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Cadmium toxicity in garden cress (*Lepidium sativum* L.): germination and vegetative stage responses

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ABSTRACT: Cadmium is a hazardous toxic element that adversely affects plant vegetative and reproductive processes. Garden cress (*Lepidium sativum* L.) is a fragrant and savory herb, widely consumed in human diets, particularly in salads. This study researched the responses of garden cress to Cd in two experimental setups: germination tests in Petri dishes and hydroponic treatments during the early vegetative stage. In the germination experiment, seeds were put in Petri dishes with filter paper, and treated with $CdCl_2$ solutions at 0, 25, 50, 100, 200, and 500 µM concentrations. The Petri dishes were kept in a controlled environment, and germination parameters, including germination percentage, germination index, radicle and plumule length, and fresh and dry weight of sprouted seeds, were recorded. Then, the hydroponic experiment was carried out, and germinated seedlings were transferred to a nutrient solution with the same Cd concentrations. At harvest, root-shoot length, fresh and dry weight were measured, later pigment and proline analyses were done. Cd treatments caused a slight, non-significant reduction in germination percentage. While no marked changes were observed in plumule length, a significant reduction in radicle length was detected, particularly at doses of 100 µM and above. The fresh weights of germinated seeds showed a non-significant decreasing trend, whereas their dry weights increased and their water contents decreased significantly. In the hydroponic experiment shoot fresh and dry weights were markedly reduced under Cd treatments. Although no significant changes were detected in root fresh and dry weights, root length was found to be significantly reduced. Pigment contents slightly increased at low Cd levels but declined significantly at ≥100 µM. Proline accumulation increased progressively, reaching the highest level at 500 µM. The results indicate that Cd exposure induces stress in garden cress by adversely affecting germination, growth, and physiological processes.

KEYWORDS: Garden cress, Cadmium, growth, proline, pigment

INTRODUCTION

Heavy metals are among the most significant environmental contaminants, and their accumulation in ecosystems constitutes a global concern. Heavy metals can be released into the environment through anthropogenic (human-induced) or natural processes and can accumulate in various ecosystems. Cadmium (Cd), similar to lead, arsenic, and mercury, is a non-essential heavy metal (not required for biological functions) that poses significant risks to living organisms due to its highly toxic and hazardous nature [1, 2, 3]. Cd is classified as a heavy metal due to its density of 8.7 g cm^{-3}, which exceeds the threshold of 5 g cm^{-3} [4]. Major sources of Cd contamination include industrial emissions, sewage pollutants, agricultural fertilizers, and atmospheric deposition [5].

Cadmium has a wide range of detrimental effects on plants, affecting processes from seed germination to maturation. It reduces germination rates, induces water and oxidative stress, disrupts nutrient uptake, impairs enzyme activities, and interferes with carbon metabolism, ultimately decreasing crop yields [6]. Cadmium exposure also triggers leaf rolling, chlorosis, necrosis, and stomatal closure [7] and inhibits photosynthetic pigments and the overall photosynthetic process [8]. Moreover, Cd induces the production of non-enzymatic antioxidants such as proline, ascorbate, glutathione, flavonoids, vitamins, carotenoids, and alkaloids as a defense mechanism [7, 9].

Leafy vegetables are known to accumulate higher levels of metal ions compared to other types of vegetables [10, 11]. Garden cress (*Lepidium sativum* L.), a leafy vegetable from the Brassicaceae family, grows rapidly and is commonly used for medicinal purposes and as a spice. This cosmopolitan plant can adapt to various climates and soil types [12]. Garden cress has also been employed to assess the phytotoxic effects of contaminated environments [13]. In the present study, it was proposed that the effects of different cadmium concentrations on garden cress in two different growth

periods: germination and the early vegetative stage, be researched.

MATERIALS AND METHODS

Plant material

Seeds of garden cress (*Lepidium sativum* L.) cv. Helen, characterized by broad, bright-green leaves and commonly used as a culinary herb, were obtained from a commercial firm and used as plant material.

Method

Two treatments were conducted for this research. The germination period was assessed using a Petri dish treatment to focus on the initial seed sprouting, and the early vegetative stage was researched in hydroponic systems. The treatments were set up in Cukurova University Biology Department Plant Physiology Laboratory, in February and March months of 2024.

Petri dish treatment

During the germination phase of this study, Petri dishes were utilized as the primary medium to research the effects of cadmium chloride ($CdCl_2$) on germination phase. *Lepidium sativum* (garden cress) seeds were initially subjected to a surface sterilization procedure to eliminate potential microbial contaminants. This process involved immersing the seeds in a 3% sodium hypochlorite (NaOCl) solution for 5 minutes, followed by multiple rinses with distilled water to clear away any residual disinfectant.

After disinfection, 25 seeds were carefully put in each Petri dish between two layers of filter paper. To assess the impact of cadmium exposure on seed germination, the filter papers were moistened with cadmium chloride ($CdCl_2$) solutions at concentrations of 0, 25, 50, 100, 200, and 500 µM. Each treatment had four replications, ensuring statistical reliability. The Petri dishes were then arranged in a completely randomized design to minimize positional effects and potential biases.

This experimental setup facilitated a controlled and systematic evaluation of the dose-dependent effects of cadmium chloride ($CdCl_2$) on seed germination, allowing for a comprehensive assessment of its phytotoxic impact. To ensure uniform environmental conditions across all treatment groups, all Petri dishes were placed in a controlled climate chamber. The incubation conditions were kept at a constant temperature of 25°C, and the seeds were kept in complete darkness throughout the germination period to prevent the influence of light on germination responses.

To provide consistent moisture levels and ensure adequate cadmium exposure, the seeds were irrigated daily with their respective $CdCl_2$ solutions, corresponding to the predetermined concentrations. The number of germinated seeds was recorded every 24 hours to track the temporal progression of germination. A seed was considered successfully germinated when its radicle reached a minimum length of 2 mm, as per established germination criteria [14, 15].

By adhering to these standardized protocols, this study aimed to provide reliable and reproducible data on the negative effects of cadmium on seed germination, contributing valuable insights into the physiological effects of plants to heavy metal stress. After four days, the lengths of the radicle and plumule, along with the total fresh weight of the sprouted seeds, were measured. Germination percentage and germination index were then determined using the following formulas. The sprouted seeds were dried at 65 °C in an oven to obtain dry weights.

Germination percentage = (number of germinated seeds on the final day/number of tested seeds) × 100 [16]

Germination index= ∑Germination seeds at a given day/Day number [17]

Hydroponic treatment

In the second experimental treatment, seeds were initially sown in a perlite medium and maintained under controlled conditions until germination was completed. Subsequently, they were carefully transferred to a hydroponic system consisting of a nutrient solution with the following concentrations: 700 µM K_2SO_4, 100 µM KCl, 2000 µM $Ca(NO_3)_2$, 750 µM $MgSO_4$, 200 µM KH_2PO_4, 100 µM Fe-EDTA, 10 µM H_3BO_3, 1 µM $MnSO_4$, 0.2 µM $CuSO_4$, 0.01 µM $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$, and 1 µM $ZnSO_4$, the solution was refreshed every five days.

To ensure uniform environmental conditions across all experimental units, the pots containing the seedlings were randomly arranged within a climate-controlled growth chamber. To maintain oxygen availability in the nutrient solution, the hydroponic system was continuously aerated using an aquarium pump.

The climate chamber conditions were strictly regulated at a temperature of 25 ± 2°C, with a 16-hour light/8-hour dark photoperiod to optimize seedling development [18]. Each treatment was conducted with three independent replicates to enhance the statistical robustness of the study.

This setup ensured a controlled and reproducible environment, allowing for an accurate assessment of plant responses under hydroponic conditions. Following a one-week adaptation period in the hydroponic system, cadmium

chloride ($CdCl_2$) was administered at concentrations of 0, 25, 50, 100, 200, and 500 µM to evaluate its effects on seedling growth. The cadmium treatments were applied directly to the nutrient solution, ensuring uniform exposure across all experimental units.

After one week of cadmium exposure, the seedlings were carefully harvested, and a random selection of four seedlings per treatment was made for morphological and physiological assessments. The selected seedlings were subjected to detailed measurements, including root and shoot lengths, as well as fresh and dry biomass.

This experimental approach enabled a systematic evaluation of cadmium-induced stress, providing insights into its impact on plant growth parameters under hydroponic conditions.

Pigment analysis

To determine the pigment content, 100 mg of fresh leaf material was extracted in 10 mL of 80% acetone. The homogenate was then filtered to remove solid residues, ensuring a clear extract for spectrophotometric analysis.

The absorbance of the filtrate was measured using a UV-Vis spectrophotometer at 470, 646, and 663 nm, which correspond to the characteristic absorption peaks of carotenoids, chlorophyll b, and chlorophyll a, respectively. The concentrations of chlorophyll a, chlorophyll b, and total carotenoids were subsequently calculated using standard equations [19, 20]. This method provides a quantitative assessment of pigment composition, allowing for the evaluation of potential cadmium-induced alterations in photosynthetic pigment levels.

Proline analysis

To determine the proline content, 500 mg of fresh plant leaf was extracted using 3% sulfosalicylic acid. The extract was then filtered to remove solid residues, ensuring a clear supernatant for further analysis.

For colorimetric quantification, 2 mL of the extracted sample was transferred into a glass test tube, followed by the sequential addition of 2 mL of ninhydrin reagent (composed of ninhydrin, orthophosphoric acid, and acetic acid) and 2 mL of acetic acid. The reaction mixture was then incubated in a boiling water bath for one hour to facilitate the development of a chromophoric complex. Immediately after incubation, the tubes were rapidly cooled in an ice bath to stabilize the reaction products.

Subsequently, 4 mL of toluene was added to the reaction mixture to extract the colored proline-ninhydrin complex. The organic phase was carefully separated, and its absorbance was measured spectrophotometrically at 520 nm. The proline concentration in the samples was determined by referencing a standard curve generated using known concentrations of L-proline [21].

Statistical analyses

The experiments were conducted using a completely randomized design (CRD) to ensure the validity and reproducibility of the results. To assess the effects of cadmium (Cd) treatments, statistical analyses were performed using IBM SPSS Statistics 22. One-way analysis of variance (ANOVA) was applied to determine the differences among groups. When the assumption of homogeneity of variance was met, Tukey's HSD test was used for multiple comparisons; when homogeneity was not met, the Games–Howell post hoc test was employed. Results were presented as mean ± standard deviation (SD), and statistical differences among groups were indicated by different letters (a, b, c). In all tests, the significance level was accepted as $p < 0.05$.

RESULTS AND DISCUSSION

The Effects of Cadmium on Germination

According to the results, differences in germination percentage among the groups were statistically significant ($p < 0.05$); however, post-hoc multiple comparison tests did not reveal significant pairwise differences. A partial decreasing trend was observed in germination percentage with increasing Cd doses, although it did not reach statistical significance. This tendency suggests that cadmium exerts a dose-dependent inhibitory effect on seed germination. The adverse impact of Cd on germination has been well-documented [22, 23], and studies on species within the *Lepidium* genus provide additional support for these findings [24]. Overall, these results contribute to a broader understanding of Cd stress in garden cress and its implications for germination and early growth. In contrast, the germination index was not significantly affected by Cd treatments.

Table 1. The effects of Cd applications on germination percentage and germination index at the germination period (Mean±SD)

	Germination percentage (%)	Germination index
C	98±4.00	25.50±1.29
25 µM Cd	91±5.03	23.75±2.06
50 µM Cd	89±5.03	24.00±1.41
100 µM Cd	98±2.31	25.75±0.96
200 µM Cd	92±6.53	24.50±1.29
500 µM Cd	90±2.31	23.75±0.96

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

Although ANOVA indicated significant differences among groups for both plumule and radicle lengths, post-hoc multiple comparison tests revealed significant variation only in radicle length (Table 2). The results indicate that while plumule length remained relatively stable across treatments, radicle length exhibited a significant reduction at higher Cd concentrations ($p < 0.05$). A significant decrease in the radicle lengths was observed, especially at doses of 100, 200, and 500 µM Cd. These results suggest that roots are more sensitive to Cd than shoots and that toxic Cd accumulation may further inhibit root growth.

Table 2. The effects of Cd applications on plumule and radicle lengths at the germination period (Mean±SD)

	Plumule length (mm)	Radicle length (mm)
C	15.40±1.70	^{a}56.80±10.91
25 µM Cd	14.85±1.39	^{a}62.05±13.08
50 µM Cd	16.55±2.67	^{ab}49.90±13.29
100 µM Cd	16.45±2.14	^{c}38.80±11.15
200 µM Cd	15.35±2.18	^{c}40.35±14.45
500 µM Cd	14.70±3.11	^{c}32.45±8.24

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

When the effects of Cd treatments on fresh weight and dry weight and water content of sprouted seeds in garden cress were examined, no significant differences were found among the groups in terms of fresh weight. Although fresh weight exhibited a decreasing trend with increasing Cd concentrations, the most pronounced reduction occurred at 500 µM (Table 3). In contrast, significant differences were detected in sprouted seed dry weight. The control and 25 µM Cd groups remained at similar levels, whereas Cd treatments at ≥50 µM significantly increased dry weight. Moreover, water content exhibited a dose-dependent decline, with particularly significant reductions observed at 100–500 µM Cd compared to the control.

Table 3. The effects of Cd applications on sprouted seeds fresh-dry weights and water content at the germination period (Mean±SD)

	Fresh weight (mg)	Dry weight (mg)	Water content (%)
C	99±15.59	^{a}5.98±0.21	^{a}94±1.15
25 µM Cd	81±14.08	^{a}5.83±0.22	^{a}93±1.26
50 µM Cd	93±11.09	^{b}7.45±0.38	^{ab}92±0.82
100 µM Cd	83±10.00	^{b}8.00±0.29	^{b}90±1.50
200 µM Cd	86±15.09	^{b}7.48±0.53	^{b}91±1.15
500 µM Cd	80±8.81	^{b}7.75±0.24	^{b}90±0.82

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

These findings indicate that high Cd exposure induces physiological stress in sprouted seeds by reducing biomass and disrupting water balance. Cadmium disrupts cellular metabolism, limits water and nutrient uptake, and induces oxidative stress [25], all of which contribute to growth inhibition. Dry weight increased in response to Cd treatments. This apparent rise is likely attributable to stress-induced cellular water loss, resulting in a relative rather than an actual increase in dry biomass. Previous studies have reported that Cd stress reduces water content in plants [26, 27], and in agreement with these findings, our results also showed a decline in water content with increasing Cd concentrations.

The Effects of Cadmium on The Early Vegetative Period

Figure 1 illustrates the dose-dependent effects of cadmium (Cd) exposure on seedling growth, with increasing Cd concentrations (0, 25, 50, 100, 200, and 500 µM) visibly inhibiting root and shoot elongation. The control group (C) exhibited the most vigorous growth, with the longest root and shoot, indicating optimal development in the absence of Cd stress. At low Cd concentrations (25 and 50 µM), growth reduction was relatively minor; however, at higher concentrations (100, 200, and 500 µM), a pronounced decline in root elongation was observed. This figure demonstrates that Cd toxicity primarily affects root development. Cadmium enters the roots through the same transporters as nutrient elements such as calcium, iron, and magnesium, competing with them for uptake. Most of the absorbed Cd is retained in the roots, while a smaller fraction is translocated to the shoots via the xylem [28, 29, 30]. Consequently, roots are more severely affected by Cd toxicity than shoots. The severe growth inhibition observed at 500 µM Cd highlights the pronounced phytotoxic nature of cadmium in plants.

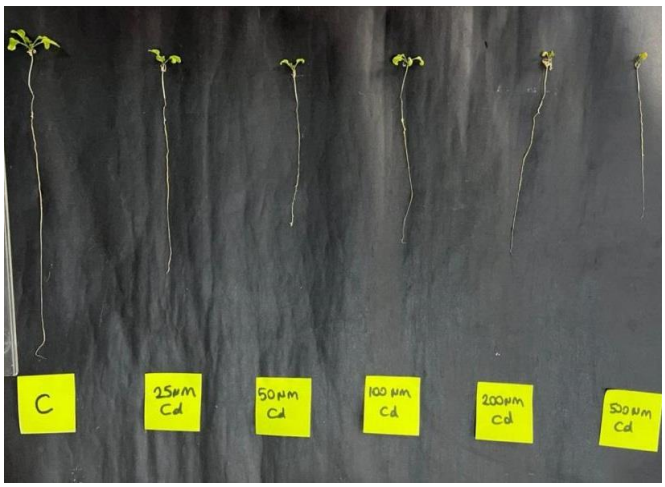

Figure 1. The effects of the Cd applications on garden cress seedlings during the early vegetative period

Shoot fresh weight, dry weight, and shoot length were found to be significantly affected by Cd treatments (Table 4). Cadmium exposure significantly reduces shoot biomass in a concentration-dependent manner, with a particularly pronounced impact on fresh weight. While shoot length does not exhibit a consistent pattern of reduction, the decline in fresh and dry weight indicates a severe physiological impact of Cd toxicity on shoot development. Although the variations among groups in root fresh and dry weights were not statistically significant, a significant reduction was observed in root length (Table 5). Cd exposure primarily inhibits root elongation rather than root biomass accumulation at lower concentrations, as evidenced by the initial decrease in root length despite stable fresh and dry weights at 25–100 µM Cd. However, at higher Cd concentrations (200 and 500 µM), both root length and biomass declined, indicating severe toxicity.

Previous studies have demonstrated that cadmium significantly decreases seed germination, reduces plant length, and suppresses root elongation [31]. The adverse effects of cadmium on root and shoot length and fresh weight are well documented [32, 33]. Moreover, cadmium may inhibit the photosynthetic mechanism [34], leading to growth retardation, particularly in shoots, and to a reduction in biomass production. The emergence of metabolic disorders may also contribute to reductions in root and shoot length. Consistent with these reports, our results clearly indicate that cadmium causes significant regression in both shoot and root length. Although a decreasing trend in pigment contents was observed in Table 6 with increasing Cd concentrations, no statistically significant differences were found. At low Cd concentrations (25–50 µM), chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll content exhibited a slight increase compared to the control, possibly reflecting a transient stress response. This response can be explained by 'hormesis,' in which low concentrations of cadmium exert a stimulatory effect [35].

Table 4. The effects of Cd applications on shoot fresh-dry weights and lengths at early vegetative period (Mean±SD)

	Shoot fresh weight (mg)	Shoot dry weight (mg)	Shoot length (mm)
C	^{a}110±21.98	^{a}9.23±1.45	^{ab}27±4.08
25 µM Cd	^{b}55±20.50	^{b}5.13±1.90	^{a}30±2.36
50 µM Cd	^{b}30±11.03	^{b}2.95±1.04	^{ab}28±2.08
100 µM Cd	^{b}36±19.14	^{b}4.93±1.65	^{b}20±6.70
200 µM Cd	^{b}34±7.44	^{b}5.30±1.87	^{ab}26±3.30
500 µM Cd	^{b}13±6.80	^{b}3.30±0.37	^{ab}28±2.89

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

Table 5. The effects of Cd applications on root fresh-dry weights and lengths at early vegetative period (Mean±SD)

	Root fresh weight (mg)	Root dry weight (mg)	Root length (mm)
C	12±6.22	1.63±0.41	^{a}198±45.45
25 µM Cd	16±1.91	2.23±0.43	^{b}133±22.20
50 µM Cd	16±12.34	2.28±0.70	^{b}105±0.96
100 µM Cd	18±7.42	2.13±0.75	^{b}111±11.36
200 µM Cd	16±7.87	2.50±0.44	^{b}95±9.22
500 µM Cd	15±3.32	1.78±0.30	^{b}104±7.59

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

Table 6. The effects of Cd applications on the pigment contents (mg/g fresh weight) at the early vegetative period (Mean±SD)

	Chla	Chlb	Total chl	Carotenoid
C	0.58±0.25	0.28±0.10	0.86±0.34	0.24±0.10
25 µM Cd	0.68±0.37	0.40±0.25	1.09±0.61	0.29±0.15
50 µM Cd	0.65±0.02	0.34±0.02	0.98±0.03	0.27±0.00
100 µM Cd	0.37±0.12	0.22±0.05	0.59±0.18	0.16±0.05
200 µM Cd	0.49±0.04	0.25±0.01	0.74±0.05	0.20±0.02
500 µM Cd	0.16±0.11	0.15±0.06	0.31±0.17	0.08±0.05

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

At moderate Cd concentrations (100–200 µM), a marked decline in all pigment levels was observed, suggesting that Cd-induced oxidative stress and chloroplast dysfunction compromised pigment stability. At the highest Cd concentration (500 µM), Chl a, Chl b, and total chlorophyll content decreased substantially, with total chlorophyll dropping to nearly one-third of the control value. Similarly, carotenoid content declined progressively with increasing Cd levels, highlighting impairment of the photoprotective mechanisms. These findings are consistent with previous reports indicating that Cd toxicity disrupts pigment biosynthesis [36, 37].

A statistically significant ($p < 0.05$) progressive increase in proline accumulation was observed with rising Cd concentrations (Table 7).

In the control group, the proline content was minimal (10 µM), reflecting normal physiological conditions. At low Cd concentrations (25–50 µM), proline levels began to increase, reaching approximately four times the control value at 50 µM Cd, indicating an early adaptive response. At moderate Cd levels (100–200 µM), proline accumulation became more pronounced, nearly sevenfold higher than the control at 100 µM Cd, emphasizing its role in osmotic adjustment and stress

mitigation. The highest proline content (134.98 µM) was observed at 500 µM Cd, suggesting an extreme stress response under severe Cd toxicity. Nitrogenous metabolites synthesized by plants play a crucial role in coping with stress. Proline amino acid is one of these metabolites and is particularly effective in reducing protein degradation. Therefore, an increase in proline levels serves as a marker of stress in plants [38]. The same phenomenon is observed in this study, that the increase in proline levels indicates the adverse effects of heavy metal stress on plants. Proline acts as an osmotic protectant under stress conditions, regulates cell structures like proteins and membranes, scavenges free radicals and buffers cellular redox potential. Its chelator ability and protective role against cadmium also explain proline's anti-stress activity in plants [39, 40, 41, 42].

Table 7. The effects of Cd applications on proline content at the early vegetative period.

	Proline content (µM)
C	^{a}10±3.97
25 µM Cd	^{a}19±2.44
50 µM Cd	^{ab}40.864±16.81
100 µM Cd	^{b}71.388±5.20
200µM Cd	^{b}75.6±21.74
500 µM Cd	^{c}134.984±4.13

Where significant differences exist among the groups, they are indicated by superscript letters above the means in the table ($p < 0.05$).

CONCLUSION

This study demonstrated that cadmium (Cd) exposure significantly affected seed germination, seedling growth, and physiological responses in garden cress. Increasing Cd concentrations led to a decline in germination percentage and germination index, confirming the adverse effects of heavy metals on early plant development. Cd treatments also caused a significant reduction in sprouted seeds fresh weight, whereas dry weight increased, likely due to stress-induced water loss. Root growth was more severely impaired than shoot growth, indicating greater root sensitivity to Cd toxicity. Moreover, Cd stress altered pigment composition, particularly at the highest concentration (500 µM), suggesting potential disruptions in the photosynthetic process. A significant increase in proline content under Cd exposure further supported the stress response, as proline accumulation served as an adaptive mechanism to counteract oxidative damage. Overall, these findings highlight the detrimental impact of cadmium on plant physiology, emphasizing its role in growth inhibition, water imbalance, and oxidative stress induction. Future research should investigate potential mitigation strategies, such as the application of antioxidants or biostimulants, to enhance plant resistance against heavy metal stress.

DECLARATION

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Competing interests

The authors declared that there is no conflict of interest.

REFERENCES

[1] Li, Y., Rahman, S. U., Qiu, Z., Shahzad, S. M., Nawaz, M. F., Huang, J., Naveed, S., Wang, X., Cheng, H. (2023): Toxic effects of cadmium on the physiological and biochemical attributes of plants, and phytoremediation strategies: A review. Environmental Pollution *325*: 121433. https://doi.org/10.1016/j.envpol.2023.121433

[2] Bortoloti, G. A., Baron, D. (2022): Phytoremediation of toxic heavy metals by Brassica plants: A biochemical and physiological approach. Environmental Advances 8: 100204. https://doi.org/10.1016/j.envadv.2022.100204

[3] Ur Rahman, S., Xuebin, Q., Yasin, G., Cheng, H., Mehmood, F., Zain, M., Shehzad, Ahmad, M. I., Riaz, L., Rahim, A., Ur Rahman, S. (2021): Role of silicon on root morphological characters of wheat (*Triticum aestivum* L.) plants grown under Cd-contaminated nutrient solution. Acta Physiologiae Plantarum 43: 1–13. https://doi.org/10.1007/s11738-021-03228-y

[4] Toppi, L. S., Gabrielli, R. (1999): Response to cadmium in higher plants. Environmental and Experimental Botany 41: 105–130. https://doi.org/10.1016/S0098-8472(98)00058-6

[5] Hocaoğlu-Özyiğit, A., Genç, B. N. (2020): Cadmium in plants, humans and the environment. Frontiers in Life Sciences and Related Technologies 1(1): 12–21.

[6] Zulfiqar, U., Ayub, A., Hussain, S., Waraich, E. A., El-Esawi, M. A., Ishfaq, Ahmad, M., Ali, N., Maqsood, M. F. (2022): Cadmium toxicity in plants: Recent progress on morpho-physiological effects and

remediation strategies. Journal of Soil Science and Plant Nutrition 22(1): 212-269. https://doi.org/10.1007/s42729-021-00645-3

[7] Abedi, T., Mojiri, A. (2020): Cadmium uptake by wheat (*Triticum aestivum* L.): An overview. Plants 9(4): 500. https://doi.org/10.3390/plants9040500

[8] Chen, X., Tao, H., Wu, Y., Xu, X. (2022): Effects of Cadmium on metabolism of photosynthetic pigment and photosynthetic system in *Lactuca sativa* L. revealed by physiological and proteomics analysis. Scientia Horticulturae 305: 111371. https://doi.org/10.1016/j.scienta.2022.111371

[9] Yılmaz, D. D., Parlak, K. U. (2011): Changes in proline accumulation and antioxidative enzyme activities in *Groenlandia densa* under cadmium stress. Ecological Indicators 11(2): 417–423. https://doi.org/10.1016/j.ecolind.2010.06.012

[10] Alexander, P. D., Alloway, B. J., Dourado, A. M. (2006): Genotypic variations in the accumulation of Cd, Cu, Pb and Zn exhibited by six commonly grown vegetables. Environmental Pollution 144(3): 736–745. https://doi.org/10.1016/j.envpol.2006.03.001

[11] Yildirim, E., Ekinci, M., Turan, M., Ağar, G., Dursun, A., Kul, R., Alim, Z., Argin, S. (2021): Humic+ Fulvic acid mitigated Cd adverse effects on plant growth, physiology and biochemical properties of garden cress. Scientific Reports 11(1): 8040. https://doi.org/10.1038/s41598-021-86991-9

[12] Abdel-Aty, A. M., Elsayed, A. M., Gad, A. A. M., Barakat, A. Z., Mohamed, S. A. (2023): Antioxidant system of garden cress sprouts for using in bio-monitor of cadmium and lead contamination. Scientific Reports 13(1): 10445. https://doi.org/10.1038/s41598-023-37430-4

[13] Oleszczuk, P. (2010): Testing of different plants to determine influence of physico-chemical properties and contaminants content on municipal sewage sludges phytotoxicity. Environmental Toxicology 25(1): 38–47. https://doi.org/10.1002/tox.20470

[14] Soltani, A., Khodarahmpour, Z., Jafari, A. A., Nakhjavan, S. (2012): Selection of alfalfa (*Medicago sativa* L.) cultivars for salt stress tolerance using germination indices. African Journal of Biotechnology 11(31): 7899–7905. https://doi.org/10.5897/AJB11.3977

[15] Özyazıcı, G. (2023): Fesleğen (*Ocimum basilicum* L.)'de çimlenme parametrelerine borikasit uygulamalarının etkisi. In: Proceedings of the 7th International Scientific Research and Innovation Congress, 16–17 December 2023, Ankara, Türkiye.

[16] Ikić, I., Maričević, M., Tomasović, S., Gunjača, J., Šatović, Z., Šarčević, H. (2012): The effect of germination temperature on seed dormancy in Croatian-grown winter wheats. Euphytica 188(1): 25–34. https://doi.org/10.1007/s10681-012-0735-8

[17] Wang, Y. R., Yu, L., Nan, Z. B., Liu, Y. L. (2004): Vigor tests used to rank seed lot quality and predict field emergence in four forage species. Crop Science 44(2): 535–541. https://doi.org/10.2135/cropsci2004.5350

[18] Hedayatzadeh, F., Banaee, M., Shayesteh, K. (2020): Bio-accumulation of lead and cadmium by radish (*Raphanus sativus*) and cress (*Lepidium sativum*) under hydroponic growing medium. Pollution 6(3): 681–693. https://doi.org/10.22059/poll.2020.297147.742

[19] Arnon, D.I. (1949): Copper enzymes in isolated chloroplasts, polyphenoxidase in *Beta vulgaris*. Plant Physiology 24: 1-15. https://doi.org/10.1104/pp.24.1.1

[20] Lichtenthaler, H.K., Wellburn, A.R. (1983): Determination of total carotenoids and chlorophyll a and b of leaf extract in different solvents. Biochemical Society Transactions 11: 591–592. https://doi.org/10.1042/bst0110591

[21] Bates, L., Waldren, R.P., Teare, I.D. (1973): Rapid determination of free proline for water-stress studies. Plant and Soil 39: 205-207. https://doi.org/10.1007/BF00018060

[22] Zhang, X., Fan, X., Li, C., Nan, Z. (2010): Effects of cadmium stress on seed germination, seedling growth and antioxidative enzymes in *Achnatherum inebrians* plants infected with a *Neotyphodium endophyte*. Plant Growth Regulation *60*: 91–97. https://doi.org/10.1007/s10725-009-9422-8

[23] Ahmad, I., Akhtar, M. J., Zahir, Z. A., Jamil, A. (2012): Effect of cadmium on seed germination and seedling growth of four wheat (*Triticum aestivum* L.) cultivars. Pakistan Journal of Botany 44(5): 1569–1574.

[24] Pavel, V. L., Sobariu, D. L., Diaconu, M., Stătescu, F., Gavrilescu, M. (2013): Effects of heavy metals on Lepidium sativum germination and growth. Environmental Engineering & Management Journal 12(4): 727–733. https://doi.org/10.30638/eemj.2013.089

[25] Arasimowicz-Jelonek, M., Floryszak-Wieczorek, J., Gwóźdź, E.A. (2011): The message of nitric oxide in cadmium challenged plants. Plant Science 181: 612–620. https://doi.org/10.1016/j.plantsci.2011.03.019

[26] Nedjimi, B., Daoud, Y. (2009): Cadmium accumulation in *Atriplex halimus* subsp. *schweinfurthii* and its influence on growth, proline, root hydraulic conductivity and nutrient uptake. Flora Morphol Distribut Funct Ecol Plants 204:316–324. https://doi.org/10.1016/j.flora.2008.03.004

[27] Younis, U., Malik, S. A., Qayyum, M. F., Shah, M. H. R., Shahzad, A. N., Mahmood, S. (2015): Biochar affects growth and biochemical activities of fenugreek (*Trigonella corniculata*) in cadmium polluted soil. Journal of Applied Botany and Food Quality *88*: 29–33. https://doi.org/10.5073/JABFQ.2015.088.006

[28] Cataldo, D. A., Garland, T. R., Wildung, R. E. (1983): Cadmium uptake kinetics in intact soybean plants. Plant Physiology 73: 844–848. https://doi.org/10.1104/pp.73.3.844

[29] Clarkson, D. T., Lüttge, U. (1989): Mineral nutrition: divalent cations, transport and compartmentation. In: Behnke, H.-D., Esser, K., Kubitzki, K., Runge, M., Ziegler, H. (eds.), *Progress in Botany*, Vol. 51, pp. 93–112. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-75154-7_7

[30] Benavides, M. P., Gallego, S. M., Tomaro, M. L. (2005): Cadmium toxicity in plants. Brazilian Journal of Plant Physiology 17(1): 21–34. https://doi.org/10.1590/S1677-04202005000100003

[31] El Rasafi, T., Oukarroum, A., Haddioui, A., Song, H., Kwon, E. E., Bolan, N., Tack, F. M. G., Sebastian, A., Rinklebe, J. (2022): Cadmium stress in plants: A critical review of the effects, mechanisms, and tolerance strategies. Critical Reviews in Environmental Science and Technology 52(5): 675–726. https://doi.org/10.1080/10643389.2020.1835435

[32] Nouri, M., El Rasafi T., Haddioui A. (2019): Responses of Two Barley Subspecies to Induced Heavy Metal Stress: Seeds Germination, Seedlings Growth and Cytotoxicity Assay. Agriculture (Pol'nohospodárstvo) 65(3): 107–118. https://doi.org/10.2478/agri-2019-0011

[33] Rao, G., Huang, S., Ashraf, U., Mo, Z., Duan, M., Pan, S., Tang, X. (2019): Ultrasonic seed treatment improved cadmium (Cd) tolerance in *Brassica napus* L. Ecotoxicology and Environmental Safety *185*:109659. https://doi.org/10.1016/j.ecoenv.2019.109659

[34] Farooq, M. A., Ali, S., Hameed, A., Bharwana, S. A., Rizwan, M., Ishaque, W., Farid, M., Mahmood, K., Iqbal, Z. (2016): Cadmium stress in cotton seedlings: physiological, photosynthesis and oxidative damages alleviated by glycinebetaine. South African Journal of Botany 104: 61-68. https://doi.org/10.1016/j.sajb.2015.11.006

[35] Zhao, X., Huang, S., Yao, Q., He, R., Wang, H., Xu, Z., Liu, D. (2024): ABA-regulated MAPK signaling pathway promotes hormesis in sugar beet under cadmium exposure. Journal of Hazardous Materials 480: 135968. https://doi.org/10.1016/j.jhazmat.2024.135968

[36] Muradoglu, F., Gundogdu, M., Ercisli, S., Encu, T., Balta, F., Jaafar, H. Z., Zia-Ul-Haq, M. (2015): Cadmium toxicity affects chlorophyll a and b content, antioxidant enzyme activities and mineral nutrient accumulation in strawberry. Biological Research 48: 1–7. https://doi.org/10.1186/s40659-015-0001-3

[37] Dikilitaş, S. K., Uğurlar, F. (2024): Kadmiyum Toksisitesinin Adaçayı (*Salvia officinalis* L.) Bitkisinin Bazı Fizyolojik ve Biyokimyasal Özelliklerine Etkisi. *ISPEC* Journal of Agricultural Sciences *8*(4): 1113–1126. https://doi.org/10.5281/zenodo.13895323

[38] Sharma, S. S., Dietz, K. J. (2006): The significance of amino acids and amino acid-derived molecules in plant responses and adaptation to heavy metal stress. Journal of Experimental Botany 57(4): 711–726. https://doi.org/10.1093/jxb/erj073

[39] Sharma, S. S., Schat, H., Vooijs, R. (1998): In vitro alleviation of heavy metal induced enzyme inhibition by proline. Phytochemistry 46(2): 1531–1535. https://doi.org/10.1016/S0031-9422(98)00282-9

[40] Ashraf, M., Foolad, M. R. (2007): Roles of glycine betaine and proline in improving plant abiotic stress resistance. Environmental and Experimental Botany 59(2): 206–216. https://doi.org/10.1016/j.envexpbot.2005.12.006

[41] Maheshwari, R., Dubey, R. S. (2007): Nickel toxicity inhibits ribonuclease and protease activities in rice seedlings: Protective roles of proline and ascorbate. Plant Growth Regulation 51(3): 231–243. https://doi.org/10.1007/s10725-006-9163-x

[42] Zhao, Y. (2011): Cadmium accumulation and antioxidative defenses in leaves of *Triticum aestivum* L. and *Zea mays* L. African Journal of Biotechnology 10(15): 2936–2943. https://doi.org/10.5897/AJB10.1230