100 $\text{mg}\cdot\text{L}^{-1}$, 200 $\text{mg}\cdot\text{L}^{-1}$, and 400 $\text{mg}\cdot\text{L}^{-1}$. Seeds were germinated at a temperature of 24 °C, and the germinated plants were cultivated in a thermostatically controlled room with lighting (24 °C, 3,000 lx). Seeds that were germinated without metals under the same conditions were used as a control. After 7 days, the seedlings were washed, dried with filter paper and weighed using a Sartorius analytical balance.

Assessment of plant resistance/sensitivity to metal

Plant resistance/sensitivity was determined by the tolerance index (TI). The tolerance index was calculated as the ratio of the weight of plants (shoots and roots separately) cultivated under metal-induced stress to the corresponding weight of the control plants.

Statistical analysis

Data were analyzed for statistical significance using analysis of variance followed by Tukey's test. Groups of measurements were tested for normal distribution using the Shapiro-Wilk test and for homogeneity of variance using the Levene test. Values were considered

significant at $p < 0.05$. Results were presented as mean and standard error (SE).

Results and Discussion

Features of the influence of Ni(II) on shoots and roots formation

The beginning of seed germination was observed after 2 days. Black sorghum plants grown in the presence of Ni(II) and without this metal differed little in shoot growth, but had significant differences in root formation (Figure 1, a–c). Thus, the average weight of shoots in the control was 0.0297 ± 0.0022 g, and in two variants in the presence of Ni(II) in concentrations of 5 $\text{mg}\cdot\text{L}^{-1}$ and 10 $\text{mg}\cdot\text{L}^{-1}$ – 0.0233 ± 0.0014 g and 0.0253 ± 0.0026 g, respectively (Figure 2). At the same time, the weight of roots in the variants was 0.0161 ± 0.0020 g (control), 0.0036 ± 0.0014 g (Ni(II) 5 $\text{mg}\cdot\text{L}^{-1}$) and 0.0016 ± 0.0001 g (Ni(II) 10 $\text{mg}\cdot\text{L}^{-1}$) (Figure 2). As can be seen from the given data, black sorghum root growth was significantly inhibited, and the weight of roots was up to ten times less than in the control.

Oil radish plants also formed shoots from seeds even in the presence of Ni(II) at a concentration of 10 $\text{mg}\cdot\text{L}^{-1}$, and there were no significant differences in the weight of the experimental samples compared to the control (Figure 1, d–f). In particular, the shoot weight was 0.0824 ± 0.0175 g in the control, and in two variants in the presence of Ni(II) at concentrations of 5 and 10 $\text{mg}\cdot\text{L}^{-1}$ it was 0.0841 ± 0.0040 and 0.0921 ± 0.0135 g, respectively (Figure 2 a). However, nickel in increased content can be considered quite toxic for plants of this species, since the root weight in the variants in the presence of Ni(II) at concentrations of 5 and 10 $\text{mg}\cdot\text{L}^{-1}$ was significantly lower than in the control (0.0182 ± 0.0029 g), and was equal to 0.0110 ± 0.0017 and 0.0094 ± 0.0012 g (Figure 2).

Tolerance indices of plants grown in the medium with Ni(II)

As can be seen from Figure 3, the shoot tolerance index (TI_{sh}) of plants of the two species was close to "1" with a slight predominance of TI_{sh} of oil radish plants (0.787 ± 0.074 and 0.853 ± 0.107 for *S. bicolor*; 1.021 ± 0.222 and 1.117 ± 0.288 for *R. sativus*). However, the root tolerance indices (TI_r) were quite different. In particular, the TI_r of black sorghum in the presence of 5 $\text{mg}\cdot\text{L}^{-1}$ and 10 $\text{mg}\cdot\text{L}^{-1}$ Ni(II) was only 0.221 ± 0.037 and 0.102 ± 0.015 u., while this indicator in oil radish was 2.7–5.1 times higher and equaled 0.604 ± 0.133 and 0.516 ± 0.105 u., respectively. In plants of both

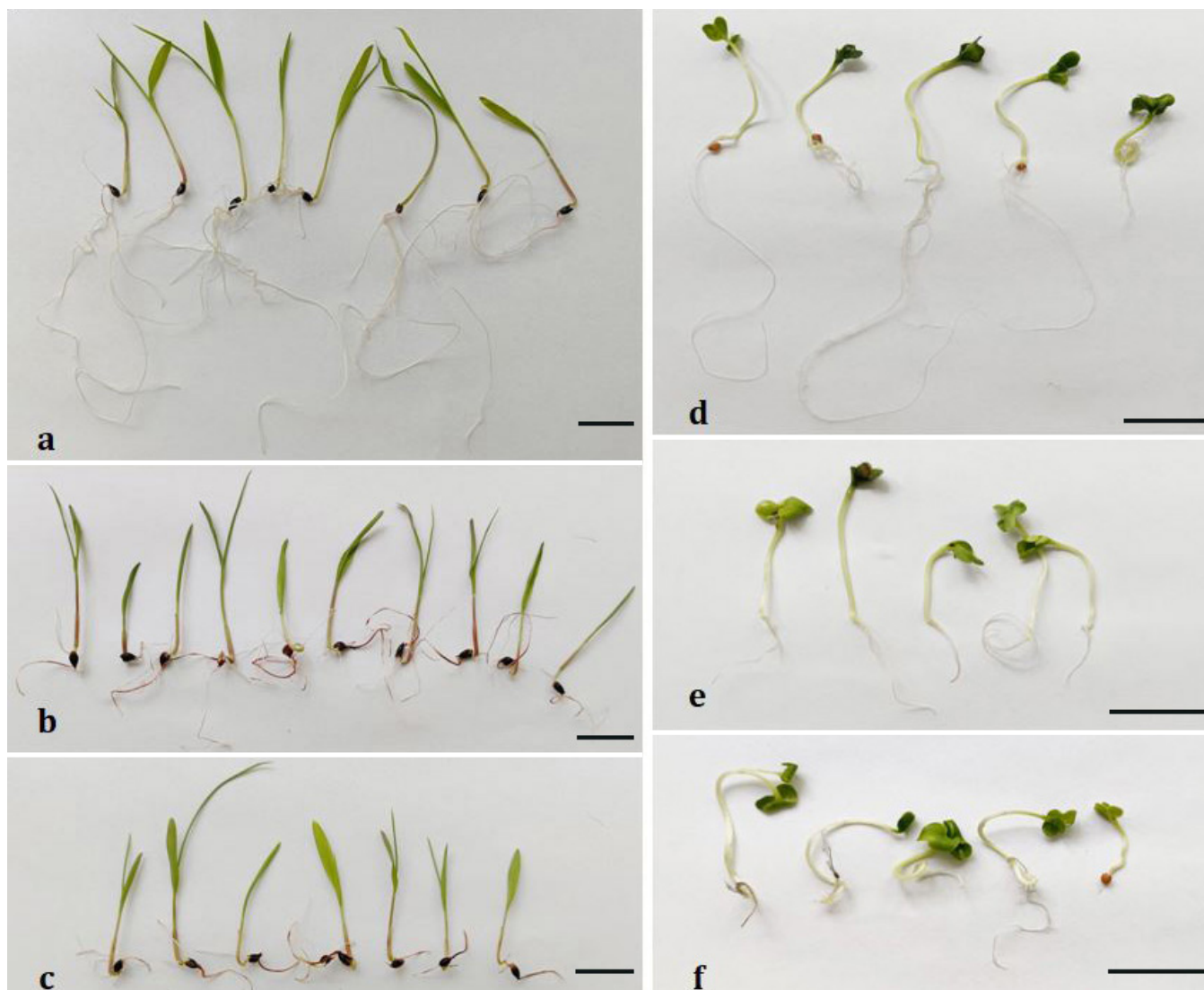


Figure 1 Seedlings of black sorghum (a–c) and oil radish (d–f) on a medium with nickel (a, d – control, b, e – 5 mg·L⁻¹ Ni(II), c, f – 10 mg·L⁻¹ Ni(II)); scale bars – 20 mm

species, there was a tendency for TI_r to decrease with increasing Ni(II) concentration, although a similar effect was not found in determining TI_{sh} . Thus, the toxic metal primarily negatively affected the process of root formation, significantly inhibiting their growth in both black sorghum and oil radish plants.

Previously, a number of studies have confirmed that plants of various species, in particular, *Alyssum*, *Sorghum*, *Peltaria*, *Thlaspi*, *Brassica*, *Bornmuellaria*, etc., are able to remove Ni(II) from the soil and accumulate it in cells (Giordani, 2005; Al Chami, 2015; Kumar 2021). However, although nickel is necessary for the normal functioning of cells, even fairly low concentrations of this metal can cause a toxic effect, which is primarily expressed in the inhibition of root cell division (Gupta et al., 2017). In particular, such studies were conducted using millet plants. A dose-dependent toxicity

of the metal for these plants was found (Gupta et al., 2017). Thus, the metal at a concentration of 20 ppm resulted in 2-fold reduction of root weight and 40 ppm nickel content 5 fold inhibited the growth of the root system, while at a much lower concentration (lower than 10 ppm) nickel did not cause such a negative effect. A dose-dependent inhibitory effect of nickel was studied on *Allium cepa*, *Vicia faba*, and *Zea mays* (Akbas, 2009; Antonkiewicz, 2016). A similar effect of inhibiting the growth of roots of plants of the two species, *S. bicolor* nothosubsp. *drummondii* f. *nigra* and *R. sativus* convar. *oleifer*, was also observed in our studies. At the same time, the tolerance index, calculated by the weight of roots, was higher in oil radish plants, which indicates a higher tolerance of plants of this species to the toxic effect of Ni(II) in increased concentrations.

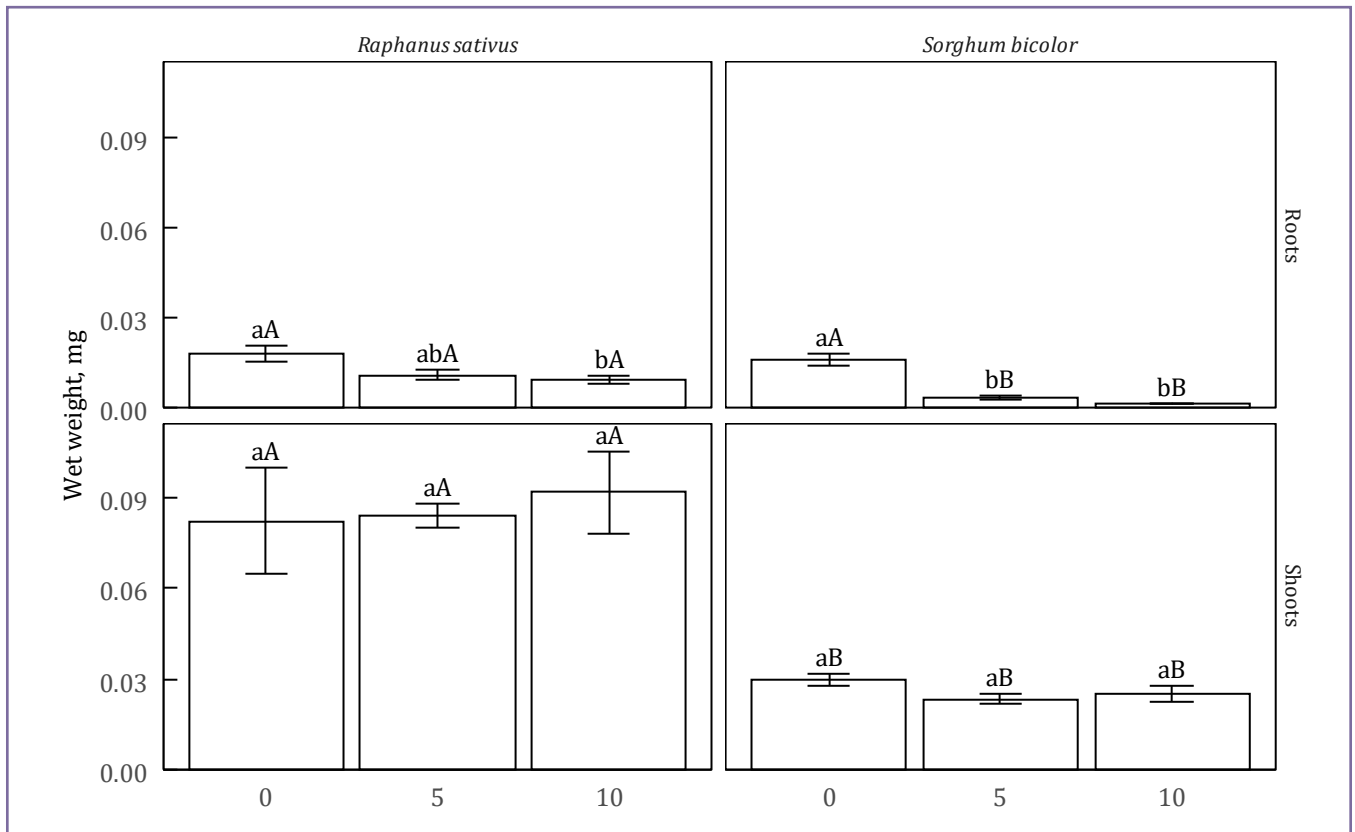


Figure 2 Weight of shoots and roots of black sorghum and oil radish seedlings depending on the concentration of Ni(II) in the medium (0, 5 and 10 mg·L⁻¹)

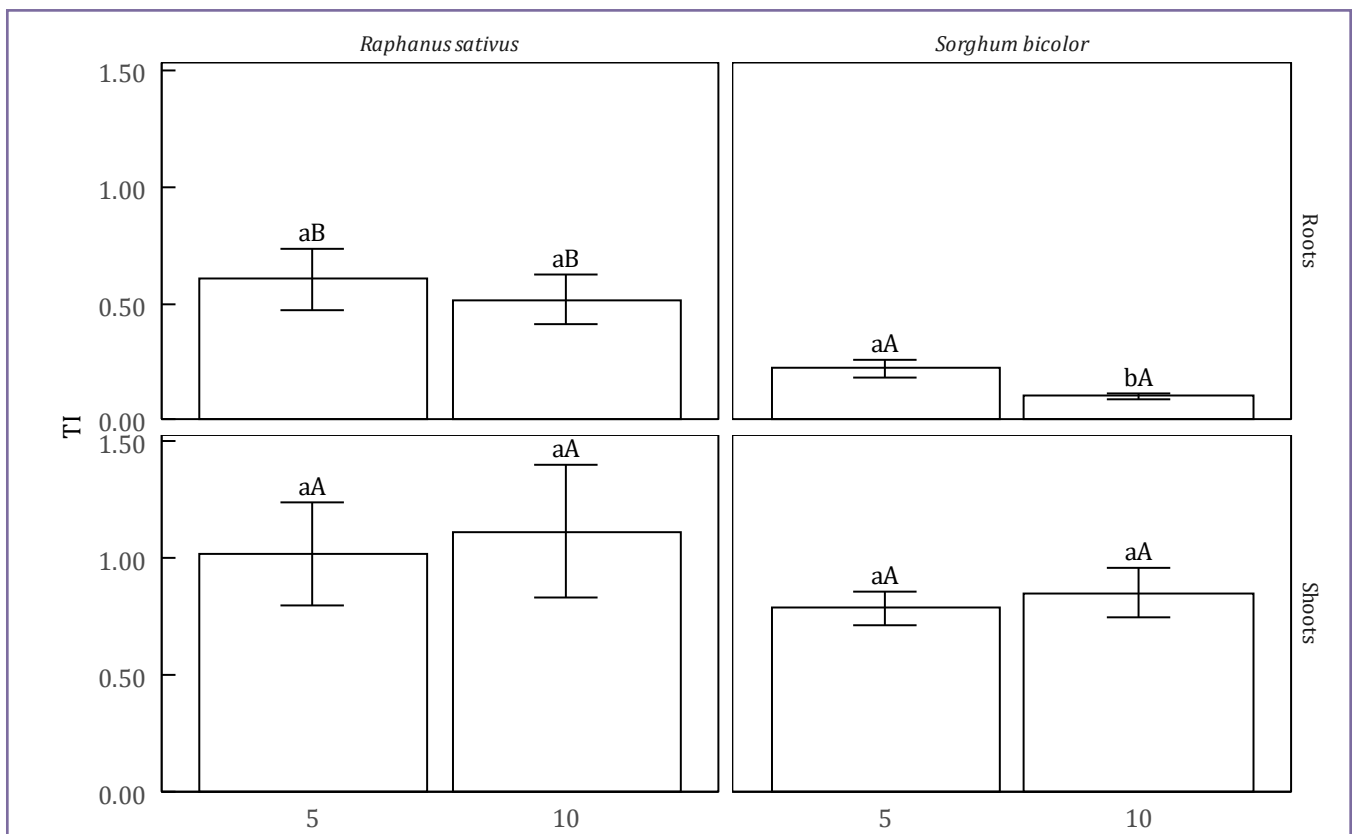


Figure 3 Nickel tolerance indices (TI) of shoots and roots of black sorghum and oil radish seedlings

The results obtained indicate a greater resistance of oil radish plants to Ni(II) at the initial stages of seed germination. Such a relatively greater resistance was manifested in a lower inhibition of root growth in the presence of Ni(II) and also in a significantly higher root tolerance index. Given these features of oil radish plants, these plants have an advantage and can be considered in further studies as those that can be used for phytoremediation of nickel-contaminated soils under the condition of a low initial concentration of Ni(II).

Influence of Pb(II) on shoots and roots formation of black sorghum and oil radish seedlings

When germinating black sorghum seeds in the presence of lead nitrate, the weight of seedling's shoots in the presence of Pb(II) at a concentration of 100, 200 and 400 mg·L⁻¹ was 0.0293 ±0.0011 g, 0.0256 ±0.0011 and 0.0217 ±0.0018 g, respectively. These weights were almost the same as the weight of shoots in the control variant (0.0259 ±0.0013 g) (Figure 4, 5). At the same time, root growth in the presence of

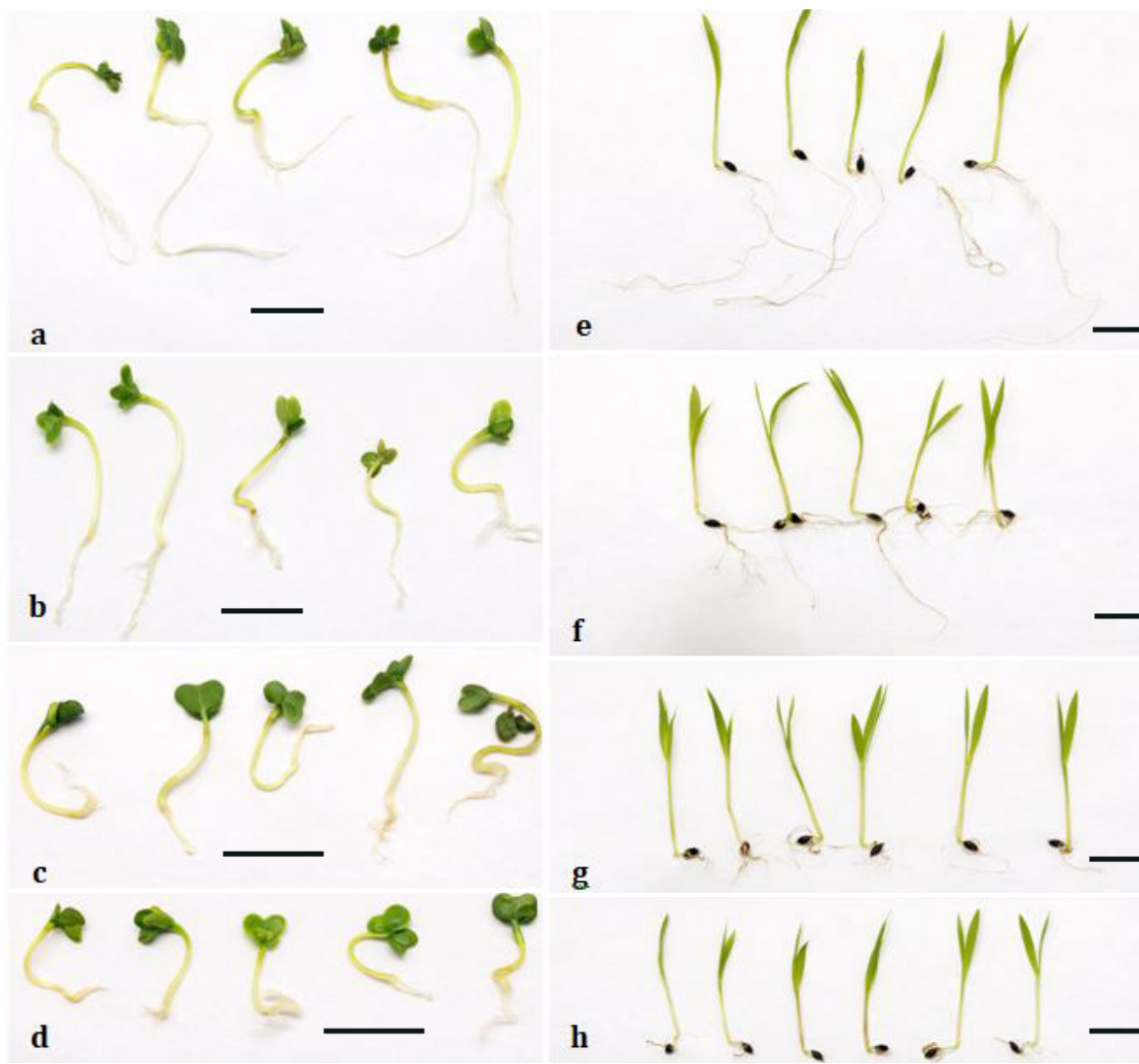


Figure 4 Plants of oil radish (a–d) and black sorghum (e–h), 7 days of germination in water: a, e – control; b, f – 100 mg·L⁻¹ Pb(II); c, g – 200 m·L⁻¹ Pb(II); d, h – 400 mg·L⁻¹ Pb(II); scale bars – 20 mm

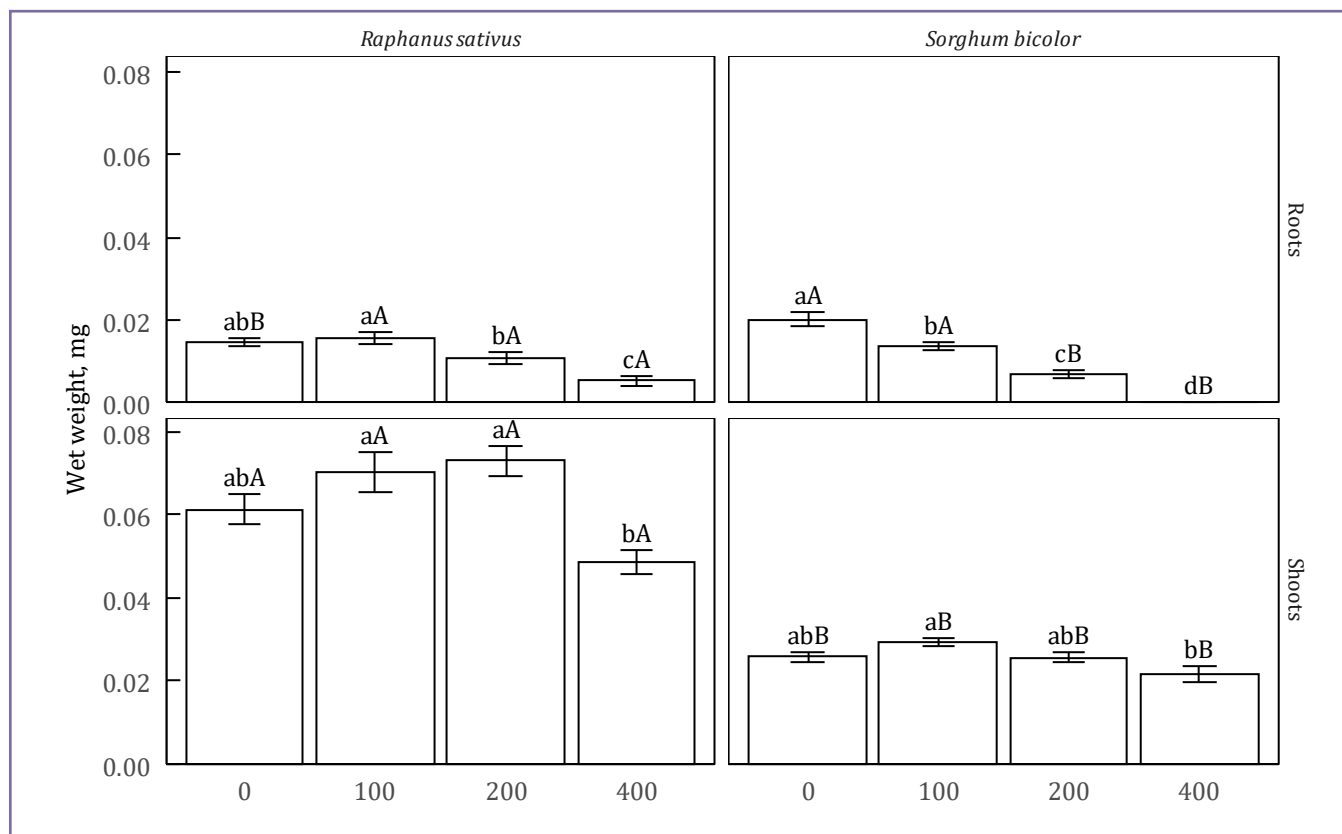


Figure 5 Weight of shoots and roots of black sorghum and oil radish plants on a medium with Pb(II) at concentrations of 0, 100, 200 and 400 mg·L⁻¹

Pb(II) at all concentrations was significantly inhibited. Root formation practically stopped in the presence of Pb(II) at a concentration of 400 mg·L⁻¹. Root weight in the control was 0.0202 ± 0.0017 g, and in the two experimental variants – 0.0138 ± 0.0010 and 0.0069 ± 0.0010 g (the initial concentration of Pb(II) was 100 and 200 mg·L⁻¹). Therefore, the root weight under such conditions was 1.46 and 2.53 fold less than in the control.

The presence of lead had a negative effect on the germination of oilseed radish seeds. In particular, shoot weight in the three experimental variants (Pb(II) 100, 200, 400 mg·L⁻¹) was 0.0703 ± 0.0047 g, 0.0731 ± 0.0036 g, and 0.0485 ± 0.0028 g, respectively, and in the control this parameter was 0.0614 ± 0.0038 g (Figure 4, 5). The root weight in the control was 0.0149 ± 0.0009 g, and in the experimental variants – 0.0157 ± 0.0015 g, 0.0108 ± 0.0014 g, 0.0053 ± 0.0011 g. Thus, significant inhibition of root growth was observed in the presence of Pb(II) at concentrations of 100–400 mg·L⁻¹.

Tolerance indices of plants grown with Pb(II)

The tolerance index of shoots (TI_{sh}) of black sorghum seedlings was 1.133 ± 0.070, 0.991 ± 0.065, 0.839

± 0.082 in the experimental variants with the addition of Pb(II) in concentrations of 100, 200 and 400 mg·L⁻¹, respectively (Figure 6). The root tolerance index (TI_r) of plants of this species was equal to 0.682, 0.341 and 0.0, respectively.

The tolerance index of shoots of oil radish plants was 1.145 ± 0.104, 1.190 ± 0.094 and 0.790 ± 0.067 in the experimental variants with the addition of Pb(II) in concentrations of 100, 200 and 400 mg·L⁻¹, respectively (Figure 6). The tolerance index of roots of plants of this species was lower (1.052 ± 0.121; 0.723 ± 0.105 and 0.356 ± 0.079), however, at the lowest concentration of Pb(II) – 100 mg·L⁻¹ – it was close to “1”, which indicates moderate resistance of plants to this metal. Thus, according to the TI_r index, oil radish plants turned out to be more resistant than black sorghum plants.

It has been previously established that plants are capable to grow in the presence of lead. In particular, such experiments were carried out using *Vigna unguiculata* (L.) Walp. (Kopittke et al., 2007), *Festuca rubra* L., (Ginn et al., 2008), *Brassica juncea* (L.) Czern. (Meyers et al., 2008), *Lactuca sativa* L., (Uzu et al., 2009) and *Funaria hygrometrica* Hedw. (Krzyszowska et al., 2009, 2010). A large number of species were used

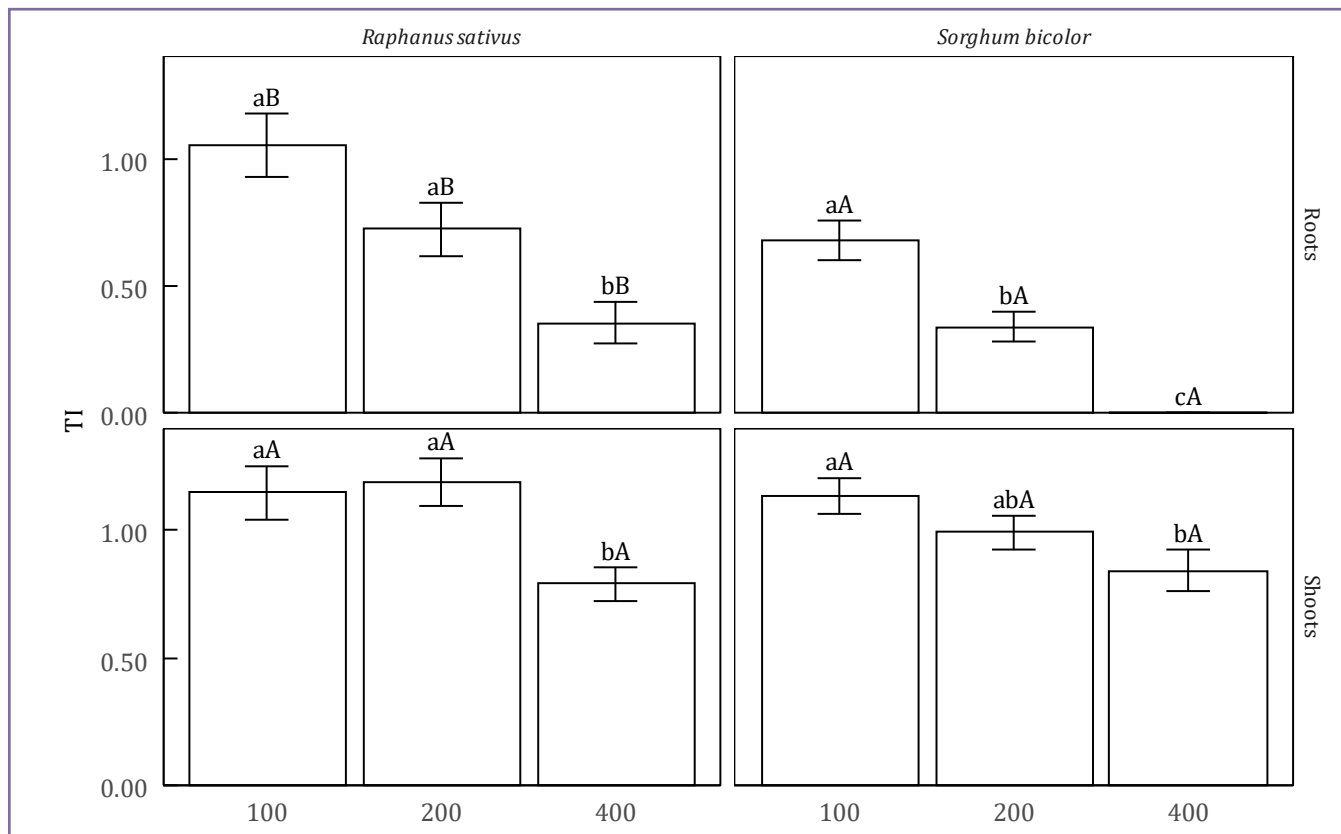


Figure 6 Lead tolerance indices (TI) of shoots and roots of black sorghum and oil radish seedlings

in the work of Cai et al. (2020). In particular, the authors determined the growth ability of 14 herbaceous plants after treatment with lead at concentrations up to 2,000 mg·kg⁻¹. The results showed that the dry weight of shoots, the tolerance index of shoots and roots in plants of all species decreased with increasing lead concentration. It was found that plants of some species such as *Trifolium repens* L., *Campsis grandiflora* Thunb., *Polygonum lapathifolium* L., *Lolium perenne* L., and *Poa annua* L. are quite tolerant to the metal. *Rudbeckia hirta* L. could effectively absorb lead with a bioconcentration factor BCF = 2.29. This also applies to *P. lapathifolium* and *Medicago sativa* L.

Plants with a high degree of metal translocation (Cai et al., 2020). Daurov et al. (2024), based on studies that included the treatment of seedlings of different sweet potato varieties with lead at a concentration of 30 mM, considered sweet potato plants suitable for phytoremediation of soils contaminated with the metal. One of the cultivars used in the experiments showed even greater tolerance to high Pb concentrations than sunflower and rapeseed, which have been well-studied earlier for phytoremediation.

Thus, according to study of numerous authors plants of different species may be quite tolerant to lead.

However, it is not possible to draw an unambiguous parallel between these data and the results of our studies, since we determined the sensitivity of plants of two species without using adult plants with a well-developed aerial part and root system. The presence of a developed and branched root system allows plants to withstand higher concentrations of toxic compounds, due to the functioning of a number of detoxification/deposition mechanisms. At the same time we think that the use of plants at early stages of development (in the process of forming seedlings from seeds) can provide additional and important information regarding the effects of toxic metals on plants and the possibility for soil remediation of sowing seeds of plants of different species in contaminated areas.

Conclusions

Thus, our studies have shown that oil radish plants are more tolerant to the effects of toxic metals such as nickel and lead. This conclusion is supported, in particular, by data on root formation at the seed germination stage, i.e. at the stage when the systems for neutralizing toxic metals by root exudates (due to the absence of a root system) and/or the systems for compartmentalizing toxicants in cells (due to the absence of significant

aboveground biomass) cannot yet function. Also, evidence of greater resistance of oil radish plants to nickel and lead is the higher tolerance index of the roots of seedlings of this species.

Conflict of interest

The authors declare no conflict of interest.

Ethical statement

This article does not contain any studies that would require an ethical statement.

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References

- Ahmad, M. S. A., & Ashraf, M. (2011). Essential roles and hazardous effects of nickel in plants. *Reviews of Environmental Contamination and Toxicology*, 214, 125–167. https://doi.org/10.1007/978-1-4614-0668-6_6
- Akbas, H., Dane, F., & Kartal, C. (2009). Effect of nickel on root growth and the kinetics of metal ions transport in onion (*Allium cepa*) root. *Indian Journal of Biochemistry and Biophysics*, 46, 332–336.
- Al Chami, Z., Amer, N., Al Bitar, L., & Cavoski, I. (2015). Potential use of *Sorghum bicolor* and *Carthamus tinctorius* in phytoremediation of nickel, lead and zinc. *International Journal of Environmental Science and Technology*, 12, 3957–3970. <https://doi.org/10.1007/s13762-015-0823-0>
- Antonkiewicz, J., Jasiewicz, C., Koncewicz-Baran, M., & Sendor, R. (2016). Nickel bioaccumulation by the chosen plant species. *Acta Physiologiae Plantarum*, 38, Article 40. <https://doi.org/10.1007/s11738-016-2062-5>
- Awasthi, S., Chauhan, R., & Srivastava, S. (2022). The importance of beneficial and essential trace and ultratrace elements in plant nutrition, growth, and stress tolerance. In V. Kumar, A. K. Srivastava, & P. Suprasanna (Eds.), *Plant nutrition and food security in the era of climate change*, 27–46. Academic Press. <https://doi.org/10.1016/B978-0-12-822916-3.00001-9>
- Azhar, U., Ahmad, H., Shafqat, H., Babar, M., Munir, H. M. S., Sagir, M., Arif, M., Hassan, A., Rachmadona, N., Rajendran, S., Mubashir, M., & Khoo, K. S. (2022). Remediation techniques for elimination of heavy metal pollutants from soil: A review. *Environmental Research*, 214(4), 113918. <https://doi.org/10.1016/j.envres.2022.113918>
- Bakshe, P., & Jugade, R. (2023). Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: A comprehensive review. *Journal of Hazardous Materials Advances*, 10, 100293. <https://doi.org/10.1016/j.hazadv.2023.100293>
- Buxton, S., Garman, E., Heim, K. E., Lyons-Darden, T., Schlekat, C. E., Taylor, M. D., & Oller, A. R. (2019). Concise Review of Nickel Human Health Toxicology and Ecotoxicology. *Inorganics*, 7(7), 89. <https://doi.org/10.3390/inorganics7070089>
- Cai, X., Yu, X., Lei, L., Xuan, B., Wang, J., Zhang, L., & Zhao, S. (2020). Comparison of lead tolerance and accumulation characteristics of fourteen herbaceous plants. *Nature Environment and Pollution Technology*, 19(4), 1547–1555. <https://doi.org/10.46488/NEPT.2020.v19i04.021>
- Charkiewicz, A. E., Omeljaniuk, W. J., Nowak, K., Garley, M., & Nikliński, J. (2023). Cadmium toxicity and health effects – A brief summary. *Molecules*, 28(18), 6620. <https://doi.org/10.3390/molecules28186620>
- Chehregani, A., & Malayeri, B. (2007). Removal of heavy metals by native accumulator plants. *International Journal of Agriculture and Biology*, 9(3), 462–465.
- Daurov, D., Lim, Y. H., Park, S. U., Kim, Y.-H., Daurova, A., Sapakhova, Z., Zhapar, K., Abilda, Z., Toishimanov, M., Shamekova, M., Zhambakin, K., Kim, H. S., & Kwak, S.-S. (2024). Selection and characterization of lead-tolerant sweetpotato cultivars for phytoremediation. *Plant Biotechnology Reports*, 18, 327–339. <https://doi.org/10.1007/s11816-024-00900-w>
- Gaetke, L.M., Chow-Johnson, H.S., & Chow, C.K. (2014). Copper: toxicological relevance and mechanisms. *Arch Toxicol.*, 88(11), 1929–1938. <https://doi.org/10.1007/s00204-014-1355-y>
- Gajewska, E., Skłodowska, M., Słaba, M., & Mazur, J. (2006). Effect of nickel on antioxidative enzyme activities, proline and chlorophyll contents in wheat shoots. *Biologia Plantarum*, 50, 653–659. <https://doi.org/10.1007/s10535-006-0102-5>
- Ginn, B. R., Szymanowski, J. S., & Fein, J. B. (2008). Metal and proton binding onto the roots of *Festuca rubra*. *Chemical Geology*, 253(3–4), 130–135. <https://doi.org/10.1016/j.chemgeo.2008.05.001>
- Giordani, C., Cecchi, S., & Zanchi, C. (2005). Phytoremediation of soil polluted by nickel using agricultural crops. *Environmental Management*, 36, 675–681. <https://doi.org/10.1007/s00267-004-0171-1>
- Gupta, V., Jatav, P., Verma, R., & Kachhwaha, S. (2017). Nickel accumulation and its effect on growth, physiological and biochemical parameters in millets and oats. *Environmental Science and Pollution Research*, 24, 23915–23925. <https://doi.org/10.1007/s11356-017-0057-4>

- Kaluarachchi, H., Chan Chung, K. C., & Zamble, D. B. (2010). Microbial nickel proteins. *Natural Product Reports*, 27, 681–694. <https://doi.org/10.1039/b906688h>
- Kopittke, P. M., Asher, C. J., Kopittke, R. A., & Menzies, N. W. (2007). Toxic effects of Pb²⁺ on growth of cowpea (*Vigna unguiculata*). *Environmental Pollution*, 150(2), 280–287. <https://doi.org/10.1016/j.envpol.2007.01.011>
- Krzyszowska, M., Lenartowska, M., Mellerowicz, E. J., Samardakiewicz, S., & Woźny, A. (2009). Pectinous cell wall thickenings formation – A response of moss protonemata cells to lead. *Environmental and Experimental Botany*, 65(1), 119–131. <https://doi.org/10.1016/j.envexpbot.2008.05.006>
- Krzyszowska, M., Lenartowska, M., Samardakiewicz, S., Bilski, H., & Woźny, A. (2010). Lead deposited in the cell wall of *Funaria hygrometrica* protonemata is not stable – A remobilization can occur. *Environmental Pollution*, 158(1), 325–338. <https://doi.org/10.1016/j.envpol.2009.06.035>
- Kumar, A., Jigyasu, D. K., Kumar, A., Subrahmanyam, G., Mondal, R., Shabnam, A. A., Cabral-Pinto, M. M. S., Malyan, S. K., Chaturvedi, A. K., Gupta, D. K., Fagodiya, R. K., Khan, S. A., & Bhatia, A. (2021). Nickel in terrestrial biota: Comprehensive review on contamination, toxicity, tolerance and its remediation approaches. *Chemosphere*, 275, Article 129996. <https://doi.org/10.1016/j.chemosphere.2021.129996>
- Küpper, H., & Kroneck, P. M. H. (2007). Nickel in the environment and its role in the metabolism of plants and cyanobacteria. In A. Sigel, H. Sigel, & R. K. O. Sigel (Eds.), *Nickel and its surprising impact in nature*, 31–61. Wiley. <https://doi.org/10.1002/9780470028131.ch2>
- Liu, D., Li, T., Jin, X., Yang, X., Islam, E., & Mahmood, Q. (2008). Lead-induced changes in the growth and antioxidant metabolism of the lead-accumulating and non-accumulating ecotypes of *Sedum alfredii*. *Journal of Integrative Plant Biology*, 50(2), 129–140. <https://doi.org/10.1111/j.1744-7909.2007.00608.x>
- Maheshwari, R., & Dubey, R. S. (2007). Nickel toxicity inhibits ribonuclease and protease activities in rice seedlings: Protective effects of proline. *Plant Growth Regulation*, 51, 231–243. <https://doi.org/10.1007/s10725-006-9163-x>
- Małkowski, E., Kita, A., Galas, W., Karcz, W., & Kuperberg, J. M. (2002). Lead distribution in corn seedlings (*Zea mays* L.) and its effect on growth and the concentrations of potassium and calcium. *Plant Growth Regulation*, 37(1), 69–76. <https://doi.org/10.1023/A:1020305400324>
- Marcin, O., Bosiacki, M., & Świerczyński, S. (2025). The Effect of Increasing Doses of Heavy Metals on Seed Germination of Selected Ornamental Plant Species. *Agronomy*, 15(6), 1262. <https://doi.org/10.3390/agronomy15061262>
- Meyers, D. E. R., Auchterlonie, G. J., Webb, R. I., & Wood, B. (2008). Uptake and localisation of lead in the root system of *Brassica juncea*. *Environmental Pollution*, 153(2), 323–332. <https://doi.org/10.1016/j.envpol.2007.08.029>
- Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University – Science*, 34(3), Article 101865. <https://doi.org/10.1016/j.jksus.2022.101865>
- Pourrut, B., Shahid, M., Dumat, C., Winterton, P., & Pinelli, E. (2011). Lead uptake, toxicity, and detoxification in plants. *Reviews of Environmental Contamination and Toxicology*, 213, 113–136. https://doi.org/10.1007/978-1-4419-9860-6_4
- Qufei, L., & Fashui, H. (2009). Effects of Pb²⁺ on the structure and function of photosystem II of *Spirodela polyrrhiza*. *Biological Trace Element Research*, 129(1), 251–260. <https://doi.org/10.1007/s12011-008-8283-8>
- Rahman, H., Sabreen, S., Alam, S., & Kawai, S. (2005). Effects of nickel on growth and composition of metal micronutrients in barley plants grown in nutrient solution. *Journal of Plant Nutrition*, 28, 393–404. <https://doi.org/10.1081/PLN-200049149>
- Reddy, A. M., Kumar, S. G., Jyothsnakumari, G., Thimmanaik, S., & Sudhakar, C. (2005). Lead-induced changes in antioxidant metabolism of horsegram (*Macrotyloma uniflorum*) and bengalgram (*Cicer arietinum* L.). *Chemosphere*, 60(1), 97–104. <https://doi.org/10.1016/j.chemosphere.2004.11.092>
- Romanowska, E., Wróblewska, B., Drożak, A., Zienkiewicz, M., & Siedlecka, M. (2008). Effect of Pb ions on superoxide dismutase and catalase activities in leaves of pea plants grown in high and low irradiance. *Biologia Plantarum*, 52(1), 80–86. <https://doi.org/10.1007/s10535-008-0012-9>
- Sengar, R. S., Gautam, M., Garg, S. K., Sengar, K., & Chaudhary, R. (2008). Lead stress effects on physiobiochemical activities of higher plants. In D. Whitacre (Ed.), *Reviews of Environmental Contamination and Toxicology*, 196, 1–26. Springer. https://doi.org/10.1007/978-0-387-78444-1_3
- Suman, J., Uhlík, O., Viktorova, J., & Macík, T. (2018). Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? *Frontiers in Plant Science*, 9, Article 1476. <https://doi.org/10.3389/fpls.2018.01476>
- Uzu, G., Sobanska, S., Aliouane, Y., Pradère, P., & Dumat, C. (2009). Study of lead phytoavailability for atmospheric industrial micronic and sub-micronic particles in relation with lead speciation. *Environmental Pollution*, 157(4), 1178–1185. <https://doi.org/10.1016/j.envpol.2008.09.053>
- Wang, L., Rinklebe, J., Tack, F. M. G., & Hou, D. (2021). A review of green remediation strategies for heavy metal contaminated soil. *Soil Use and Management*, 37, 936–963. <https://doi.org/10.1111/sum.12717>
- Wani, A.L., Ara, A., Usmani, J.A. (2015). Lead toxicity: a review. *Interdiscip Toxicol.*, 8(2), 55–64. <https://doi.org/10.1515/intox-2015-0009>

- Wu, Y-S., Osman, A.I., Hosny, M., Elgarahy, A.M., Eltaweil, A.S., Rooney, D.W., Chen, Z., Rahim, N.S., Sekar, M., Gopinath, S.C.B., Izzati Mat Rani, N.N., Batumalaie, K., & Yap, P-S. (2024). The Toxicity of Mercury and Its Chemical Compounds: Molecular Mechanisms and Environmental and Human Health Implications: A Comprehensive Review. *Cite this: ACS Omega*, 9(5), 5100–5126. <https://doi.org/10.1021/acsomega.3c07047>
- Yan, G., Gao, Y., Xue, K., Qi, Y., Fan, Y., Tian, X., Wang, J., Zhao, R., Zhang, P., Liu, Y., & Liu, J. (2023). Toxicity mechanisms and remediation strategies for chromium exposure in the environment. *Front. Environ. Sci.*, 11, 1131204. <https://doi.org/10.3389/fenvs.2023.1131204>
- Zaitsev, Yu. O., Hryshchenko, M., Romanova, A., & Zaitseva, I. O. (2022). Vplyv boyiovuh diy nav mist valovuh form vazhkuh metaliv u gruntah Sums'koho ta Ohturs'koho rayoniv Sums'koyi oblasti [Influence of combat actions on the content of gross forms of heavy metals in the soils of Sumy and Okhtyrka districts of Sumy region]. *Agroecological Journal*, 3, 136–149. [In Ukrainian] <https://doi.org/10.33730/2077-4893.32022.266419>