https://doi.org/10.15407/frg2026.02.152
UDC 581.1/.4:504.064.4:631.95

HEAVY METAL EFFECT ON GERMINATION AND ROOTS DEVELOPMENT IN *SORGHUM BICOLOR* NOTHOSUBSP. *DRUMMONDII* F. *ALBA*

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The study was aimed to assess the impact of toxic metals (Ni, Pb, Cu) on soil contamination in Ukraine caused by military actions, and to evaluate their phytotoxic effects on plants, with a focus on *Sorghum bicolor* nothosubsp. *drummondii* f. *alba* as a potential candidate for phytoremediation. Seeds of *S. bicolor* were germinated under controlled conditions with varying concentrations of $Ni(NO_3)_2$, $Pb(NO_3)_2$, and $CuSO_4$. Growth parameters of shoots and roots were measured, and tolerance indices (TI) were calculated. Statistical analyses included ANOVA, Tukey's post hoc test, Shapiro—Wilk test, and Levene's test, with significance set at $p < 0.05$. Nickel at 5—10 mg/L inhibited root growth but had little effect on shoots. Lead at 400 mg/L completely suppressed root formation, while lower concentrations caused moderate inhibition. Copper strongly affected root development, reducing biomass by up to 87 % at 100 mg/L, while shoots showed relative tolerance. Overall, roots were more sensitive to metal toxicity than shoots. *Sorghum bicolor* demonstrated moderate tolerance to heavy metal stress, maintaining shoot growth under contamination while restricting metal translocation to aerial parts. This suggests its potential use in phytostabilization strategies for soils polluted by military activities. The findings highlight the urgent need for bioremediation approaches to restore agricultural productivity and mitigate ecological risks in war-affected regions of Ukraine.

Key words: *Sorghum bicolor* nothosubsp. *drummondii* f. *alba,* toxic metals, phytoremediation, nickel, lead, copper, tolerance.

With the start of Russia's full-scale invasion in 2022, Ukraine faced not only a humanitarian and economic crisis but also massive environmental consequences. The war on Ukrainian territory has caused large-scale pollution of the environment, particularly soils, with toxic metals. The main sources of contamination have been ammunition explosions, destruction of industrial facilities, fires at chemical warehouses, and prolonged mining of territories. Military actions bring significant material losses to the Ukrainian economy. For example, according to preliminary calculations by

Citation: Matvieieva N.A., Lioshyna L.G., Duplij V.P., Bohdanovych T.A., Bulko O.V., Kuchuk M.V. Heavy metal effect on germination and roots development in *Sorghum bicolor* nothosubsp. *drummondii* f. *alba*. *Fiziol. rosl. genet.*, 2026, 58, No. 2, pp. 152—167. https://doi.org/10.15407/frg2026.01.152

the State Environmental Inspectorate, in line with approved methodologies, the damage from military actions amounts to 5,975 trillion UAH, and 10,065 cases of environmental harm have been recorded (https://ecozagroza.gov.ua/). The State Environmental Inspectorate calculated that in just the first 10 months of the full-scale war, more than 280,000 square kilometers of soil were contaminated with hazardous substances. Overall, according to estimates by the Ukrainian environmental organization, nearly one-third of Ukraine's land area may be contaminated with ammunition and harmful substances (Center for Public Monitoring and Control, https://naglyad.org/uk/2023/03/13/v-25-raziv-bilshe-shkidlivih-metaliv-u-gruntah-yak-vijna-zabrudnyuye-rodyuchi-chornozemi-ta-chi-mozhna-yih-vidnoviti/; https://uncg.org.ua/a-third-ua-crops/). To overcome the consequences of this environmental disaster, the Ministry of Environmental Protection and Natural Resources of Ukraine is developing a roadmap for assessing and cleaning contaminated territories (https://mepr.gov.ua/dorozhnya-karta-realizatsiyi-punktu-8-formuly-myru-prezydenta-volodymyra-zelenskogo-yiyi-klyuchovi-napryamy-obgovoryly-z-predstavnykamy-inozemnyh-dypustanov/).

One of the most acute challenges is soil contamination with toxic metals. As a result, soils show excessive concentrations of heavy metals — lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), mercury (Hg), and others — that exceed pre-war levels by 25 times. The most common toxic elements entering the environment are lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), mercury (Hg), nickel (Ni), and chromium (Cr). These metals are highly toxic, capable of bioaccumulation, and have a long decomposition period, posing a threat to the health of humans, animals, and plants [1]. They can penetrate the food chain, causing chronic poisoning, developmental disorders in children, as well as oncological and cardiovascular diseases.

Metals and their effect on plants. Nickel (Ni) has both essential and toxic effects on plants [2]. At low concentrations, it is a vital micronutrient required for enzyme activity and nitrogen metabolism [3]. Nickel, as an essential micronutrient, is required in trace amounts for plant growth and development. It is a cofactor of urease, an enzyme that hydrolyzes urea into usable nitrogen forms, making Ni crucial for nitrogen metabolism [4—6]. Adequate Ni levels support proper germination, leaf expansion, and reproductive development [7]. This metal can also enhance plant tolerance to certain stresses by regulating metabolic pathways [8].

However, at elevated levels, nickel becomes phytotoxic, disrupting photosynthesis, growth, and mineral nutrition, and causing oxidative stress. Excess Ni suppresses cell division in meristems, leading to reduced root and shoot growth [9—11]. High Ni concentrations reduce chlorophyll content, damage chloroplasts, and inhibit photosynthetic activity. Nickel toxicity induces the formation of reactive oxygen species (ROS), which damage lipids, proteins, and DNA, leading to necrosis and premature ageing of leaves; chronic exposure to high Ni levels decreases biomass accumulation and crop productivity [7, 12—15].

Lead (Pb) is one of the most toxic metals. Its toxicity is a serious concern for plant health, especially in areas affected by industrial pollution, mining, or heavy use of lead-containing pesticides and fertilizers. Unlike nickel, lead has no known beneficial role in plant metabolism, and its presence can be profoundly disruptive. Pb interferes with chlorophyll synthesis, leading to chlorosis and reduced photosynthetic efficiency. It affects key enzymes, like catalase and peroxidase, which are vital for energy production and stress response. It induces the formation of ROS, damaging cellular structures and DNA. This metal inhibits root elongation and shoot development, often leading to blackened or malformed roots. Seeds exposed to lead show lower germination rates and weaker seedlings. Thus, crops grown in Pb-contaminated soils often suffer from reduced productivity and poor quality [16—22].

Copper (Cu) is one of the key micronutrients in plant mineral nutrition, ensuring the proper functioning of enzymatic systems, the stability of metabolic processes, and plant adaptation to changing environmental conditions. One of the important copper-containing enzymes is Cu/Zn superoxide dismutase, which catalyzes the dismutation of the superoxide anion to produce hydrogen peroxide and molecular oxygen. In this reaction, the enzyme plays a crucial role in the cellular antioxidant defence system and helps prevent the development of oxidative stress [23]. Another important copper-containing enzyme is polyphenol oxidase, which participates in photosynthetic processes, the development of plant resistance to pests and diseases, the regulation of growth and development, as well as the formation of flower coloration [24]. Copper also plays an important role in energy metabolism. In particular, it is a component of plastocyanin, a protein involved in electron transfer in the photosynthetic electron transport chain [25]. In addition, copper is a component of cytochrome-c oxidase, which catalyzes the transfer of electrons to molecular oxygen during cellular respiration, contributing to the formation of a proton gradient and the subsequent synthesis of ATP [26]. Another important function of copper is its involvement in iron metabolism. As a component of Cu-dependent ferroxidases, it facilitates the oxidation of Fe^{2+} to Fe^{3+}, thereby promoting the binding of iron to transport proteins and its subsequent translocation within the plant [27].

However, excessive accumulation of copper in soil can exert toxic effects on plants. The main anthropogenic sources of soil contamination include the mining and processing of copper ores, waste incineration, transport activities, the use of fungicides and mineral fertilizers, as well as other types of economic activity [28]. The most common symptoms of copper excess include growth inhibition, shortened roots, root thickening, and reduced branching. In addition, a decrease in the number and size of leaves, the development of chlorosis, disturbances in flowering processes, and reduced seed germination are often observed [29]. Elevated copper concentrations may also lead to oxidative stress due to excessive production of ROS. This results in the oxidation of cellular membranes, proteins, and nucleic acids, stimulates lipid peroxidation processes, and consequently disrupts carbohydrate metabolism in plant cells [30]. Moreover, excess copper negatively affects the functioning of the photosynthetic apparatus. In particular, it disrupts the electron transport chain during photosynthesis, reduces the number and volume of chloroplasts, and inhibits the activity of photosystem II, ultimately leading to leaf yellowing and chlorosis [31]. High concentrations of copper in soil can also interfere with the uptake of other essential mineral nutrients, particularly iron, zinc, and phosphorus, which significantly reduces plant viability [32].

Biological approaches to soil purification from toxic metals. There are several biological methods for purifying soil contaminated with toxic metals. These include microbial bioremediation (the use of bacteria and fungi capable of immobilizing or transforming metals into less toxic forms), vermiremediation (the involvement of earthworms that facilitate the breakdown of organic matter and improve soil structure), phytoremediation (the use of plants that naturally absorb and accumulate metals from the soil), and co-remediation approaches [33—35].

Phytoremediation is the purification of soil from toxic compounds using plant-based technologies. Certain plants absorb toxic metals from contaminated soils and store them in their tissues. This method offers several advantages: it is cost-effective, environmentally friendly, and scalable over time. Phytoremediation encompasses processes such as phytostabilization, in which metals are immobilized in the underground parts of plants [36], and phytoextraction, whereby toxic metals are removed from the soil and transported to the above-ground biomass [37].

Numerous studies have documented the use of different plant species for phytoextraction and hyperaccumulation of toxic metals. In particular, such species as *Alyssum*, *Sorghum*, *Peltaria*, *Thlaspi*, *Brassica*, and *Bornmuellaria* have been identified as hyperaccumulators of nickel, lead, zinc, and other metals [38—42].

This study was aimed to assess the effect of toxic metals — nickel, lead, and copper on the growth of *Sorghum bicolor* nothosubsp. *drummondii* f. *alba* (white sorghum) during the early seedling formation stage. White sorghum is an annual crop belonging to the *Sorghum* genus, cultivated for green fodder, hay, silage, and pasture. It is characterized by rapid growth, drought resistance, thermophilicity, and vigorous regrowth after mowing.

Materials and methods

Seeds germination. The sensitivity of plant seeds to metals (nickel, lead, and copper) was determined at the early stage of seed germination (7—10 days). For this, seeds were placed on filter paper in Petri dishes with water solutions of $Ni(NO_3)_2$, $Pb(NO_3)_2$, and $CuSO_4$ in the appropriate concentrations expressed as metal ions: Ni(II) — 5 mg/L and 10 mg/L; Pb(II) — 100 mg/L, 200 mg/L, 400 mg/L; Cu(II) — 25 mg/L and 50 mg/L. Seeds germinated on filter paper moistened with water without these metals were used as a control. Seeds were cultivated at a temperature of 24 °C. After 7 days, the seedlings were washed, dried with filter paper and weighed using a Sartorius H60 analytical balance.

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

Statistical analysis. Data were analyzed for statistical significance using analysis of variance followed by Tukey's post hoc test. Groups of measurements were tested for normal distribution using the Shapiro—Wilk test and for homogeneity of variance using the Levene test. The same letters indicate no significant differences. Values were considered significant at $p < 0.05$. Results were presented as mean and standard error (x±SE).

Results and discussion

Effect of Ni(II) on plant growth characteristics. The average weight of shoots of *S. bicolor* was 0.0248±0.0019 g, 0.0275±0.0035 g and 0.0273±0.0011 g, respectively, in the control and two experimental treatments (Fig. 1 and 2, *a*). At the same time, the weight of roots was 0.0163±0.0018 g (control), 0.0064±0.0009 g (Ni(II) 5 mg/L), and 0.0070±0.0003 g (Ni(II) 10 mg/L) (Fig. 2, *a*). According to the data presented, the growth of plant roots was significantly inhibited by Ni(II), and the root weight was 2.55 and 2.33 times less than in the control. Therefore, the presence of nickel in the medium had no effect on the formation of shoots, but inhibited the formation of seedling roots. The shoot tolerance index (TIsh) was close to 1 u.u. At the same time, the root tolerance index (TIr) was significantly lower and was 0.395±0.067 and 0.427±0.048 (at the presence of Ni(II) 5 mg/L and 10 mg/L, respectively).

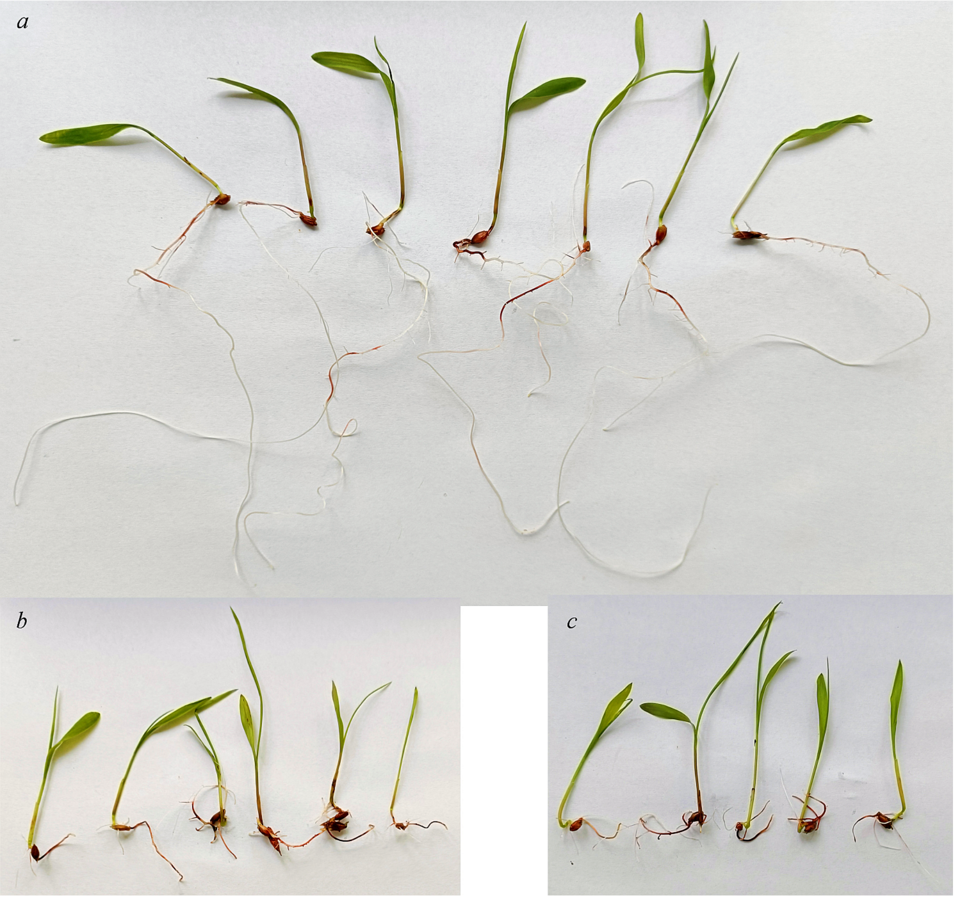


Fig. 1. *Sorghum bicolor* seedlings grown on a medium with Ni(II):
a — control; *b* — 5 mg/L; *c* — 10 mg/L

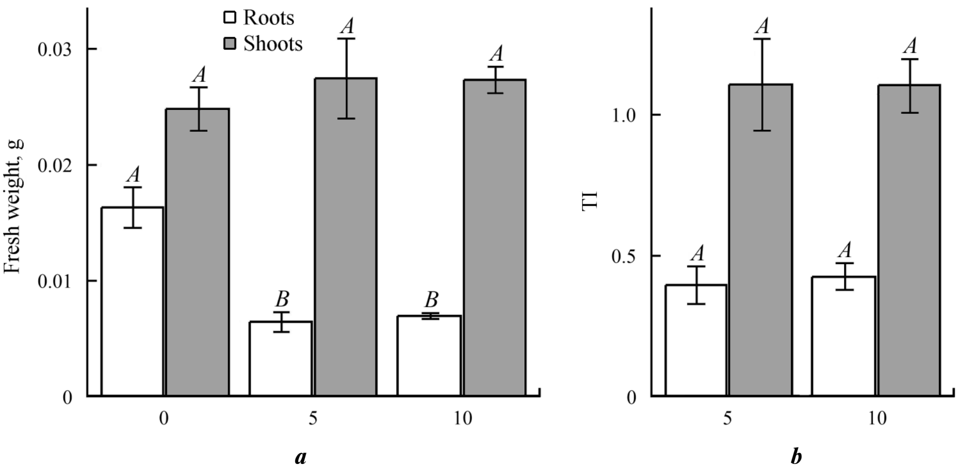


Fig. 2. Growth characteristics of *Sorghum bicolor* seedlings (*a*) on a medium with Ni(II) and tolerance indices of shoots and roots (*b*)

The effect of lead on the germination of plant seeds. The average weight of shoots of *S. bicolor* seedlings under control conditions was 0.0288±0.0014 g, and in the three experimental treatments — 0.0292±0.0011 g, 0.0305±0.0018 g and 0.0200±0.0014 g (Fig. 3). Thus, any differences in the average shoot weight were observed at the presence of Pb(II) at 100 and 200 mg/L compared to the control, and a small decrease in the corresponding index at a higher metal concentration was observed (Fig. 4, *a*). The average root weight in the control was 0.0176±0.0016 g, and in the experimental treatments it was 0.0138±0.0015 g, 0.0113±0.0014 g and 0.00 g at the presence of Pb(II) in concentrations of 100, 200 and 400 mg/L, respectively (Fig. 4, *a*). Therefore, the roots of these plants did not form at the highest metal concentration. The tolerance indices of plant shoots of this species were 1.014±0.063, 1.059±0.081 and 0.694±0.058 (at the presence of Pb(II) at concentrations of 100, 200 and 400 mg/L, respectively). The tolerance indices of roots were 0.782±0.108, 0.641±0.097, and 0.0 (Fig. 4, *b*).

Comparison of the specific effects of lead at concentrations of 100, 200 and 400 mg/L showed that seedlings of *Sorghum bicolor* are quite sensitive to this metal. The inhibitory effect of lead was especially evident in root formation during seed germination. At the presence of the metal in the highest concentration (400 mg/L), plant seedlings did not form roots. However, at a relatively low metal concentration (up to 100 mg/L), the plants showed quite high resistance, as evidenced by the root tolerance index, which was close to unity (maximum value 0.782±0.108).

The effect of copper on the germination of plant seeds. After ten days of seedling growth, it was established that the addition of copper to the nutrient medium affected plant germination, growth, and development, and the nature of this effect depends on the applied dose (Fig. 5). As the concentration of copper sulfate increased, inhibition of the main morphophysiological parameters of the seedlings was observed.

The average shoot weight of *S. bicolor* seedlings was 0.0330±0.0042 g, 0.0270±0.0010 g, and 0.0250±0.0015 g in the control and the two experi-

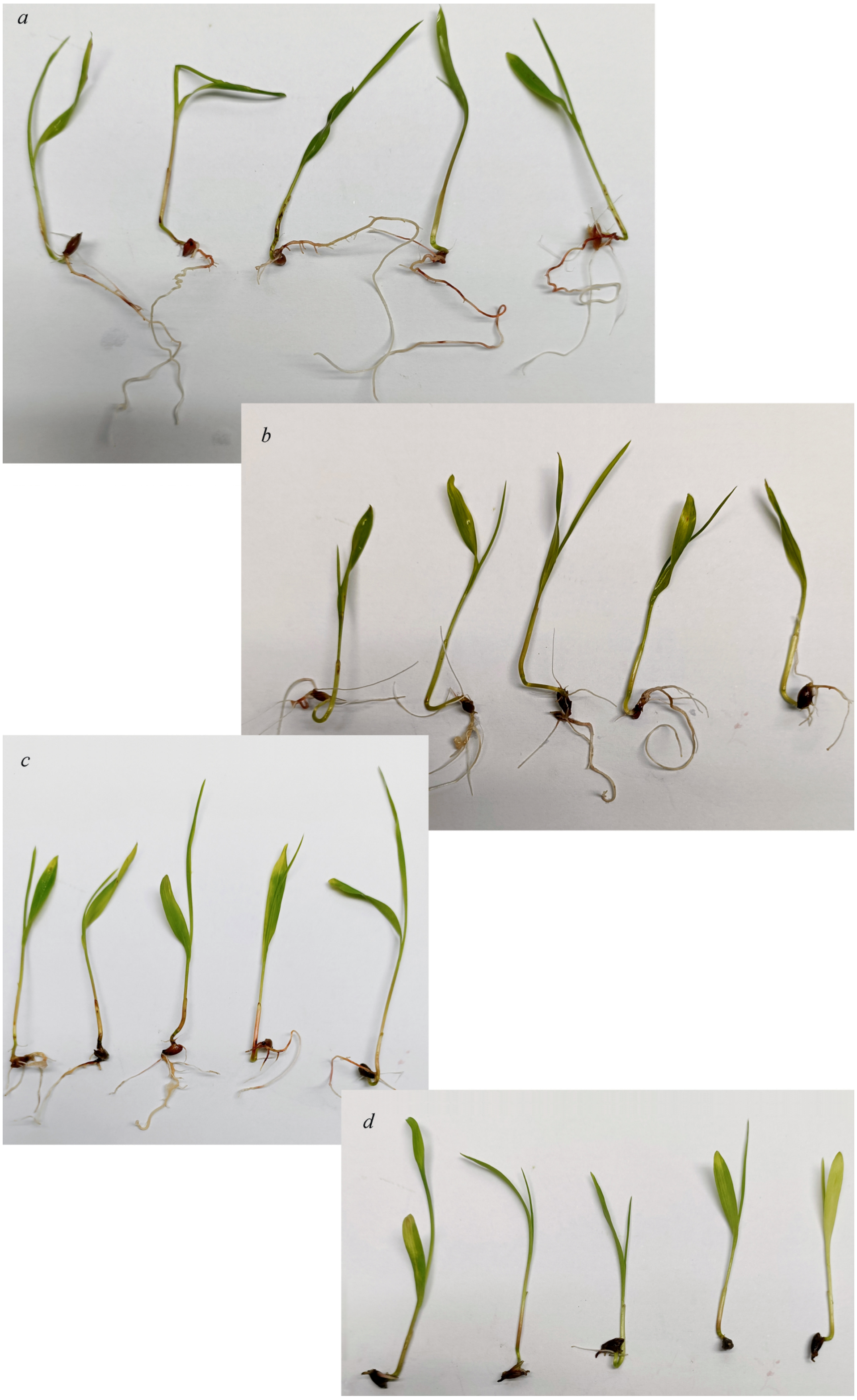
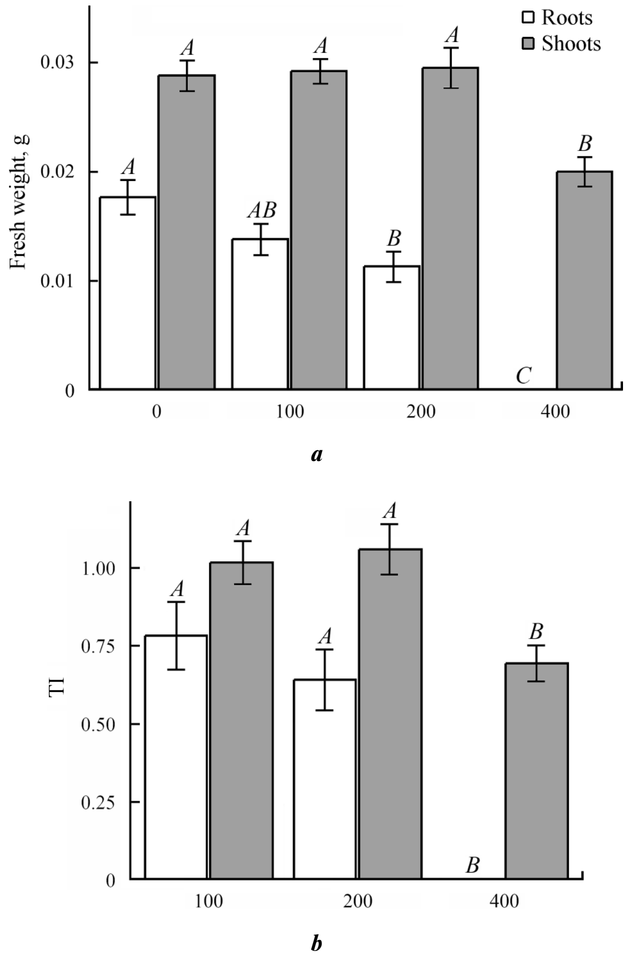


Fig. 3. *Sorghum bicolor* seedlings grown on a medium with Pb(II):
a — control; *b* — 100 mg/L; *c* — 200 mg/L; *d* — 400 mg/L



a

b

Fig. 4. Growth parameters of seedlings (shoots and roots) of *Sorghum bicolor* (*a*) on a medium with Pb(II) at concentrations of 0, 100, 200 and 400 mg/L and tolerance indices of shoots and roots (*b*)

mental treatments, respectively (Fig. 6, *a*). The average root weight was 0.0617±0.0015 g, 0.0293±0.0020 g, and 0.0080±0.0012 g, respectively. When Cu(II) concentration in the medium was 50 mg/L, root weight decreased by 53.3 %, whereas the shoots maintained relatively normal development, although their weight was reduced only by 18.2 %. An increase of metal concentration to 100 mg/L resulted in a more pronounced decrease in shoot weight (24.2 %), while root weight declined substantially by 87.1 % compared with the control. These results confirm the high sensitivity of the root system of *S. bicolor* seedlings to the presence of copper in the nutrient medium.

The TIsh of *S. bicolor* seedlings grown with the addition of 50 mg/L Cu(II) was 0.818±0.108, and at 100 mg/L of Cu(II) — 0.758±0.106 (Fig. 6, *b*). For roots, this parameter was significantly lower — 0.476±0.035 and 0.130±0.019, respectively. This indicates the high sensitivity of *S. bicolor* roots to the toxic effects of copper (TIr significantly lower than 1), whereas the shoots exhibit relative tolerance to the metal (TIsh approaching 1). However, the suppression of root growth limits long-term growth, stabili-

Fig. 5. *Sorghum bicolor* seedlings grown on a medium with Cu(II):
a — control; *b* — 50 mg/L; *c* — 100 mg/L

ty, and viability of the plant, allowing it to survive only up to a certain level of contamination, beyond which its physiological condition gradually deteriorates.

It is known that plants of different species can accumulate toxic metals. Several authors summarized and discussed strategies of plant use for

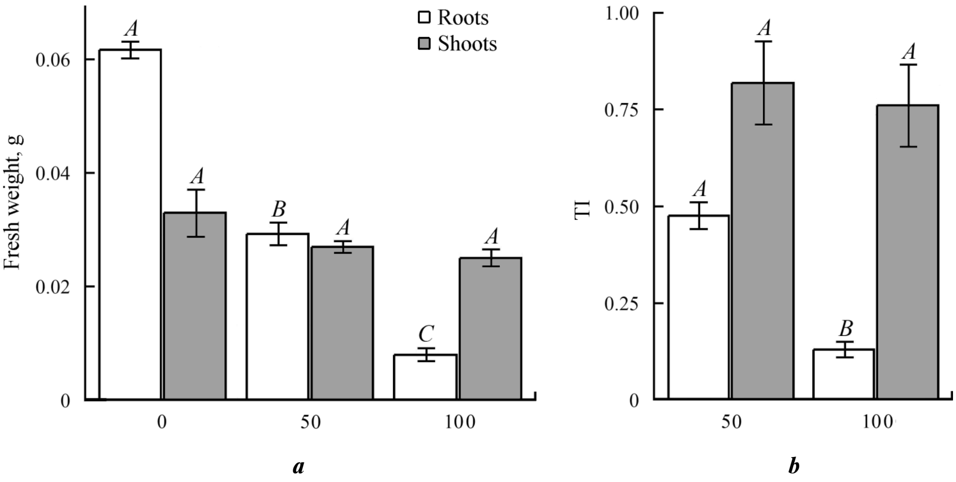


Fig. 6. Growth parameters of seedlings (shoots and roots) of *Sorghum bicolor* (*a*) on a medium with Cu(II) at concentrations of 0, 50, and 100 mg/L and tolerance indices of shoots and roots (*b*)

remediation of lead pollution [43, 44]. *Zea mays* L. plants were able to accumulate Pb; an increase in the metal content in the soil resulted in a decrease in the plant's weight [45]. Efficacy of *Vigna unguiculata*, *Brassica pekinensis*, *Gomphrena globose*, and *Helianthus annuus* for removing and immobilizing Pb in soil was evaluated [46]. The authors concluded that *V. unguiculata* was the best candidate for Pb accumulation and immobilization. *Pteris vittata*, *Trachelospermum asiaticum*, *Liriope muscari*, *Stenotaphrum secundatum*, *Asparagus setaceus*, and *Cynodon dactylon* landscape groundcover plants were successfully grown in soil containing 250 ppm and 500 ppm Pb [47].

Molnár et al. (2025) cultivated *Tagetes erecta* plants on Ni-contaminated soil [48]. These plants possess great phytoremediation potential because *T. erecta* exhibited growth and increased biomass production at Ni concentrations up to 2000 mg/kg dry weight. De Bernardi et al. (2020) compared the growth of *Spinacia oleracea, Sorghum vulgare,* and *Helianthus annuus* in contaminated soil in order to decrease the concentration of the soluble Ni [49]. Phytoremediation of Ni from agricultural soils using *Brassica napus* plants was studied by several authors [50].

The higher sensitivity of roots observed in our study is consistent with earlier experimental data showing that copper and lead primarily affect the root system, which is the first site of metal uptake and accumulation. Experimental studies comparing the toxicity of copper and lead in several agricultural crops, including sorghum, have shown that root growth is a more sensitive indicator of metal toxicity than shoot growth, and copper exhibits particularly strong phytotoxic effects at elevated concentrations [51].

The physiological mechanisms underlying these responses involve disruption of cellular metabolism and induction of oxidative stress. Exposure to heavy metals stimulates the ROS formation, which can damage membranes, proteins, and nucleic acids, ultimately leading to reduced plant growth and biomass accumulation [52]. In sorghum, antioxidant defence systems play an important role in tolerance to copper-induced stress. Molecular studies have shown that the activity of antioxidant enzymes, particularly superoxide dismutase (SOD), plays a role in protecting plant tissues from oxidative damage caused by copper toxicity [53].

At the cellular level, excess copper may also interfere with nutrient uptake and metabolic regulation in roots. Proteomic studies of *Sorghum bicolor* roots exposed to copper have revealed significant changes in the expression of proteins associated with stress responses, metabolism, and ion transport. Elevated copper concentrations were found to disrupt the uptake of essential elements such as Fe, Zn, Ca, and Mn, which further contributes to growth inhibition [54].

Several studies have reported that sorghum tends to retain heavy metals predominantly in the root system, with limited translocation to shoots. This mechanism reduces the toxic impact on the photosynthetic apparatus but leads to strong suppression of root growth at high metal concentrations [55].

Despite copper's inhibitory effects on root development, sorghum is often considered a relatively tolerant species that can grow on moderately contaminated soils. Such tolerance is associated with mechanisms of metal sequestration and the activation of antioxidant defence systems [56].

The results of the present study are also consistent with the findings reported in work [57], where authors assessed the ecological condition of soils contaminated with heavy metals following military activities in agricultural areas of Ukraine. This study demonstrated that *Sorghum bicolor* exhibits measurable growth inhibition in highly contaminated soils while maintaining viability in areas with moderate levels of pollution. These observations indicate that sorghum exhibits some tolerance to heavy metal stress but shows significant physiological responses at high levels of contamination.

Taken together, the results of our experiment and the data reported in the literature suggest that *Sorghum bicolor* demonstrates moderate tolerance to copper-induced stress, which is manifested by relatively stable shoot development but stronger inhibition of root growth. The root system appears to act as the primary barrier preventing excessive translocation of metals to aerial organs. At the same time, the ability of sorghum to survive under moderate heavy metal stress, produce relatively high biomass, and retain metals in the root system supports its potential use in phytostabilization and phytomanagement of contaminated soils.

Previous experiments have investigated the potential of *Sorghum* spp. for soil purification from toxic metals. For example, the effects of Cd and Zn on plant growth have been studied [58]. The use of white sorghum for removing toxic compounds from soil is particularly promising, given the potential to utilize the harvested biomass as a source of bioenergy. According to the experiments of De Bernardi et al. (2020), sorghum had a good phytostabilization potential due to the ability of Ni accumulation mainly at the roots [49].

Perlein et al. (2021) [59] investigated the growth of two cultivars, Biomass 133 and Trudan Headless, in fields contaminated with Cd, Pb, and Zn in northern France, assessing their suitability for phytoattenuation strategies. These cultivars demonstrated tolerance to high levels of metal pollution under field conditions. Similarly, the potential of *Sorghum* spp. as copper phytoextractors has been evaluated [56]. The authors found that plant growth was not adversely affected by increasing Cu(II) concentrations, suggesting that these plants exhibit tolerance to copper.

Conclusions

Experimental data on *Sorghum bicolor* revealed that roots are highly sensitive to heavy metal stress, particularly to copper and lead, while shoots exhibit relative tolerance. This differential response underscores the importance of root system as primary barrier in metal uptake, and as indicator of toxicity.

Nickel at low concentrations did not significantly affect shoot development but strongly inhibited root growth, confirming that roots are the primary site of metal sensitivity. Lead exhibited a dose-dependent inhibitory effect, with complete suppression of root formation at the highest tested concentration (400 mg/L), highlighting its extreme phytotoxicity. Copper was particularly damaging to root biomass, reducing it by more than 80 % at elevated concentrations, while shoots retained relative tolerance.

A common trend across all tested metals was greater sensitivity of roots than of shoots. This pattern reflects the physiological role of roots as the first barrier to metal uptake and accumulation. While shoots maintained partial tolerance, the suppression of root growth inevitably limits long-term plant viability, nutrient uptake, and productivity. Despite these inhibitory effects, *Sorghum bicolor* demonstrated moderate tolerance to heavy metal stress. Its ability to maintain shoot growth under contamination indicates potential for phytostabilization. This species can survive in moderately polluted soils, produce biomass, and immobilize metals, thereby reducing their translocation into the food chain. Such traits make sorghum a promising candidate for phytomanagement strategies in war-affected agricultural regions.

This work was supported by grant of the National Academy of Sciences of Ukraine No. 0125U000980 «Biotechnological plants for combating infectious bacterial diseases and phytodestruction of military-origin pollutants».

Author Contributions: study conception and design: Mykola Kuchuk, Nadiia Matvieieva, Liudmyla Lioshina; data collection: Taisa Bohdanovych, Olga Bulko; analysis and interpretation of results: Nadiia Matvieieva, Liudmyla Lioshina, Volodymyr Duplj; writing — original draft: Nadiia Matvieieva, Liudmyla Lioshina, Taisa Bohdanovych; writing — review & editing: Mykola Kuchuk, Nadiia Matvieieva, Liudmyla Lioshina.

All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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Received 06.04.2026. Accepted 22.04.2026. Published 08.05.2026.

ВПЛИВ ВАЖКИХ МЕТАЛІВ НА ПРОРОСТАННЯ ТА РОЗВИТОК КОРЕНІВ У *SORGHUM BICOLOR* NOTHOSUBSP. *DRUMMONDII* F. *ALBA*

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Метою дослідження було оцінити вплив токсичних металів (Ni, Pb, Cu) на забруднення ґрунту в Україні, спричинене військовими діями, та дослідити їхній фітотоксичний вплив на рослини, зосереджуючись на *Sorghum bicolor* nothosubsp. *drummondii* f. *alba* як потенційному кандидаті для фіторемедіації. Насіння *S. bicolor* пророщували в контрольованих умовах з різними концентраціями $Ni(NO_3)_2$, $Pb(NO_3)_2$ та $CuSO_4$. Були виміряні параметри росту пагонів і коренів, а також розраховані індекси толерантності (TI). Статистичний аналіз включав дисперсійний аналіз (ANOVA), тест Тьюкі, тест Шапіро—Вілка та тест Левена зі значущістю, встановленою на рівні $p < 0,05$. Нікель у концентрації 5—10 мг/л пригнічував ріст коренів, але мав незначний вплив на пагони. Свинець у концентрації 400 мг/л повністю пригнічував утворення коренів, тоді як нижчі концентрації спричинювали помірне пригнічення. Мідь дуже впливала на розвиток коренів, зменшуючи біомасу до 87 % за 100 мг/л, тоді як пагони демонстрували відносну толерантність. Загалом, корені були чутливішими індикаторами токсичності металів, ніж пагони. Сорго двоколірне продемонструвало помірну стійкість до стресу від важких металів, підтримуючи ріст пагонів при забрудненні, обмежуючи при цьому переміщення металів у надземну частину. Це свідчить про можливість його потенційного використання у стратегіях фітостабілізації ґрунтів, забруднених військовою діяльністю. Отримані результати підкреслюють нагальну потребу в підходах до біоремедіації для відновлення сільськогосподарської продуктивності та зменшення екологічних ризиків у постраждалих від війни регіонах України.

Ключові слова: Sorghum bicolor nothosubsp. *drummondii* f. *alba*, токсичні метали, фіторемедіація, нікель, свинець, мідь, толерантність.

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