

Dose dependent phytotoxic effects of Cd, Ni, and Cu on cauliflower *in vitro*

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Abstract

This study was carried out to evaluate the effects of cadmium (Cd), nickel (Ni), and copper (Cu), which are significant components of industrial pollution, on germination and early seedling development in cauliflower (*Brassica oleracea* var. *botrytis*). Experiments were carried out in MS nutrient medium using heavy metal doses of 0 (control), 100, 300, and 500 μ M under *in vitro* conditions. Morphological and physiological parameters such as germination percentage, germination index, mean germination time, shoot-root length, and fresh and dry weight were examined. The results showed that the phytotoxic effect varied depending on the metal type and dose. Cd particularly suppressed germination at high doses (42.00% at Cd-500). Cu showed toxic effects even at low doses, with germination values varying between 50.00% and 53.00% between treatments. Ni, on the other hand, showed a stimulating effect on some parameters, such as root length (50.73 mm at Ni-100), at low and medium doses. The longest shoot length was recorded in the control group (42.40 mm), while significant reductions were observed at higher metal doses. Correlation analysis revealed positive relationships between growth parameters and a negative relationship between root dry weight and germination measurements. PCA showed that most of the variance was concentrated in the first three components, which together explained 73.4% of the total variation.

Keywords: *Brassica oleracea* var. *botrytis*, Heavy Metal Stress, PCA, *In vitro*

INTRODUCTION

Heavy metal pollution is currently regarded as one of the priority environmental problems worldwide due to its impacts on both ecosystem health and human life (Ashraf et al., 2022; Zaheer et al., 2022). Metals such as cadmium (Cd), nickel (Ni), and copper (Cu) are released into the environment from various anthropogenic sources, especially mining, industrial activities, chemical wastes, and urbanization. Over time, these metals accumulate in soil, water, and plant systems, resulting in toxic effects (Nazir et al., 2011; Zainab et al., 2021). The presence of heavy metals can adversely affect vital plant processes, including nutrient balance, gas exchange, enzyme and protein synthesis, and photosynthesis (Sanjosé et al., 2021).

The presence of heavy metals in the plant growth medium leads to pronounced adverse effects, especially on seed germination and early seedling development. In many plant species, exposure to heavy metals reduces germination percentage and germination index and prolongs the time required for germination; moreover, root and shoot elongation of seedlings is markedly slowed (Sethy and Ghosh, 2013; Sanjosé et al., 2021). In seedlings subjected to heavy metal stress, fresh and dry biomass decrease, and metabolic disturbances such as oxidative damage, membrane disruption, and impaired nutrient uptake may occur (Sethy and Ghosh, 2013). This situation severely limits the survival of plant and yield potential due to limitations in germination and seedling development (Sanjosé et al., 2021).

Cadmium, nickel, and copper are among the most frequently found heavy metal pollutants in the environment because of their extensive industrial use (Khan et al., 2022). These metals together with lead commonly cause toxic effects in plants, restricting growth, reducing yield, and imposing stress on agricultural ecosystems (Sethy and Ghosh, 2013). Their accumulation in plant tissues can cause growth retardation and problems in water and nutrient uptake, especially during germination and early development. In addition, they may induce multifaceted physiological disorders, including inhibition of photosynthesis and oxidative stress (Semane et al., 2010; Faryal et al., 2022). Among these metals, cadmium is regarded as one of the most toxic; at the cellular level, it promotes the accumulation of reactive oxygen species (ROS) and disrupts metabolic processes (Ismael et al., 2019; Saleem et al., 2022). Nickel, although required for certain plant processes at low levels, exhibits inhibitory effects at elevated concentrations, including suppression of germination, inhibition of root development, and disruption of the photosynthetic system (Georgiadou et al., 2018; Nawaz et al., 2022).

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Brassica oleracea comprises a broad group of economically and nutritionally important vegetables, including cauliflower, broccoli, and cabbage. The domestication of this group members began in the eastern Mediterranean region and extended through the periods of Ancient Greece and Roman Empire, subsequently spreading to many vegetable growing regions worldwide (Maggioni et al., 2018). Today, Asia accounts for approximately 81% of global broccoli and cauliflower production, whereas the Mediterranean Basin stands out as an important production area with an 8% share. Spain, Italy, France, and the United Kingdom are among the major producer countries (FAOSTAT, 2025).

Cauliflower is widely cultivated worldwide and has high economic value among *Brassica* vegetables, while also occupying an important place in human nutrition (Zhang et al., 2024). Due to its rich vitamin, mineral, and bioactive compound content, this species is important in terms of nutrition, and investigating environmental stress factors that can affect yield and quality is of great importance. (Ahmed and Ali, 2013; Zhang et al., 2024). In this context, examining the effects of industrial heavy metal pollution on germination and early seedling development in a widely produced species like cauliflower provides meaningful and practical data in terms of both the sustainability of agricultural production and food safety.

In this context, it is of great importance to evaluate the effects of heavy metals on plant development depending on the species and dose level. This study aims to investigate the effects of different doses (0, 100, 300 and 500 μM) of cadmium, nickel and copper in cauliflower (*Brassica oleracea* var. *botrytis*) on germination and seedling development under *in vitro* condition.

MATERIALS AND METHODS

This study was carried out in the plant tissue culture laboratory of the Agricultural Sciences and Technology Faculty of Sivas University of Science and Technology (Sivas, Türkiye). Cauliflower seeds (*Brassica oleracea* var. *botrytis* cv. Iglo) were used as the plant material. All experiments were carried out under controlled laboratory conditions *in vitro*. Prior to sowing, seeds were surface sterilized by immersing them in a 20% sodium hypochlorite solution for 15 min, followed by three rinses with sterile distilled water. The sterilized seeds were aseptically placed into petri dishes containing Murashige and Skoog (MS) (Murashige and Skoog, 1962) medium adjusting the pH to 5.8 and supplemented with different heavy metals and concentrations.

The effects of different concentrations of cadmium (Cd), nickel (Ni), and copper (Cu) were investigated. Heavy metals were mixed into the MS medium before to sterilization to obtain final concentrations of 0 (control), 100, 300, and 500 μM . Separate experimental sets were planned for each metal, and each treatment was conducted in 3 replicates, with 20 petri dishes in each replicate and 5 seeds in each petri dish. Cultures were incubated at $25 \pm 2^\circ\text{C}$ under a 16 h light / 8 h dark photoperiod.

Seed germination was monitored daily, and the following parameters were evaluated:

Germination percentage (%): seed sowing, seeds were counted Daily during one month, and those with a radicle length of 2 mm were considered germinated (International Seed Testing Association; Ertekin and Bilgen, 2021). After germination was completed, germination percentage was calculated as the ratio of germinated seeds to total seeds.

Mean germination time (days): In accordance with ISTA rules, germinated seeds were counted daily, and mean germination time was calculated using the formula developed by Ellis and Roberts (1981):

$$\text{MGT} = \sum(D \times n) / \sum n \text{ where}$$

D: Number of days counted from the start of the test

n: Number of seeds germinated on day D

Germination index: Germinated seeds were counted daily and the germination index was calculated using the formula originally proposed by J. D. Maguire (1962) (Copeland and McDonald, 2001):

$$\text{GI} = \sum(n / d)$$

n: Number of normal seedlings obtained on day d

d: Number of days from the start of the test

After germination, the following morphological traits were measured at the end of the specified growth period: shoot length (mm), root length (mm), shoot fresh weight (g), root fresh weight (g), shoot dry weight (g), and root dry weight (g) (Ertekin and Bilgen, 2021). For dry weight determination, plant samples were oven dried at 55°C until constant weight was achieved.

The data were statistically analyzed. Differences among treatments were evaluated using one way analysis of variance (ANOVA), and mean separations were performed using the LSD test. Pearson correlation analysis was used to determine relationships among variables. In addition, principal component analysis (PCA) was applied to assess the multivariate data structure, and results were visualized using biplot and scree plot graphs. All analyses were performed using JMP 8.0.1.

RESULTS

In the cauliflower cv. Iglo used in this study, the effects of different industrial heavy metals (Cd, Ni, and Cu) and their doses on germination and seedling development parameters were evaluated. According to the analysis of variance results, treatment effects were statistically highly significant for all measured traits ($p < 0.001$) (Table 1).

When germination parameters were evaluated, the effects of heavy metal concentrations on germination percentage (%), germination index, and mean germination time were statistically significant (Table 1). Germination percentage reached its highest value with 90% at 100 μM cadmium (Cd-100), which was significantly higher than the control (61.11%). This result should not be considered as evidence of a beneficial effect of Cd, but rather as a possible low-dose adaptive response, potentially related to transient metabolic stimulation and/or biological variation among seeds. Nevertheless, the substantially reduced germination index under the same treatment clearly indicates that the germination process was negatively affected. Since germination percentage and germination index describe different dimensions of seed behavior, these findings suggest that Cd-100 did not improve germination performance in a physiological sense. Instead, although a relatively high proportion of seeds ultimately germinated, the reduced germination index points to delayed and less vigorous germination, indicating that physiological stress was still present. However, at 300 μM and 500 μM Cd, germination percentage declined to 60.00% and 42.00%, respectively (lower than the control group) which shows that Cd suppresses germination at high concentrations.

Similarly, nickel affected germination. Relatively high germination percentages were recorded at 100 μM Ni (68.00%) and 300 μM Ni (76.67%). These data show that low and moderate levels of Ni exposure do not have a suppressive effect on germination in cauliflower seeds; in fact, at moderate doses, it may even have a stimulating effect. On the other hand, at a dose of 500 μM Ni, germination decreased to 62.00%, remaining close to the control value, suggesting that high dose toxicity may be limiting on germination.

Copper applications showed more negative results in terms of germination compared to other metals. At all Cu doses, the germination percentage was between 53.00% and 50.00%, these values were below the control group. The lowest germination was recorded at 50.00% with the 500 μM Cu application. This indicates that copper has a toxic effect on seeds at high concentrations.

When the average germination time data were evaluated, the shortest germination time was observed in the Cd-100 group with 1.33 days. This time is significantly shorter than the control group (1.93 days) and indicates that Cd can accelerate germination at low doses. On the other hand, the longest average germination time values were determined in the Cu-100 (2.18 days) and Ni-300 (2.15 days) groups. These data show that high doses delay germination and slow down metabolic processes. The highest value in terms of germination index was recorded in the control group (65.65), and all heavy metal applications were significantly below this value. The lowest values in this parameter were found in the Cd-300 (18.61) and Cd-100 (19.23) groups. These findings show that although Cd increases the germination percentage at low doses, it suppresses the germination index, thus creating physiological stress. The longest shoot (42.40 mm) and root (34.50 mm) values were recorded in the control group. All heavy metal applications showed a statistically significant decrease in these values. In Cd applications, shoot length decreased with dose; especially at 500 μM Cd, this value dropped to 21.31 mm. Similarly, root length reached its lowest level at 9.80 mm. This shows that Cd significantly inhibits morphological development by suppressing cell division and elongation at high doses. It was determined that shoot lengths were higher in nickel applications compared to Cd and Cu groups. Especially at Ni-100 (35.50 mm) and Ni-300 (29.60 mm) doses, these parameters remained significantly higher than in Cd-300 and Cd-500 groups. The root length in the Ni-100 group (50.73 mm) was the highest among all groups. This result suggests that nickel may have a root development-promoting effect at low doses. In copper applications, a decrease in root and shoot lengths was observed with increasing dose. The lowest shoot and root lengths were recorded in the Cu-500 application (20.10 mm and 10.00 mm). These values were 53% and 71% lower than the control group, respectively. This clearly shows the growth-suppressing effect of copper at high doses.

The highest fresh shoot weight was measured at 0.085 g in the Cu-100 dose group, while the lowest value was 0.017 g in the Ni-500 group. The higher fresh weight in the Cu-100 group suggests that Cu may temporarily increase metabolic activity at low doses. Regarding root fresh weight, the maximum value of 0.035 g was recorded in the Cd-300 group. When dry weight data were evaluated, the highest values in terms of shoot dry weight were obtained from the Cu-100 (0.0072 g) and Ni-100 (0.0066 g) groups. In terms of root dry weight, the highest values were recorded in the Cd-300 (0.0030 g) and Cu-300 (0.0021 g) groups. These results show that tissue density can be preserved in some parameters depending on the metal types and doses; however, in general, all metal applications significantly reduce dry matter accumulation. A screen plot was created to evaluate the explained variance ratios and cumulative contributions of the PCA components (Figure 1). Examining the graph, the first principal component (PC1) explains 38.9% of the variance, and the second component (PC2) explains 19.5%. Together, the first two components explain 58.4% of the total variance, with a large portion of the data clustered around these two components. With the contribution of the third component (PC3), the total explained variance increases to 73.4%. This indicates that a significant portion of the relationships between variables can be represented by the first three components. Adding the fourth component explains 83.4% of the variance, exceeding the 80% threshold generally accepted in multivariate analyses. These results demonstrate that PCA is effective in reducing data dimensionality and highlighting fundamental sources of variation, and that biplot analysis allows for meaningful interpretations. PCA biplot analysis was performed to visualize the multivariate relationships between germination and seedling development parameters (Figure 1). The direction and length of the vectors in the biplot reflect the contribution level of each parameter to the components and

its relationship with other variables. Parameters such as 'shoot length', 'root length', and 'shoot fresh weight' grouped along the PC1 axis, indicating that this component represents the variance associated with growth. 'Root dry weight' and 'root fresh weight' are more prominently located along the PC2 axis, suggesting that this component is related to water retention and root biomass accumulation. On the other hand, 'mean germination time' and 'germination index' are located in opposite regions of the component plane, revealing that these two parameters represent different stress responses. These findings indicate that developmental responses to heavy metal stress in cauliflower plants are shaped in different physiological dimensions.

Table 1. Effects of different heavy metals and concentrations on germination, morphological, and biomass parameters in cauliflower

Dose	Germination percentage (%)	Mean germination time (day)	Germination index	Shoot length (mm)	Root length (mm)	Shoot fresh (g)	Root fresh (g)	Shoot dry (g)	Root dry (g)
Control	61.11de	1.93cd	65.65a	42.40a	34.50b	0.073b	0.008ef	0.0058bc	0.0010d
Cd-100	90.00a	1.33g	19.23e	38.10b	22.70cd	0.063bc	0.017cd	0.0062ab	0.0009d
Cd-300	60.00e	1.81de	18.61e	30.20cd	26.30c	0.049de	0.035a	0.0059bc	0.0030a
Cd-500	42.00h	2.03bc	14.71f	21.31e	9.80e	0.0435g	0.02c	0.0050cd	0.0019bc
Ni-100	68.00c	1.52f	29.02b	35.50b	50.73a	0.071b	0.027ab	0.0066ab	0.0014cd
Ni-300	76.67b	2.15ab	25.56c	29.60cd	32.60b	0.058cd	0.023bc	0.0042d	0.0017d
Ni-500	62.00d	2.03bc	21.11d	16.50f	12.80e	0.017h	0.007f	0.0061b	0.0011d
Cu-100	53.00f	2.18a	18.40e	31.70c	34.00b	0.085a	0.016cde	0.0072a	0.0014cd
Cu-300	52.00f	2.08ab	18.73e	26.87d	19.98d	0.046ef	0.023bc	0.0057bc	0.0021b
Cu-500	50.00g	2.03bc	19.70de	20.10e	10.00e	0.035g	0.010def	0.0049cd	0.0018bc
LSD	1.97***	0.14***	1.48***	3.38***	4.65***	0.01***	0.008***	0.001***	0.0005***

(1) Differences between averages showed by different letters are statistically important

(2) *** $p < 0.001$

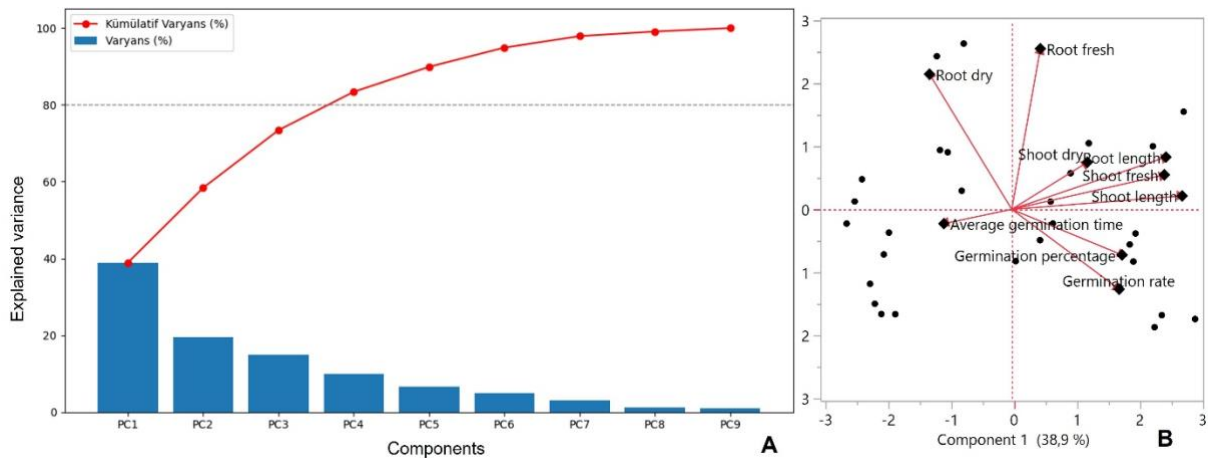


Figure 1. Principal Component Analysis (A Scree Plot + Cumulative Variance, B PCA Biplot)

This study has evaluated the effects of heavy metal applications on germination and seedling development in cauliflower. The relationships between measured morphological and physiological parameters were evaluated using correlation analysis. This analysis reveals which characteristics change together and which parameters are more strongly linked to growth processes. The correlation analysis provided a holistic assessment of plant responses to heavy metal stress (Figure 2). Correlation analysis revealed a significant negative correlation between germination percentage and average germination time ($r = -0.4477$, $p = 0.0131$). This indicates that seeds with a high germination rate germinate in a shorter time. Therefore, seeds that germinate quickly have a higher overall success rate. This is an important indicator of germination capacity under stress. A significant positive correlation was found between germination percentage and shoot length ($r = 0.4902$, $p = 0.0060$). This suggests that seeds with good germination also exhibit stronger shoot development. This relationship between germination performance and early seedling development is important for agricultural success. A high and significant positive correlation exists between shoot length and root length ($r = 0.7040$, $p < 0.0001$). This indicates that shoot development progresses in conjunction with root development, with both parts growing in parallel. A statistically significant positive correlation was also found between shoot dry weight and root length ($r = 0.3956$, $p = 0.0305$). This suggests that

root system development is directly linked to overall plant growth. A significant positive correlation was found between root fresh weight and root length ($r = 0.3667$, $p = 0.0462$). This indicates that root development is parallel to water-holding capacity and fresh tissue development. A strong negative correlation was found between root dry weight and germination percentage ($r = -0.5423$, $p = 0.0020$). Root dry matter accumulation was lower in groups with a high germination rate. This suggests that under some stress conditions, rapid germination may be inversely proportional to the accumulation of permanent biomass in root tissues. The negative and significant correlation between root dry weight and germination index supports the idea that dry matter accumulation in roots remains limited in rapidly developing individuals ($r = -0.3852$, $p = 0.0355$).

In conclusion, this study comprehensively evaluated the effects of Cd, Cu, and Ni on germination and seedling development; it was confirmed that Cd is the most toxic metal, Cu is moderately toxic but can cause similar damage to Cd under certain conditions, and Ni has beneficial effects at low doses but harmful effects at high doses. Root development and seedling biomass were found to be the most sensitive physiological indicators, while seed germination rate was observed to be more tolerant to heavy metal stress. These findings highlight the importance of monitoring root/seedling development parameters in the early detection of heavy metal pollution in agricultural production and reveal that the phytotoxic effects of different metals may vary depending on the species.

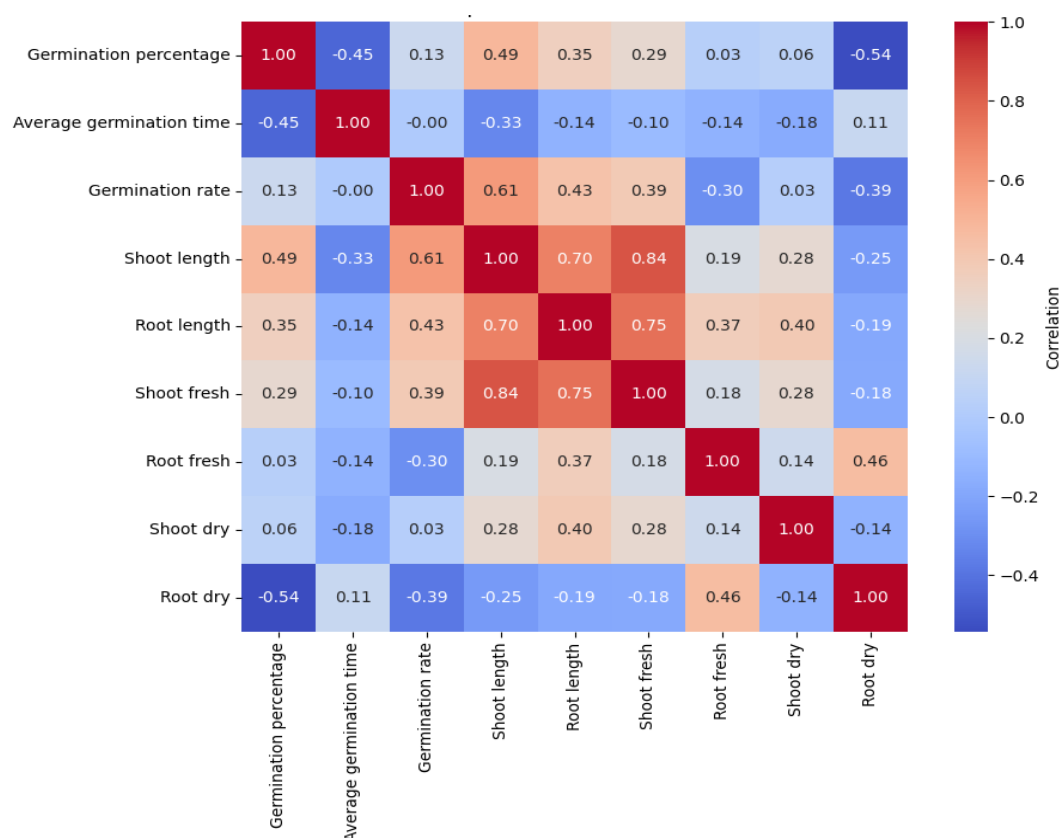


Figure 2. Correlation heatmap of germination and growth parameters

DISCUSSION

The effects of different doses of Cd, Ni, and Cu applications on the germination and seedling development of cauliflower seeds were evaluated, and significant differences in toxicity were observed among the metals. Overall, our results show that Cd is the most toxic metal, Cu has moderate toxicity but can have equally negative effects as Cd in some cases, and Ni shows a stimulating effect at low doses but becomes toxic at high doses. The literature also reports that heavy metals cause metabolic and structural damage in plants, disrupting development from the early stages of the life cycle (Kichchou et al., 2025). Seed germination and seedling development are the most sensitive periods for plants and are considered particularly susceptible to metal pollution (Muszyńska and Labudda, 2019; Kichchou et al., 2025). Our findings support the general consensus that Cd is one of the most toxic heavy metals for plants (Riyazuddin et al., 2021). Cd is an element not needed by plants and can have toxic effects even at very low doses (Kiran and Sharma, 2022; Shahid et al., 2024; Kichchou et al., 2025). Indeed, there are numerous studies in the literature reporting that Cd exposure strongly suppresses seed germination and seedling development (Liu et al., 2021; Khanna et al., 2022; Shahid et al., 2024). For example, a study on chia (*Salvia hispanica*) seeds found that Cd application inhibited root and shoot elongation by up to 76%. Furthermore, the same study reported that cadmium significantly reduced both fresh and dry biomass, while the total germination rate remained close to the control level (Kichchou et al., 2025). This indicates that Cd strongly inhibits the morphological development of seedlings,

but may not completely prevent the germination capacity of seeds initially. In different studies, cadmium at concentrations of 400 and 500 μM was found to limit root development in cucumber (Baran et al., 2022) and sorghum (Sevim et al., 2022). Similarly, Acila et al. (2024) reported that when 100-200 μM Cd was applied to squash (*Cucurbita pepo*) seeds, there was no significant change in germination percentage, but significant decreases were observed in embryo axis length and dry weight. The high toxicity of Cd is attributed to the fact that its ion causes irreversible damage to plant tissues and has no beneficial role (Kiran and Sharma, 2022). Furthermore, a study by Kara et al. (2022a) reported a decrease in pepper seed development as the amount of cadmium in the medium increased. They found that seed germination was highest in the control group, in a medium with a dose of at least 500 μM . Another study on sorghum reported that increasing cadmium concentrations did not significantly affect germination rate (Ertekin et al., 2020). Our findings also showed significant decreases in seed germination rate, root and shoot length, and biomass at high Cd doses (300, 500 μM). Ma et al. (2022) found that the tolerance of *B. oleracea* to Cd stress varied depending on genotypes and Cd dose. The greatest reduction in growth parameters and germination characteristics was observed at the highest Cd dose (20 μM). The same study reported strong positive correlations among the parameters examined, indicating that Cd stress had a significant effect on the growth and physiology of all *B. oleracea* varieties.

Although copper (Cd) is an essential micronutrient for plants and can be relatively tolerable or usable in plant metabolism in low amounts, it exhibits serious toxic effects at high concentrations (Kichchou et al., 2025). While our study showed that Cu had a lower toxicity effect compared to Cd, the literature emphasizes that copper can be at least as inhibitory as Cd in some species. For example, some studies comparing plant responses to heavy metal exposure have shown that growth retardation caused by Cu at equivalent concentrations can be more severe than that caused by Cd (Acila et al., 2024). Therefore, the toxicity effect of Cu can vary depending on the conditions and species, and in some cases, it can restrict growth at levels close to Cd. Baktemur (2023) reported that leaf number, leaf and stem lengths were more tolerant to increasing Cu doses, while root number and length were sensitive. It was found that root development did not occur at doses of 300 μM and above.

Ni has shown different effects compared to other metals. It has been observed that growth is partially stimulated at low Ni doses, while it is suppressed at high doses. This is consistent with the hormetic effect described in the literature for Ni. Ni is an essential element in trace amounts for many plants; at low doses it promotes seed germination and seedling development, while it becomes toxic as the dose increases (Shweti and Verma, 2018; Kara et al., 2022b; Wang et al., 2024). In a study conducted on fava beans (*Vigna unguiculata*) by Bharti and Ahrodia (2023), it was reported that Ni, Cu, and Zn increased germination and seedling growth at low concentrations, while Cd and Pb showed inhibitory effects even at the lowest dose. In the same study, it was clearly shown that significant decreases occurred in growth parameters with increasing Ni concentration, meaning that the beneficial effect of Ni at low doses turned into toxicity at high doses. Similarly, Shweti and Verma (2018) reported that Ni application at a level of 5 mg/L in wheat seeds did not harm germination and seedling development, but higher doses significantly reduced root and shoot elongation in particular. High Ni doses delay germination and inhibit seedling growth by suppressing seed enzyme activities and disrupting cell metabolism (Sethy and Ghosh, 2013). A comparable dose dependent growth inhibition has also been reported for cobalt *in vitro*, where increasing Co concentrations significantly constrained early plant development (Bekiş Hasdeniz et al., 2025).

When evaluating the response of plants to different doses of heavy metals, the sensitivity of the measured parameters is of great importance. In our study, root length and seedling biomass were identified as the most sensitive indicators to metal stress. Especially, root development reacted immediately to increasing metal concentrations and significantly declined. In contrast, seed germination percentage was a relatively more resistant parameter and was largely preserved at low and moderate levels of metal stress. The literature also states that heavy metal toxicity primarily affects root and young seedling growth, and that germination rate generally decreases significantly at higher doses or longer exposure times (Al-Qurainy et al., 2017; Baktemur, 2023; Acila et al., 2024; Kichchou et al., 2025). For example, in the previously mentioned chia study, while the total germination rate remained at the control level in Cu and Cd applications, the radicle and hypocotyl elongation decreased by more than 50%, and the fresh/dry weights of the seedlings also decreased (Kichchou et al., 2025). Similarly, in a study carried out on squash seeds, it was shown that Cd and Cu did not affect the germination percentage after 8 days of germination, but significantly reduced the seed vigor index and embryonic axis length (Acila et al., 2024). These findings reveal that parameters such as root development and seedling biomass are more sensitive as early warning indicators, while the seed emergence value is affected later by heavy metal stress.

Our results are largely consistent with studies conducted on different plant species in recent years. Many studies report that the toxicity ranking of heavy metals is $\text{Cd} > \text{Cu} > \text{Ni}$, and that the most sensitive growth indicators are biomass measures such as root elongation and dry/fresh weight. However, there are also examples in the literature showing that metal toxicity can vary depending on the plant species and experimental conditions. For example, in a study conducted by Parera et al. (2023) on two plant species native to the Andes Mountains, it was found that Ni and As were the metals that most reduced germination percentage, while the application of similar concentrations of Cd did not significantly affect germination in these species. In the same study, it was emphasized that early seedling development is more sensitive than germination, meaning that even at low levels, heavy metals can have a strong inhibitory effect on seedling height and weight. These different results show that heavy metal tolerance can vary depending on the plant species, the structural characteristics of the seed, and the type and dose of metal applied.

CONCLUSION

This study investigated the effects of industrially sourced heavy metals, cadmium, nickel, and copper, on the germination and early seedling development of cauliflower. Experiments conducted under *in vitro* conditions revealed that all heavy metals caused varying degrees of physiological and morphological impairment in plant development. While Cd increased germination percentage at low doses, it suppressed the germination index and seedling development. High doses showed the most significant phytotoxic effects (significant reductions in all parameters in the Cd-500 group). Ni was found to be less toxic at low and medium doses, particularly in terms of root development and dry weight, suggesting that it may exhibit stimulating effects at certain doses. Cu generally suppressed germination and seedling development at all doses; however, unexpected positive effects (high fresh and dry shoot weight) were observed in some parameters in the Cu-100 group. The study concluded that cadmium was the most toxic metal at high doses, while nickel remained within tolerance limits at certain doses; and copper suppressed growth parameters even at lower doses. These findings provide important scientific data for understanding the effects of different metal types on plant growth and determining tolerance levels.

Conflict of interest

The author state there is no competing interest.

Author contribution

Ecem Kara: The author solely conceived, designed, and conducted the study, analyzed the data, and wrote the manuscript.

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