Agronomy Research **22**(1), 227–237, 2024
https://doi.org/10.15159/AR.23.108

Phytoremediation potential of oat (*Avena sativa* L.) in soils contaminated with cadmium

B. Piršelová[1,*] Ľ. Galuščáková[1], L. Lengyelová[1], V. Kubová[1], R. Matúšová[2], K. Bojnanská[3] and M. Havrlentová[3,4]

[1]Department of Botany and Genetics, Faculty of Natural Sciences and Informatics, Constantine the Philosopher University in Nitra, Nábrežie mLádeže 91, SK949 74 Nitra, Slovak Republic
[2]Institute of Plant Genetics and Biotechnology, Plant Science and Biodiversity Centre, Slovak Academy of Sciences, Akademická 2, P.O. Box 39A, SK950 07 Nitra, Slovak Republic
[3]National Agricultural and Food Centre, Research Institute of Plant Production in Piešťany, SK921 68 Piešťany, Slovak Republic
[4]Department of Biotechnologies, Faculty of Natural Sciences, University of Ss. Cyril and Methodius in Trnava, 917 01 Trnava, Slovak Republic
[*]Correspondence: bpirselova@ukf.sk

Received: October 1st, 2023; Accepted: November 28th, 2023; Published: December 15st, 2023

Abstract. Human activities can cause enormous damage to agricultural soils through the accumulation of toxic metals in the soil. The identification of plants capable of accumulating relatively large amounts of these compounds in plant tissues with the aim of reducing or limiting soil toxicity is of great interest. Two independent pot experiments were conducted to evaluate the phytoremediation potential of different varieties of oat (*Avena sativa* L.) grown in soil contaminated with cadmium (Cd, 50 mg kg^{-1} soil). Eight varieties were cultivated for 21 days in Cd- contaminated soil. Five varieties of oat were exposed to Cd at the third leaf stage, followed one week later by exposure to oat powdery mildew (*Blumeria graminis* f. sp. *avenae*) for 35 days. In general, the tested varieties accumulated more Cd in the roots than in the shoots and showed a high tolerance to Cd. Metal accumulation in shoots was lower after 21 days of cultivation (8.30–17.27 mg Cd kg^{-1}) than after 42 days (13.72–35.20 mg Cd kg^{-1}) and was the highest in tissues of plants infected with *B. graminis* (48.17–96.20 mg kg^{-1}). In conclusion, our results indicate a good phytostabilization and remediation potential of oat (varieties Racoon and Vaclav) for soil contaminated with cadmium.

Key words: *Avena sativa* L., cadmium tolerance, phytostabilization, remediation.

INTRODUCTION

Soil contamination by heavy metals is a serious environmental problem due to industrialization, urbanization, and intensive agricultural practices. Soil detoxification is quite complicated and technologically difficult. Current remediation methods include physicochemical and biological remediation with the aim of reducing the bioavailability of heavy metals and thus their toxic effects. Physicochemical remediation involves redox, adsorption, and complexation reactions, but it is expensive and it is not possible to completely eliminate toxic compounds (Luo & Zhang, 2021). A promising approach is so-called phytoremediation. Phytoremediation involves the use of plants that accumulate larger amounts of toxic compounds in their tissues. Plants suitable for soil phytoremediation should grow rapidly, produce substantial biomass, have accumulation of toxic elements in their tissues without causing damage, and the overall management should be done in a simple manner (Raskin et al., 1997; Kasiuliene et al., 2016). Plants that are able to accumulate large amounts of risk compounds are hyperaccumulators. However, hyperaccumulators are often not suitable for phytoremediation due to their slow growth and low biomass production. Therefore, the identification of alternative plants that are tolerant to toxic compounds and can produce a considerable amount of biomass with relatively good accumulation potential is of interest.

Cadmium (Cd) is a non-essential element for plants and is considered one of the most toxic heavy metals due to its high mobility and ability to induce toxicity even at low concentrations in organisms (Benavides et al., 2005). Agricultural soils in many parts of the world are contaminated with cadmium as a result of the long-term use of phosphate fertilizers, various wastes in the form of composts and sludge from wastewater treatment plants (Niño-Savala et al., 2019; Tytła, 2019).

Limit for Cd in soil of Slovak Republic is 1.0 mg kg^{-1} of dry matter (Decree No. 59/2013). Cadmium content above 3 mg kg^{-1} soil is generally thought to indicate contaminated soils (Alloway, 1995). The toxic effects of cadmium on plant growth and metabolism are well documented: Cd inhibits cell division, impairs photosynthesis, nutrient assimilation, and the activity of various enzymes (Benavides et al., 2005, Lux et al., 2011; Alle et al., 2019; Pivková et al., 2022). Previous studies indicate large differences in metal accumulation among plant species and varieties (Murtic et al., 2019). Hyperaccumulators of cadmium are plant species that accumulate more than 100 mg Cd kg^{-1} dry weight in shoots (Baker & Walker, 1990). However, several studies with tolerant plants in remediation programs were unsuccessful because the specific interactions between genotype and environment were not considered.

Oat (*Avena sativa* L.), which belongs to the *Poaceae* family, is a multi-purpose cereal grown in many parts of the world. Oat is an exceptional crop in terms of its use in crop production, as it is not only an important forage crop, but also a food with high dietary and nutritional value (Ibrahim et al., 2022). Although several studies indicated a good accumulation potential of oat for Cd from soils contaminated with heavy metals (Azizian et al., 2011; Boros-Lajszner et al., 2020), data on the remediation potential of oat for Cd are scarce. Interesting in this respect is black oat (*Avena strigosa* Schreb.). Uraguchi and co-workers (2006) grew black oat seedlings for 4 weeks in hydroponic culture and then treated them with Cd for four days. *A. strigosa* showed high tolerance to Cd at a dose of 5 mg L^{-1}. Long-term Cd treatment of black oat (seedlings were grown on vermiculite for 2 weeks and then transferred to a hydroponic solution containing 1.1 mg L^{-1} Cd for 4 weeks) resulted in the accumulation of 74 mg Cd kg^{-1} dry weight (DW) in leaves, 140 mg kg^{-1} DW in stems, and 958 mg kg^{-1} DW in roots, placing black oat among the Cd-hyperaccumulating species (Uraguchi et al., 2009).

The aim of this study was to evaluate the remediation potential of oat varieties for soils contaminated with cadmium, of uninfected oats and of oats infected with the fungal pathogen *Blumeria graminis* f. sp. *avenae* in the case of short- and long-term exposure of oat seedlings to cadmium.

MATERIAL AND METHODS

Ten varieties of oat (*Avena sativa* L., Pushinskij, Vok, Valentin, Vaclav, V2 6/19, Prokop, Racoon, Aragon, Bay Yan 2, and Ivory) were used for the present study. Varieties Valentin, Vaclav and Prokop are Slovak registered varieties commonly available in the European Union (EU). The unregistered variety V2 6/19 is a variety bred in Slovakia, but it is not commonly available in the EU. Other varieties - Russian Pushkinskij, Chinese Bay Yan 2, German Aragon, German Ivory, Czech Vok and British Racoon are not commonly available in the EU. The seeds were obtained from the Gene Bank of the Slovak Republic. The genotypes used in the experiment were selected according the content of beta-glucans (cell wall polysaccharide of selected Poales with putative protecting function in the cell) (unpublished data). Another way for genotypes selection was the availability and possibility of cultivation of these materials.

Pot experiment 1

Seeds of eight oat varieties (Pushinskij, Vok, Valentin, Vaclav, V2 6/19, Prokop, Racoon, and Aragon) were sown in pots (15 seeds/pot, pot diameter 15 cm) containing a white peat potting substrate (Klasmann KTS 2, Klasmann-Deilmann GmbH, Germany, pH KCl 6.7, gravimetric soil water content max. 70%, EC in µS 400, total cadmium content 1.2 mg kg^{-1}, nitrogen content 1.65 g kg^{-1}, carbon content (C organic) 81.59 g kg^{-1}, phosphorus content 0.38 g kg^{-1}, potassium content 0.43 g kg^{-1}). The plants were grown in the FitotronII plant growth chamber under working conditions: temperature 24 °C, humidity 60%, with a 12/12 hour photoperiod and a light intensity of 20, 000 lux.

The plants were treated with tap water (control) or with a Cd solution irrigated at a dose of 50 mg Cd per kg substrate in three biological replicates. Cd was used in the form of $CdCl_2.2H_2O$. Plants were watered regularly throughout the experiment to maintain the maximum sorption capacity of the soil.

After three weeks, the seedlings were removed from the substrate and carefully cleaned from the substrate. The fresh weight (FW) of the roots and shoots of each plant was determined. The samples were then dried at 60 °C for two days to determine the dry weight (DW). The shoot tolerance index was calculated: TI (%) = (average biomass content of Cd treated plants/average biomass content of control plants) x 100.

Pot experiment 2

Seeds of five oat varieties (Aragon, Bay Yan 2, Ivory, Vaclav, and Racoon) were sown in plastic pots (diameter 25 cm) filled with 1,250 g Klasmann TS 2 substrate and grown in the FitotronII plant growth chamber under working conditions: temperature 15–24 °C, humidity 62–82%, with a 16/8 hour photoperiod and a light intensity of 20,000 lux, at 10 plants per pot.

After 22 days of cultivation in the given conditions (at the third leaf stage), 50 mg Cd per kg soil was added to the soil. After a seven-day Cd treatment, some seedlings were exposed to Cd for another 35 days (total of 42 days of Cd treatment) and some were also inoculated with the fungal pathogen *Blumeria graminis* f. sp. *avenae* for 35 days (variant Cd + *Bg*). The seedlings were inoculated with spores of *B. graminis* at a dose of 1,000–2,500 spores per cm^2 in a settling tower. The spores were dispersed in turbulent air in a settling tower, the density of inoculation was determined on Petri dishes with agar medium placed on the inoculated pots. Control plants were grown under conditions without Cd and infection. The experiment was performed with three biological replicates. After 64 days of growth, the roots were separated from the shoots and the dry matter was determined by drying the biomass at 60 °C for 48 hours.

Detection of cadmium in plant tissue and soil

Plant material and soil sample (0.5 g each) were digested in a mixture of 5 mL water, 5 mL HNO_3 (Merck, Darmstadt, Germany), and 1.5 mL H_2O_2 (30%, Slavus, Bratislava, Slovakia) using the Mars Xpress microwave oven (CEM Corporation, Matthews, NC, USA). Cadmium was detected by inductively coupled plasma optical emission spectroscopy (ICP-OES 725, Varian 725 ES ICP, Melbourne, Australia) according to Kováčik et al. (2019).

Evaluation of the efficiency of plant uptake

Based on the Cd content in the tissues, the bioaccumulation factor (BAF) was calculated to measure the relative Cd concentration in the plant organ compared to the cadmium content in the soil and the translocation factor (TF), which indicates the ability of the plant to transport Cd from the below-ground parts to the above-ground parts (Usman et al., 2019): BAF = cadmium content in plant organ/cadmium content in soil; TF = cadmium content in shoots/cadmium content in roots.

Statistical analyses

The obtained results were statistically analysed using the XLSTAT software. The basic statistical characteristics (arithmetic mean, standard deviation) were determined. The differences between the experimental variants were analysed using the t-test or the Kruskal-Wallis test followed by a Dunn's post hoc test ($p < 0.05$).

RESULTS

To evaluate the phytoremediation potential of different varieties of oat (*A. sativa* L.) grown in soil contaminated with cadmium (Cd), we conducted two independent experiments. The results are presented grouped by experiment. The tested oats showed a high tolerance to 50 mg kg^{-1} Cd in the soil.

As a result of the tested dose of Cd, in the case of the varieties Pushinskij, Vok, Valentin, Racoon and Aragon, there was even a significant elongation of shoots by 6.9%, 5.6%, 6.8%, 4.7% and 9.0% respectively. An increase in the fresh biomass of the shoots (by 25.9%, 16.7% and 20%) was observed in Pushinskij, Vok and Aragon varieties. An increase in dry matter content (by 11.1%) was also observed in the Aragon variety (Table 1).

Table 1. Effect of cadmium on shoot growth parameters of oat varieties

Variety	Variant of experiment	Length (cm)	Fresh weight (g)	Dry weight (g)
Pushinskij	Control	29.46 ± 5.10	0.27 ± 0.07	0.030 ± 0.010
	Cd	31.48 ± 5.03*	0.34 ± 0.06*	0.037 ± 0.009
Vok	Control	30.11 ± 4.76	0.36 ± 0.05	0.041 ± 0.006
	Cd	31.79 ± 4.68*	0.42 ± 0.05*	0.043 ± 0.005
Valentin	Control	29.28 ± 4.14	0.39 ± 0.06	0.039 ± 0.006
	Cd	31.26 ± 3.95*	0.41 ± 0.06	0.042 ± 0.004
Vaclav	Control	31.83 ± 3.95	0.37 ± 0.06	0.041 ± 0.006
	Cd	30.16 ± 4.24	0.39 ± 0.07	0.040 ± 0.009
V2 6/19	Control	29.33 ± 3.23	0.31 ± 0.08	0.032 ± 0.008
	Cd	29.36 ± 4.17	0.35 ± 0.06	0.035 ± 0.004
Prokop	Control	30.29 ± 4.35	0.37 ± 0.05	0.038 ± 0.006
	Cd	30.98 ± 5.00	0.35 ± 0.05	0.035 ± 0.004
Racoon	Control	31.13 ± 4.48	0.39 ± 0.06	0.040 ± 0.006
	Cd	32.59 ± 4.64*	0.41 ± 0.06	0.039 ± 0.005
Aragon	Control	30.49 ± 4.26	0.35 ± 0.05	0.036 ± 0.005
	Cd	33.22 ± 5.09*	0.42 ± 0.06*	0.040 ± 0.006*

Data are presented as *means* ± *SD* of three biological replicates. * the significance level of the differences compared to the control at $p < 0.05$ (*t*-test).

The tolerance indexes ranged from 93.50 to 125.43% (for the fresh weight of the shoots) and 94.53–122.96 (for the dry matter content of the shoots). The highest tolerance was found in the Pushinskij variety (TI_{DW} = 122.96%) and the lowest in the Prokop variety (TI_{DW} = 94.53 for the DW) (Fig. 1).

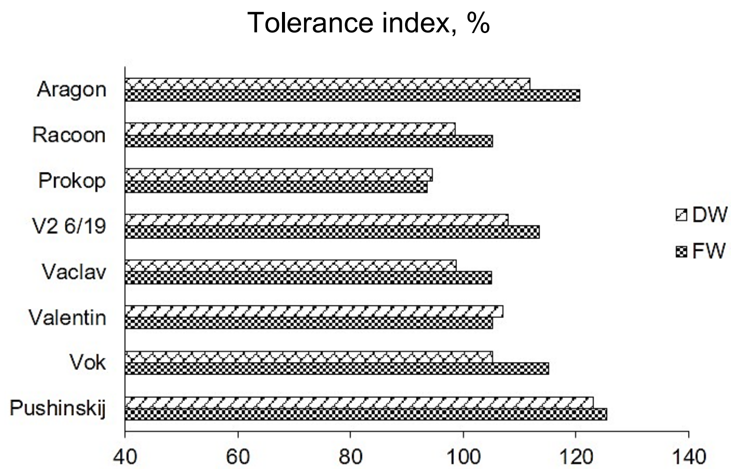

Figure 1. The tolerance index determined based on the fresh weight (FW) and the dry weight (DW) of the shoots.

The varieties differed in the amount of Cd accumulated in the tissues. Seedlings grown for 21 days in the presence of Cd accumulated from 8.3 mg Cd kg^{-1} in the variety Valentin to 17.27 and 14.67 mg Cd kg^{-1} shoot DW in the V2 6/19 and Pushinskij. The accumulation of cadmium in roots was higher in all samples and ranged from

28.4 mg Cd kg^{-1} DW in the variety Vok to 50.45, 49.35, and 48.05 mg Cd kg^{-1} DW in the V2 6/19, Aragon, and Pushinskij, respectively (Fig. 2).

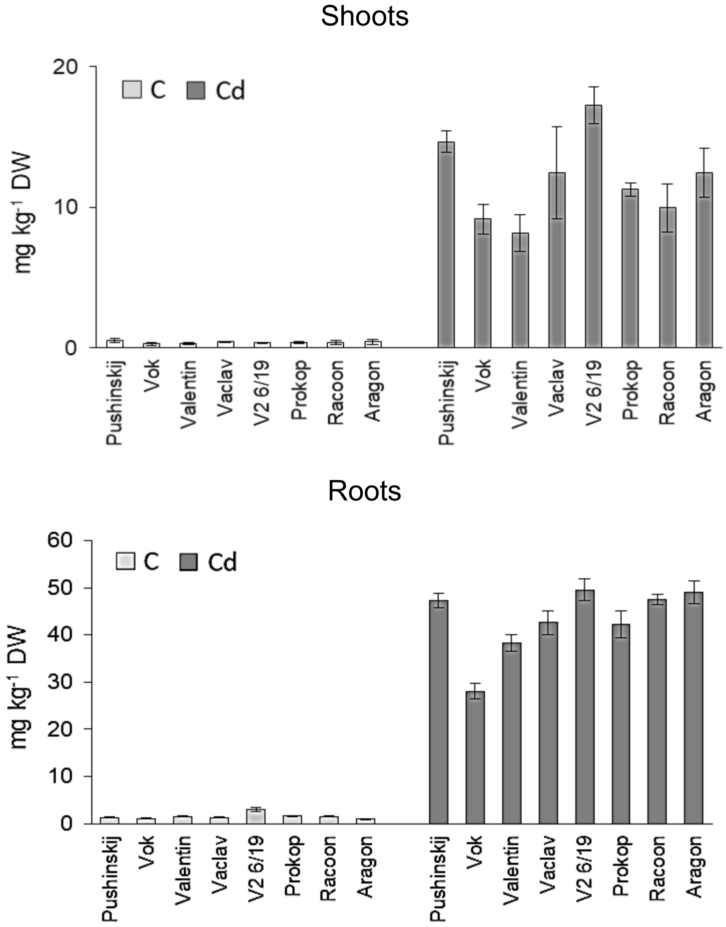

Figure 2. Cadmium content in shoots and roots of the tested oat varieties exposed to cadmium (Cd 50 mg kg^{-1} soil) for 21 days. Data are presented as *means* ± *SD* of three biological replicates. Control plants (C), cadmium-treated plants (Cd).

To evaluate the remediation potential of oat, the bioaccumulation factor (BAF) and translocation factor (TF) were determined. The BAF expresses the efficiency of metal accumulation in the plant tissue in relation to the amount in the soil and the TF expresses the ability of the plants to translocate the metal into the shoots. The BAF values reflect the amount of Cd in the tissues. BAF values for roots were higher (0.57–1.00) than for shoots (0.18–0.29). The highest values of BAF for roots were achieved by the varieties V2 6/19 (1.00), Aragon (0.99), Pushinskij and Racoon (0.96), the lowest by the varieties Vok (0.57) and Valentin (0.77). The highest values of BAF for shoots were achieved by the varieties Pushinskij (0.29), Vaclav and Aragon (0.25), the lowest by the varieties Vok (0.18) and Valentin (0.19).

Relatively low TF values (0.21–0.35) also indicate low metal transport from roots to shoots (Table 2). The most efficient Cd transport to the shoot was shown by the varieties V2 6/19 (0.35), Vok (0.32) and Pushinskij (0.30).

Table 2. Bioaccumulation factor (BAF) and translocation factor (TF) for the tested oat varieties (Experiment 1)

Variety	BAF for roots	BAF for shoots	TF shoots/roots
Pushinskij	0.96 ± 0.01 ab	0.29 ± 0.02 a	0.30 ± 0.02 abc
Vok	0.57 ± 0.03 d	0.18 ± 0.02 b	0.32 ± 0.06 ab
Valentin	0.77 ± 0.03 cd	0.19 ± 0.02 b	0.22 ± 0.05 cd
Vaclav	0.85 ± 0.05 bcd	0.25 ± 0.07 ab	0.29 ± 0.06 acd
V2 6/19	1.00 ± 0.04 a	0.22 ± 0.09 ab	0.35 ± 0.01 a
Prokop	0.86 ± 0.06 bcd	0.22 ± 0.01 ab	0.26 ± 0.01 bcd
Racoon	0.96 ± 0.02 abc	0.21 ± 0.06 b	0.21 ± 0.03 d
Aragon	0.99 ± 0.05 ab	0.25 ± 0.03 ab	0.25 ± 0.04 bcd

Data are given as *means* ± *SD* of three biological replicates. Differences between varieties were determined using the Kruskal-Wallis test followed by the Dunn's post-hoc test for multiple comparisons. Different letters indicate a significant difference ($p < 0.05$) between varieties for each parameter tested.

In experiment 2, as in experiment 1, higher Cd accumulation was observed in the roots compared to the shoots (Fig. 3), with the roots of infected plants accumulating slightly more Cd (151.00–307.33 mg kg^{-1} DW) than those of uninfected plants (63.52–308.85 mg kg^{-1} DW). Ivory and Racoon varieties accumulated the most Cd (Fig. 3).

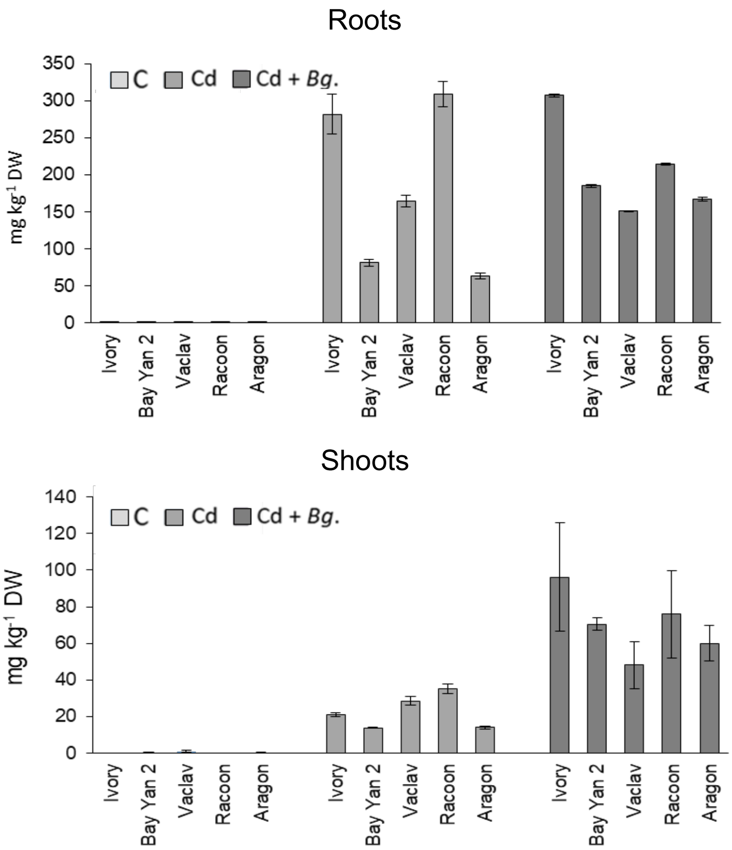

Figure 3. Cadmium (Cd) content in shoots and roots of the tested oat varieties grown in pots for 22 days and then exposed to Cd for 42 days or to Cd for 42 days plus *Blumeria graminis* (*Bg*) for 35 days. Data are presented as *means* ± *SD* of three biological replicates. Control plants (C), cadmium-treated plants (Cd), cadmium plus *Blumeria graminis* (Cd + *Bg*).

The Cd accumulation in the shoots also differed significantly depending on the type of exposure. 1.69–5.14 times more Cd was accumulated in the shoots of infected plants than in plants exposed to Cd only. Cadmium accumulated most in shoots of the Cd-exposed variety Racoon (35.20 mg kg^{-1} DW) and in infected shoots with the fungus *B. graminis* in the variety Ivory (96.20 mg kg^{-1} DW) (Fig. 3). In the experiment 2, the growth parameters were not evaluated, the infected variants showed signs of chlorosis and infection (white growth mycelium).

The accumulated Cd amounts in the tissues also reflect the BAF and TF values (Table 3). BAF for roots reached values of 1.27–6.18 for the Cd variant and 3.02–6.15 for the Cd + *Bg* variant. BAF values for shoots were lower, 0.27–0.70 for the Cd variant and 0.96–1.92 for the Cd + *Bg* variant. Thus, translocation of Cd from roots to shoots was higher for the Cd + *Bg* variant (TF = 0.31–0.38) than for the Cd variant (TF = 0.08–0.22) (Table 3).

Table 3. Bioaccumulation factor (BAF) and translocation factor (TF) for the tested oat varieties (Experiment 2)

Variety	BAF for roots	BAF for shoots	TF shoot/root
	Cd		
Ivory	5.63 ± 0.54^{ab}	0.42 ± 0.02^{cde}	0.08 ± 0.01^{d}
Bay Yan 2	1.63 ± 0.10^{de}	0.27 ± 0.01^{e}	0.17 ± 0.01^{cd}
Vaclav	3.28 ± 0.16^{bcde}	0.57 ± 0.05^{bcde}	0.17 ± 0.02^{bcd}
Racoon	6.18 ± 0.33^{a}	0.70 ± 0.05^{bcde}	0.11 ± 0.01^{d}
Aragon	1.27 ± 0.09^{e}	0.28 ± 0.02^{de}	0.22 ± 0.06^{abcd}
	Cd + *Bg*		
Ivory	6.15 ± 0.04^{a}	1.92 ± 0.59^{a}	0.31 ± 0.09^{abc}
Bay Yan 2	3.70 ± 0.04^{abcd}	1.41 ± 0.07^{ab}	0.38 ± 0.02^{a}
Vaclav	3.02 ± 0.02^{cde}	0.96 ± 0.26^{abcd}	0.32 ± 0.08^{abc}
Racoon	4.29 ± 0.03^{abc}	1.52 ± 0.48^{ab}	0.35 ± 0.11^{ab}
Aragon	3.35 ± 0.05^{bcde}	1.20 ± 0.19^{abc}	0.36 ± 0.05^{a}

Data are presented as *means* ± *SD* of three biological replicates. Differences between varieties/variants were determined using the Kruskal-Wallis test followed by the Dunn's post-hoc test for multiple comparisons. Different letters indicate a significant difference ($p < 0.05$) between the varieties/variants for each parameter tested. Cadmium-treated plants (Cd), cadmium plus *Blumeria graminis* (Cd + *Bg*).

DISCUSSION

The aim of this study was to evaluate and compare the remediation potential of selected oat varieties within different experimental approaches to abiotic and biotic stress.

The eight tested oat varieties showed high tolerance after 21 days of growth in contaminated soil (Tables 1, 2). The plants exposed to the metal for 42 days (experiment 2) also showed no visible symptoms of toxicity. Data evaluating the tolerance of oat to Cd ions are relatively sparse and controversial. High tolerance to Cd up to 20 mg kg^{-1} soil is indicated, for example, by Ciecko et al. (2004), Uraguchi et al. (2009), Tůma et al. (2014), and Marchel et al. (2018). On the other hand, growth inhibition, a decrease in photosynthetic pigment content and lower yield were already at doses of 10 mg kg^{-1} soil (Rolka, 2015; Boros-Lajszner et al., 2020). Astolfi et al. (2004) recorded a 32% and 33% decrease in fresh shoot biomass content and dry matter content of oat shoots exposed to a Cd dose of 0.154 mg kg^{-1} soil for 21 days. A significant reduction in fresh shoot biomass was also observed after 10 days of growth in soils with a Cd dose of 6.25 mg kg^{-1} soil (da Rosa Corrêa et al., 2006).

The amount of accumulated Cd in plant tissues was dependent on both genotype and experimental conditions, with plants preferentially accumulating Cd in roots, in agreement with other studies (Uraguchi et al., 2009; Tůma et al., 2014; Kasiuliene et al., 2016; Boros-Lajszner et al., 2020). Metal accumulation in the tissues was lower after 21 days of cultivation (experiment1) than after 42 days (experiment 2) and was higher in the tissues of infected plants (Figs 1, 2). Thus, the highest remediation potential was achieved by infected plants, while the Cd content in the shoots of some varieties (Ivory & Racoon) approached that of the hyperaccumulating species (96.20 and 75.83 mg kg^{-1} DW). These varieties also reached relatively high BAF values (0.42 and 0.70) after 42 days of cultivation in Cd-contaminated soil.

The higher accumulation of Cd in the shoots of infected plants is probably the result of the failure of defense mechanisms that help to prevent the transport of Cd to higher parts of the plant. Oats accumulated relatively high levels of Cd in the roots, 28.40–50.45 mg kg^{-1} DW after 21 days of cultivation, 63.52–308.85 mg kg^{-1} DW after 42 days of Cd exposure, and 151.00–307.33 mg kg^{-1} DW in the case of infected plants (Figs 1, 2).

The higher BAF values also correspond to the given data (Tables 3, 4). Comparable levels of Cd were also found in the tissues of oat (variety Moozart) at a dose of 53.61 mg kg^{-1} soil (Azizian et al., 2011). Tůma et al. (2014), on the other hand, measured 11.37 mg kg^{-1} Cd in younger leaves, 55.97 mg kg^{-1} Cd in older leaves, and 235.33 mg kg^{-1} Cd in roots at a dose of 20 mg Cd on 1 kg soil. The present results suggest genotypic variability in Cd accumulation. It is also interesting to note that Cd translocation from roots to shoots was comparable in infected plants (TF = 0.31–0.36) and in plants cultivated in Cd-contaminated soil for 21 days (0.21–0.34), but was generally slightly lower in plants exposed to Cd for 42 days (TF = 0.08–0.22). Relatively low values of TF (0.072) at a dose of 16 mg kg^{-1} soil were also found by Boros-Lajszner et al. (2020) for oat shoots. Our study shows that the remediation potential of oat is significantly determined by genotype, time of Cd exposure, and other environmental factors. The preferential and significant accumulation of Cd in the roots indicates a high phytostabilization potential of this plant species. The choice of varieties for remediation or phytostabilization of contaminated soils requires a complex approach and optimization of the methodology applied, taking into account the possible effects of different environmental factors.

CONCLUSION

The presented study showed that the tested oat varieties had a high tolerance to cadmium and accumulated Cd preferentially in the roots. Metal accumulation in tissues was lower after 21 days of cultivation than after 42 days and was higher in tissues of plants infected with *B. graminis.* Thus, the remediation potential of oat was the highest in infected plants which were simultaneously exposed to the metal for 42 days (BAF for shoots = 0.96–1.92). In non-infected plants, the BAF after 42 days of Cd exposure reached the highest values in the varieties Vaclav and Racoon (BAF = 0.57 and 0.70, respectively). The high tolerance of the tested oat genotypes to Cd and at the same time, the high accumulation potential of the roots both indicate the possibility of using these oat varieties for phytostabilization of Cd-contaminated soils. A more detailed investigation of the mechanisms of Cd tolerance of oat may help to increase the accumulation and remediation potential of oat.

ACKNOWLEDGEMENTS. This work was supported by the Slovak Research and Development Agency under Contract No. APVV-18-0154 and by the Ministry of Education, Science, Research and Sport of the Slovak Republic: grant VEGA 1/0073/20. We thank Ing. Peter Hozlár, PhD. for providing the seeds used within this work.

REFERENCES

Alle, V., Osvalde, A., Vikmane, M. & Kondratovics, U. 2019. The effect of cadmium and lead pollution on growth and physiological parameters of field beans (*Vicia faba*). *Agronomy Research* **17**(S2), 1261–1272.

Alloway, B.J. 1995. *Heavy Metals in Soils*. Blackie Academic and Professional, Chapman and Hall, London, 368 pp.

Astolfi, S., Zuchi S. & Passera, C. 2004. Effects of cadmium on the metabolic activity of *Avena sativa* plants grown in soil or hydroponic culture. *Biologia Plantarum* **48**, 413−418.

Azizian, A., Amin, S., Noshadi, M., Maftoun, M. & Emam, Y. 2011. Phytoremediation potential of corn and oat for increased levels of soil cadmium under different irrigation intervals. *Iran Agricultural Research* **30**, 47−59. doi: 10.22099/IAR.2012.493

Baker, A.J.M. & Walker, P.L. 1990. *Ecophysiology of metal uptake by tolerant plants*. In Shaw A.J. (ed.): Heavy Metal Tolerance in Plants: Evolutionary Aspects, Boca Raton, FL: CRC Press, 155–177.

Benavides, M.P., Gallego, S.M. & Tomaro, M.L. 2005. Cadmium toxicity in plants. *Brazilian Journal of Plant Physiology* **17**, 21−34. doi: 10.1590/S1677-04202005000100003

Boros-Lajszner, E., Wyszkowska, J. & Kucharski, J. 2020. Application of white mustard and oats in the phytostabilisation of soil contaminated with cadmium with the addition of cellulose and urea. *Journal of Soils and Sediments* **20**, 931–942. doi: 10.1007/s11368-019-02473-6

Ciecko, Z., Kalembasa, S., Wyszkowski, M. & Rolka, E. 2004. The effect of elevated cadmium content in soil on the uptake of nitrogen by plants. *Plant Soil Environment* **50**, 283–294. doi: 10.17221/4034-PSE

Da Rosa Corrêa, A., Rörig, L., Verdinelli, M., Cotelle, S., Férard, J. & Radetski, C. 2006. Cadmium phytotoxicity: Quantitative sensitivity relationships between classical endpoints and antioxidative enzyme biomarkers. *Science of the Total Environment* **357**, 120−127. doi: 10.1016/j.scitotenv.2005.05.002

Decree of the Ministry of Agriculture and Rural Development of the Slovak Republic No. 59/2013 (Decree No. 59/2013). Available online: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2013/59/20130401. Accessed 18.11. 2023.

Ibrahim, M., Aav, A. & Jõudu, I. 2022. The potential and limitations for applications of oat proteins in the food industry. *Agronomy Research* **20**(1), 161–173. doi: 10.15159/AR.22.008

Kasiuliene, A., Paulauskas, V. & Kumpiene, J. 2016. Influence of nitrogen fertilizer on Cd and Zn accumulation in rapeseed (*Brassica napus* L.) biomass. *Agronomy Research* **14**(2), 418–427.

Kováčik, A., Tvrdá, E., Miškeje, M., Árvay, J., Tomka, M., Zbynovska, K., Andreji, J., Hleba, L., Kováčiková, E., Fik, M., Čupka, P., Nahácky, J. & Massányi, P. 2019. Trace metals in the freshwater fish *Cyprinus carpio*: Effect to serum biochemistry and oxidative status markers. *Biological Trace Element Research* **188**, 494–507. doi: 10.1007/s12011-018-1415-x

Luo, J.S. & Zhang, Z. 2021. Mechanisms of cadmium phytoremediation and detoxification in plants. *The Crop Journal* **9**, 521−529. doi: 10.1016/j.cj.2021.02.001

Lux, A., Martinka, M., Vaculík, M. & Philip, J.W. 2011. Root responses to cadmium in the rhizosphere: A review. *Journal of Experimental Botany* **62**, 21–37. doi: 10.1093/jxb/erq281

Marchel, M., Kaniuczak, J., Hajduk, E. & Właśniewski, S. 2018. Response of oat (*Avena sativa*) to the addition cadmium to soil inoculation with the genus *Trichoderma fungi*. *Journal of Elementology* **23**, 471–482. doi: 10.5601/jelem.2017.22.1.1391

Murtic, S., Jurkovic, J., Basic, E. & Hekic, E. 2019. Assessment of wild plants for phytoremediation of heavy metals in soils surrounding the thermal power station. *Agronomy Research* **17**(1), 234–244. doi:10.15159/AR.19.005

Niño-Savala, A.G., Zhuang, Z., Ma, X., Fangmeier, A., Li, H., Tang, A. & Liu, X. 2019. Cadmium pollution from phosphate fertilizers in arable soils and crops: an overview. *Frontiers of Agricultural Science and Engineering* **6**, 419–430. doi: 10.15302/J-FASE-2019273

Pivková, I., Kukla, J., Hniličková, H., Hnilička, F., Krupová, D. & Kuklová, M. 2022. Content of cadmium and nickel in soils and assimilatory organs of park woody species exposed to polluted air. *Life* **12**, 2033. doi:10.3390/life12122033

Raskin, I., Smith, R.D. & Salt, D.E. 1997. Phytoremediation of metals: Using plants to remove pollutants from the environment. *Current Opinion* in *Biotechnology* **8**, 221–226. https://doi.org/10.1016/S0958-1669(97)80106-1

Rolka, E. 2015. Effect of soil contamination with cadmium and application of neutralizing substances on the yield of oat (*Avena sativa* L.) and on the uptake of cadmium by this crop. *Journal of Elementology* **20**, 975–986. doi: 10.5601/jelem.2014.19.4.810

Tůma, J., Skalický, M., Tůmová, L. & Flidr, J. 2014. Influence of cadmium dose and form on the yield of oat (*Avena sativa* L.) and the metal distribution in the plant. *Journal of Elementology* **19**, 795–810. doi: 10.5601/jelem.2014.19.3.448

Tytła, M. 2019. Assessment of heavy metal pollution and potential ecological risk in sewage sludge from municipal wastewater treatment plant located in the most industrialized region in Poland-Case study. *International Journal of Environmental Research and Public Health* **16**, 2430. doi: 10.3390/ijerph16132430

Uraguchi, S., Kiyono, M., Sakamoto, T., Watanabe, I. & Kuno, K. 2009. Contributions of apoplasmic cadmium accumulation, antioxidative enzymes and induction of phytochelatins in cadmium tolerance of the cadmium-accumulating cultivar of black oat (*Avena strigosa* Schreb.). *Planta* **230**, 267–276. doi: 10.1007/s00425-009-0939-x

Uraguchi, S., Watanabe, I., Yoshitomi, A., Kiyono, M. & Kuno, K. 2006. Characteristics of cadmium accumulation and tolerance in novel Cd-accumulating crops, *Avena strigosa* and *Crotalaria juncea*. *Journal of Experimental Botany* **57**, 2955–2965. doi:10.1093/jxb/erl056

Usman, K., Al-Ghouti, M.A. & Abu-Dieyeh, M.H. 2019. The assessment of cadmium, chromium, copper, and nickel tolerance and bioaccumulation by shrub plant *Tetraena qataranse*. *Scientific Reports* **9**, 5658. doi: 10.1038/s41598-019-42029-9