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LEAD ACCUMULATION AND REMOVAL BY AMARANTH CULTIVATION ON GREY FOREST SOILS IN WESTERN UKRAINE

Razanov S.F. *– Doctor of Agricultural Sciences,*
Professor at the Department of Forestry and Horticulture,
Vinnytsia National Agrarian University
orcid.org/0000-0002-4883-2696
Tyrus M.L. *– Candidate of Agricultural Sciences, Associate Professor,*
Acting Head of the Department of Crop Production Technologies,
Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies of Lviv
orcid.org/0000-0002-9882-9540
Razanova A.M. *– PhD Degrees in Environmental Studies,*
Senior Lecturer at the Department of Forestry and Horticulture,
Vinnytsia National Agrarian University
orcid.org/0000-0002-3546-3692
Kovka N.S. *– Assistant Professor at the Department of Ecology*
and Environmental Protection,
Vinnytsia National Agrarian University
orcid.org/0000-0002-4556-2678
Nedashkivska V.V. *– Student at the Faculty of Animal Husbandry*
and Aquatic Bioresources,
National University of Life and Environmental Sciences of Ukraine
orcid.org/0009-0006-9217-5554

Anthropogenic pressure on agricultural soils, especially under intensive farming conditions, requires constant monitoring of toxicant content and their migration in the soil → plant production system. Among these, lead is the most dangerous, characterized by high toxicity, bioaccumulation, and absence of threshold effects. Phytoremediation is one of the promising methods for reducing its content in soils. Amaranth (Amaranthus spp.) is of significant interest as it combines high metal accumulation capacity with economic value.

The aim of this study was to determine the intensity of lead accumulation and removal by amaranth harvest on grey forest soils of Lviv region. A field experiment was conducted with 4 replications. Lead concentration in soil, vegetative mass, and seeds was determined using atomic absorption spectrometry. Bioaccumulation coefficients and hazard quotients were calculated to assess phytoremediation potential.

Amaranth actively accumulated lead in aboveground biomass. The concentration was 1.52±0.4 mg/kg, which is 3.28 times lower than the MPC for feed. The hazard quotient was 0.30, indicating that the biomass is suitable for feed purposes. Lead content in seeds was lower, but the concentration of 0.66±0.031 mg/kg exceeded the MPC for cereals by 1.32 times. Phytoremediation efficiency was high. Lead removal with harvest amounted to 34.2 g/ha with vegetative mass and 1.4 g/ha with seeds. The aboveground biomass accumulated 23.7 times more metal than seeds.

Therefore, amaranth can be used as a dual-purpose crop – for obtaining relatively safe feed products and for phytoremediation, particularly for cleaning soils slightly contaminated with lead. The results are of great importance for the development of bioecological technologies for the restoration of degraded agricultural lands in Ukraine.

Key words: *amaranth, yield, vegetative mass, seeds, phytoremediation, lead.*

Разанов С.Ф., Тирусь М.Л., Разанова А.М., Ковка Н.С., Недашківська В.В. Накопичення та винесення свинцю амарантом за вирощування на сірих лісових ґрунтах у Західній Україні

Техногенне навантаження на ґрунти сільськогосподарських угідь, особливо в умовах інтенсивного землеробства, вимагає постійного контролю за вмістом токсикантів та їх міграцією в системі ґрунт → рослинна продукція. Серед них найбільш небезпечним є свинець, який характеризується високою токсичністю, біоакумуляцією та відсутністю порогової дії. Одним із перспективних методів зниження його вмісту у ґрунтах є фіторемедіація. Значний інтерес становить амарант (Amaranthus spp.), що поєднує високу здатність до акумуляції металів із господарською цінністю.

Мета дослідження – визначити інтенсивність накопичення та винесення свинцю з урожаєм амаранту на сірих лісових ґрунтах Львівщини. Польовий дослід проведено у 4 повтореннях. Визначення концентрації свинцю у ґрунті, вегетативній масі та насінні здійснювалося методом атомно-абсорбційної спектрометрії. Розраховано коефіцієнти накопичення та небезпеки для оцінки фіторемедіаційного потенціалу.

Амарант активно акумулював свинець у надземній біомасі. Концентрація становила 1,52±0,4 мг/кг, що у 3,28 раза нижче ГДК для кормів. Коефіцієнт небезпеки дорівнював 0,30, тобто біомаса є придатною для кормових цілей. У насінні вміст свинцю був нижчий, однак концентрація 0,66±0,031 мг/кг перевищувала ГДК для зернових у 1,32 раза. Фіторемедіаційна ефективність була високою. Винесення свинцю з урожаю становило 34,2 г/га з вегетативною масою та 1,4 г/га – з насінням. При цьому надземна біомаса акумулювала у 23,7 раза більше металу, ніж насіння.

Отже, амарант може застосовуватись як культура подвійного призначення – для отримання відносно безпечної кормової продукції та фіторемедіації, зокрема очищення слабко забруднених свинцем ґрунтів. Результати мають важливе значення для розробки біоекологічних технологій відновлення деградованих сільськогосподарських земель в Україні.

Ключові слова: *амарант, фіторемедіація, урожайність, вегетативна маса, насіння, свинець.*

Problem statement. Soil contamination with heavy metals, particularly lead, is one of the most pressing environmental challenges of today, posing a serious threat to food security and human health. The technogenic load on agricultural soils resulting from the intensive use of mineral fertilizers, industrial emissions, and vehicular transport leads to the accumulation of toxic elements in the soil environment and their subsequent migration into food products. Lead, as one of the most hazardous heavy metals, is characterized by high toxicity, the ability to bioaccumulate, and the absence of a threshold effect, which makes it particularly dangerous even at low concentrations [1]. In Ukraine, the problem of soil contamination with lead is becoming especially acute due to significant technogenic pressures and the urgent need to ensure food security.

Phytoremediation, as an environmentally safe and economically efficient method of cleaning contaminated soils, is attracting increasing attention from researchers. Among the promising phytoremediant crops, amaranth (*Amaranthus* spp.) holds a special place, combining high phytoremediation potential with valuable agronomic traits. Grey forest soils, which predominate in the western region of Ukraine, require further investigation in terms of the intensity of lead accumulation and removal by amaranth. In this regard, the analysis of heavy metal accumulation processes in amaranth and the assessment of its phytoremediation properties are of particular relevance.

Analysis of recent research and publications. Soil contamination with heavy metals, particularly lead, is one of the most pressing environmental issues of today, posing a serious threat to food security and human health [2]. Rapid industrialization, intensive agricultural practices, mining activities, and the use of contaminated irrigation water contribute to the input of heavy metals into the soil environment [3-4]. Lead (Pb) is one of the most hazardous toxins, lacking a threshold effect, meaning that it can cause harm to the organism even at very low concentrations [5].

In the context of searching for environmentally safe and economically efficient methods of remediating contaminated soils, phytoremediation – the use of plants to remove pollutants from soils – acquires particular importance [6-7]. This method is considered a promising alternative to traditional physico-chemical technologies due to its environmental friendliness, low cost, and potential to restore soil fertility [8].

Among phytoremediant plants, particular attention of researchers is drawn to amaranth (*Amaranthus* spp.) – an annual herbaceous plant of the Amaranthaceae family with a wide range of applications. Amaranth is characterized by high tolerance to environmental stress factors, a significant potential for heavy metal accumulation, and unique ecological plasticity and adaptability, which is manifested in its ability to thrive under diverse soil and climatic conditions [9].

The plant has a powerful root system – the taproot can penetrate to a depth of up to 7 meters, which enables effective interaction with contaminated soil layers and contributes to natural loosening of the soil without destroying its structure. Additionally, amaranth serves as a green manure crop, enriching the soil with nitrogen and suppressing weeds due to its strong root system [10].

Studies have shown that invasive amaranth species possess a strong ability to accumulate cadmium and lead even in areas with low levels of contamination by these metals [11]. In Ukraine, where soil and climatic conditions allow the cultivation of almost all amaranth varieties, this crop can become an effective tool for the ecological restoration of contaminated areas.

Rahman et al. (2013) demonstrated that amaranth can effectively accumulate copper and lead from contaminated industrial soils, while the application of nitrogen fertilizers significantly enhances the efficiency of phytoextraction. The authors found that the use of nitrogen fertilizers at a rate of 190-380 mg/kg of soil contributes to an increased accumulation of heavy metals in the aboveground parts of the plants [12]. The particular importance of amaranth for phytoremediation is confirmed by the studies of Haller et al. (2023), which showed that amaranth is a documented hyperaccumulator of cadmium and other pollutants and is commonly cultivated in Asia and South America. Importantly, amaranth is capable of functioning effectively under suboptimal conditions, including nutrient-poor acidic soils [13].

The effectiveness of amaranth as a phytoremediant is determined by specific physiological and biochemical mechanisms. The study by Kelechi et al. (2022) on *Amaranthus spinosus* showed that the plant is capable of efficiently absorbing heavy metals from soils of automobile workshops and waste dumps, with the rate of heavy metal loss indicating that achieving 100% reduction in vegetated soil requires less time compared to non-vegetated soil [14].

Under Ukrainian conditions, amaranth acquires particular importance as a dual-purpose crop – with a high level of productivity and the ability to accumulate toxicants. According to Romanchuk et al. (2022), the application of mineral fertilizers contributes to increased green mass yield of amaranth and enhances its capacity for heavy metal phytoextraction [15].

The study by Tyrus (2025) in the Forest-Steppe zone of Western Ukraine showed that the yield of different amaranth varieties ranged from 1.97 to 4.03 t/ha, providing a profitability level from 11 to 127%. Such results indicate the promising potential of amaranth as a highly profitable food and forage crop, as well as an object for phytoremediation programs [16].

In addition, amaranth has high biological value as a forage crop [17]. According to Kryvyi (2023), the yield of green mass of amaranth in the Polissia region reached

24.55 t/ha, while the crude protein content varied depending on the growth stage, reaching a maximum of 24.7% at the beginning of panicle emergence. The optimal inclusion of amaranth in mixed silage (20-26%) had a positive effect on the productivity of fattening pigs [18]. This highlights the versatility of the crop, which combines forage, food, and ecological functions.

Of particular importance are studies conducted on grey forest soils in the Lviv region, which demonstrated the ability of amaranth to effectively remove the radionuclide Cesium-137. In particular, it was established that the aboveground biomass accumulates about 336,000 Bq per hectare, whereas the seeds accumulate only about 9,000 Bq – 37 times less. At the same time, the specific activity in both biomass and seeds was significantly lower than the permissible limits (by 40 and 120 times, respectively). This makes amaranth a promising dual-purpose crop: both for phytoremediation and for use in animal husbandry [19].

In the context of Ukraine, research on the phytoremediation potential of agricultural crops is of particular relevance due to the technogenic contamination of vast areas, especially in industrial regions. The western region of Ukraine, despite a lower level of industrial pollution compared to the eastern regions, also requires constant monitoring and the development of effective methods for remediating contaminated soils. Considering the urgency of the problem of soil contamination with lead and the promising potential of amaranth for phytoremediation, the **aim of this study** is to determine the intensity of lead accumulation and removal with the amaranth yield when cultivated on grey forest soils in the western region of Ukraine in order to assess the phytoremediation potential of this crop.

Materials and methods of research. The study on assessing the intensity of lead accumulation in the aboveground vegetative mass and seeds of amaranth was conducted on grey forest soils in the western region of Ukraine (Lviv Oblast). The field experiment was established with four replications using the randomized block design. The cultivation technology of amaranth followed generally accepted agronomic standards for field crops, taking into account the biological characteristics of the crop and the soil and climatic conditions of the region.

Soil samples for chemical analysis were collected using the «envelope» method from the arable layer (0-20 cm), while samples of the aboveground vegetative mass and seeds were taken using the point sampling method followed by pooling into composite samples [20]. Preparation of plant samples was carried out according to standard procedures. The determination of lead content in the soil, vegetative mass, and seeds was performed using the atomic absorption spectrometry method.

The accumulation coefficient (AC) of lead in the vegetative mass and seeds of amaranth was calculated as the ratio of the metal concentration in plant material to its content in the soil. The hazard coefficient (HC) of lead in the vegetative mass and seeds of amaranth was determined as the ratio of the actual concentration of the metal in the respective sample to the maximum permissible concentration (MPC) established by sanitary standards for plant products. For the vegetative mass, the MPC for forage crops (5.0 mg/kg) was used, while for seeds – the MPC for cereal crops (0.5 mg/kg). This approach makes it possible to assess the degree of hazard of amaranth products under conditions of soil contamination with lead. The obtained results were processed using standard statistical methods, including the calculation of arithmetic means, standard errors, and coefficients of variation. Statistical data analysis was performed using Microsoft Excel software.

Summary of the main research material. The analysis of the obtained research results (Table 1) showed that with an average lead content in grey forest soil of 0.68±0.04 mg/kg, the concentration of this toxicant in the aboveground vegetative mass of amaranth averaged 1.52±0.4 mg/kg, which was 3.28 times lower than the permissible level (with the MPC for forage crops being 5.0 mg/kg).

The accumulation coefficient of lead in the aboveground vegetative mass of amaranth was found to be quite high, ranging from 2.0 to 2.4, with an average of 2.2±0.3. This indicates the ability of amaranth to actively absorb lead from the soil solution and transport it into the aboveground parts of the plant. The hazard coefficient of lead in the aboveground vegetative mass did not exceed the threshold limit (1.0) and ranged from 0.28 to 0.32, with an average value of 0.30±0.024. This indicates the absence of a health risk for animals when using this product as fodder.

Table 1

Intensity of lead accumulation in aboveground vegetative mass of amaranth

Trial variant	MPC, mg/kg	Actual content in vegetative mass, mg/kg	Actual content in soil, mg/kg	Bioaccumulation coefficient	Hazard coefficient
I	5.0	1.53	0.64	2.4	0.30
II	5.0	1.44	0.71	2.0	0.28
III	5.0	1.62	0.68	2.4	0.32
IV	5.0	1.50	0.72	2.1	0.30
Average	5.0	1.52±0.4	0.68±0.04	2.2±0.3	0.30±0.024

The results of the study on lead removal from grey forest soil by the aboveground vegetative mass of amaranth (Table 2) indicate high efficiency of this process. With an average yield of aboveground biomass of 22.4 t/ha, lead removal from 1 ha amounted to an average of 34,175 mg, which is a considerable value for phytoremediation purposes. The variation of lead removal among individual treatments ranged from 32,256 to 35,964 mg/ha, which correlates with the yield of the aboveground biomass and the metal concentration in plant tissues.

Table 2

Intensity of lead removal by aboveground vegetative mass of amaranth

Trial variant	Yield, t/ha	Actual lead concentration in vegetative mass, mg/kg	Lead removal from soil, mg/ha
I	22.7	1.53	34,731
II	22.4	1.44	32,256
III	22.2	1.62	35,964
IV	22.5	1.50	33,750
Average	22.4	1.52±0.4	34,175

The concentration of lead in amaranth seeds grown on grey forest soil with an average toxicant content of 0.68±0.04 mg/kg (Table 3) ranged from 0.63 to 0.71 mg/kg, with an average of 0.66±0.031 mg/kg. It should be noted that the concentration of lead in amaranth seeds exceeded the permissible level (MPC 0.5 mg/kg for cereal crops) by 1.32 times. The accumulation coefficient of lead in amaranth seeds was significantly lower compared to the vegetative mass, ranging from 0.90 to 1.04, with an average of 0.96±0.024 across treatments. This indicates the presence of certain barrier mechanisms in the transport of lead to the reproductive organs of the plant. The hazard coefficient of lead in amaranth seeds exceeded the maximum permissible limit (1.0) by 1.33 times, indicating a certain risk when using seeds as food products without prior processing.

Table 3

Intensity of lead accumulation in amaranth seeds

Trial variant	MPC, mg/kg	Actual content in seeds, mg/kg	Actual content in soil, mg/kg	Bioaccumulation coefficient	Hazard quotient
I	0.5	0.67	0.64	1.04	1.34
II	0.5	0.71	0.71	1.00	1.42
III	0.5	0.63	0.68	0.92	1.26
IV	0.5	0.65	0.72	0.90	1.30
Average	0.5	0.66±0.031	0.68±0.04	0.96±0.024	1.33±0.042

The removal of lead from grey forest soil by amaranth seeds (Table 4) was significantly lower compared to the aboveground vegetative mass. With an average seed yield of 2.17±0.22 t/ha, lead removal ranged from 1420 to 1474 mg/ha, averaging 1443±12 mg/ha.

Table 4

Intensity of lead removal by amaranth seeds from grey forest soil

Trial variant	Yield, t/ha	Actual lead concentration in seeds, mg/kg	Lead removal from soil, mg/ha
I	2.2	0.67	1,474
II	2.0	0.71	1,420
III	2.3	0.63	1,449
IV	2.2	0.65	1,430
Average	2.17±0.22	0.66±0.031	1,443±12

It is important to note that lead removal by the aboveground vegetative mass of amaranth from grey forest soil was 23.7 times higher compared to the seeds of this crop (34,175 mg/ha versus 1,443 mg/ha). This indicates the predominant accumulation of the heavy metal in the vegetative organs of the plant.

Висновки. When cultivated on grey forest soils in Western Ukraine, amaranth exhibits active accumulation of lead in plant tissues. The accumulation coefficient in the aboveground vegetative mass was 2.2±0.3, which indicates a high ability of the crop to absorb and translocate the metal from the soil solution. In seeds, this indicator was lower (0.96±0.024), demonstrating differences in the distribution of the toxicant between plant organs. The concentration of lead in the vegetative mass of amaranth (1.52±0.4 mg/kg) did not exceed the permissible levels for forage crops by 3.28 times, which is confirmed by a hazard coefficient of 0.30±0.024. This makes it possible to consider the use of biomass for fodder purposes. In amaranth seeds, the lead content (0.66±0.031 mg/kg) slightly exceeded the maximum permissible values for cereal crops (by 1.32 times), which correlates with a hazard coefficient of 1.33±0.042.

The phytoremediation efficiency of amaranth is characterized by significant lead removal from the soil: 34.2 g/ha with the vegetative mass and 1.4 g/ha with the seeds. The predominant accumulation of the toxicant in the aboveground biomass (23.7 times higher than in seeds) confirms the promising potential of amaranth for cleaning lead-contaminated soils. The research results indicate the feasibility of using amaranth as a dual-purpose crop – both for the phytoremediation of lead-contaminated soils and for obtaining relatively safe forage products, which is of great importance for the development of bioecological technologies for the restoration of degraded agricultural lands.

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